

Three-Dimensional Geologic Mapping for Groundwater Applications

Workshop Extended Abstracts

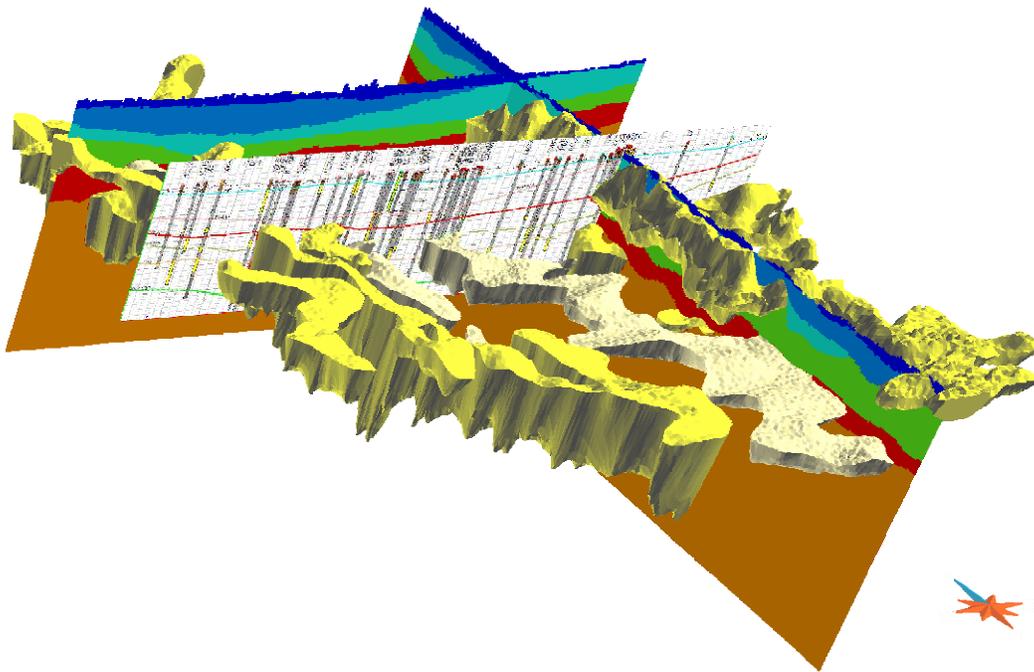
Salt Lake City, Utah – 15 October 2005

Convenors:

Hazen Russell, Geological Survey of Canada

Richard C. Berg, Illinois State Geological Survey

L. Harvey Thorleifson, Minnesota Geological Survey



2005 Annual Meeting
Geological Society of America
Salt Lake City, Utah

GEOLOGICAL SURVEY OF CANADA

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**Geological Society of America Annual Meeting
October 15, 2005 - Salt Lake City, Utah**

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PRESENTATION SCHEDULE

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08:30	Sharpe	Geological Frameworks In Support Of Source Water Protection In Ontario
08:50	Keefer	Estimating the Uncertainty of 3D Geologic Maps
09:10	Pullan	The Role Of Geophysics In 3D Mapping
09:30	Moran	Using Groundwater Age And Other Isotopic Signatures To Delineate Groundwater Flow And Stratification
09:50		<i>Discussion</i>
10:00		BREAK and Poster Viewing
10:20	Weissmann	Application Of Transition Probability Geostatistics In A Detailed Stratigraphic Framework
10:40	McGaughey	Advances In 3D Earth Modelling
11:00	Wexler	Regional Groundwater Flow Modeling In The Oak Ridges Moraine Area: Building On The 3D Geologic Model
11:20	Shafer	Incorporation Of Groundwater Flow Into Traditional Sensitivity Analysis Of A Southeast Coastal Plain Layered Aquifer System
11:40		<i>Discussion</i>
12:00		LUNCH
12:40	Keller	3D Geological Model Of The Red River Valley, Central North America
13:00	Kessler	3D Geoscience Models And Their Delivery To Customers
13:20	Bolduc	A 3D Esker Geomodel For Groundwater Research: The Case Of The Saint-Mathieu – Berry Esker, Abitibi, Québec, Canada
13:40	Bajc	3D Modelling Of Quaternary Deposits In Waterloo Region, Ontario; A Case Study Using Datamine Studio Software®
14:00	Malolepszy	Three-Dimensional Geological Model Of Poland And Its Application To Geothermal Resource Assessment
14:20		<i>Discussion</i>
14:35		BREAK and Poster Viewing
15:10	Parks	Lowering Barriers To Public Communication With 3D Groundwater Mapping At Alberta Geological Survey: Examples From Canada's Oil Sands Areas
15:30	Troost	Cost Of 1:12,000-Scale Geologic Map, \$500,000; Cost Of 3D Data, Priceless
15:50	Artimo	The Role Of 3D Geologic Modeling And Database Solutions In The Virttaankangas Artificial Recharge Project, Southwestern Finland
16:20	Berg	Toward A Goal Of A "Super" Three-Dimensional Geological Map
16:40		<i>Discussion</i>
17:00		Poster Viewing

POSTER PRESENTATIONS

First Author	Title
Dey	Three-Dimensional Geologic Mapping Of Groundwater Resources In Kane County, Illinois
Dickson	An Example Of IGS Glacial-Terrain Mapping: Exploration Of Deep Quaternary Valley-Fill Sequences In Central Indiana
Kessler	Thames Gateway Project
MacCormack	Making The Most Of What You've Got: Creating 3D Subsurface Models With Data Of Varying Quality
Ross	From Geological To Groundwater Flow Models: An Example Of Inter-Operability For Semi-Regular Grids
Russell	Sediment Architecture And Composition Of The Waterloo Moraine, Southern Ontario: Emerging Insights
Stiff	Aquifer Maps For County Planners In Lake County, Illinois: Three-Dimensional Geologic Mapping, And Aquifer Sensitivity Classification For The Antioch Quadrangle.
Stumpf	How Much Data Is Enough? Detailed Geologic Mapping Near A Superfund Site, Wauconda, Illinois
Taylor	Using Borehole Data And Three-Dimensional Models To Map The Ground-Water System In The Amargosa Desert Basin, Nevada And California
Thorleifson	3D Geological Modeling In Support Of Ground Water Inventory In The Fargo-Moorhead Region, Minnesota And North Dakota

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The help of Geological Society of America staff in facilitating the workshop is much appreciated. The assistance of Ms. E. Collis was particularly helpful to the successful completion of the workshop.

The presenters and respective funding agencies are thanked for making this workshop possible

INTRODUCTION - THREE-DIMENSIONAL GEOLOGICAL MAPPING FOR GROUNDWATER APPLICATIONS

Russell, H.¹, L.H. Thorleifson², and R.C. Berg³

¹Geological Survey of Canada; ² Minnesota Geological Survey; ³ Illinois State Geological Survey

This workshop is the fourth in an ongoing series discussing three-dimensional (3D) geological mapping for groundwater applications. A central theme of the workshops has been development of techniques for reconciling disparate archival and high quality data sets to produce 3D stratigraphic and hydrostratigraphic models. Reflecting this objective, attendance at the workshops has been predominantly government survey staff (e.g., state, provincial, federal) involved in geological mapping of surface and subsurface glacial sediment. In an attempt to breach the divide between application (government surveys) and research (universities), each workshop has included a number of academic researchers. Attendance has been predominantly from the northern American states and central Canada. Successive workshops, however, have had an increase in participation by Europeans (Finland, Great Britain, The Netherlands, Poland).

This workshop signals a change in timing, and perhaps an opportunity for reflection on the value of these workshops. The past workshops have been on an 18-month schedule alternating between a GSA Annual Meeting (Thorleifson and Berg, 2002) and either a GSA Annual Sectional Meeting (Berg and Thorleifson, 2001) or Geological Association of Canada Annual Meeting (Berg et al., 2004). This meeting is the first to be part of the formal GSA Annual Meeting program. Following this workshop, it is planned to continue on a less frequent basis, possibly a two-year interval.

REFLECTIONS ON WORKSHOP CONTENT

The focus of these workshops has been on 3D geological mapping and this is reflected in the content for the four workshops (Table 1). Studies focused on the generation of 3D models have dominated the workshop proceedings. Most of this work has been on the development of stratigraphic – hydrostratigraphic models. Proportionally fewer studies have emphasized the population of model volumes with physical parameter data. Talks under the heading of basin analysis have discussed the issue of data collection using geophysics,

hydrochemistry, sedimentology, and the role of conceptual models. In an attempt to maintain connection with the needs of the groundwater community, there has been a number of groundwater modeling presentations. Communication of the results of geological mapping must be conveyed beyond the technical level. The point has been made forcefully in the past, that it is necessary to make this work relevant and understandable to the general public. This significant task should not be trivialized if we expect to receive continued funding for mapping activity.

CURRENT WORKSHOP

The majority of talks in this workshop (16) discuss various aspects of 3D model development. Models being discussed span four orders of magnitude in scale from site-specific studies of 10's km² to national or state and provincial scales covering areas of 100,000 km². Similarly the depth of interest ranges from 10's metres to 1000's metres as both glacial and bedrock units are integrated into seamless models. A number of European nations have embraced 3D basin modeling at nested scales from national to watershed (Artimo et al., Gunnink, Kessler, and Malolepszy; citations with no date are in this vol). In North America, a number of states and provinces are developing models at scales of > 10,000 km² (Keeler et al., Thorleifson et al.). Models of an order of magnitude smaller are being developed to fill the demands of municipal and county governments (Bajc and Newton, Dey et al., Dickson et al., Stiff et al., Wexler & Kassenaar) and other jurisdictions (Taylor & Sweetkind). Individual geological settings are also being modelled, in this example, an esker of significant municipal groundwater supply (Buldoc et al.). At the

Table 1. Summary of content of successive workshops

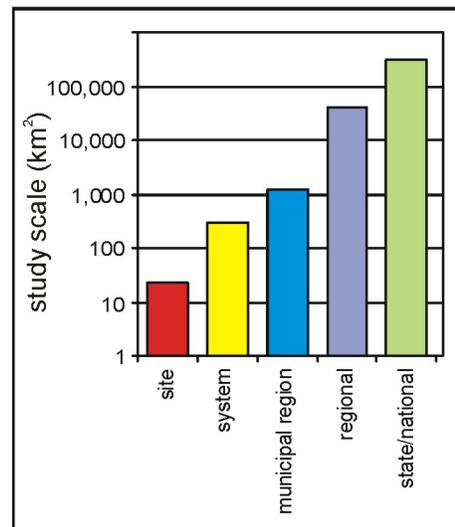
	2001	2002	2004	2005
3-D models	10	8	11	14
Basin Analysis	2	6	5	4
Data models	2	1	2	1
Groundwater	2	4	3	1
Communications	1	2	3	3
Geostatistics	1	2	0	2
GIS technique	0	2	0	2
Miscellaneous	2	0	0	0
Total	20	25	24	27

scale of most groundwater modeling, site contaminate mitigation, two talks discuss geological model development as it relates to contamination issues (Schafer, Stumpf).

In a series of more technique orientated presentations McGaughey overviews 3D modeling issues including transformation between 3D vector (wireframe) and raster (grid) models. He also examines the capability to manage a large number of spatial variables including continuous (e.g. porosity) and categorical (e.g. facies) types, and the modeling of uncertainty. The issue of uncertainty is picked up by Weissmann who highlights a geostatistical approach to modeling an alluvial fan setting using a sequence stratigraphic framework. The issue of grid transformations is also covered in a poster presentation by Ross et al. who illustrate the conflicting grid structures that can occur between geological and flow modeling software. Issues of data structures and data quality are discussed by MacCormack et al..

Under the banner of basin analysis a number of talks address issues of data collection, understanding of fluid flow, stratal architecture, and conceptual models (Pugin, Moran & Hudson, Russell et al., Sharpe & Russell). Rounding out the program are talks on public outreach, one detailing the development of a web based viewing tool (Berg & Sollar), and a second the experience of the Alberta Geological Survey (Parks and Andriashek).

Figure 1. Illustration of scale of models presented in this workshop.



COMMUNICATIONS

The past year has seen enormous developments in the promotion of geographic data through online programs such as Goggle Earth. In a similar vein, the British Geological Survey's national Lithoframe model (Kessler) and The Netherlands 3D modeling program (Gunnink) , illustrate approaches for 3D geological mapping on national scales. Google Earth, and perhaps examples of large scale 3D models will hopefully capture the imagination of viewers and serve valuable public outreach purposes. As highlighted at the third meeting, by Jackson (2004) of the British Geological Survey, an important aspect of national (state, provincial) geological surveys is serving public need. One aspect of this is demonstrating the relevance of geological mapping, whether it is 2D or 3D. To this objective Troost & Booth provide an interesting perspective on the economic cost and value of geological mapping

SUMMARY

The issues of conflicting land use that currently stimulates interest in 3D models for groundwater studies will continue to be a significant issue. Often in jurisdictions with abundant water, the resource is not equally distributed or accessible. Furthermore, dwindling aggregate resources, increasing practice of industrial agriculture, and the demand for alternative energy supplies (geothermal, coal bed methane, heavy oil), will ensure that groundwater issues remain a central theme of western countries. Geologists need to embrace other disciplines (geostatistics, hydrochemistry, hydrogeology) as they attempt to move beyond first order stratigraphic models to more complete models of the basin subsurface. It is evident that geologists have responded to a criticism of Anderson (1989). Through the development of GIS based digital geological models geologists are becoming better positioned to support hydrogeological flow modeling exercises.

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THE ROLE OF 3D GEOLOGIC MODELING AND DATABASE SOLUTIONS IN THE VIRTAAKANGAS ARTIFICIAL RECHARGE PROJECT, SOUTHWESTERN FINLAND

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The artificial recharge project of the Virttaankangas Aquifer was launched to provide the 285,000 inhabitants of the Turku area in southwestern Finland with good quality potable water by the end of this decade. The total budget of this project will be about 100 million euros. Pre-treated river water from the River Kokemäenjoki (Figure 1) will be led through a pipeline to the Virttaankangas Aquifer for infiltration. The residence time of the water in the aquifer should be at least 3 months to ensure that natural purification can occur. After sufficient time of flow, the water will be pumped from the aquifer to the Turku region for consumption.

The planning and building of the 100 km pipeline and affiliated construction constitute the largest items of expenditure in the water supply project. However, the research and geological understanding of the Virttaankangas Aquifer will be the decisive factors for its success.



Figure 1. A view over the River Kokemäenjoki at the site of the planned water intake channel.

Artificial recharge (Figure 2) is a process that requires control and understanding of various fields of geology including, hydrogeology, sedimentology, geochemistry, and geophysics. Commonly, the studies conducted in one of these fields of geology do not significantly overlap with the other fields, which has been the case in previous

investigations for the Virttaankangas area. Therefore, a tailor-made database was required to assemble all of the available data into a commensurable form. This allows the users of the database to analyze and compare data from different sources simultaneously.

The described approach to integrate and control the data became essential when the first 3D geologic modeling study was conducted. The 3D model data was not unambiguously integrated with other data, and the updating of the model ended up being a time-consuming task. Therefore, to overcome these difficulties, both the database and the 3D model were designed to be constantly evolving. The current database is either automatically or manually updated with field data from several sources. The automated tasks include, for example, hydraulic head measurements, raw water quality data from the River Kokemäenjoki, air and water temperature data, rainfall information, and soil moisture content data.

All of the new data affecting the extent and structure of the hydrogeological units will be first interpreted by a geologist and then added into the database. This information is processed with the help of tailor-made macros that link the database with other programs. For example, these macros can create internally consistent hydrogeological units for 3D modeling and create slices of the 3D model at a given z-surface. The 3D model units are then used to produce the 3D architecture of the Virttaankangas groundwater flow model. In addition, the macros can be used to produce animations of the hydraulic head changes during pump and infiltration tests.



Figure 2. Testing of an infiltration area by the sprinkling method, July 2005. The location of the infiltration area was determined on the basis of the drilling data, 3D geological model, and ground penetrating radar data. Presently, only natural groundwater from the Virttaankangas Aquifer is used in the infiltration tests.

The nature of the 3D geologic modeling effort has changed during the course of the Virttaankangas artificial recharge project; the model has become a dynamic, constantly updating part of a larger research entity. The 3D model not only consists of the data obtained from the sedimentological studies, drill hole logs, and geophysical studies, but is also closely connected with hydrogeological and geochemical data.

The 3D model has become an important tool for planning and building of the facilities connected with the artificial recharge. For example, the 3D model has been used for finding suitable locations for water intake wells and infiltration areas (Figure 3). Therefore, the database solutions and modeling tools are not only serving the needs of scientific research, but also contributing to the progress of the artificial recharge project in its present stage, and later on, during the actual groundwater production phase.



Figure 3. Building of the new water supply well, March 2005. The location of the well was determined on the basis of the data obtained from the 3D geological model, and verified with some new drilling data. The well has a stainless steel casing and the screen consists of a slotted PVC pipe. The depth of the well is 26 meters and the diameter of the screen is 500 mm. The measured yield of this well is 7500 m³/d (265,000 ft³/d).

* Sami Saraperä's work has been funded by the Maj and Tor Nessling Foundation.

3D MODELLING OF QUATERNARY DEPOSITS IN WATERLOO REGION, ONTARIO; A CASE STUDY USING DATAMINE STUDIO SOFTWARE®

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INTRODUCTION

With the recent release of draft legislation on the development and approval of watershed-based source protection plans, the Government of Ontario is implementing one of the key recommendations of the O'Connor Report; a document stemming from the Walkerton Inquiry (O'Connor 2002). It is becoming increasingly clear that geological input will be an important requirement for the successful development and implementation of source protection plans for all regions of the province. To this end, the Ontario Geological Survey has embarked on a new program designed to provide basic geoscience information for the protection and preservation of the provincial groundwater resource.

A pilot project of three-dimensional mapping of Quaternary deposits within Waterloo Region was initiated in 2002 as part of this geoscience initiative. The objectives of this project were to develop protocols for the construction of interactive 3D models of Quaternary geology and derived products that could: 1) aid in studies involving groundwater extraction, protection and remediation; 2) assist with the development of policies surrounding land use and nutrient management; and 3) help to better understand the interaction between ground and surface waters. Waterloo Region was one of two areas chosen for this pilot project as it is one of the largest municipal users of groundwater in Canada; relying almost exclusively on bedrock and overburden aquifers for their potable water supply. Waterloo Region also has a population which is projected to increase by an estimated 20% in the next decade. This dramatic increase will undoubtedly apply pressure to an already stressed groundwater resource. A better understanding of the geometry and inherent properties of the Quaternary sediments that overlie the bedrock surface within the region will assist with the development of source water protection plans and with the development of a geoscience-based management plan for the groundwater resource.

Summaries of Quaternary geology, data compilation and standardization and new programs of data acquisition are contained in the extended abstracts of the last two 3-dimensional mapping workshops (Bajc 2002 and Bajc et al., 2004) as well as in a guidebook of a Geological Association of Canada fieldtrip which was run in conjunction with the last workshop (Bajc and Karrow 2004).

THE DATABASE AND CONCEPTUAL GEOLOGICAL MODEL

Our working copy of the subsurface database for Waterloo Region; an area of just under 1400 square kilometers, contains approximately 26 000 records and nearly 73 000 sediment units. Nearly 20% of the borings are classed as "definitive" which means they were logged by a trained geoscientist. These definitive boreholes consist of monitoring wells, engineering testholes, large, natural and man-made exposures and cored boreholes. We currently have approximately 110 cored boreholes within the region, thirteen of which were completed as part of this project. These "golden spikes" are an invaluable source of stratigraphic information and are essential for the development and verification of the conceptual geological model. In addition, approximately 450 geophysically interpreted borehole logs, 17.5 kilometres of seismic reflection data and 16 kilometres of ground penetrating radar served to assist with the interpretation.

The conceptual geological model developed for the Region of Waterloo consists of an aquifer/aquitard sequence with 19 layers. Many of these layers have limited aerial extent, their outer edges defined by the limits of ice advance, the elevation of meltwater channels and other paleotopographic control. Our approach involved extensive subdivision of the Quaternary sequence bearing in mind that units could be merged subsequently if data quality prevented their full definition from a regional perspective. The time-transgressive nature of some of these units proved difficult to model in 3-dimensions. For example, an ice advance/retreat sequence will result in the deposition of a layer of till out to a given ice margin. Beyond the ice margin there is continuous deposition of glaciofluvial/glaciolacustrine sediment whereas inside the ice margin the stratified deposits are subdivided into an upper and lower sequence separated by a layer of till. It is difficult to subdivide the stratified deposits beyond the ice margin into a similar upper and lower sequence as data quality generally prevents this. Similar bifurcating sequences occur in till units along the eastern and western edges of the region. In the east, a single layer of Port Stanley Till

may correlate and span the same time interval as 3 layers of till in the central parts of the region (eg. Catfish Creek, Maryhill and Port Stanley tills). Diachronic subdivision of Port Stanley Till along the eastern margin of the region was not attempted. Rather, a lithostratigraphic approach was chosen whereby Port Stanley Till was classified as a single unit.

INTERPRETATION

Two tables were created during the assembly of the subsurface database. These include a "Location" table which contains information about the borehole such as its original identification, source, location (X,Y,Z) and type of hole, and a "Formation" table which contains descriptive information regarding the sediment layers present in each borehole. Included in the "Formation" table was a "Formation" field where we could input a stratigraphic interpretation of the layer described (eg. Port Stanley Till, Catfish Creek Till, Canning Till....). This interpretation was generally available for cored boreholes and from logs of surface exposures described as part of Quaternary mapping programs and other field investigations. The tops of units with "Formation" identifiers were later translated to the aquifer/aquitard scheme and exported to a "Picks" table containing "X,Y,Z" and "STRATUM" attributes. "Bedrock" and "DeepOB" picks were also included in this table. "DeepOB" picks were determined by interpolating a "Bedrock" surface in ArcInfo® software using "Bedrock" picks only then searching for deep overburden boreholes that pierce the bedrock surface. The elevation of the bottom of these boreholes was then added to the "Picks" table and attributed as "DeepOB" picks. By applying this method of "push-down", we are less apt to miss potential buried bedrock valleys defined by deep overburden wells. This table of "definitive" picks was then used to generate a series of "training" surfaces to work from and guide further interpretations of lower quality borehole information. Viewlog® software was used initially in the interpretation process to pick formation tops from lower quality boreholes.

In an attempt to ensure that the three-dimensional model honored materials mapped at the surface, the surficial units present on 1:50 000 scale Quaternary geology maps were translated to the 19 layer stratigraphic model. Only 8 of the 19 layers are represented by surface sediments in Waterloo Region. For example, areas mapped as Mornington Till were translated to hydrostratigraphic unit "ATB1" and areas mapped as glaciofluvial outwash were translated to hydrostratigraphic unit "AFA2". The provincial digital elevation model (DEM) was then sampled on a 200 m spacing producing a secondary picks table with "X,Y,Z" coordinates populated with the attribute "STRATUM" representing the surface material at that site. This table contains over 39 000 entries. We found a serious discrepancy between areas mapped as ice-contact stratified drift (AFB1) and the uppermost strata of boreholes in these areas. This is not unexpected as moraine areas tend to be heterogeneous. For this reason, we opted to omit these points (AFB1) from the secondary picks table and rely exclusively on the borehole records from these areas to define where the aquifer (AFB1) is confined versus unconfined. This reduced surface picks table has nearly 32 000 entries. The surficial geology map showed a close correspondence with the borehole information in the remaining regions.

MODELLING

The approach taken for modeling the Quaternary deposits in Waterloo Region is slightly different than that followed by other jurisdictions doing regional 3-dimensional modeling. For example, the Geological Survey of Canada opted for an automated approach guided by expert knowledge and a conceptual stratigraphic framework in its regional assessment of the Oak Ridges Moraine (Logan et al., in press). The Illinois State Geological Survey, in its 3-dimensional study of Antioch Quadrangle, chose to evaluate and pre-screen the greater than 4000 driller's logs that exist for this area and base their model on the best 275 borehole records (Hansel et al., 2004). For the Waterloo study, a decision was made to manually interpret, where possible, the 26 000 borehole records in section guided by the training surfaces and attempt to selectively extract as much information as possible from logs of disparate or lower quality. Although considered to be a poor source of subsurface information, water well records frequently contain valuable information concerning the tops of bedrock and important aquifer and aquitard units. Since most water wells are screened in the first productive, water-bearing horizon, one can feel fairly confident that the lowest unit in a given water well is an aquifer. The tops of these units form an important component of our picks table.

A number of software packages were looked at and evaluated for their ability to meet our specific 3D mapping needs. The main elements of interest in a software package were: 1) strong 3D visualization capability for data interpretation; 2) excellent linkage and live update capacity with our working database; 3) ability to interpolate surfaces and apply logical rules that allow for laws of superposition to be honoured; 4) ability to create wireframe surfaces, solid models and calculate volumes; 5) ability to import ArcInfo® shape files and drape base information over a 3D model; 6) ability to import raster images such as seismic sections into the model for added interpretation; 7) ability to create isopach maps of individual strata; 8) ability to create elevation maps of the tops of individual strata; 9) ability to export in, ASCII format, top of formation data at a specified grid spacing; and 10) the ability to provide a free viewing software that allows for flexible client interaction with the 3D model. Datamine Studio®, a software package used primarily by the mining sector for mine design and orebody modeling was chosen for this study. This

software met all of the criteria listed above and appeared to be suitable for 3D modeling of Quaternary sediments where units frequently pinch out forming lenses. This software has been successfully used to model coal seams as well where pinch outs often exist.

Another strength of Datamine Studio that was used to great effect on this project is the customizable interface that allows a series of repeatable tasks to be defined and presented to the user through a scripted interface using the same tools that are available for creating web sites. This makes it very easy for the user to carry out complex modeling procedures.

The Datamine Solution

In a process similar to that undertaken with Viewlog[®] software, the drillhole database was further examined in Datamine Studio[®] along east-west sections spaced at 100 m with 50 m offset/clipping limits. A set of scripts were created to assist with the display and manipulation of the drillhole and picks data. This process assisted with the refinement of the picks table generated initially in Viewlog[®]. In most cases, the upper surface of a given stratum was identified by creating a 3D point on the drillhole. Alternatively, 3D points were digitized off drillholes to assist with the refinement of stratum geometry. Over 38,000 picks have been created to date in this manner. As mentioned previously, we also have nearly 32 000 3D surface data points sampled from the DEM on a 200 m square grid that can optionally be used in conjunction with the picks data.

If all strata were identified in all holes then modeling would be a straight forward process. However, because of data quality and varying borehole depth, there are on average only 2.2 strata identified per hole suggesting a fair amount of missing information. In addition, not all strata exist over the entire area so there are holes in and limits to the surfaces. The simplest method would be to create a Digital Terrain Model (DTM) wireframe surface for each stratum from the known picks. However, because of the scarcity of the data for some layers, this leads to a large number of overlaps between the surfaces, which are difficult to adjust. An alternative approach would be to interpolate the elevations for each stratum onto a regular grid using inverse power of distance or normal kriging and then apply a suite of rules to sort out the overlaps. In this instance, the rules would be complex as they would need to take into account both the sequence of strata at every model column and also the elevations of the strata in adjacent columns of cells in order to avoid large steps in elevation between the cells. To avoid this problem, the method selected was to interpolate the stratum elevations onto each borehole, apply a set of rules to resolve any overlaps within the holes and then to create a DTM wireframe surface for each stratum. This method ensures that the wireframes do not overlap. The spaces between each successive pair of wireframes are then filled with model cells in order to create a block model of the aquifers and aquitards.

The process for creating the models is very much an iterative one. The models are created using the initial data and then they are checked visually in the 2D and 3D graphics windows. Data problems are identified and fixed, and extra data is added to control the position of the strata. A new set of models is then generated and validated and the process repeated. In order to facilitate the procedure, the total area can be divided into user defined sub-areas and models generated for each individual sub-area.

Data Preparation

The system that has been implemented allows the option of whether to use just the digitized picks or both the digitized picks plus the surface picks. Where digitized picks correspond to positions down a borehole, the borehole collar elevation is retrieved from the collars file. Where digitized picks do not correspond to a borehole, the points are projected onto the topography wireframe in order to find the topography elevation. Although the description in the previous section refers to interpolation onto the borehole, what happens in practice is that a 2-D block model is generated with cell centres at each X,Y location in the picks file. Therefore some of the cells include several picks whereas others will include just a single pick as is the case with the surface pick points. All cells will also include the topography elevation.

The data are validated to ensure that the elevations for all picks are in the correct sequence. If any inconsistencies are found then the data for that cell is copied to an errors file, and is removed from the current run. The problem picks can then be edited before any subsequent runs of the system occur.

Interpolating Elevations

The model cells are reformatted into a 2D point data file which is then used to estimate elevations of every stratum into every cell. These estimates are combined with the actual picked elevations so that if an actual pick value exists, the estimate is discarded. If there are insufficient data within the search radius then an absent data elevation is assigned. The estimation process allows for a full range of interpolation methods to be selected. This includes

polygonal, inverse power of distance and various types of kriging. Currently, isotropic inverse square of distance is used. The search radius was manually assigned for each stratum. This was done by creating a DTM from the actual picks and varying the maximum length of the edge of any triangle until a suitable value was achieved (i.e. the modelled extent of the given stratum appeared to closely reflect it's actual extent). Search radii vary from 1000 m to 3000 m. Larger search radii were used for strata that are considered to be more continuous such as Bedrock and Catfish Creek Till. In addition, aquitards were assigned larger search radii since they are assumed to be more continuous than aquifers. A minimum of 3 data points is required for most strata inside the search area before the elevation is interpolated. This variable is adjustable as well.

Creating the DTMs

At the end of the interpolation stage, every stratum in every cell will have one of the following elevation values: 1) an actual value defined by a pick; 2) an estimated value defined by interpolation; or 3) absent data indicating insufficient data exists within the search area. However, because of the sparsity of the data and the large number of estimated values, elevations are frequently out of sequence. To correct this, the following rules were applied where $Z(n)$ is the elevation of stratum "n" with 1 being the youngest (top elevation) and 19 being the oldest (lowest elevation). The rules are applied to each stratum in turn starting from bedrock ($n=19$) and working up to ATA1 ($n=1$). Lower and upper strata refer to the stratum immediately below or above the current stratum.

- If $Z(19) = \text{absent}$ then exit.
i.e. make sure bedrock $Z(19)$ is estimated into all cells. Otherwise exit.
- If $Z(n)$ is an actual pick then no adjustment will be made. The following adjustments therefore only apply to estimated or absent values.
- If $Z(n) < Z(n+1)$ then $Z(n) = Z(n+1)$
i.e. if the elevation of the current stratum is estimated below the lower stratum then set it equal to the elevation of the lower stratum. This means the thickness is estimated as zero.
- If $Z(n) = \text{absent}$ then $Z(n) = Z(n+1)$
i.e. if the elevation of the current stratum is absent then set it equal to the elevation of the lower stratum. This means the stratum is being pinched out on the lower stratum.
- If $Z(n-1)$ is "actual" and $Z(n) > Z(n-1)$ then $Z(n) = Z(n-1)$
If the upper stratum is an actual value and the elevation of the current stratum is estimated to be above the upper stratum then reset it equal to the upper stratum. In this case, the current stratum should actually be reset to the base of the upper stratum. This is difficult to achieve in an automated fashion since the base of the upper stratum may not be defined. These picks need to be flagged for manual adjustment.

Using the above rules it is still possible to have strata out of sequence and so a second set of rules is applied. Starting at the top ($n=1$) and working downwards:

- If $Z(n)$ is estimated and $Z(n) > Z(n-1)$ then $Z(n) = Z(n-1)$
i.e. If the current elevation is estimated and is above the elevation of the upper stratum then reset it equal to the elevation of the upper stratum.

The logic also includes one final check working from the bottom upwards to ensure that there are no remaining overlaps. The method for estimating strata elevations described above ensures that all 19 strata have elevations for each cell. The DTMs for each stratum are created from these elevations and so all DTMs extend over the full extent of the data (Figure 1) and is referred to as DTM1.

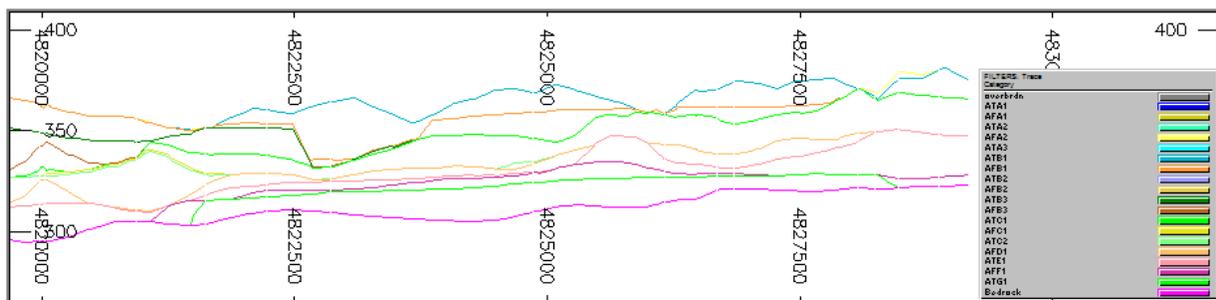


Figure 1. Section view of DTMs (wireframes) for a portion of the study area (vertical exaggeration 20X).

When DTM1 is created the average Z coordinate for each triangle is calculated. This means that by

comparing successive strata it is possible to identify where the thickness of a stratum is zero and then to remove that triangle. This will introduce holes into the DTMs where there is no data and where the thickness is zero. This new set of DTMs is referred to as DTM2 (Figure 2).

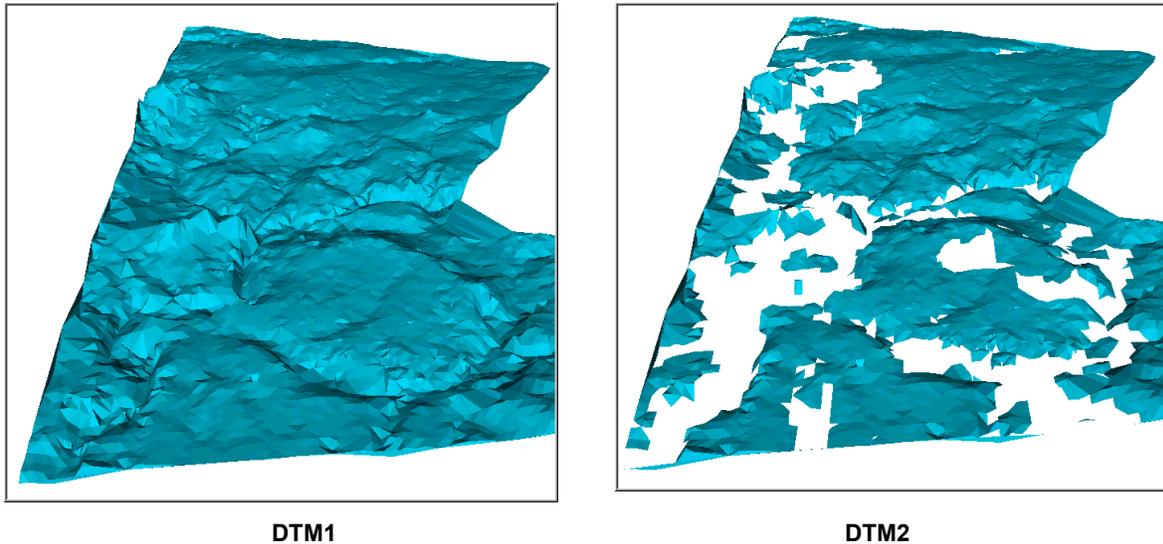


Figure 2. Perspective view of DTMs for aquitard surface ATB1. The left DTM displays the unit as a continuous surface with no holes whereas the one on the right has holes cut out where the unit is not present (vertical exaggeration 20X).

Creating 3D Block Models

The block modeling techniques described so far have been used to interpolate elevations onto a 2D grid of irregular points corresponding to the X,Y coordinates of one or more picks. These points are at the centres of the model cells but the actual dimensions of the cells are not used.

A 3D block model representing all strata is created by filling the space between each stratum in DTM1 with subcells (Figure 3). The planar dimensions of a subcell are user definable, but it was decided that 200m x 200m provided a good resolution without creating too many cells – there are approximately 140,000 cells in the full model. The dimension of each subcell in the vertical direction is calculated automatically so that it fits exactly between the strata. The model created using this method is referred to as model 1.

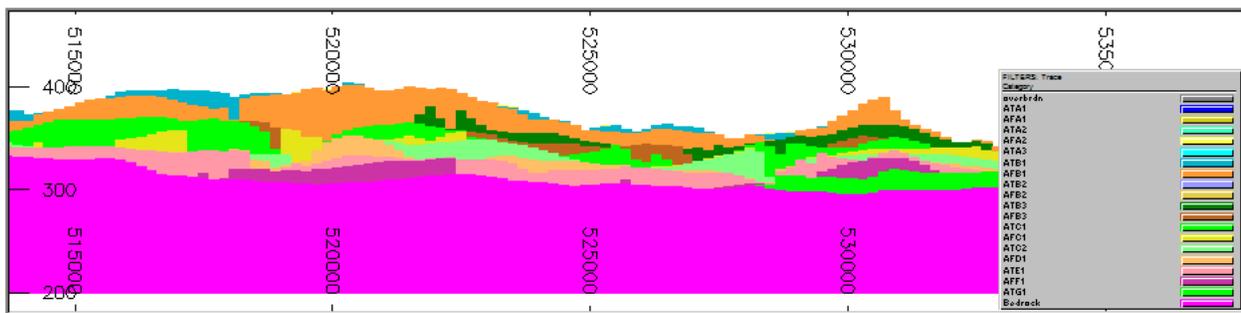


Figure 3. Section view of block model created for a portion of the study area (vertical exaggeration 20X).

A second model, model 2, is created in which all subcells are split along the horizontal planes corresponding to 10m benches. Thus the thicker strata will contain several full 10m subcells plus both an upper and lower subcell of less than 10m. The number of cells in this model is approximately four times that of model 1. The advantage of model 2 is that the subcells for an individual stratum can be displayed and coloured according to the elevation of each subcell.

Calculating Volumes and Grids

The volume of each stratum over the whole area or over a subset of the area can be calculated from either DTM1 or either model. The results are classified both by stratum and by aquifer / aquitard. Model 1 includes the coordinates of each subcell centre and the thickness of each subcell on a regular XY grid. Hence, the elevation of the top of each stratum can be calculated and exported to a text file, which can be used as input to other software packages for hydrogeological modeling and visualization.

CONCLUSIONS

The flexible and comprehensive database and modeling options available in Datamine Studio have allowed a method to be created that follows a logic which is appropriate for the modeling of aquifers and aquitards. As is often the case in this type of study the modeling steps are repeated many times during the course of a project as data gets refined and corrected and interpretations change. The ability to put the entire model build behind a single button on a tailored interface has been a major contributor to the success of this project.

The high quality 3D visualization and display options allow the different data types (boreholes, points, wireframes, block models) to be selectively displayed and manipulated. This greatly facilitates the validation of the base data from which the models are created. The ability to easily select subsets of the project area and create models for these sub-areas means that the models can be created in a matter of minutes which makes it a very practical tool. Few modifications would be required to apply the system to other similar project areas.

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landfills and for identification, delineation, and protection of aquifers (Figures 2 and 3). Although those maps accurately depict the vertical succession of materials in specific areas, they have significant limitations: their complex map unit labels make it very difficult to visualize regional geologic patterns; map legends and map unit labels can be difficult to decipher; and the maps must be restricted in their depth of portrayal for materials to minimize the complexity of map unit labels.

Color coding of vertical successions of geologic units also has been attempted. Figure 4 displays a 1:500,000-scale map of part of southern Illinois and surrounding states. There, the 3D geology of the upper 15m was relatively simple to portray. The map was fairly easy to construct, with a simple legend and map unit labels, regional geologic trends can be visualized, and detailed local information is portrayed within the context of broader regional trends. However, showing additional complexity and mapping to greater depths is quite restricted – colors and patterns must be carefully chosen to clearly show the different stack units. Therefore, producing similar maps for other, more geologically complex parts of Illinois, was found to be not feasible.



Figure 4. Color-coded stack-unit map (1:500,000-original scale) to 15m for the Paducah 2-degree Quadrangle (Berg and Greenpool, 1993).

Figure 5 displays another method of using colors and patterns to show the succession of materials, as applied to a map of the thickness and character of Quaternary deposits east of the Rocky Mountains (Soller, 1993-1998). In this method, color hue indicates the type of geologic material at land surface, color intensity indicates the total thickness of Quaternary deposits, and colored patterns indicate selected

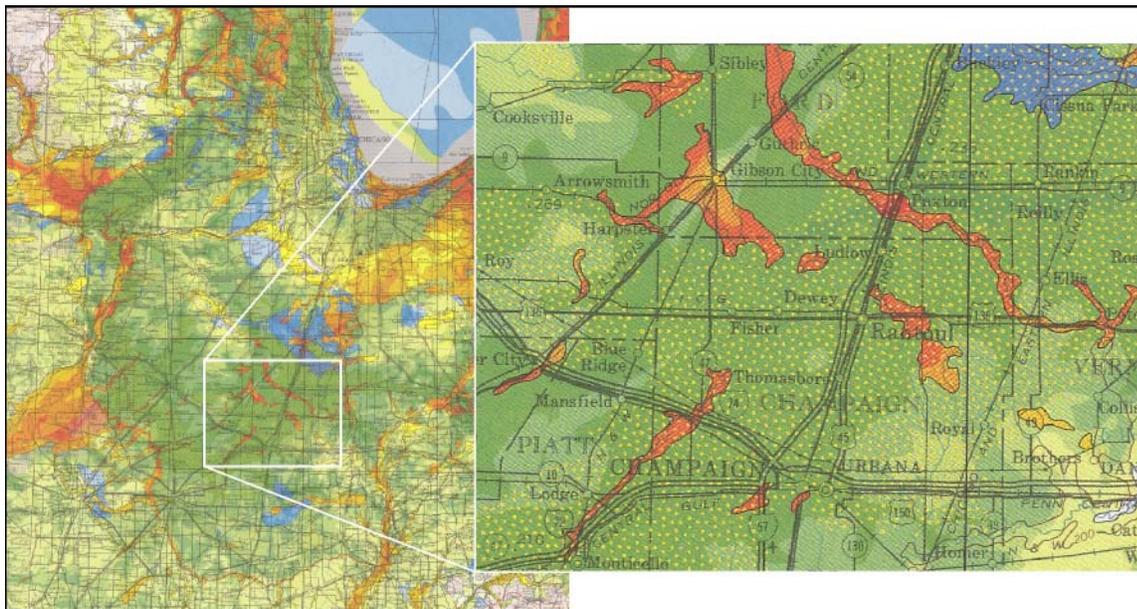
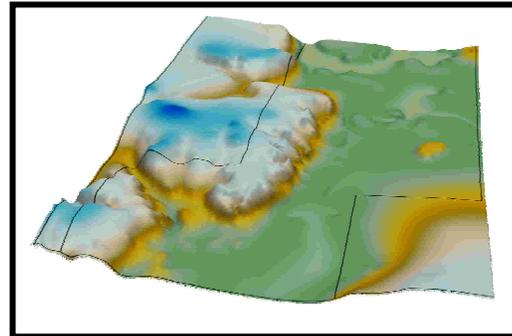
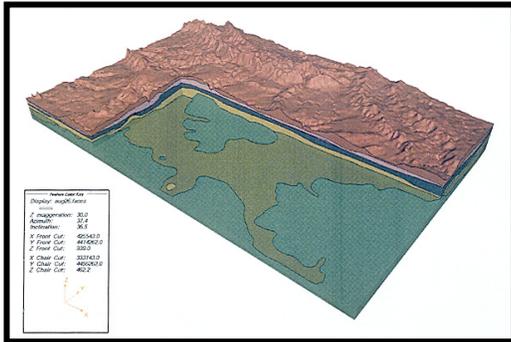


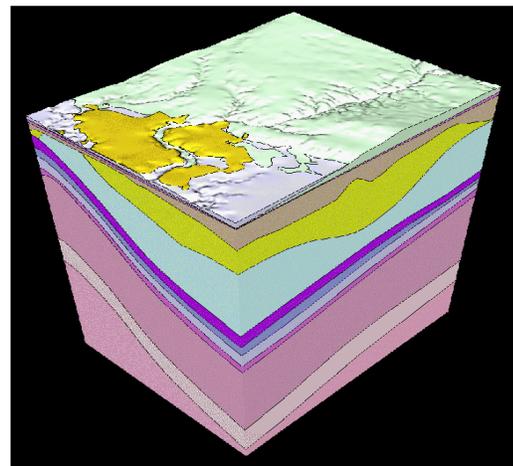
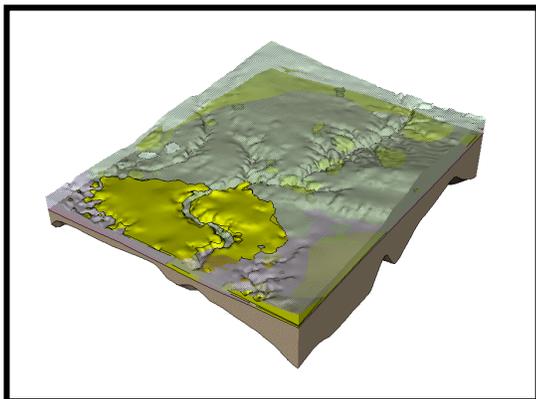
Figure 5. Using colors and patterns for a regional stack-unit map (Soller, 1993-1998). Inset map shows with yellow dot pattern the extent (but not the depth) of the buried, pre-Illinoian-age Mahomet Sand in east-central Illinois. Southern Lake Michigan is in upper right of less-detailed map view.

buried geologic units such as regional aquifers. Because this map depicts all deposits overlying bedrock, it is suitable for a regional map, but is less appropriate for local map areas where a detailed vertical succession of geologic units needs to be shown.

Throughout the 1990s and into the 2000s, products that more realistically show the three-dimensionality of the deposits have been produced with the help of computers; these products tend to be not traditional or stack-unit maps, but instead are 3D models that can display geologic units and structures from any chosen perspective. (Figures 6-9). These 3D models allow geologists to depict all surfaces, depths, and thicknesses, and they are a valuable tool for visually analyzing and interpreting the geology and its history. The 3D images are created by geologic interpretation and rigorous use of raw data and statistical methods. Preparation of these maps requires the geologist to adopt new approaches to creating, managing, and manipulating geologic data. In return, the computer model provides products that are easily released on-demand, and updatable as new information is made available to the geologist. Also, this type of product greatly aids the non-geologist to visualize and understand the geology.



**Figure 6 (left). A cutaway, or “chair” slice, from a map of east-central Illinois (Soller et al, 1999).
Figure 7 (right). Bedrock topography north of Peoria, IL (Keifer, 2004).**



**Figure 8 (left). Perspective view of entire Villa Grove (IL) 24K Quadrangle showing unlithified glacial deposits and yellow-shaded sand and gravel (Lasemi and Berg, 2001).
Figure 9 (right). Complete Villa Grove (IL) 24K Quadrangle model showing bedrock units and overlying glacial deposits (brown and pale-green layers above lime green unit) (Lasemi and Berg, 2001).**

However, there are some disadvantages to this type of 3D portrayal. For example, it can be more time-consuming and expensive to build these map databases and 3D models in the computer than to create a stack-unit map in paper format. These 3D maps and images require (1) highly sophisticated map producers and users, (2) large amounts of data whose quality, integrity, and location must be carefully verified, (3) sophisticated software/other support to develop products, (4) a sophisticated data model and considerable expertise in database management, and (5) new computer-based user interfaces to visualize information. Such interfaces can be highly complex and expensive to design and build.

Because there are advantages and disadvantages to both the stack-unit mapping approach and the 3D modeling approach, how then do we combine the complexly detailed information that can be shown on a stack-unit

map with the visually appealing and more understandable information shown by a true 3D geologic model? In summary, the problems include:

- it is difficult to comprehend the information shown on stack-unit maps because of the complexities of subsurface geology and the difficulty in creating readable, comprehensible map unit labels
- there are, practically speaking, depth restrictions on stack-unit maps owing to the complexities of subsurface geology
- three-dimensional geologic models tend to be generalized and it is very difficult for the user to clearly identify the vertical succession of materials at any particular area.
- in essence, stack-unit maps provide location-specific information in a format that can be difficult to decipher, and 3D models provide generalized, visually-appealing renderings that are less useful for location-specific purposes.

To bring the best aspects of stack-unit mapping and 3D modeling together to provide a more useful product, we are developing a new tool for displaying 3D geologic information. We envisioned this approach more than a dozen years ago, during construction of databases and a geologic map atlas of Quaternary sediments in east-central Illinois (Soller et al., 1999), but reluctantly set the work aside to address other duties. Figure 6 is an example of one of the 3D maps. Below, we show the simple concepts of this approach by referring to our prototype display tool.

Our guiding principle was to build a display tool that is simple and intuitive enough for anyone to use, and to make it accessible via a Web browser without reliance on special software or browser plug-ins. The user would begin by identifying an area of interest on the geologic map, for example, their home, farm, or town (Figure 10). Then, with a mouse-click at that location, the tool will dynamically generate a stratigraphic / lithologic log showing all geologic units beneath that point (Figure 11). This capability to query the 3D map database and model at any location, and to be provided with a graphical summary of the geologic column will be, we hope, a simple yet powerful method of accessing and visualizing the rich information in the database.

The prototype of this tool is written in simple HTML, using an image map linked to geologic columns that provide a general representation of the geology of mapped regions. It cannot yet show dynamically generated, location-specific geologic information that will be provided in the actual tool. We invite you to evaluate the prototype, and we ask for your comments as we endeavor to design the publicly available tool.

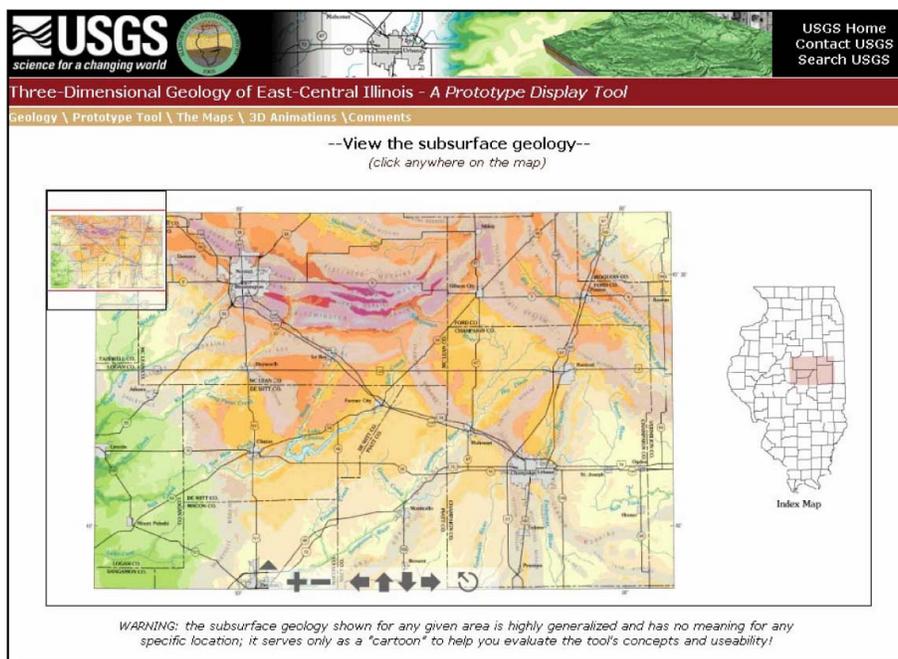


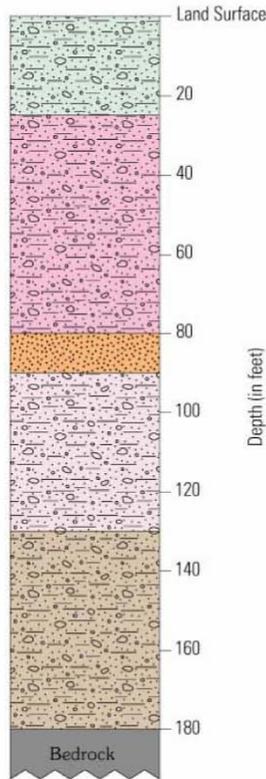
Figure 10. Home page of the prototype display tool. Clicking on a map area will generate a popup window that shows the subsurface geology.



Three-Dimensional Geology of East-Central Illinois - A Prototype Display Tool

Geology \ Prototype Tool \ The Maps \ 3D Animations \ Comments

Here's the Geology



DESCRIPTION OF UNITS

- Mostly glacial till**—Wedron and Mason Group, of Wisconsin age. In some places overlain by clay, sand and gravel of Holocene-age Cahokia Formation
- Mostly glacial till**—upper Glasford Formation, of Illinoian age
- Sand and gravel**—lies at base of upper Glasford Formation
- Mostly glacial till**—lower Glasford Formation, of Illinoian age
- Mostly glacial till**—upper Banner Formation, of pre-Illinoian age

Explanation of these geologic terms:

- [Brief](#)
- [Detailed](#)

WARNING: the subsurface geology shown for any given area is highly generalized and has no meaning for any specific location; it serves only as a "cartoon" to help you evaluate the tool's concepts and useability.

INDEX MAP

(the geologic column depicts geology for the area shaded in gray)

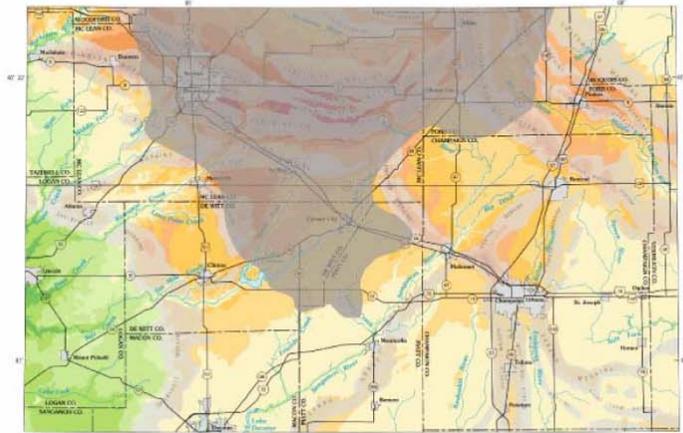


Figure 11. A view of the subsurface geology, created by a query of the map in Figure 10. The column depicts geology for the area shaded in gray.

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A 3D ESKER GEOMODEL FOR GROUNDWATER RESEARCH: THE CASE OF THE SAINT-MATHIEU – BERRY ESKER, ABITIBI, QUÉBEC, CANADA

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INTRODUCTION

As part of a groundwater thematic study by the Geological Survey of Canada (GSC 2005), a 3D geomodel (24 x 11 km) was developed for a continuous esker segment in the Abitibi area of Québec, Canada (Figure 1). This segment was chosen because it is representative of a glaciated environment where the ice retreated in contact with a large water body, here Glacial Lake Ojibway. The esker is water bearing, and the high groundwater quality and conflicting usage of the esker, such as sand and gravel exploitation, commercial water bottling, etc., have raised concerns from the principal user, Amos: a municipality of 14 000 people. Our goal is to understand the architecture of the surficial geology in relation with groundwater circulation patterns in the esker and surroundings to provide local authorities with a decision making tool for regulating activities on and near the esker.

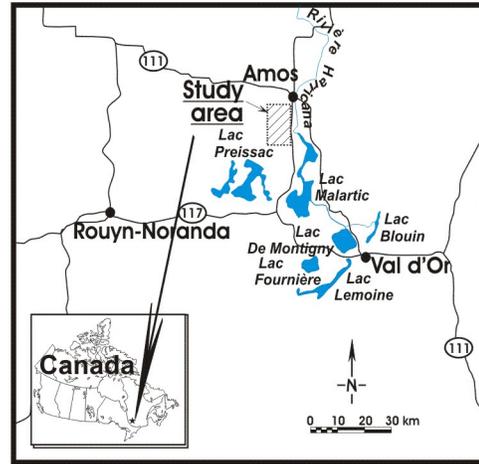


Figure 1. Location of the study area in western Québec

THE GEOMODEL

We have chosen to work with the 3D modeling and visualisation software gOcad[®] of Earth Decision Sciences, in order to recreate a six-layer (bedrock, till, esker, Ojibway clay, nearshore sand and organic deposits) model of the surficial geology. Following Ross *et al.* (2004), we have integrated archival data (surface information from bedrock and surficial geology maps and borehole data from mining exploration and water wells), supplemented by our own ground penetrating radar surveys and soundings. Data sets (pointsets) were created for each layer and used as control nodes (allowing some flexibility to the elevation of the point) and control points (fixed points that cannot move during interpolation) to build each of the surfaces. For example, data used to create the bedrock surface (Figure 2) range from highly reliable mining exploration well markers (control nodes) to approximate location of bedrock outcrops from surficial geology maps (control points). Preliminary results are found in Bolduc *et al.* (2004) and Riverin *et al.* (2005).

Each of the six surfaces, plus a base, were used in pairs (base-bedrock; bedrock-till, till-esker, etc.) to make 3D geobodies (Sgrids) with cell sizes of 100 m X 100 m X the thickness between the two stratigraphically superposed units, except for the esker Sgrid which was designed to have a maximum cell thickness of 1 m. This design was chosen because the esker is the only groundwater-bearing unit of consequence and the only one having some stratigraphic details. The six Sgrids were merged into a single, relatively light, Sgrid to allow for faster manipulations. A visual comparison between the geomodel (the six merged Sgrids) and the original surficial geology map (Figure 3) shows that the geomodel closely reflects the observed surface data, a test of the reliability of the geomodel.

In the esker Sgrid, it then becomes possible to insert regions defined by well markers and zones that are more gravelly. The gravelly units described in well logs appear to correspond to the central esker ridge, suggesting a coarser unit is present in the otherwise sandy deposit (Figure 4). Although we only have detailed logs for the northern (Amos area) and the central (where the commercial bottling company is located) esker portions, it is reasonable to assume the presence of the gravelly layer along the entire esker segment. This will be taken into account during the numerical modelling of groundwater flow. Well logs and particularly resistivity profiles also suggest that some silty lenses may be present, but their distribution does not allow a coherent reconstruction.

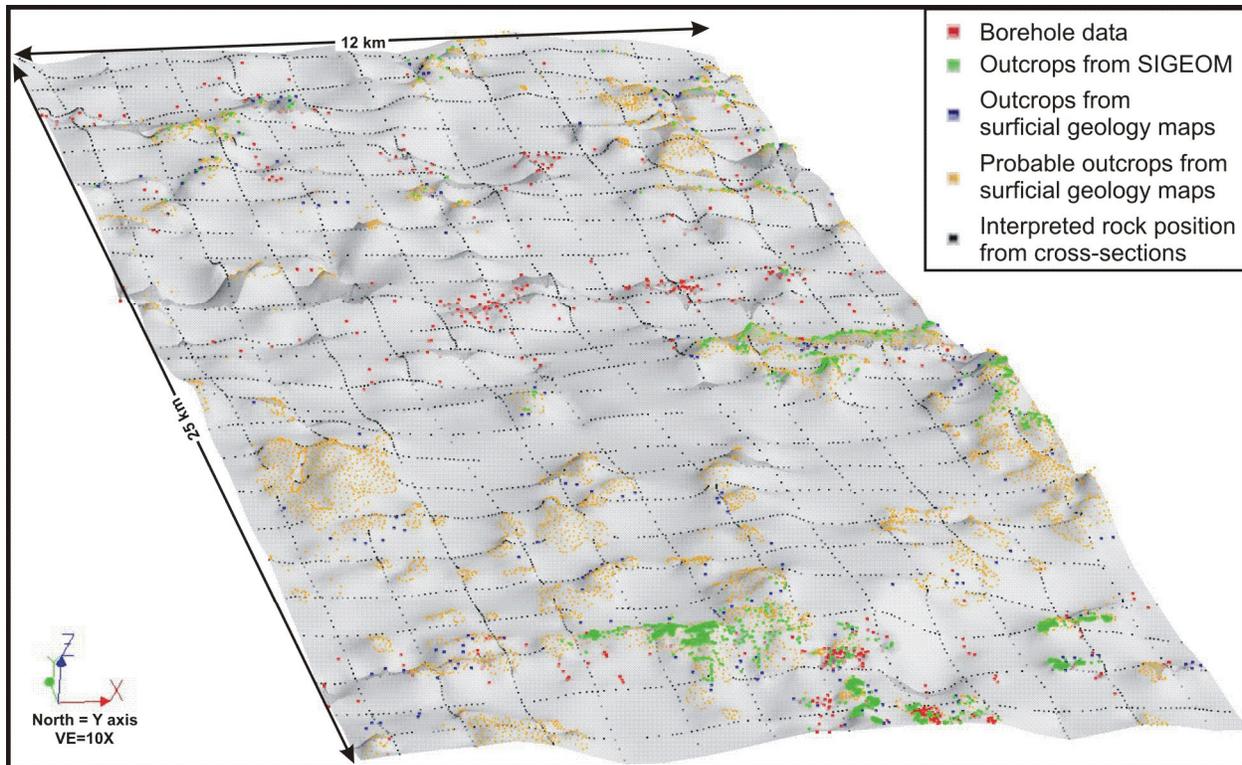


Figure 2. Bedrock surface (grey) reconstructed from various datasets. Borehole and outcrop data are control nodes (surface must honour these points), probable and interpreted bedrock positions are control points (surface may move vertically to achieve a better fit).

A piezometric surface was constructed from our field data (wells and geophysical profiles) and archival water level data in areas we did not access. The piezometric surface (Figure 5) extrapolates above the ground surface in areas where a clay cover is present. This suggests that the groundwater is locally under artesian conditions and explains the presence of flowing wells in these areas. From the geomodel, the esker aquifer volume is $1.34 \times 10^9 \text{ m}^3$, 65% of which is saturated. With an average porosity of 30%, the total water volume in the esker is $2.71 \times 10^8 \text{ m}^3$. The water balance (Riverin *et al.*, 2005) indicates that annual recharge to the aquifer is $14.6 \times 10^6 \text{ m}^3$ and withdrawal for water consumption and bottling ranges from $4.9 - 6.1 \times 10^6 \text{ m}^3$, while $6 \times 10^6 \text{ m}^3$ leaves the esker through springs and wetlands. At the moment, the overall quantity of water in the aquifer doesn't seem to be the

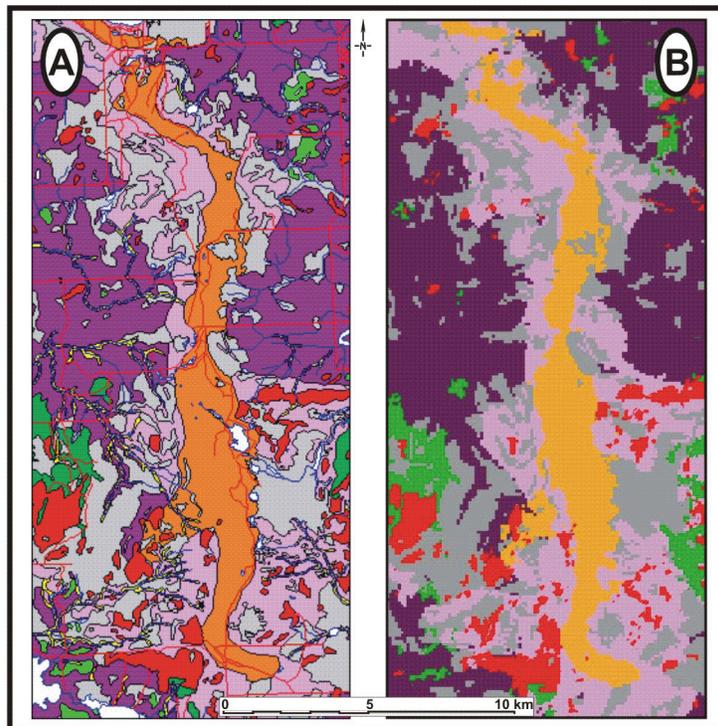


Figure 3. A comparison between (A) the surficial geology map (Veillette *et al.*, 2003) and (B) the result of the geomodelling in plan view. Patterns of roc (red), till (green) esker (orange) clay (deep purple) littoral sand (light purple) and organic deposits (grey) are very similar. Alluvial deposits (yellow on the surficial geology map) have not been included in the geomodelling.

main concern, but because of the groundwater flow, as explained further in this paper, excessive withdrawal in the north might affect the groundwater levels in the north and even dry out completely the southern third of the esker which is topographically much higher than the central and northern portions.

Concerns were raised, however, that groundwater withdrawal from the water bottling company would affect the municipal wells. There also was the assumption that, based on scattered well information, municipal wells were located in a completely disconnected groundwater sub-basin from the commercial wells. Based on the geomodel (Figure 5), although the bedrock surface is highly undulating, no bedrock ridges were found to separate the northern esker basin (where the municipality draws its water) from the central esker basin (where the commercial wells are located). The implications are thus that there needs to be good cooperation between the stakeholders as the activities of one may impact directly on the other.

THE HYDROGEOLOGICAL MODEL

The geomodel suggests that there is a primary control on water circulation from the underlying bedrock topography (Riverin *et al.*, 2005). Longitudinal groundwater flow is to the north from a bedrock high located underneath the southern tip of the esker (Figure 6). There is a secondary, transverse, shallow flow from infiltration at the ridge crest to springs at the clay-esker contact. Water levels are up to 25 m below the esker surface with the piezometric surface being remarkably flat in the northern third of the esker. The saturated thickness of sediments is in the 10-20 m range. In areas where the aquifer is confined by glaciolacustrine clays, as well as due to depressions in the bedrock topography, fossil groundwater is found. Other areas have young groundwater recharged by modern precipitation. This is supported by radiocarbon and tritium analyses which give age values from modern to a few thousand years. Local interconnected groundwater sub-basins defined by fossil versus modern groundwater are not separated by tight physical barriers. In the northern part of the esker segment, the flatness of the piezometric surface and the mobility of the groundwater sub-basin boundaries suggest that small changes in the natural water regime by groundwater removal through pumping might substantially change circulation patterns.

Groundwater modelling results in this aquifer system should show the interaction between different water withdrawal systems by defining their capture area. The hydrogeological model will also allow the simulation of various pumping scenarios to understand the impact they would have on this valuable resource.

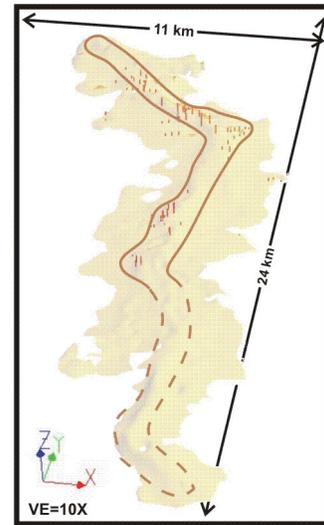


Figure 4. Location of the gravelly units described in well logs. These correspond to the central, ridged axis of the esker (solid brown line) and can be extrapolated (dashed brown line) to the southern tip of the esker. North is along the Y-axis.

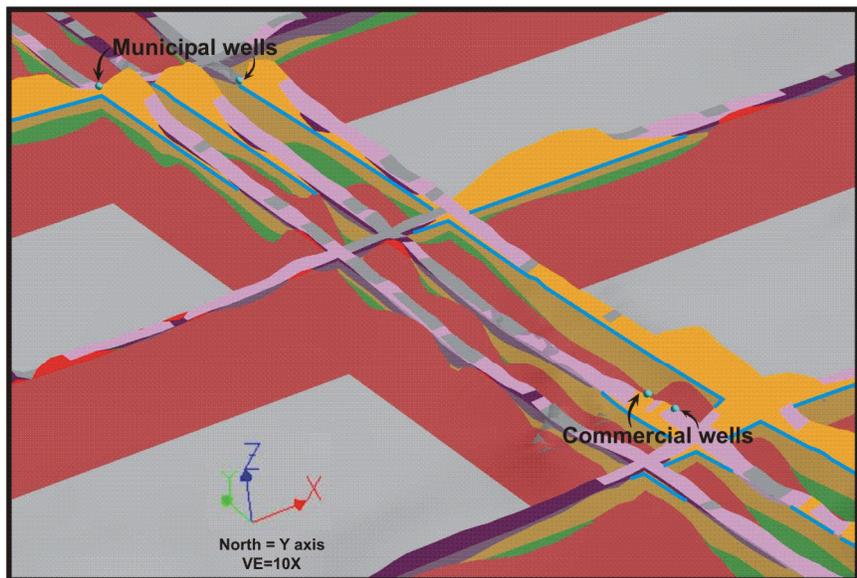


Figure 5. Sections across the geomodel. The north-south sections are 400 m apart, and the east-west sections are 3.5 km apart. The color scheme is the same as for Figure 3. The change from the bright color to the shaded tone below the blue line indicates the saturated portion of the esker.

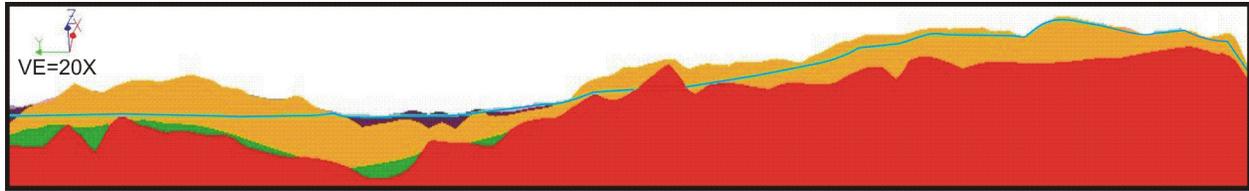


Figure 6. Cross-section (19 km long) at about mid-esker, north is indicated by Y-axis. The blue line represents the piezometric surface intersection with the section. Water levels are high in the south (382 m), and lower in the north (318 m). Groundwater flow is thus from south to north, with local depressions where the municipal wells (309 m) and the commercial wells (304 m) are located. A 2D section suggests that there might be local sub-basins, but with a true 3D vision, it becomes clear that the bedrock highs are not ridges, but hills and that the water can flow around those obstacles.

CONCLUSION

With the appropriate tools and enough field data, it is possible to reconstruct aquifer volumes. While the geomodel can by no means be an exact representation of the aquifer, when properly constrained by reliable well log data, it is the most reliable representation available. Multiple uses of the geomodel are: a tool to provide answers to geologic questions (such as whether there are sub-basins in the aquifer); a planning tool to locate future water wells; and an excellent communication tool for local authorities. We hope that the model will help local authorities in the Amos area better manage their groundwater resource.

ACKNOWLEDGMENTS

This project was carried out by the Geological Survey of Canada (GSC-Québec), in collaboration with INRS-Eau, Terre & Environnement (INRS-ETE) and Université du Québec en Abitibi-Témiscamingue (UQAT) and funded by the Groundwater Program of the Earth Sciences Sector. We thank Éric Boisvert for his internal review of the paper. The collaboration of the municipality of Amos, the water bottling company Eaux Vives Harricana, the municipality of Saint-Mathieu d'Harricana, Roger Périgny, Daniel Goulet, M. Gérard Gagnon and many private owners who gave access to their wells, and the work of all students are greatly appreciated.

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THREE-DIMENSIONAL GEOLOGIC MAPPING OF GROUNDWATER RESOURCES IN KANE COUNTY, ILLINOIS

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Kane County, Illinois has been undergoing tremendous population growth. Its population was 404,119 in 1996 and is projected to grow to 710,000 by 2030. Because of current water resource limitations and in anticipation of much larger, future demands, the County has contracted with the Illinois State Water Survey (ISWS) and the Illinois State Geological Survey (ISGS) to assess its water resources. The results of this assessment will provide Kane County with the scientific basis for developing policies and management strategies for more effective management of its water resources (Dey et al., 2004, Dey et al., 2005a).

The ISGS is performing three-dimensional geologic mapping of Quaternary deposits and shallow bedrock in Kane County and adjacent areas with an emphasis on groundwater resources. The study area was defined to extend one township (approximately 6 miles) beyond all edges of Kane County in order to prevent distortions of interpretations near the county line and to aid in the assessment of hydrogeologic influences from outside the county.

A conceptual model of the geology of Kane County and adjacent areas was developed from a compilation of the current understanding of the County's geology and the processes by which it formed. This model reflects current interpretations of information from previously published materials, knowledge gained by ISGS staff and colleagues from other studies in Kane County and northeastern Illinois, and the efforts for this mapping project. The basic components of the conceptual model are the lithostratigraphic units, which are the layers of sediment that occur in a particular position in the succession of materials. Initially 32 lithostratigraphic units were identified in the conceptual model.

Records of water wells and other borings on file at the ISGS were the main source of data for the three-dimensional geologic modeling. A project database was constructed to facilitate the use of these records. For simplicity, the term well(s) is used to describe data from water wells or other types of borings. Currently, the project database contains 27,794 well records and 9,313 other forms of point data, such as seismic data, outcrop descriptions, and other observations made at the land surface.

A primary data set was created as a subset of all well records and point data in the project database. Wells were selected for the primary data set based on the quality of both the data and location information. Wells included in the primary data set are referred to in this report as primary wells. A goal was to have a somewhat evenly distributed set of primary wells across the study area, with one well per each quarter section. This goal was not achieved in some areas and was exceeded in others. Wells have continually been added to the primary data as additional wells useful to mapping the geology of the area have been identified. A total of 4,830 wells have been designated as primary wells.

Efforts were made to verify the location of all wells in the primary data set, both by inspection in the field and reference to records in the office. Verification of a well location in some instances resulted in new location information being added to the project database. All wells have been ranked for the quality or accuracy of the information describing their location. With the location of each well accurately defined, a digital elevation model (DEM) was used to define the elevation of land surface at the location of each well.

Lithostratigraphic assignments to recognized Quaternary or bedrock stratigraphic units were made based on the geologic information in the drillers' descriptive logs of the primary wells and by using the conceptual model, published stratigraphic interpretations, and the professional judgment of geologists working on the project.

Some simplifications were made to the assigned lithostratigraphic units before any litho-stratigraphic surfaces were created. For example, one simplification made in constructing the current model was to model the fine-textured facies of the Cahokia Formation, the Grayslake Peat, and surficial and near-surface deposits of the Equality Formation as a single near-surface unit. All three units tend to occupy low-lying spots on the landscape and occur often in association throughout the study area. These simplifications resulted in 19 major lithostratigraphic units being represented in the geologic model.

Upper and lower surfaces were created for each major lithostratigraphic unit using contouring software and an interpolation algorithm, in our case kriging. A node spacing of 1/8 mile was used on the output grids.

Having completed the initial modeling of the surfaces, constraints were established to reshape the surfaces

to follow certain logical and geological rules. For example, the top of any glacial deposit cannot be above the ground surface, nor can the base be below the bedrock surface. In addition, a given unit must be above all older units and below any younger units. Each surface was compared to each adjacent surface to identify void spaces between surfaces or overlap; where significant discrepancies occurred, a geologist's judgment was used to adjust previous stratigraphic assignments or to make new assignments to correct each case. Following each round of comparisons and new stratigraphic assignments, new surfaces were generated for each unit. The comparison/correction process was repeated until all the surfaces conformed.

The lithostratigraphic surfaces were imported into 3D modeling software. The surfaces were combined to produce a three-dimensional model. The software allowed the mappers to see the relationships between geologic units and make adjustments where the geologic units are out of accordance with the conceptual model. Figure 1 displays 12 units from the initial modeling effort. In addition, the model was queried to produce other maps of Kane County at a scale 1:1000:000, including maps of major Quaternary aquifers, aquifer sensitivity to contamination, bedrock geology, and geologic cross sections across the study area (Dey et al., 2004).

A revised three-dimensional model was created in the Spring of 2005 using additional data. Revised versions of the major Quaternary aquifer map (Figure 2) and the bedrock geology map were produced. In addition, the three-dimensional geologic model has been incorporated into a groundwater flow model by the ISWS. The flow model is being calibrated using head data collected in private wells by the ISWS within the study area (Locke and Meyer 2005).

Final versions of all these publications are scheduled to be completed in April 2007. They will be accompanied by a report summarizing the geological investigations. A report on the results of the groundwater flow modeling by the ISWS is scheduled for completion at the same time

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**PRELIMINARY THREE-DIMENSIONAL GEOLOGIC MODEL
KANE COUNTY, ILLINOIS**

Curt C. Abert, William S. Dey, Alec M. Dwin, B. Brandon Curry and John C. Sieving
2004

Department of Natural Resources
and Biological Director
ILLINOIS STATE GEOLOGICAL SURVEY
William W. Saha, Chief

Illinois Preliminary Geologic Map
P30M Kane-03

Three-Dimensional Geologic Model

This model was produced for the Internet Report on Geological Investigations for Kane County (Abert et al., 2004) as part of a contract report for the Three-Dimensional Investigation for Kane County, Illinois (Abert et al., 2004). The purpose of this study is to describe the geology of Kane County as best as current data allow. The preliminary model is the basis for preparing work sheets for the Internet Report on Three-Dimensional Modeling for Kane County, and for the Internet work sheets for the Internet Report on Three-Dimensional Modeling for Kane County and Supporting Hydrologic Studies for Kane County (Abert et al., 2004).

Upper and lower surfaces were mapped for the major lithostratigraphic units in Kane County. Each surface is a map depicting the distribution of that unit or horizon of that unit across the county and shows where it is absent. The method used to produce these surfaces is described in the accompanying report. To produce this model, the surfaces were imported into ArcView and overlaid on a 30-m grid. The resulting model is shown in Figure 1. The surfaces were overlaid to produce a three-dimensional model similar to that of the 3DGS (Abert et al., 2000; Abert, 2003). The model shows geologic units in the relationship between geological units and visually assess the validity of two lithostratigraphic concepts in a three-dimensional context.

The images presented were created by separating each lithostratigraphic unit from the three-dimensional model and displaying it in a consistent perspective. The perspective is a view from the southeast at 25 degrees above horizontal. A cell size of 1/4 mile horizontal and 5 feet vertical was used in creating the model.

The following Three-Dimensional Model of Kane County provides a visual representation of the geology of the county. It allows visualization of the individual lithostratigraphic layers and how they relate to one another. In addition, it can be described as more abstract than reality, i.e. the model is not intended for regulatory purposes.

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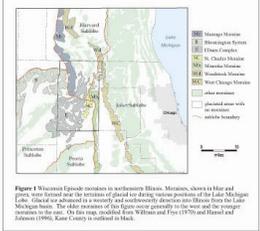
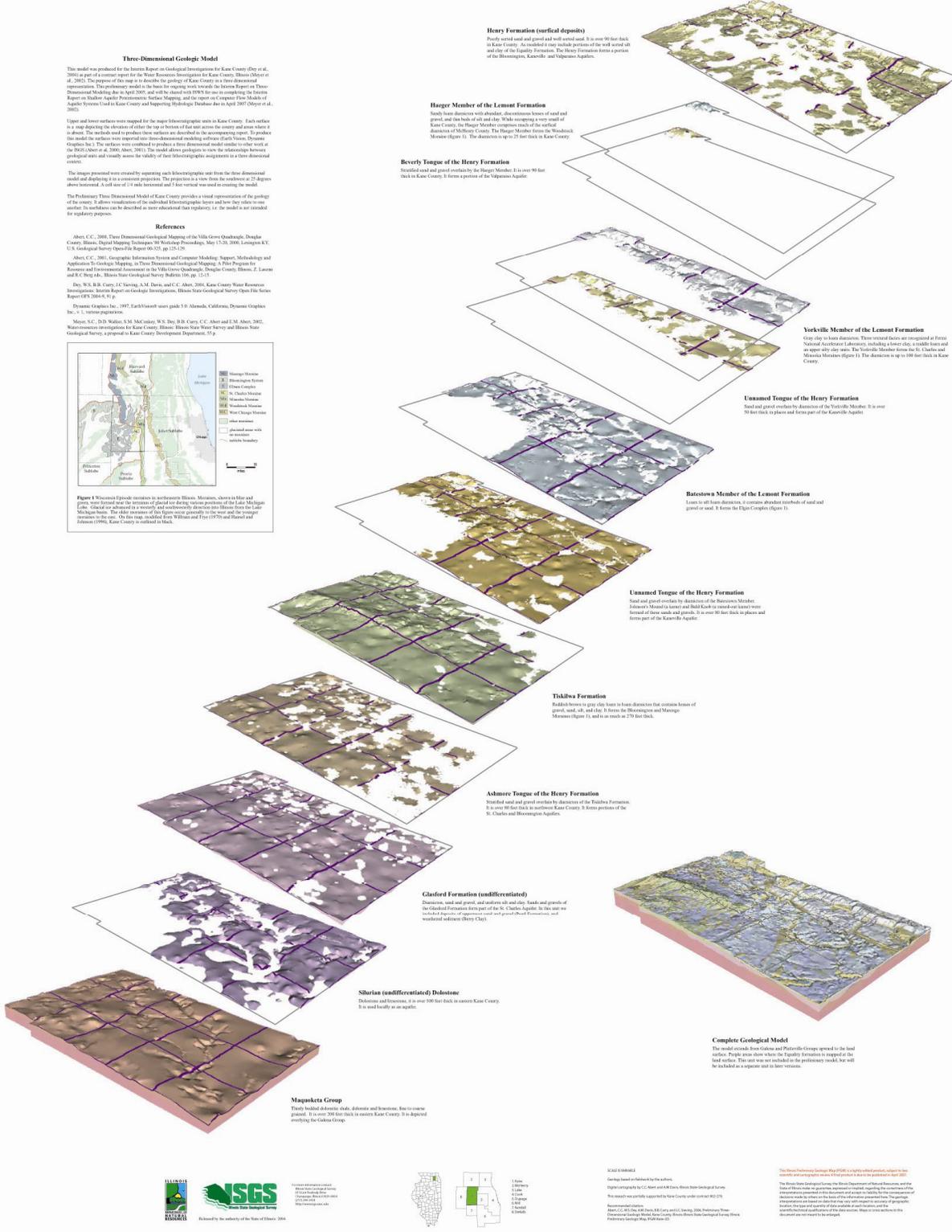


Figure 1 Shows geologic units in southeastern Illinois. Maquoketa, shown in blue and green, is the only unit that is a water-bearing unit. The other units are shown in various colors. The color of the unit is shown in a legend and is used to identify the unit. The color of the unit is shown in a legend and is used to identify the unit. The color of the unit is shown in a legend and is used to identify the unit.



Henry Formation (vertical deposits)
Thinly bedded sand and gravel and well-sorted sand. It is over 90 feet thick in Kane County. An unsorted fine to medium sand is overlain by the Henry Formation in a portion of the Henryton, Knoxville, and Valparaiso Aquifers.

Hager Member of the Leont Formation
Sandstone, sand and gravel, dolomite, dolomite lenses of sand and gravel, and thin beds of sand and clay. It is overlain by the Henry Formation in a portion of Kane County. The Hager Member forms the Westwood Member (Figure 1). The thickness is up to 15 feet thick in Kane County.

Beverly Tongue of the Henry Formation
Well-sorted sand and gravel overlain by the Hager Member. It is over 90 feet thick in Kane County. It forms a portion of the Valparaiso Aquifer.

Yorkville Member of the Leont Formation
Clay shale to loess. Three vertical faces are recognized as Penn National Accelerator Laboratory, including the Yorkville, Yorkville, and Yorkville Members (Figure 1). The thickness is up to 100 feet thick in Kane County.

Unnamed Tongue of the Henry Formation
Sand and gravel overlain by the Yorkville Member. It is over 90 feet thick in places and forms part of the Knoxville Aquifer.

Bateson's Member of the Leont Formation
Loess in all thicknesses. It contains dolomite horizons of sand and gravel or sand. It forms the Elgin Complex (Figure 1).

Unnamed Tongue of the Henry Formation
Sand and gravel overlain by the Yorkville Member. It is over 90 feet thick in places and forms part of the Knoxville Aquifer.

Tiskilwa Formation
Sandstone to gray clay loess to brown shales that contains lenses of gravel, sand, silt, and clay. It forms the Dixonton and Manning Members (Figure 1), and is over 200 feet thick.

Ashmore Tongue of the Henry Formation
Well-sorted sand and gravel overlain by the Yorkville Member. It is over 90 feet thick in Kane County. It forms a portion of the St. Charles and Dixonton Aquifers.

Glasford Formation (undifferentiated)
Dolomite, sand and gravel, and sandstone silt and clay. Sands and gravels of the Glasford Formation form part of the St. Charles Aquifer. In the east are included horizons of sandstone and gravel (Dixon Formation), and well-sorted dolomite (Henry Clay).

Silurian (undifferentiated) Dolomite
Dolomite and limestone. It is over 100 feet thick in eastern Kane County. It is deposited mostly as an aquifer.

Maquoketa Group
Thinly bedded dolomite, shale, dolomite and limestone. Here to coarse grained. It is over 200 feet thick in eastern Kane County. It is deposited overlying the Carbon Group.

Complete Geologic Model
The model shows the geologic units and their relationships in the field surface. People can show when the Tipton Formation is overlain by the field surface. This map was not included in the preliminary model, but will be included as a separate unit in later versions.

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Figure 1: Preliminary three-dimensional geologic model of Kane County, Illinois (Abert et al 2004).

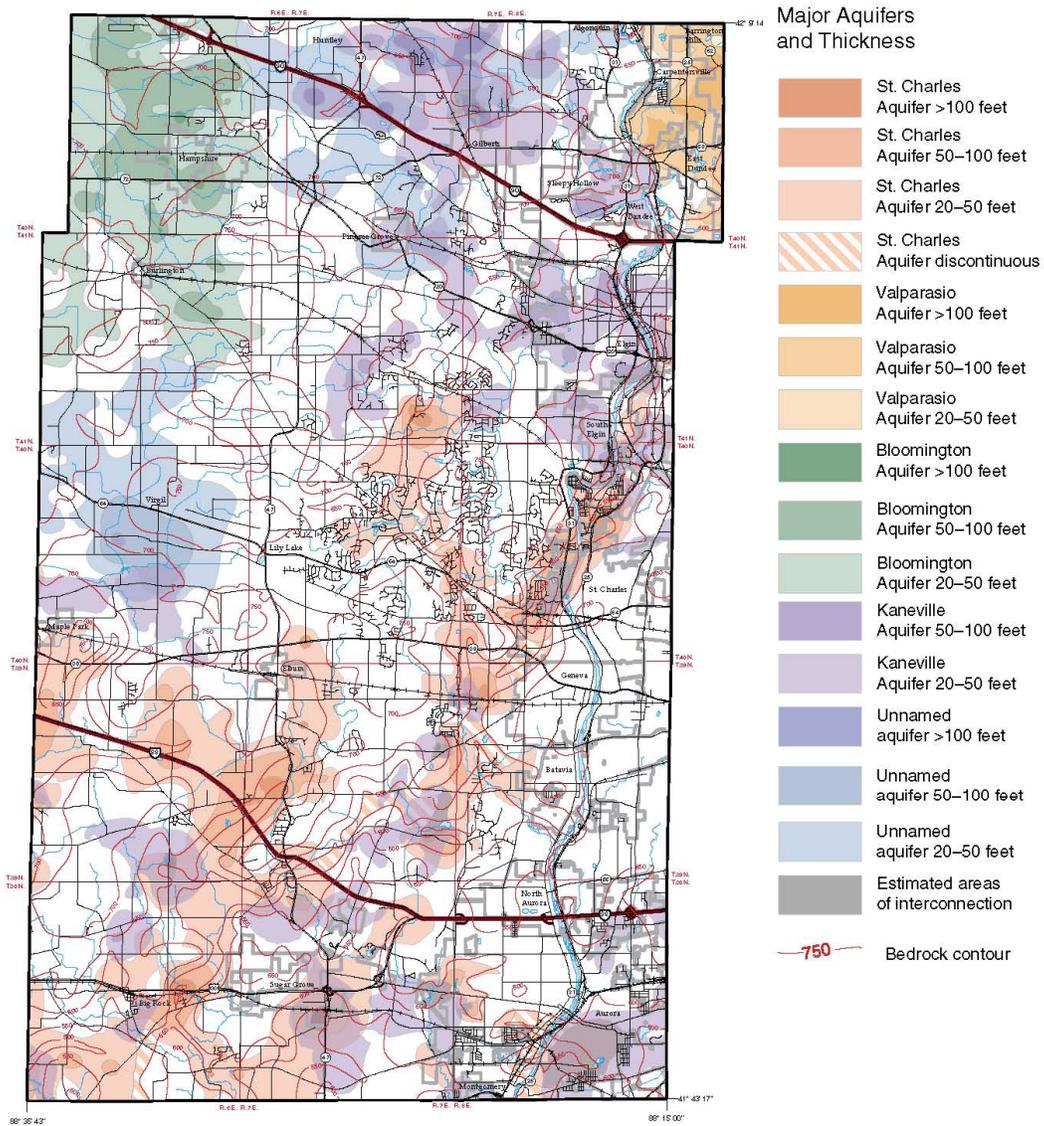


Figure 2. Interim map of major Quaternary aquifers, Kane County, Illinois (Dey et al 2005b)

AN EXAMPLE OF IGS GLACIAL-TERRAIN MAPPING: EXPLORATION OF DEEP QUATERNARY VALLEY-FILL SEQUENCES IN CENTRAL INDIANA

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The Indiana Geological Survey (IGS) protocol for glacial-terrain mapping and exploration combines a variety of digital data and imagery to produce images that enhance even the most subtle landscape features and elucidate the nature of the subsurface. The IGS protocol involves the use of databases, GIS, and Adobe™ graphic arts software, allowing a seamless flow of data. Tasks are concentrated in the application which processes them most effectively and efficiently, and enables the best possible output in a variety of formats. This computer-aided analysis provides a powerful tool for recognition of these features in the field, as ArcPad™ GIS software by ESRI™ is used with GPS technology to compare digital data with on-the ground investigations.

The cornerstone of the terrain mapping is the standardized iLITH database, constructed from the Indiana Department of Natural Resources (DNR) water-well database. The database contains x and y coordinates that can be used to display location point data and z values representing subsurface "geologic" information reported by water-well drillers for each location. The massive amount of information (100,000+ location records) makes this database one of the state's most useful compilations of subsurface geologic information.

Another set of data used by IGS geologists is the Gamma-log database (GLDB). The IGS has run a 'Holes-of-Opportunity' gamma-logging program for over 25 years, amassing over 4500 records and 1800 sample sets across the state. The database includes location information, well and drilling specifications, and various other types of information such as sample set availability and operator information. At present, the IGS has over 3500 numeric digital logs files for plotting in GIS applications and over 1900 gamma-logs in image formats. These gamma-logs provide yet another view of the subsurface, enabling cross-sectional views and sequence correlations.

The availability of masses of data and the ability to manipulate them effectively enables and encourages geologists to ask questions and develop models, which previously seemed unfeasible. This has resulted in a multitude of subsurface models, including bedrock topography, drift thickness, the 'unknown' surface, depth to aquifer, and 'slices' of total clay/granular material thickness (0-25 ft, 0-100 ft, 25-50 ft). The ability to visualize the data using these methods allows IGS geologists unique views of the subsurface never before possible.

This mapping protocol provides a framework for examining the glacial geology of Indiana, and producing informative geologic maps and other derivative map products. An example of its application is current Indiana STATEMAP investigations of central Indiana.

Identification of deep valley fill in buried bedrock valleys of central Indiana is a wholly subsurface-based, sequence-stratigraphic approach. The Anderson-New Castle Valley (ANC), a tributary segment of the classic Teays Valley, extends north and northwestward from southeastern Indiana into central Indiana, opening into the Frankfort Lowland Section of the Lafayette Bedrock Valley System (Figure 1). The ANC is expected to provide the simplest record of valley-filling and landscape change related to first glaciation of the valley.

Geophysical surveys were used to locate five testholes, ranging in depth from 250 feet to over 480 feet. These investigations began with Indiana Geological Survey (IGS) gravimetry transects, built upon previous refraction and water-well data, to locate the primary valley thalweg. In addition, a single reflection line (Illinois State Geological Survey Landstreamer methodology), a 5-mile transect perpendicular to the assumed course (through iLITH-derived bedrock topography) of the New Castle Valley, indicated sequence packages within a tributary-thalweg setting and a possible deepest valley testhole location (Figure 2).

Several other deep testholes, including the deepest (504 feet) IGS glacial testhole, were located using data from the IGS iLITH and Gamma-log databases. Sample sets and downhole geophysical logs revealed a variety of vertical-sequence packages composed of: chert gravels, West Lebanon till lithologies, lake clays/silts, alluvial sediments, and glacial advance-sequence sediments. The character of these sediments gives indications of the nature of the earliest glacial influence on the valley.

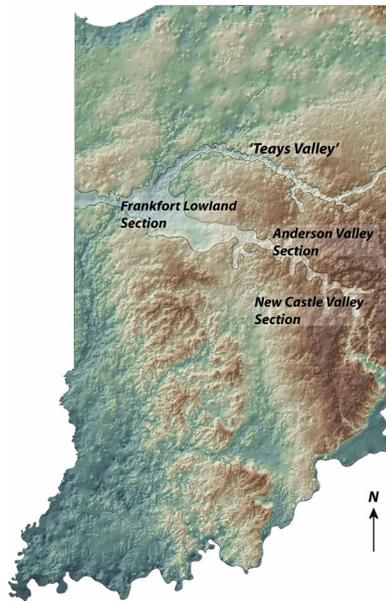


Figure 1. iLITH -derived bedrock topography of Indiana, highlighting the Lafayette Bedrock Valley System

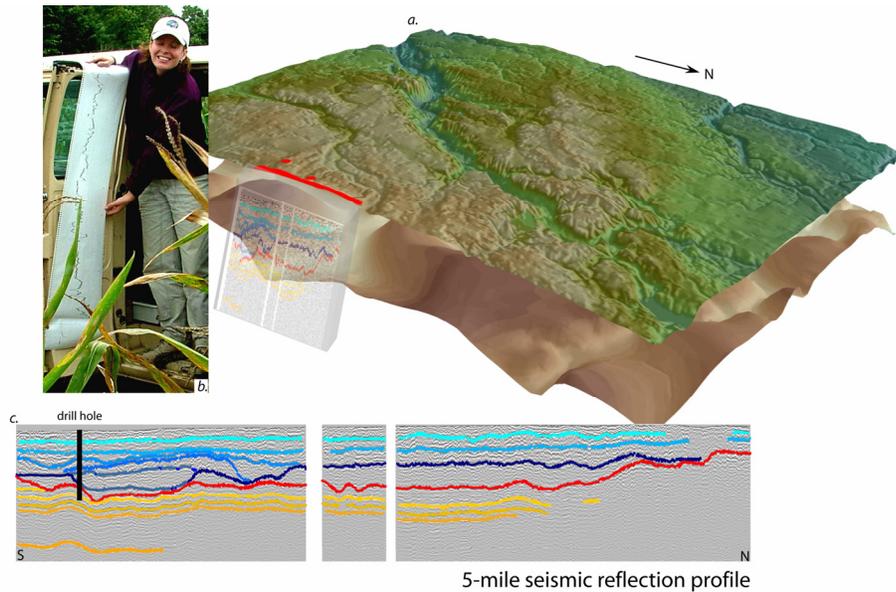


Figure 2. 5-mile Landstreamer seismic reflection survey: a) digital elevation model of study area, underlain by bedrock topography, showing location of profile and resulting testhole locations; b) natural gamma-log of testhole; and c) seismic reflection profile with interpreted sequence packages.

Resultant data from field investigation are combined with existing data and imagery in Adobe Illustrator™ with Avenza MaPublisher™, where geologists can produce a geologic map on their desktop. The final map and map products are the result of effect and efficient data management and manipulation to produce geologic models used to guide geologists in their investigations of the glacial geology of Indiana.

GEOLOGICAL MAPPING IN THE NETHERLANDS: THE CASE OF THE SHALLOW SUBSURFACE (- 500 M)

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INTRODUCTION

The Geological Survey of the Netherlands started the mapping of the shallow subsurface (-500m) with the goal to provide a comprehensive and consistent geological framework for applications that need knowledge and information of the subsurface.

The Netherlands in the Pleistocene and Holocene era is positioned in the delta of the large rivers of Western Europe (Rhine, Meuse, Eridanos), at the edge of the European continent. There was (and still is) a constant interplay between the marine sedimentation and fluvial sedimentation, with superimposed at least three major glaciations that have deposited both glacial and periglacial sediments.

To bring order in the sediments that are deposited during the last 3 Ma, a new stratigraphic framework was developed, in which the Miocene to Holocene deposits are lithostratigraphically defined on basis of:

- Lithology
- depositional domain (genesis, i.e. marine, fluvial, glacial and others (local, periglacial, organic))
- position in the stratigraphic sequence

The strict application of these principles led to a system of 22 lithostratigraphic formations for the Netherlands (onshore).

This new lithostratigraphy was applied to a sub-set of the drillings in the database. Working from large-scale interpreted profiles, showing the general structure of the geology (see figure 1), to regional cross-profiles and the finally to local profiles and interpretations ensured a consistent dataset of some 14,000 drilling records that were labeled with the new lithostratigraphic classifications. This forms the basis for the subsequent modeling phase.

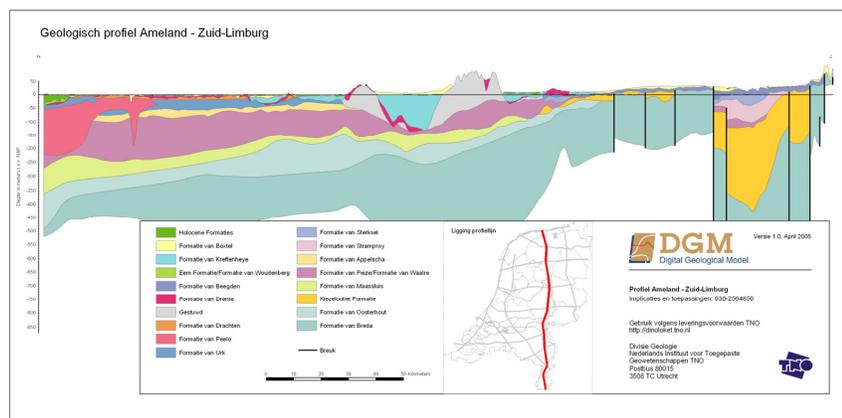


Figure 1. Large scale Geological profile

The geological model of the subsurface of the Netherlands is a so-called “stacked-layer” model. The model is a vehicle that carries geometric information of the lithostratigraphic units on a national scale. Each lithostratigraphical unit is bounded by a top and a bottom surface, that is stored in raster grid format. The size of the grid cells is 250 by 250 meter. Since the lithostratigraphic record is only known at borehole locations, interpolation is used to construct bottom surfaces of each unit. After interpolation of the bottom surfaces of the formations, these units are stacked and the subsequent model constructed.

DATA SELECTION

Boreholes

The basis of the current subsurface model is formed by a selection from the total of about 370,000 boreholes that are stored in the DINO-database (www.Dinoloket.nl). This selection of boreholes is based on spatial coverage, quality and covering the interval of the Holocene and Pleistocene record, see figure 2.

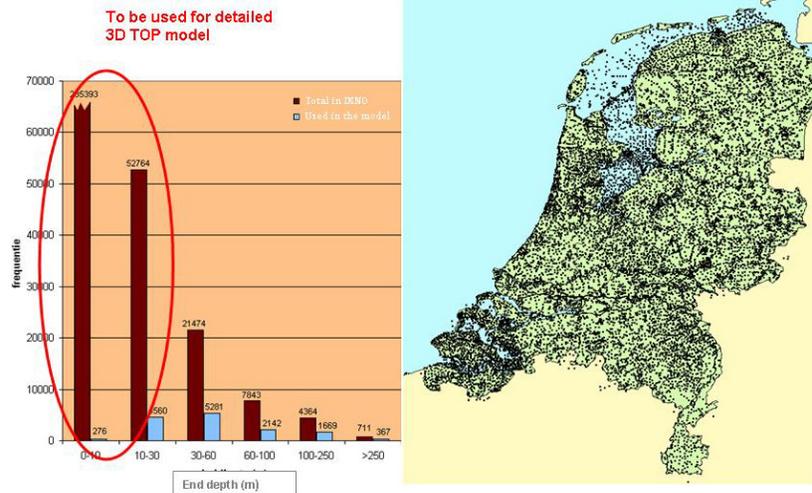
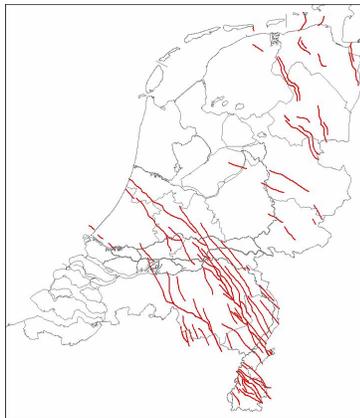


Figure 2. Data configuration

Faults

Seismic surveys were used to obtain the position of faults. From detailed borehole information and local high-resolution seismic surveys on the Meuse and adjacent canals a detailed pattern of faults could be determined, and also the vertical movement and evt. tilting. In figure 3, the faults affecting the Pleistocene and Holocene formations are depicted.



INTERPOLATION AND MODELING

The main interpolation algorithm that was applied to obtain continuous surfaces from borehole data was block kriging; for each lithostratigraphical unit the base was calculated for every gridcell within its depositional extent; the base of the unit was calculated since the base reflects the effect of geological processes that are uniquely related to that unit, while the top is often the result of multiple geological processes from various overlying units.

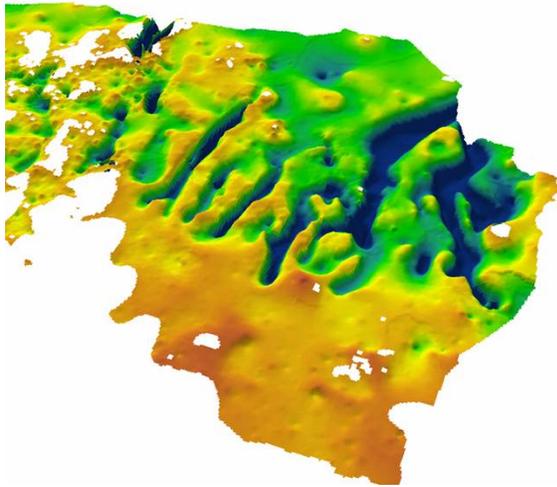
Straight forward application of interpolation like kriging often produce geological structures that are not satisfactory, since no prior geological knowledge can be inserted in the interpolation method. There are several geological issues that require special attention so that they can be modeled correctly.

Figure 3. Faults in the Netherlands

1. distinct geological structures: deep glacial basins and tunnel valleys, ice-pushed ridges, Holocene marine channels, incising into the Pleistocene surface, salt dome structures, influencing the overlying strata
2. faults, SE / NW aligned, that form Horst-Graben structures
3. at the edge of the depositional extent, formations should gradually become thinner, instead of ending abruptly
4. Lower to middle Pleistocene Formations show a declining trend to the Northwest
5. low data densities and irregular data distribution

To tackle the above described issues, several custom-made additions were applied to the interpolation.

Distinct geological structures were modeled using reference surfaces that were specifically constructed. For example, the depth and position of the glacial basins are well known from previous work on a more detailed scale. These surfaces were used to act as a reference surface from which the residuals were calculated and subsequently interpolated. The results honor the data (boreholes) and depict the geological structure that are known to be present.



Faults represent sharp transitions that are not easily modeled in standard interpolation software. Separating the data points at each side of the faults ensures that only the correct subset is used for interpolation.

Modeling the gradually thinning out along depositional extent is achieved by automatically adding datapoints where the thinning out is expected. The depth assigned to these additional points is taken from the overlying unit, defining the top of the unit under study, see figure 5.

Irregular data distribution often results in undesired artifacts in the interpolation, mainly due to too few datapoints in the neighborhood. To prevent this from happening, additional points are placed automatically in low density areas; its value is taken from a prior interpolated surface using the irregular space datapoints.

Figure 4. incised tunnel valleys

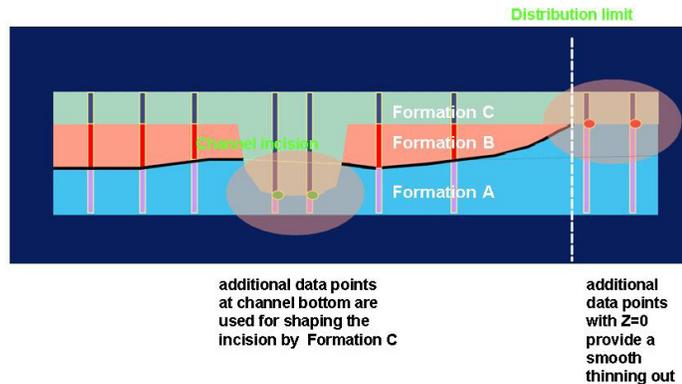


Figure 5. Shapping and thinning out

Layer stacking

After constructing the base of each formation, stacking the base of all the formations creates a stratigraphically consistent model. Stacking causes intersecting and these intersections can be dealt with in 3 ways, depending on the geological setting

1. the upper unit eroded the lower units, causing the lower units to be clipped away
2. the upper unit was deposited on top of the lower unit
3. the intersection is an artifact of the interpolation; the solution is to adjust the base of the formations in such a way that the intersection disappears

Workflow managing and presentation

Updating and adjusting is an important issue in modeling. Therefore, a flexible workflow was constructed, in which the dataflow from database to stacked layer model is completely defined. This allows quick updating and readjusting, without going through each step by hand. All the required actions are stored hierarchically into groups of actions: data extraction, interpolation, stacking etc.

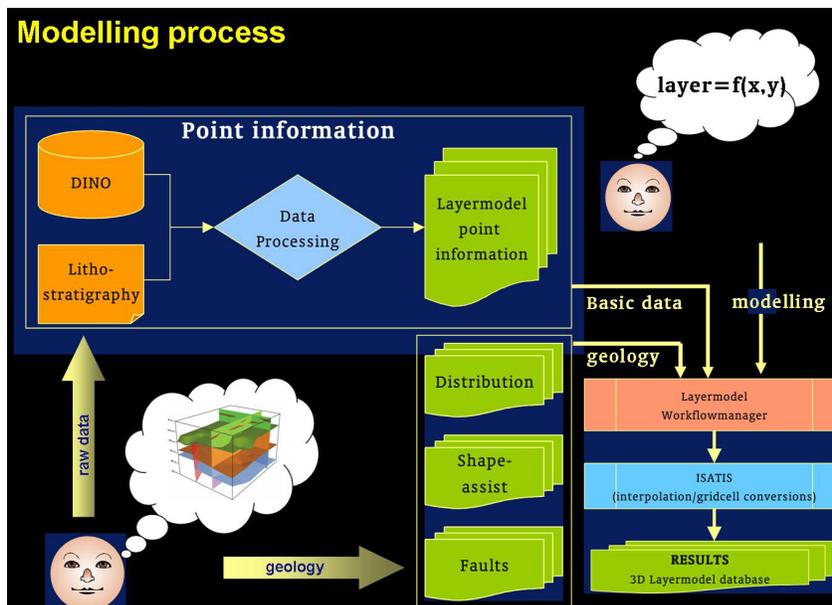


Figure 6. Modeling process

RESULTS AND APPLICATION

The resulting geological model was used for the mapping of the geohydrological properties of the subsurface of the Netherlands. Within the geological framework, aquifers and aquitards were determined and mapped, bounded by the geological strata. This resulted in a nationwide geohydrological model, consistent with the geological framework.

FUTURE WORK

The modeling of the subsurface is now focused on the upper 30-50 m. In this area the most important questions arise, and the pressure on the surface and subsurface is increasing. In modeling we are now building 3D voxel models, in which each voxel represents the most likely facies. The geological framework for this 3D modeling is derived from the 2.5D stacked model, in which the area between the bottom and the top is further refined.

ADDITIONAL INFORMATION

Data and Information of the Dutch Subsurface:

<http://www.nitg.tno.nl/eng/appl/general/214.shtml>

From 2D mapping to a 3D knowledge base for characterisation and modelling:

<http://www.nitg.tno.nl/eng/appl/general/715.shtml>

ESTIMATING THE UNCERTAINTY OF 3D GEOLOGIC MAPS

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End users of geologic maps are increasingly interested in estimates of the uncertainty of the maps to guide them in their application. While traditional geologic mapping methods allow for the integration of geologic insight, they don't provide any tools for the easy estimation of uncertainty in the maps. Geostatistics provides tools for estimating the uncertainty of maps, but most of these methods work on 3D maps that were created using other geostatistical methods. For this study, we were interested in identifying and using geostatistical methods that were compatible with traditionally-generated geologic maps. Our objectives were to identify techniques for estimating the uncertainty associated with 3D geologic maps, and to test these techniques using the 3D geologic map that was developed for Kane County, Illinois.

The 3D geologic map of Kane County (Dey et al., 2005; Dey et al., 2004) includes 12 different lithostratigraphic units. For our study, we evaluated the uncertainty associated with 8 of these units. The units we examined are the thickest and most extensive Quaternary deposits in the map area. These 8 units included the Glasford Formation (undifferentiated), Ashmore Formation, Tiskilwa Formation, sub-Batestown tongue of the Henry Formation, Batestown Member of the Lemont Formation, sub-Yorkville tongue of the Henry Formation, Yorkville Member of the Lemont Formation, and the surficial Henry Formation (undifferentiated). We did not evaluate any bedrock units or Quaternary deposits that are thin or occur in only a few limited areas in the county.

Rather than attempt a rigorous delineation of all the sources and impacts of uncertainty associated with the data and maps from the Kane County project, we focused instead on the uncertainty caused by data distribution, data value variability and the incorporation of a conceptual model into the mapping process. We approached this effort by utilizing a 4-step series of recognized data analysis and simulation tools.

Our first step involved meetings with the geologists responsible for mapping in Kane County. During these meetings we discussed and documented, for each unit, their conceptual models governing the direction of ice movement and the location of ice boundaries. We discussed their understanding of the general depositional framework, and from these discussions we clarified their conceptual model of the type and thickness of sediment distribution and any associated heterogeneities and anisotropies. When appropriate, we divided the county into zones of distinct heterogeneity and anisotropy. These zones were used to better describe and analyze the variability of the deposits due to regionalized differences in data value variability. Some units, e.g. the Batestown Member of the Lemont Formation, were not divided into separate zones. The Tiskilwa Formation, by comparison, was divided into 4 zones.

The second step combined the use of insights gained from Step 1 with spatial analysis tools to evaluate how and where the resulting maps were constrained primarily by the data versus the conceptual models. We recognized that the 3-D map was the expression of the geologists' conceptual model. This meant that to compare the conceptual models to the data values, all we had to do was compare the values within the map to the original data values that were used to define the map. We analyzed the map values and the well data using histograms, semivariogram maps and experimental semivariograms. When a stratigraphic unit had zones delineated from Step 1, we subdivided all of the map and data values into their respective zones before analyzing them. The results from this step revealed that in almost all situations, the thicknesses of units in the map were significantly smoother (less variable from place to place) than the original data indicated. While smoothing was not unexpected, the amount of smoothing provided by the maps was larger than expected. Most of the semivariograms and semivariogram maps displayed very little continuity between the well data thickness values (Figure 1); most were almost pure nugget, or uncorrelated, random distributions even at small distances. The semivariograms and semivariogram maps from the geologic map, however, were much smoother over short distances and in many places showed a range of over 1 mile for the major features (Figure 2). In several situations, there was pronounced anisotropy evident in specific zones on the maps and in their associated semivariograms. The semivariograms from the data in these same zones, however, rarely supported this same interpretation; again most of these semivariograms showed a large amount of variability in the semivariogram values, over short distances. These differences between the maps and the data in these situations indicate that the variability (i.e., heterogeneity and anisotropy) of the maps were due more to the conceptual model of the sediment distributions than the observed thickness values from the original data.

Step 3 involved the application of the area of influence method to the wells that were used for mapping each of the units. This analysis was developed by Singer (1976) to evaluate exploration strategies for mining ore deposits, and Keefer (2002) demonstrated its application to evaluation of uncertainty in geologic mapping. This method is based on the recognition that the spatial distribution of data points 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. To be meaningful, the method must be used in situations where the target is easily identifiable from accurate borehole data. This criterion can be met by thickness data or sedimentologic/textural data. Elevation data will be more problematic since a given elevation is not always clearly indicative of a specific landform feature. In these situations, the targets would be features on a thickness map or distinct sediment assemblages (e.g. sand and gravel deposits within a diamicton sequence). The output maps from this analysis are useful in conveying the relative likelihood of identifying targets of various sizes.

In the fourth step, we developed multiple quantitative estimates of the uncertainty of thickness distributions for each of the mapped units. We used the experimental semivariograms from Step 2 to create model semivariograms for the thickness of each unit. We then used a geostatistical technique called conditional simulation, with a turning bands algorithm, to create 50 plausible thickness maps for each unit. We then ranked these 50 maps based on the cumulative thickness. From the ranked maps, we identified the 10th, 50th, and 90th percentile maps (Figure 3) and we calculated the mean and standard deviation maps of thickness (Figure 4). We used these maps, together, to identify areas that had greater uncertainty due to data distributions and data values. This method was a more sophisticated approach than the area of influence analysis because it accommodated the zonations of the map area and the incorporation of the conceptual model guidelines on heterogeneity and anisotropy within each zone.

While this approach to conditional simulation provided a useful understanding of the bulk uncertainty of thickness for each unit, we found another conditional simulation method that would allow us to evaluate the likelihood that any unit would exceed, or fail to exceed, one or more specific thickness thresholds. For this threshold approach, we first looked at the basic thickness maps for each unit. We then identified between 3 and 5 different thresholds for each unit. We transformed the data using a binary coding for each threshold, and created new semivariograms for the binary data. We used a conditional simulation algorithm called sequential indicator simulation to create approximately 50 different maps for each threshold and each unit. We then compiled these 50 maps to create a single map that expressed the probability that the unit would be greater than the specified thickness threshold. These maps are very helpful in identifying areas of the county where diamicton units are thin or absent, or where sand units might be thickest and most continuous (Figure 5a).

The 4-step approach that we used with the Kane County 3D map allowed us to address the uncertainties within the mapped thicknesses of the Quaternary deposits that were due to data distribution, data value variability and conceptual model impacts. Some of the analyses pointed to conclusions that were common knowledge among the mappers. For example, several of the discrepancies between the map and the data were well known; importantly, some discrepancies we found were not known to the geologists. This approach provided a consistent and objective evaluation that could be used to document these characteristics and identify map areas that showed the most uncertainty.

For the Kane County 3D map, we found that the conceptual models for the individual units were highly structured, and provided specific interpretations on the variability (i.e., heterogeneity and anisotropy) of unit thicknesses. The data points, although densely spaced, were still highly variable in their thickness values and in many places did not clearly support the interpretations of heterogeneity and anisotropy expressed in the conceptual models. Rather than seeing this as an indication of problems with the conceptual models, we felt that this discrepancy indicated the importance of the conceptual models in creating geologic maps that reflected the interpretation of the mappers. We feel the use of conditional simulation in this approach provided a useful means of quantifying the uncertainty surrounding important aspects of the 3D map. The results from the various simulations should also be of value to users of the maps (e.g., planners, groundwater hydrologists) who are interested in identifying areas of high confidence and areas where the confidence is lower and alternate interpretations may be worth considering.

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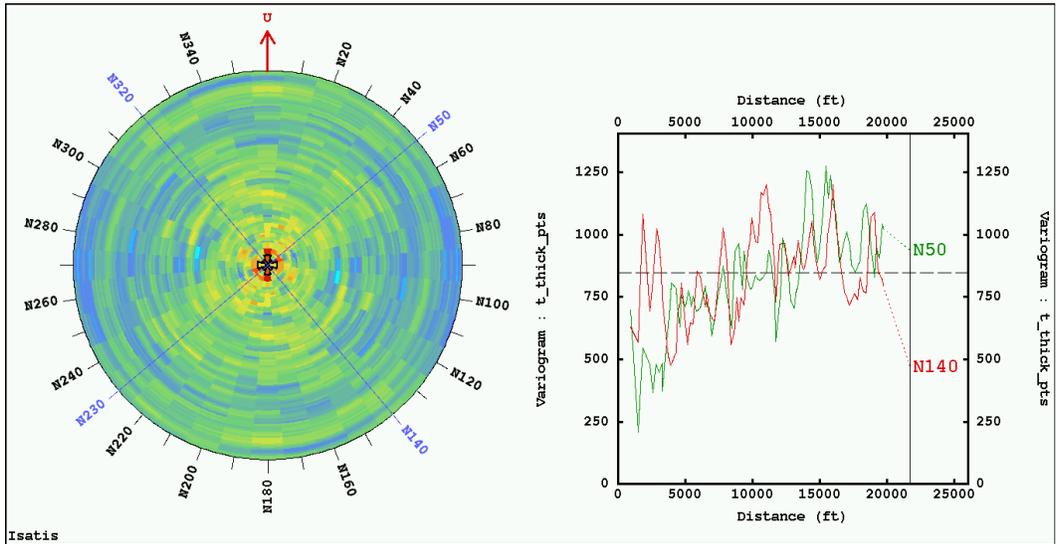


Figure 1. Variogram map and experimental semivariograms of the thickness values from the well data of Zone 3 of the Tiskilwa Formation.

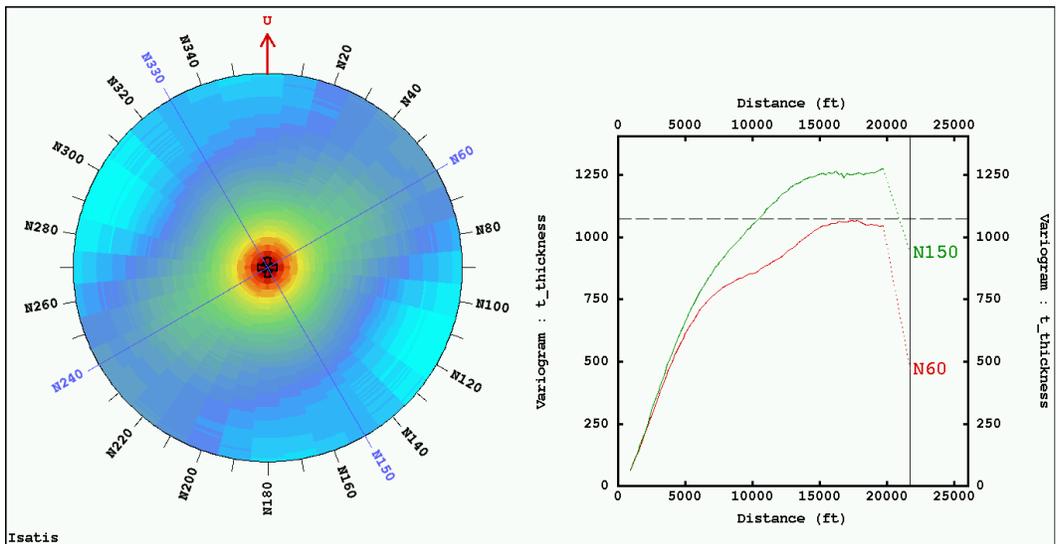


Figure 2. Variogram map and experimental semivariograms of the thickness values from the map of Zone 3 of the Tiskilwa Formation.

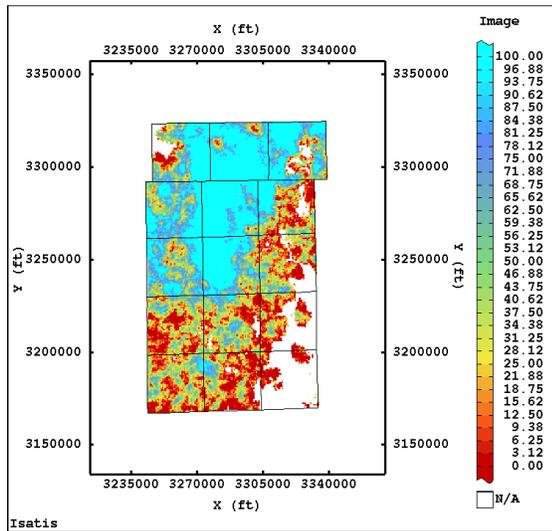


Figure 3. The 90th percentile distribution of the thickness of the Tiskilwa Formation. Color-scale values are in feet.

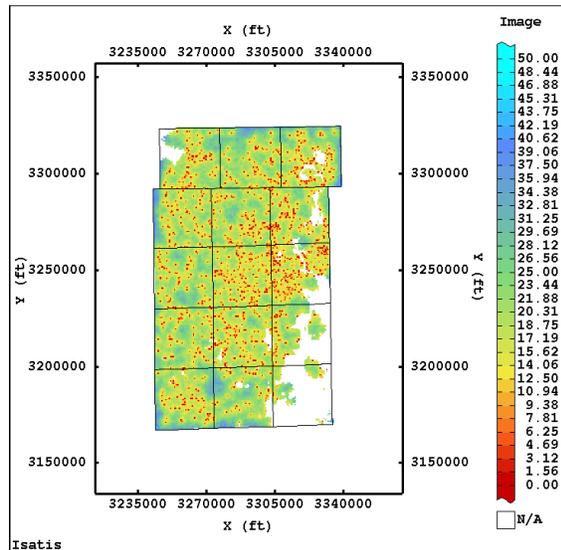


Figure 4. Standard deviation of the thickness of the Tiskilwa Formation, based on 50 separate maps generated using a turning bands implementation of conditional simulation. Color-scale values are in feet

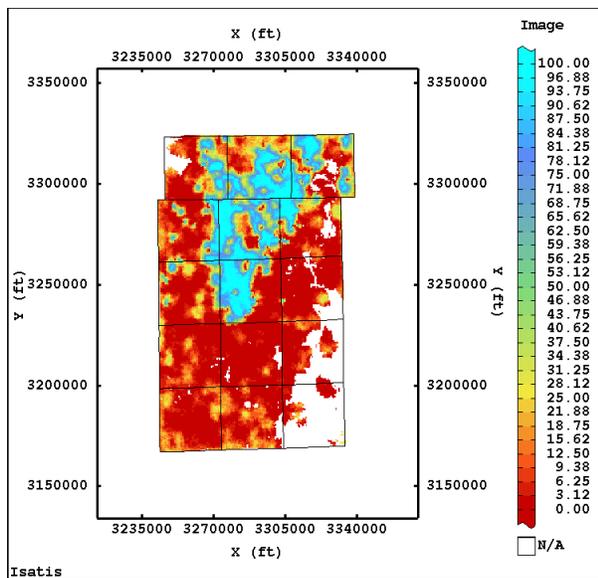


Figure 5. Probability that the thickness of the Tiskilwa Formation will exceed 100 feet thick. Color-scale values are percent probability of exceedance.

3D GEOLOGICAL MODEL OF THE RED RIVER VALLEY, CENTRAL NORTH AMERICA

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INTRODUCTION

The increasing reliance of a growing population on groundwater has precipitated the development of new geological mapping tools and products for better understanding, sustaining, and protecting this valuable resource. Improved access to digital surficial maps, associated soils maps, and digital drillhole databases, as well as digitization and reconciliation of existing paper geological maps and increasing computer power, have given us the ability to produce regional 3D geological models. Starting in 2000, after six years of data compilation, a hydrostratigraphic model was built for the 200 km by 230 km Winnipeg area of southeastern Manitoba (Figure 1). A corresponding groundwater-flow model was completed by Paula Kennedy of the University of Manitoba in 2002. Since then, the 3D geological model has been extended northward to include the Lake Winnipeg basin. As modeling continues, the need for cross-border co-ordination increases. To this end, Co-operative 3D geological modeling projects have been initiated with Saskatchewan; the Williston basin architecture and hydrocarbon potential project, and with Minnesota and North Dakota; 3D geological model of groundwater-bearing strata in the Fargo-Moorhead region (Figure 2). The focus of the Williston basin architecture project is rock units, which will provide a base for continued 3D Quaternary modeling in southwestern Manitoba.

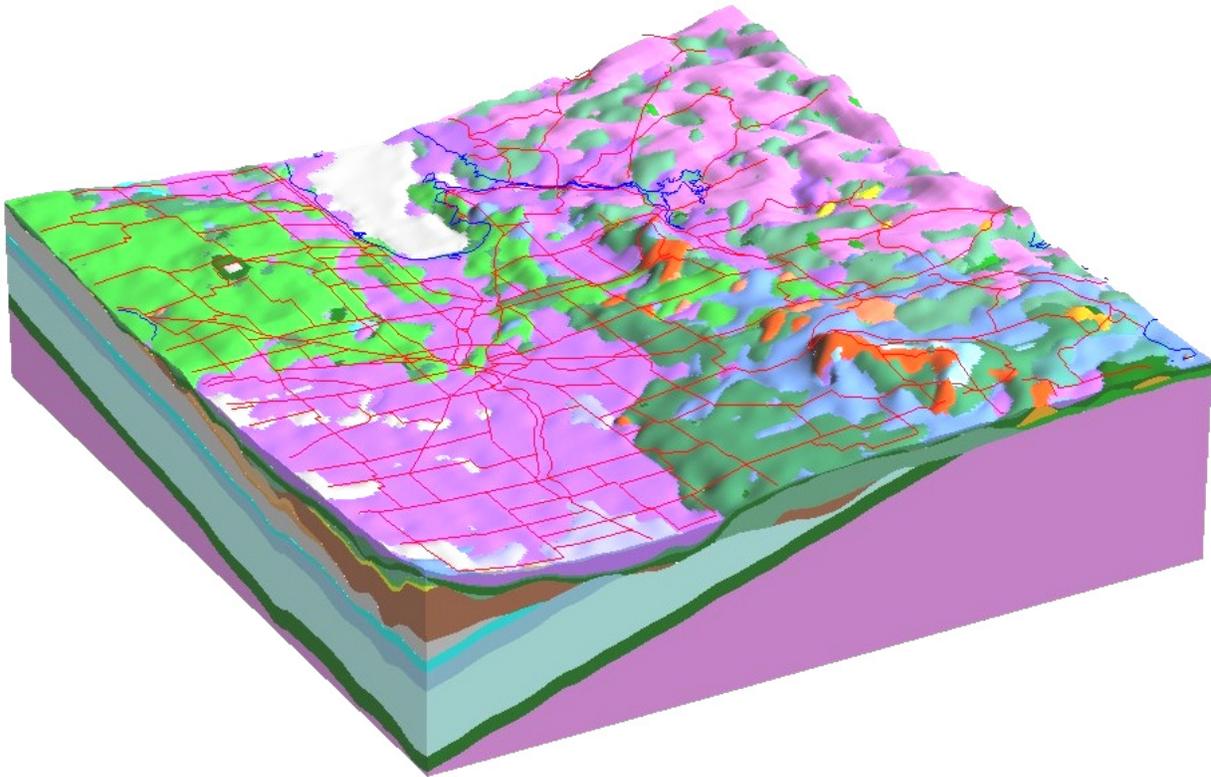


Figure1. 3D geological model of the 200 km by 230 km Winnipeg region.

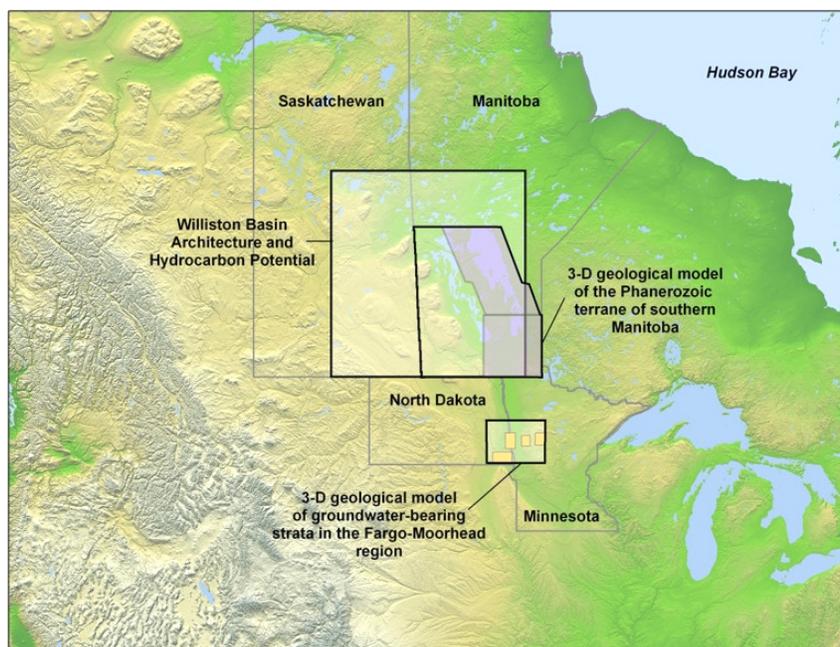


Figure 2. Index map of the three model areas. Small rectangles in the Fargo-Moorhead area are more detailed than the regional model, while the lighter western portion of the southern Manitoba area is currently incomplete. The Williston basin project is in progress.

3D GEOLOGICAL MODEL OF THE PHANEROZOIC TERRANE OF SOUTHERN MANITOBA

In 1990, with funding from Canadian federal and provincial governments, a National Geoscience Mapping Program (NATMAP) project to promote multidisciplinary, computer-based, geological mapping began in southern Manitoba. In association with the Winnipeg region NATMAP project, the Manitoba Geological Survey (MGS) and the Geological Survey of Canada (GSC) co-operated to construct a 3D geological model for all deposits above the Precambrian surface in the Winnipeg region of southeastern Manitoba. As a direct result of this work, the MGS embarked on a larger project to construct a 3D geological model for all of the Phanerozoic terrane in southern Manitoba, an area of 400 km by 700 km, to help guide efforts to protect groundwater resources in that region.

To facilitate modeling, the following datasets were compiled into standardized formats for use in a GIS environment: digital elevation data, initially using geo-rectification data from digital airphotos and gridded at a resolution of 100 m, and then using the Shuttle Radar Topography Mission (SRTM) digital elevation data (DEM) made available in 2003, large lake bathymetry was acquired by digitizing 31,607 soundings from 22 hydrographic charts, which were gridded with shoreline data at a grid resolution of 100 m, offshore geology of Lake Winnipeg which was interpreted from geophysical and coring data collected during two Coast Guard ship cruises, surficial geological maps, digitized and reconciled to guide 3D modeling of the uppermost strata, cored holes logged by geologists, stacked 1:1 million bedrock polygons for the Phanerozoic rock units, geophysical land surveys, and water well data from 80,000 sites. The 200 km x 230 km Winnipeg region was divided into 46 transects each 5 km wide. Large colour charts, 91 x 132 cm, were printed for each transect, showing all geological data available for the transect area (Figure 3). The drillhole data were correlated lithostratigraphically by a geologist, the correlation was digitized at 5 km spacing, the digitized data were entered into a database comprising regularly spaced, virtual drillholes, and the drillholes were modelled in gOcad.

WILLISTON BASIN ARCHITECTURE AND HYDROCARBON POTENTIAL

The stratigraphic framework and hydrocarbon potential of the Williston Basin are currently being re-examined in southwestern Manitoba and southeastern Saskatchewan as part of the Williston Basin Architecture and Hydrocarbon Potential Project. This two-year collaborative program involves Saskatchewan Industry and Resources, MGS, Natural Resources Canada, the University of Alberta, and the University of Saskatchewan. The primary objective of this Targeted Geoscience Initiative project is to develop an integrated geoscience dataset incorporating new stratigraphic data, hydrogeological mapping, seismic, gravity and aeromagnetic information, and remotely sensed imagery over a large area encompassing the Phanerozoic succession of the northeastern Williston Basin. To enhance our knowledge of subsurface mineral (e.g. brines and potash) potential and hydrocarbon migration and

entrapment, a seamless 3D geological model of Paleozoic- and Mesozoic-aged rocks from subsurface to outcrop for the area will also be developed.

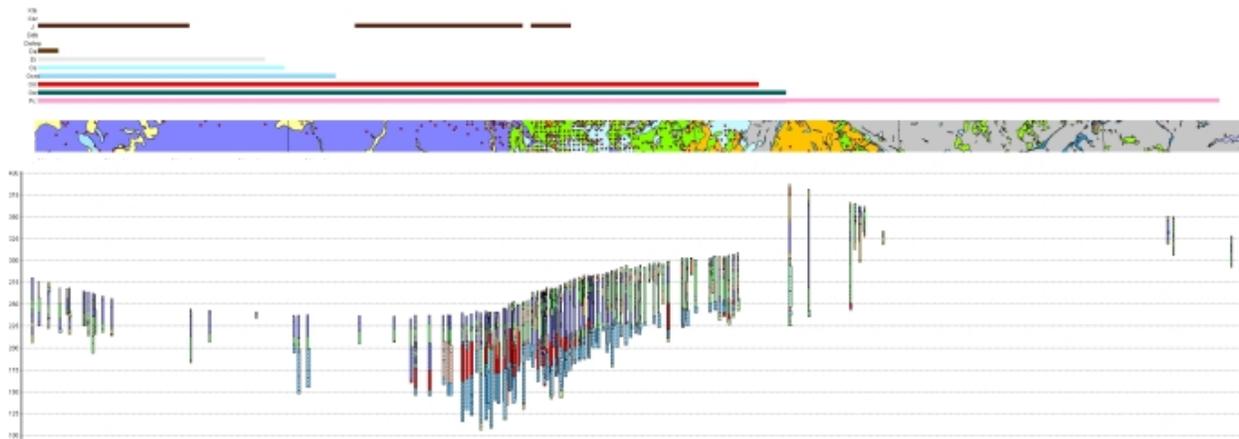


Figure 3. Typical 5 km east-west transect in the Winnipeg region, showing rock unit extent across the top, surficial geology and drillhole locations in the middle, and subsurface data (primarily drillhole data) in profile view below.

Whereas the drillhole data in the southern Manitoba project was screened through the geological interpretation of 5 km transects, drillhole data in the Williston basin project is being screened directly, by re-logging five to eight deep, stratigraphically significant drillholes per township (10 km by 10 km). These screened drillholes

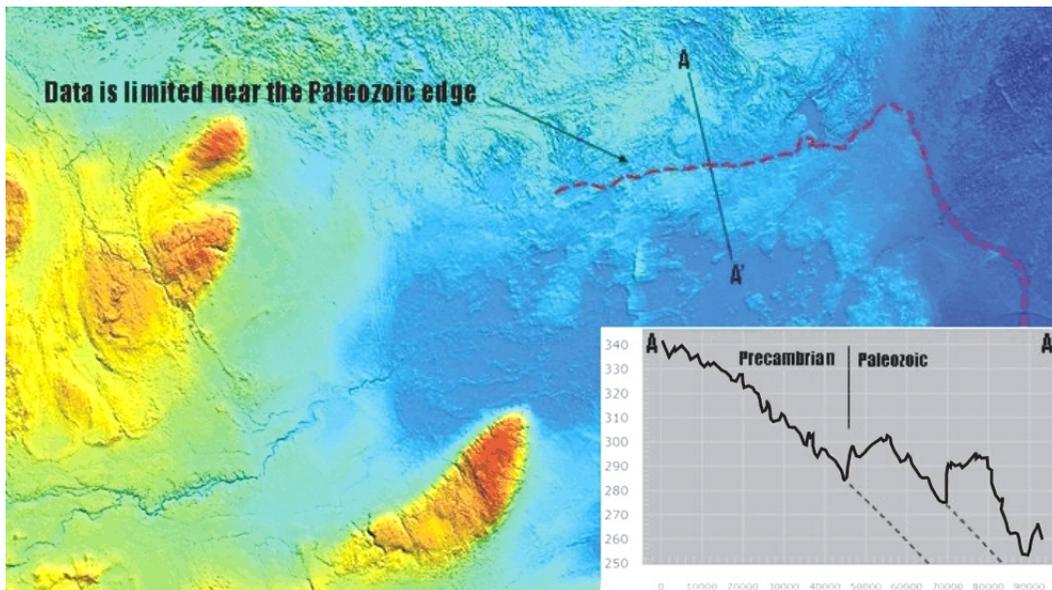


Figure 4. In the absence of drillhole data, the edges of Phanerozoic rock units can be controlled, in the 3D model by projecting the plunge of the Precambrian surface into the sub-surface and measuring the unit thickness and elevation.

will then be used to generate the 3D model in gOcad. The problem with this method is that drillhole data is not always available where you need it. In this case, in the fringe areas of the Phanerozoic terrane, there is very limited drillhole data; not enough data to control edge effects. To resolve this issue, cross-sections were drawn at regular intervals across the problem areas through the SRTM DEM. These cross-sections show the local plunge of the Precambrian surface, and in conjunction with the known limits of the Phanerozoic rock units, allowed us to estimate unit thicknesses (Figure 4).

3D GEOLOGICAL MODEL OF GROUNDWATER-BEARING STRATA IN THE FARGO-MOORHEAD REGION

To provide the broad overview of the groundwater sources across the region required for the environmental impact statement for the Red River Valley Water Supply Project, the Minnesota Geological Survey, in co-operation with the Minnesota Department of Natural Resources, the North Dakota Geological Survey, the North Dakota State Water Commission, the US Department of the Interior, Bureau of Reclamation, and the US Geological Survey, has developed a 3D model of currently utilized and potential aquifers and their associated sediments and sedimentary rocks in the Fargo-Moorhead area (Harris et al., 2005).

The 3D geological model encompasses an area of 166 km by 228 km at a regional scale, including four smaller, more detailed areas (Figure 5). Data inputs include: published and unpublished surficial geology maps, a lithostratigraphic database which has been classified using cluster analysis based on textural and lithologic information from 6,533 sediment samples, 30,000 drillholes from North Dakota and Minnesota which were standardized into one database, 60 Quaternary stratigraphic reference sites with formally defined stratigraphy, a newly defined bedrock surface, and bedrock geology. The lithostratigraphic database allows for the definition of the finer-grained stratigraphic units, mostly till, which enclose the sand deposits, and in turn allows the geologist to define the enclosed aquifers.

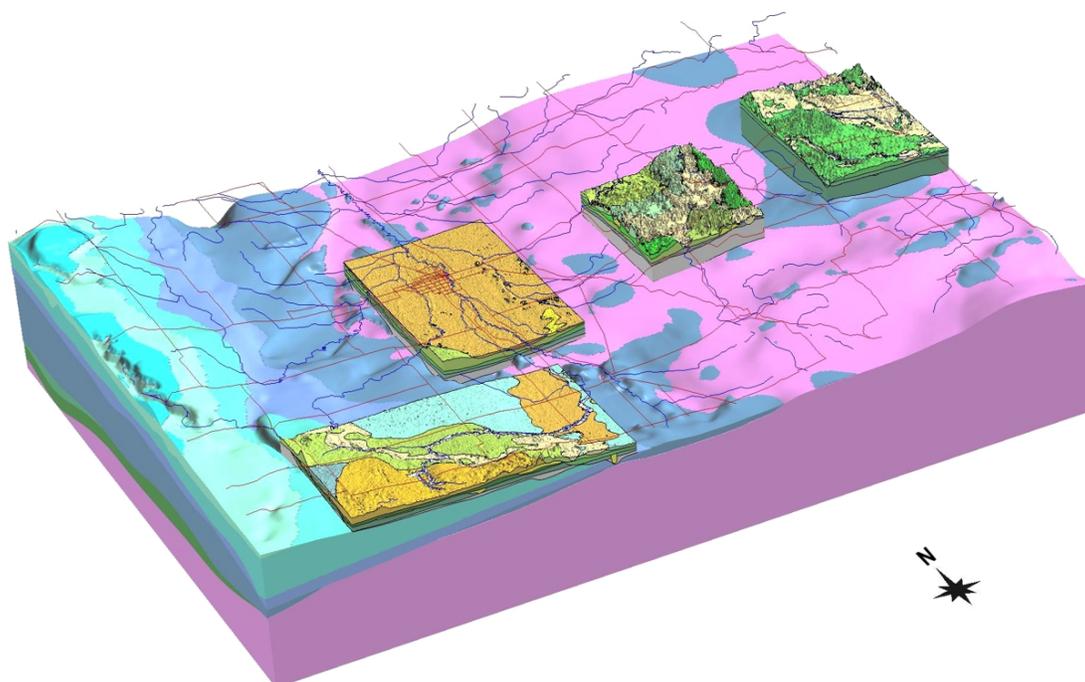


Figure 5. Perspective view of the Fargo-Moorhead model showing bedrock strata at a regional scale and Quaternary stratigraphy of the four detailed areas.

The regional model is based on transects spaced at 5 km which were scanned and registered in 3D space using gOcad software. Once registered, the unit contacts from the transects were digitized and used to create 3D surfaces. Adjacent unit tops were then joined to form hollow solids. The same procedure was used for the four detailed areas; however, the transect spacing in the detailed areas varied from 0.5 to 4 km, depending on the density of sub-surface data, making possible the identification of aquifers larger than 1 km in extent. In this manner, 130 sand deposits were defined in 3D from known and potential aquifers. Plans are being developed to populate the 3D model with such hydrological characteristics as water chemistry to enable us to better understand the connectivity between sand deposits and thereby better manage the resource.

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3D GEOSCIENCE MODELS AND THEIR DELIVERY TO CUSTOMERS

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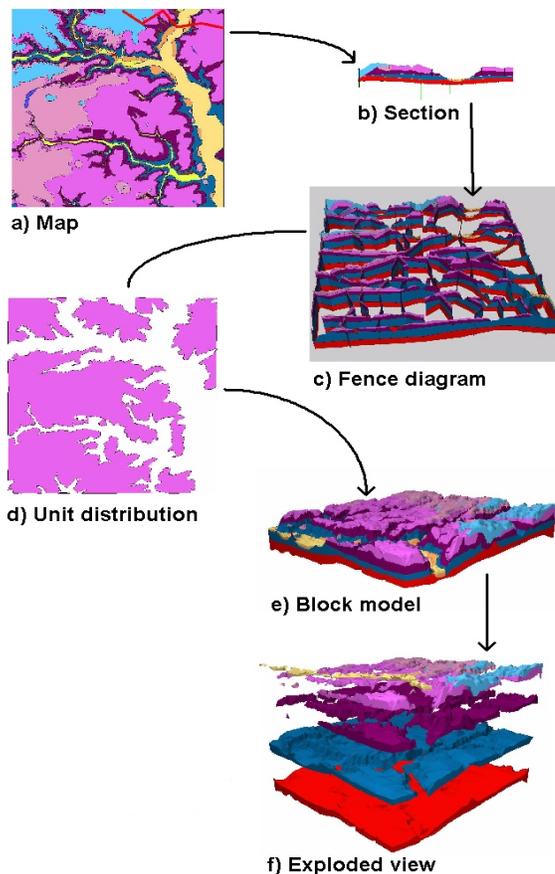
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BACKGROUND

Over the past few years, the creation of systematic three dimensional (3D) geological subsurface models has become standard practice of national Geological Surveys. The methods for construction of 3D models are well documented (e.g. Hinze et al., 1999; Sobisch, 2000; Kessler et al., 2004) and software tools like GSI3D (Geological Surveying and Investigation in 3 Dimensions; ©INSIGHT Geologische Softwaresysteme GmbH) use section-building techniques that are familiar to all geologists. (Kessler and Mathers, 2004)



The GSI3D method utilizes a digital terrain model, geological surface linework and downhole borehole data to enable the geologist to construct regularly spaced, intersecting cross sections. These are combined in a fence diagram (Figure 1, a-c) which displays the correlation of individual units and their lateral extent in the subsurface. Mathematical interpolation between nodes that define the base of each unit produces a solid model comprised of a series of stacked triangulated objects corresponding to each of the geological units present (Figure 1d-f).

Geologists interpret their sections based partly on factual information where the borehole information and correlation is secure and partly on geological experience - the shape 'looks right'. This 'looks right' element pulls on the modellers' wealth of understanding of geological processes and knowledge gathered over a career in geology. For example, something observed in sediments at the margin of a glacier in Iceland might well influence the way a geologist draws the base of a till unit on a geological section in Scotland. In a fluvial environment, the erosive power of a river in flood might inspire the geologist to draw a scoured base to a braided river deposit.

Figure 1. GSI3D workflow (Kessler and Mathers, 2004)

Following 5 years of research into systems and methods for 3D modeling the BGS has now embarked on a campaign to systematically build 3D models, at various scales, and to national standards across the entire country. The task, known as LithoFrame, will be organised regionally and linked to local and national environmental and development policies. The LithoFrame concept is described more fully on the BGS website <http://www.bgs.ac.uk/science/3dmodelling/home.html>

The LithoFrame models will be structured and attributed to meet the needs of a wide range of applied users, and ultimately, may take the place of the traditional geological map. However, this will only happen if the models are accessible, can be delivered to the user community at realistic costs, and the underlying databases are maintained to

allow rapid model update. The following table lists some of the main customers and related outputs from a standard 3D geological model.

Table 1. Typical customers and products of systematic 3 dimensional models

Water Industry and Environment Agency Sections with hydrostratigraphical attribution, grid export of thicknesses and bases of aquifers and aquitards for groundwater flow modeling.
Minerals Industry Isopachytes of resources and overburden, predictive boreholes.
Town Planners and Civil Engineers Maps of unstable ground, subsurface maps for planning excavations, sections along roads and tunnels.
The Public and Academia Standard geological maps, 3D geological animations, exploded views.

RECENT APPLICATIONS

The principal application for 3D modeling in Britain is for groundwater protection and management. The main driver is the EU Water Framework Directive (European Parliament, 2000), which has clear objectives to improve the status of all waters (surface and subsurface) and to reduce the pollution of these waters by hazardous substances. In implementing this Directive, there is a recognition by both water companies and the regulator that the 3D geological model has an important role in conceptualising the geological setting of the aquifer and determining surface-groundwater interactions.

The following are examples of three recent projects commissioned to solve problems in groundwater management and abstraction licensing as well as town and environmental planning.

The first 3D model (Ford et al., 2003) was commissioned by the Environment Agency (EA) York, north-east England, in order to aid regional groundwater modeling and gain an overview of the Quaternary deposits overlying the Triassic Sherwood Sandstone Group, one of the UK's major aquifers. The Vale of York is filled with up to 25 m of thick clay and silt deposited in an ice dammed a glacial lake formed during the Last Glaciation by meltwaters draining to the North Sea. Several regional sections were constructed using boreholes coded according to their lithological properties. Figure 2 displays the 40 x 60km large open fence diagram coloured by a) lithostratigraphy and b) hydrostratigraphy. These sections formed the main part of the deliverable to the client.

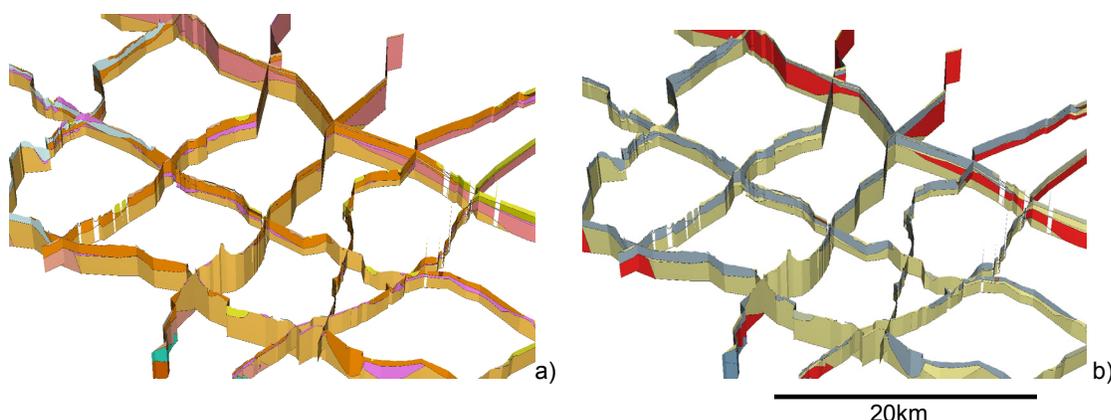


Figure 2. Regional fence diagram (Ford et al 2003) showing clayey deposits in grey and sandy deposits in yellow overlying sandstone aquifer in green and non-aquifer in red.

The second example is a full geological block model of 100 km², commissioned by the EA in Warrington, north-west England (Kessler et al., 2004). The main focus of the study was Trafford Park one of the biggest industrial estates in Europe. There are important issues of over-abstraction, contaminated land, surface sealing and waste water treatment. A critical part of the study was an examination of the hydrogeological role of the Manchester Ship Canal, a major waterway that links Manchester to the Irish Sea. The geological setting is comparable to the Vale of

York with the Sherwood Sandstone aquifer, here covered by up to 50 m of glacial and post-glacial deposits (outwash sand, till, lacustrine clay and alluvium). Man-made deposits (canal dredgings, colliery spoil) are a ubiquitous feature of this heavily industrialised area (Bridge, 2004). The full block model of the superficial deposits enabled the construction of customer-defined sections, annotated with the groundwater piezometric surface in the Sherwood Sandstone aquifer. Figure 3 displays one of these sections along the Ship Canal. The user can clearly assess in which areas the canal may be in direct contact with the aquifer and where clayey deposits such as till or lacustrine sediments may be forming a barrier to contaminant flow. A second major deliverable of this project was the creation of an aquifer vulnerability map (Figure 4). This map was created by GIS calculation directly from the model, following classification of the system into hydro geological domains. The client was also provided with the tops and bases of all geological units as grids for use in quantitative groundwater flow modeling.

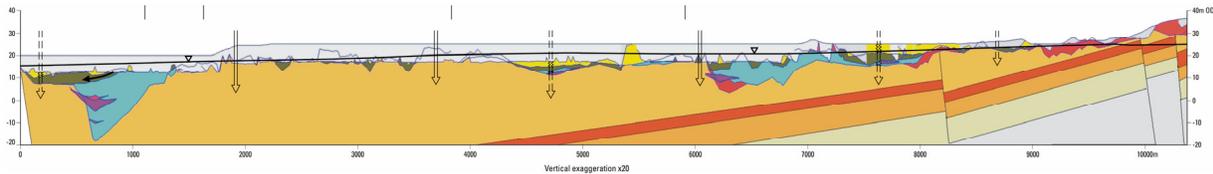


Figure 3. Synthetic section (8 km) along the Manchester ship canal showing areas of direct and indirect potential recharge and the groundwater piezometric surface in the Sherwood Sandstone aquifer. (Kessler et al 2004)

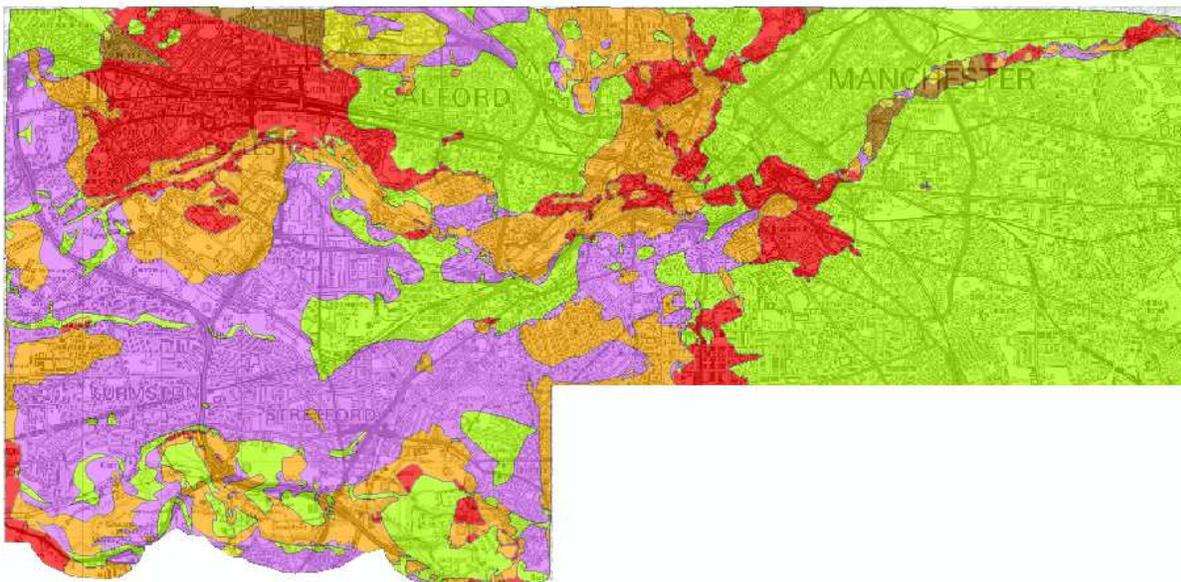


Figure 4. Hydrogeological Domains, red: high recharge potential, green: low recharge potential, purple: possible perched aquifer (Kessler et al 2004)

These 2 examples have illustrated the most common requirements of the hydrogeological community. They highlight the diversity of formats, scales and interpretations demanded from the standard geological framework model. In order to deliver the full richness of the models and its attributes avoid inefficiency in data handling a cheap and simple to use viewing system had to be found which must allow the client to interrogate the model without specialist knowledge.

The final example is from work carried out in collaboration with Glasgow City Council, where a standard LithoFrame model has been commissioned to assist the town planners with everyday decision making. Using cutting edge viewing and delivery software the model and its attributes are encapsulated together with maps and the software in one single file and can then be distributed by the customer in an unlimited way. Figure 5 displays this 5 by 5 kilometre tile of 3D geological data. The software enables the user to create predictive drill logs and vertical and horizontal sections, contoured views of all geological units, as well as subcrop and supercrop maps. All data can be exported as images and GIS compatible files (polygons and contour lines). The 3D window enables the full view of the geology with moving sections and exploded views. These views have long been the dream of geoscientists and truly help to communicate the geological vision to experts and laymen alike.

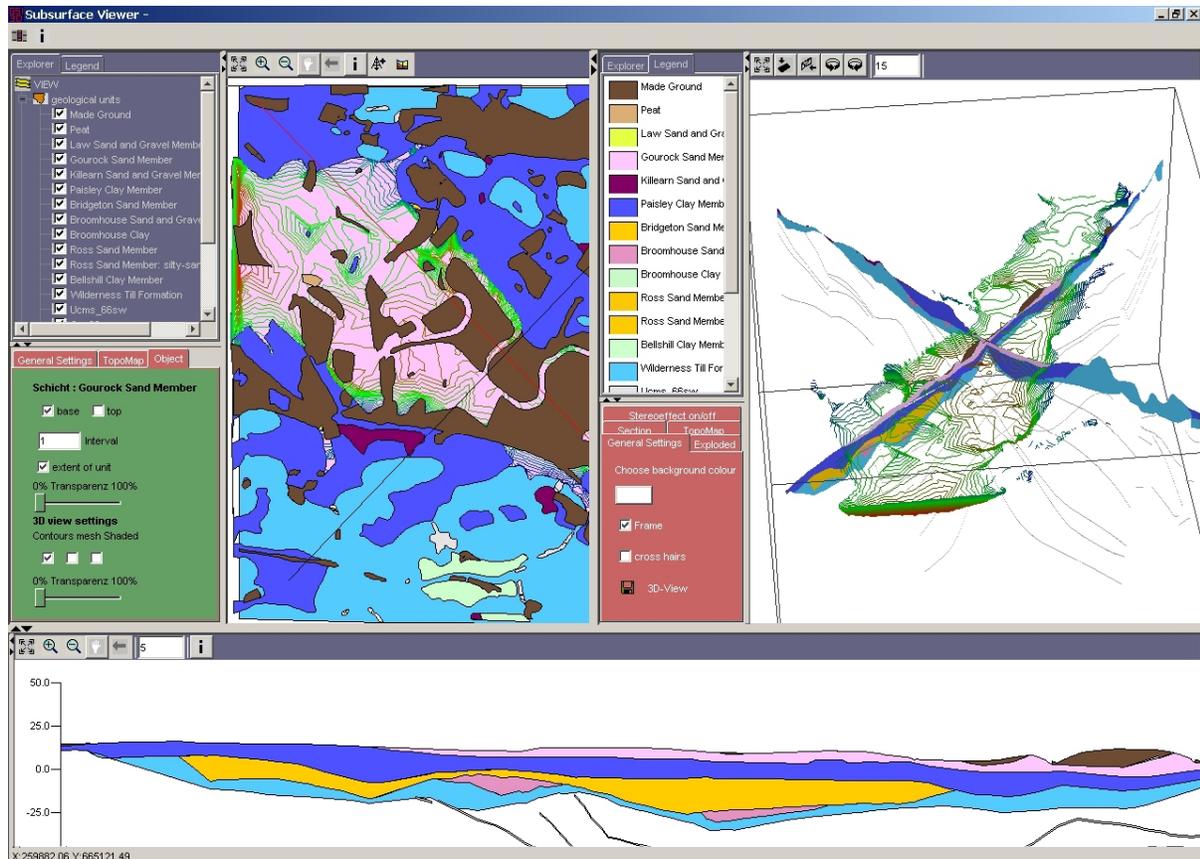


Figure 5. The user interface of the 3 dimensional geological map of the city centre of Glasgow, showing examples of contouring, synthetic sections and 3D views of the model. (SUBSURFACE VIEWER © INSIGHT)

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MAKING THE MOST OF WHAT YOU'VE GOT: CREATING 3D SUBSURFACE MODELS WITH DATA OF VARYING QUALITY

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INTRODUCTION

There have been significant technological advances in 3-dimensional (3D) subsurface geologic modeling in recent years allowing for a variety of modeling techniques to be developed that provide the ability to model relatively large data sets in regions underlain by complex geology. However, the accuracy and reliability of model outputs are still constrained by the quality of input data and the spatial analytical techniques used to visualize and analyze these data. The choice of modeling techniques used is dependent largely on the purpose of the project, the nature of available input data, expertise of personnel and time constraints. This presentation will discuss three types of 3D subsurface modeling applications and their relative advantages and limitations. The first is a basic model application using digitized data from readily available sources such as regional water well databases and is most effectively applied in areas underlain by relatively simple 'layer cake' stratigraphies. The second involves creation of an integrated database by the addition of information taken from geotechnical reports, highway construction reports and outcrop descriptions and may also involve the application of a variety of spatial analytical techniques to improve model output. This method is most appropriate for use in areas underlain by complex stratigraphies. Finally, the quality of model output can be greatly improved by the implementation of various filtering techniques in areas where simple spatial interpolation of data points produces erroneous results due to the presence of geological barriers such as faults, escarpments and large surface water bodies.

BASIC MODELING TECHNIQUE

In many areas of North America a rich repository of regionally extensive subsurface geological information exists in water well databases (e.g. the Ontario Ministry of the Environment water well database, the Water Branch of Manitoba Conservation database, the Ministry of Water, Land and Air Protection water well database). These datasets are available in digital form and are readily transferable into usable database format for rapid data entry into a 3-dimensional modeling software package (e.g. Rockworks, gOcad, TrapTester, etc.). It is important to note, however, that although water well databases can offer a large quantity of data, there are limitations to the distribution and quality of data they contain. Data coverage is focused in rural areas and may be patchy, concentrating particularly along roads. Many of the records are relatively shallow and rarely extend to bedrock, as the wells are generally drilled only to depths sufficient to penetrate productive aquifers. Data quality is a particular concern with water well databases as drillers do not always apply consistent terminology to describe sediment texture and the depth of textural changes may not be accurately recorded. In addition, well location may be difficult to establish for older records in the absence of GPS data. To reduce the number of erroneous data points incorporated into the 3D subsurface model, a water well database can be queried to isolate only the more reliable wells. For example, the Ontario water well database has two reliability codes assigned to each well; one is for the overall quality of the log, and the other is for the accuracy of the elevation measurement. The code is a value between 1 and 9 with a value of 1 representing low accuracy and 9 being highly accurate. It is important that only wells with reliability codes of 9 for both the overall quality and elevation accuracy be used to create the model.

In order to accurately identify texturally distinct stratigraphic units from a water well database, it is important to construct a number of cross sections through the study area using selected data points. These cross-sections should be closed whenever possible (i.e. start and end at the same well) in order to check that individual units are correctly identified and are laterally consistent. This is an essential step in the modeling process as incorrect stratigraphic classification of units can dramatically affect model output.

Once the selected data are organized in a database that is compatible with the modeling software, it is possible to run a model for basic applications using default settings to interpolate between data points (e.g. Rockworks v.2002 uses the inverse distance method of interpolation). In areas where there is some understanding of subsurface geological conditions, model output can be improved by changing the default settings to better reflect spatial trends. For example, if the area is thought to be underlain by features with some directional trends (such as buried valleys or shorelines) it is appropriate to run the model using the directional weighting or kriging algorithm. Cross-validation of the model output can be done by manually checking individual borehole records from selected sites in the study area.

This type of basic 3D subsurface modeling is most appropriate in areas underlain by relatively simple stratigraphy (Fig. 1A), essentially comprising of stacked planar tabular ("layer cake") geologic units. The most common problem with relying on water well data as the only data source is the variable quality of input data and requires that erroneous points or 'outliers' are carefully identified and removed. Some modeling programs (e.g. Rockworks v.2002) contain algorithms that provide information specifically about data quality. These algorithms include 'distance to point' which identifies spatial locations of poor data coverage, and 'trend residual' which identifies extreme highs and lows within the dataset. These algorithms should be run on the dataset prior to the creation of a model. The major advantage of using a basic approach to subsurface modeling is that models can be produced relatively quickly.

INTEGRATED DATABASE TECHNIQUE

A more sophisticated form of 3D subsurface modeling involves the integration of a number of different data sources to create a more comprehensive database. This is recommended for study areas underlain by complex stratigraphy that include such features as unit pinch-outs, channels or irregular geometries (Fig. 1B). Subsurface geological data can be obtained from geotechnical reports from engineering and construction projects, the Ministry of Transportation, geological surveys and urban geology databases compiled by government agencies (e.g. the Urban Geology Database of Hamilton, Ontario). Data obtained from these sources often requires digitizing prior to integration into a master database that may already include water well data. The major limitations of these sources of data are that they have patchy and uneven distributions, and are focused predominantly along highways or in urbanized areas. If feasible, primary geological data collected from surface outcrops or boreholes are a valuable and reliable addition to such a database and may be weighted more heavily in some programs as 'Golden Spikes'. A broad understanding of the geological history of the region can also greatly improve the delineation of stratigraphic units to be used in the model as textural units may either be combined or subdivided according to their depositional origin. This background geological knowledge can also be used to guide decisions regarding the choice of suitable algorithms with which to interpret the data. In Rockworks v.2002 algorithms include closest point, directional weighting, inverse distance, kriging, multiple linear regression, trend polynomial, triangulation, and hybrid algorithm. In situations where subsurface units show considerable spatial variability (Fig. 1B) multiple models should be created using a variety of algorithms in order to determine which one produces the most realistic representation of the subsurface stratigraphy. Manual checking of the model output with selected data points is also recommended to ensure consistency with the known geological history of the area.

APPLICATION OF MODEL FILTERS

The most sophisticated method of 3D subsurface modeling is necessary in areas underlain by complex stratigraphy that include significant geological boundaries such as major faults, escarpments, and lake basins (Fig. 1C). In order to effectively model the 3D subsurface stratigraphy in such situations, a variety of filtering procedures need to be implemented to allow more accurate extrapolation of data. The types of filters applied to the model are dependent on the nature of the boundaries and characteristics of the study area and include distance, grid, range, rounding, smoothing and polygon clip filters. For example, the polygon clip filter may be used to remove part of the study area, such as a lake basin where data are sparse or non-existent, from consideration by the model. Appropriate application of filters significantly increases the accuracy of the model output and improves the reliability of 3D models in areas where subsurface stratigraphy are affected by major geologic boundaries.

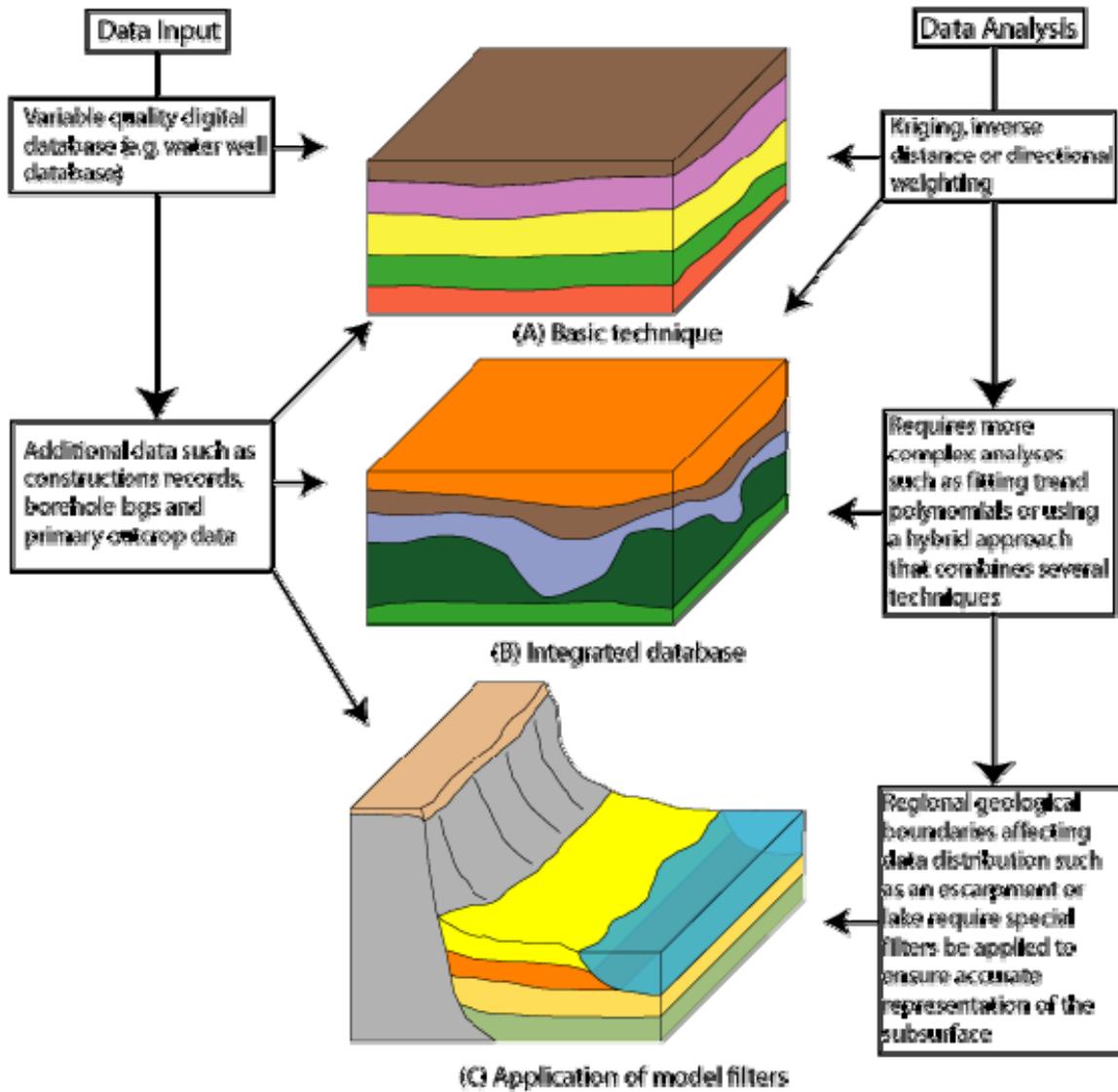


Figure 1. Schematic diagram showing types of data input and analysis required for different 3D subsurface modeling applications.

THREE-DIMENSIONAL GEOLOGICAL MODEL OF POLAND AND ITS APPLICATION TO GEOTHERMAL RESOURCE ASSESSMENT

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INTRODUCTION

Poland is located in Central Europe between the Baltic Sea and the northern part of the Carpathian Mountains. The NW-SE Teysere-Tornquist tectonic zone runs across Poland, separating the East European Craton from Paleozoic Europe. Along this zone, a Permian and Mesozoic sedimentary basin has developed in the Polish Lowlands as the SE part of the Danish-Polish basin, consisting of a sequence of deposits whose thickness has been estimated as up to 7000 m. During the second part of the past century, extensive exploration for oil and gas in this area resulted in completion of several thousand deep drillholes and seismic profiles that were used to construct detailed lithostratigraphic and structural analyses. Subsurface models of bedrock geology were created, such as horizontal slice maps (Kotanski, 1997), and isoline maps of lithostratigraphic horizons (Sokolowski, 1987). These models, created using previously available subsurface mapping methods, effectively depicted deep geology, including complex structures. The limitations of the methods, however, resulted in inconsistencies based in most cases on differing map scales and projections, as well as uncertainty in the location of drillholes. This previous generation of models has, however, served as the basis and inspiration for a new three-dimensional (3D) geological model of Poland (Figure 1) that is now being used for many applications, including geothermal resource assessment.

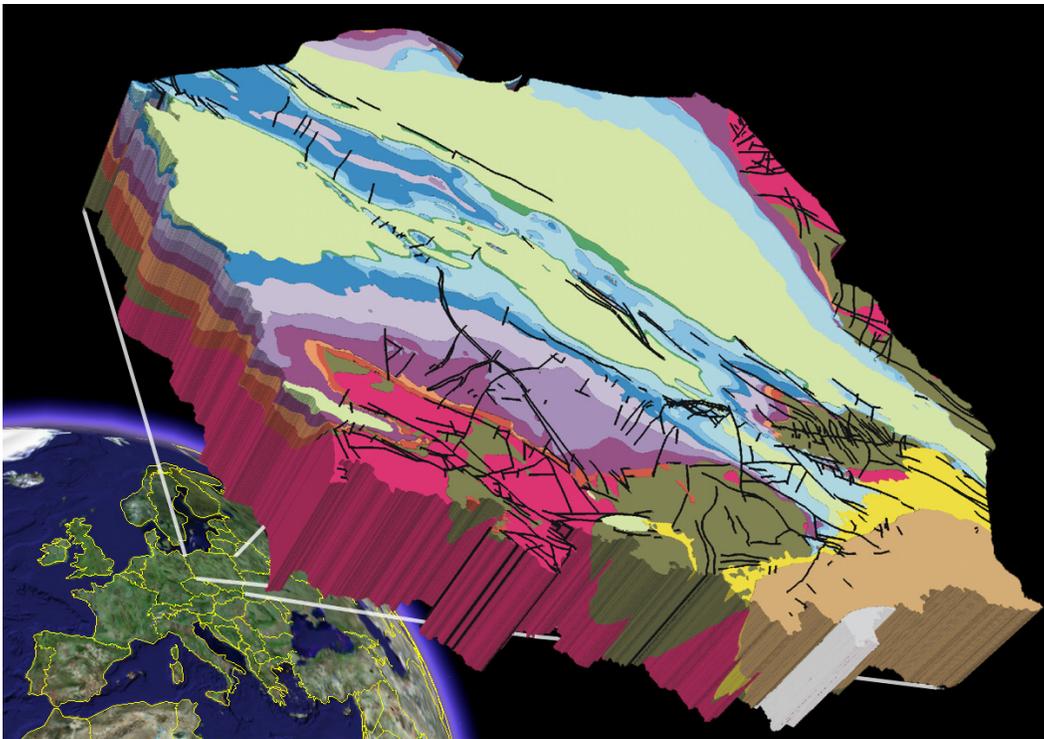


Figure 1. 3D, digital geological model of Poland for the depth interval from -500 to -6000 m (Piotrowska, et al., 2005); see figure 3 for color legend.

3D GEOLOGICAL MODEL OF POLAND

For some time, the escalating availability of subsurface geological data collected in or converted to digital formats and stored in large databases has required development of new methods for processing and visualization. Previously, however, these data commonly lacked information on their elevation. In recent years, 3D geological mapping has therefore come into more common use, and new techniques for multidimensional mapping in geological

cartography have been extensively utilized for detailed mapping. Regional-scale models remain, however, limited in their development, due in part to the challenges presented by construction of high-resolution grids that depict structural, lithologic, and stratigraphic features whose scale ranges widely (Malolepszy, 2005). The methods presented here therefore are being developed to deal with this challenge, and concurrently to deal with the need for regular grid techniques using data of variable quality and quantity.

The current 3D geological model of Poland, developed by the Polish Geological Institute and the University of Silesia (Piotrowska, et al., 2005), is one of the first country-scale models in Europe. It was built using regular grid solids with a horizontal resolution of 500 m, a depth interval from -500 to -6000 m, an extent of 649 km from north to south and 689 km from east to west, and an area of 312,000 km². Previously completed horizontal slice, tectonic structure, and isoline subsurface maps as well as cross-sections were used for model construction (Figure 2). A filtered drillhole database with nearly 9000 records was used as the major source of data for new interpretations and refinement of the compiled materials. Depicted stratigraphy was simplified to the subsystems of the Permo-Mesozoic sequence, and older rocks were divided into Paleozoic and Precambrian sedimentary rocks and crystalline basement (Figure 3). Current plans call for refinement of the model to a higher horizontal and vertical resolution.

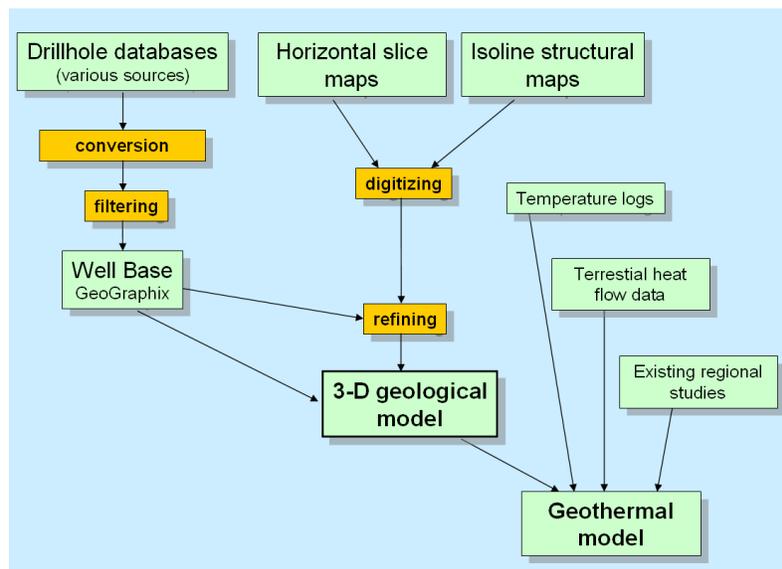


Figure 2. Data sources and workflow chart for the 3D geological model of Poland

GEOHERMAL RESOURCES OF POLAND

Both detailed and regional 3D geological models have recently been increasingly used for application to natural resource assessment and management. In addition to their principal use in petroleum exploration, significant advances in multidimensional geological mapping have occurred in the field of mineral resource and groundwater exploration. These applications have required incorporation of large databases of geological, geophysical and hydrogeological data into 3D geological models. Methods developed for subsurface analysis of oil and groundwater resources are now being extended for application to geothermal resource assessment. The distribution of reservoir and petrophysical rock properties, as well as thermal regime of rock units, are a significant factor for assessment of geothermal reservoirs as a potential source of renewable energy. Regular grid solids created in a 3D model can be converted into a tetrahedral mesh for finite element modeling of reservoir properties as well as complex mass and heat flow analyses. Thus, application of 3D geological modeling in hydrogeology of geothermal waters is becoming increasingly important in natural resource assessment.

A geothermal model therefore has been developed on the basis of the current 3D geological model of Poland. This model has been used to assess potential geothermal energy resources to a depth of 5000 m. The formation temperature distribution in the range of 8 to 180°C, and terrestrial heat flow density in the range of 20-95 mW/m², were interpolated from well and surficial measurements. Reservoir and petrophysical rock properties were used to characterize the thermal and hydrogeologic regime of rock units. Formations characterized by positive thermal anomalies and relatively high porosity and permeability were selected as having potential for geothermal exploration, and detailed maps of their formation temperature and geothermal gradients were extracted from the

3D property model (Figure 4). These maps show the close relationship between geologic structures and geothermal anomalies, thus drawing attention to the critical need for optimal 3D geological mapping in the field of natural resource assessment.

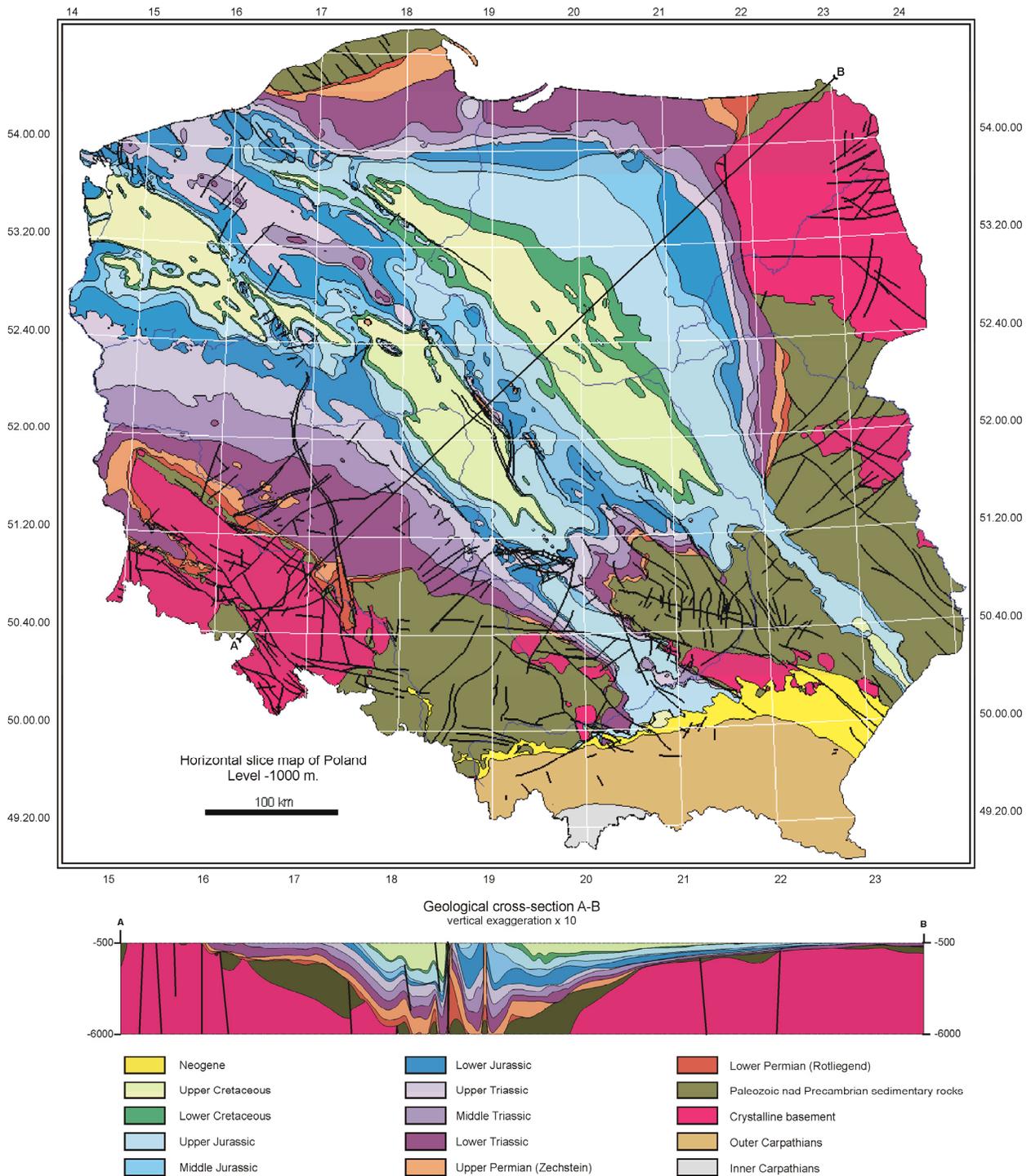


Figure 3. 3D geological model of Poland presented as a horizontal slice map for -1000 m and as a cross-section orthogonal to the axis of the Polish Lowlands sedimentary basin.

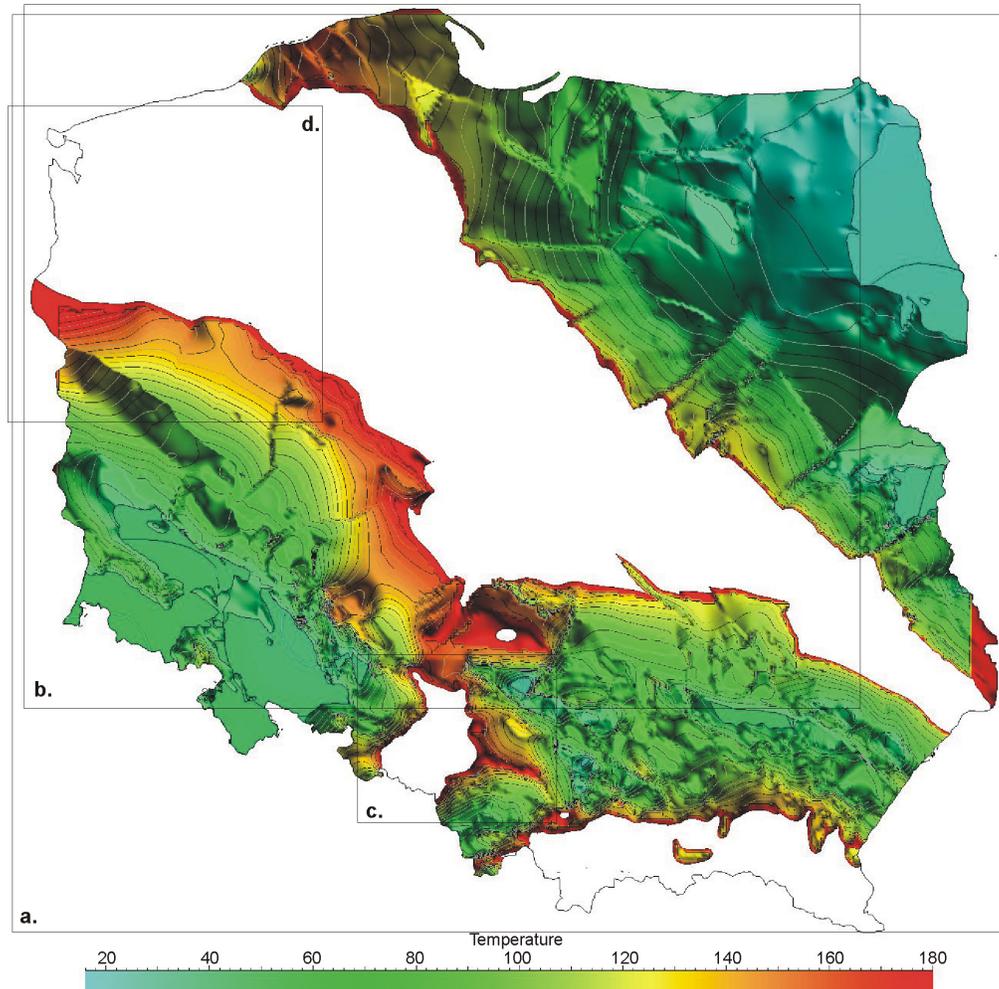


Figure 4. Formation temperature map for the top of Polish crystalline basement the depth interval from -500 to -5000 m; showing extents of study areas for previous detailed geothermal data compilations: a. Sokolowski et al. (1995); b. Gorecki et al. (1995); c. Malolepszy (2000); d. Kurowska (2005).

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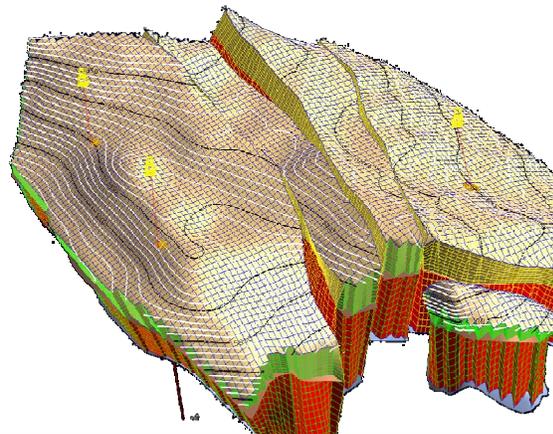
ADVANCES IN 3D EARTH MODELLING

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3D earth modeling provides a critical foundation for much of the applied geosciences, including groundwater modeling. Objectives of groundwater modeling include meaningful interpretations of fluid flow, aquifer characteristics, contaminant transport, and other factors important to decision making. Modern 3D earth modeling systems are capable of providing the complex stratigraphic, folded, faulted, and fractured frameworks necessary for the most advanced fluid flow modeling. They are also capable of providing a powerful framework for interpreting the results, including data-constrained, quantitative assessments of uncertainty and risk. Such applications are demanding in terms of a visual and computational software environment, requiring the capability of multi-disciplinary 3D spatial modeling of complex geology. The values and uncertainty of many irregularly sampled, spatial rock-property variables must be consistently managed. The critical requirements of 3D modeling in this context are rapid transformation between 3D vector (wireframe) and raster (grid) models, the capability to simultaneously manage an arbitrarily large number of spatial variables on any model object, modeling of structural geological (volumetric) uncertainty, and modeling the uncertainty of spatial variables that are both continuous (e.g. porosity) and categorical (e.g. facies). Models must be built relatively rapidly and be convenient to edit as new data arise. Query capabilities are necessary to provide users with a dynamic interaction with the model, particularly the ability to quickly highlight spatial volumes in which a number of criteria are satisfied. Advanced 3D visualisation of the model and its variables is important for interpretation.

Pictured at right is an example of a folded and faulted 3D grid suitable for connection to a fluid flow modeller. Grid topology, stratigraphy, facies modelling, porosity modelling, and uncertainty are all managed by the 3D earth modelling system. The resulting fluid flow model can be directly visualized and queried with respect to all other data in the model.



(Courtesy Earth Decision Sciences Corp.)

Figure 1. Example of a folded and faulted 3D grid suitable for connection to a fluid flow modeller.

USING GROUNDWATER AGE AND OTHER ISOTOPIC SIGNATURES TO DELINEATE GROUNDWATER FLOW AND STRATIFICATION

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INTRODUCTION

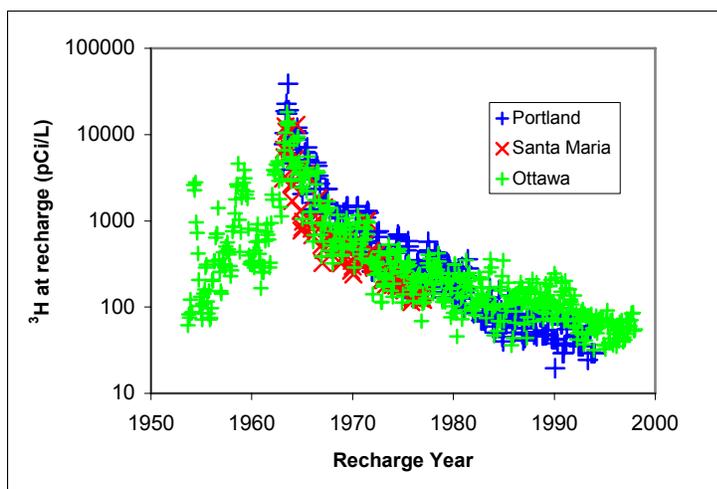
Isotopic tracers, such as stable isotopes of the water molecule and tritium, have been used in investigations of groundwater flow and transport and recharge water source for several decades. While these data can place hard constraints on groundwater flow rates, the degree of vertical flow between aquifers and across aquitards, and recharge source area(s), they are rarely used, even for validation, in conceptual or numerical models of groundwater flow. The Groundwater Ambient Monitoring and Assessment Program, sponsored by the California State Water Resources Control Board, and carried out in collaboration with the U.S. Geological Survey, has provided the means to gather an unprecedented number of tritium-helium groundwater ages in the basins of California. As the examples below illustrate, a collection of groundwater ages in a basin allows delineation of recharge areas (youngest ages), bulk flow rates and flowpaths, as well as a means of assessing susceptibility to anthropogenic contaminants.

GROUNDWATER AGE-DATING TECHNIQUE

Tritium (^3H) is a very low abundance (around 1 part in 10^{17} of total hydrogen), radioactive isotope of hydrogen with a half-life of 12.34 years. Atmospheric nuclear weapons testing in the 1950's and early 1960's released tritium to the atmosphere at levels several orders of magnitude above the background concentration (Fig. 1). This atmospheric tritium enters groundwater (as HTO, with one hydrogen atom as tritium) during recharge. Its concentration in groundwater decreases by radioactive decay, dilution with non-tritiated groundwater, and dispersion. While the presence of tritium is an excellent indicator of water that recharged less than about 50 years ago, age dating groundwater using tritium alone results in large uncertainties due to spatial and temporal variation in the initial tritium at recharge. Measurement of both tritium and its daughter product helium-3 (^3He) allows calculation of the initial tritium present at the time of recharge (Fig. 2), and ages can be determined from the following relationship:

$$\text{Groundwater Age (years)} = -17.8 \times \ln(1 + {}^3\text{He}_{\text{trit}}/{}^3\text{H})$$

The age measures the time since the water sample was last in contact with the atmosphere. The ${}^3\text{He}_{\text{trit}}$ indicated in the equation is the component of ${}^3\text{He}$ that is due to the decay of tritium. Methodologies have been developed for correcting for other sources of ${}^3\text{He}$, such as the earth's atmosphere and potential small contributions from thorium and uranium decay (Aesbach-Hertig et al., 1999; Ekwurzel et al., 1994).



Well water samples are always a mixture of water molecules with an age distribution that may span a wide range. A tritium-helium groundwater age is the mean age of the mixed sample, and furthermore, is the age only of the portion of the water that contains measurable tritium. Groundwater age dating has been applied in several studies of basin-wide flow and transport (Poreda et al., 1988, Schlosser et al., 1988, Solomon et al., 1992, Ekwurzel et al., 1994, Szabo et al., 1996).

Figure 1. The tritium concentration measured in precipitation at three North American locations. Nuclear weapons testing introduced a large amount of tritium into the atmosphere in the 1960's, peaking in 1963.

Groundwater age is especially useful for determining the degree of stratification or conversely, of vertical transport in a layered aquifer system. The following examples illustrate this point. The Alameda County Water District (ACWD), in the East San Francisco Bay area of northern California artificially recharges 2.5×10^{10} L of water per year. Recharge facilities consist of several abandoned quarries and of temporary reservoirs impounded behind inflatable rubber dams, in a creek channel that is adjacent to recharge ponds.

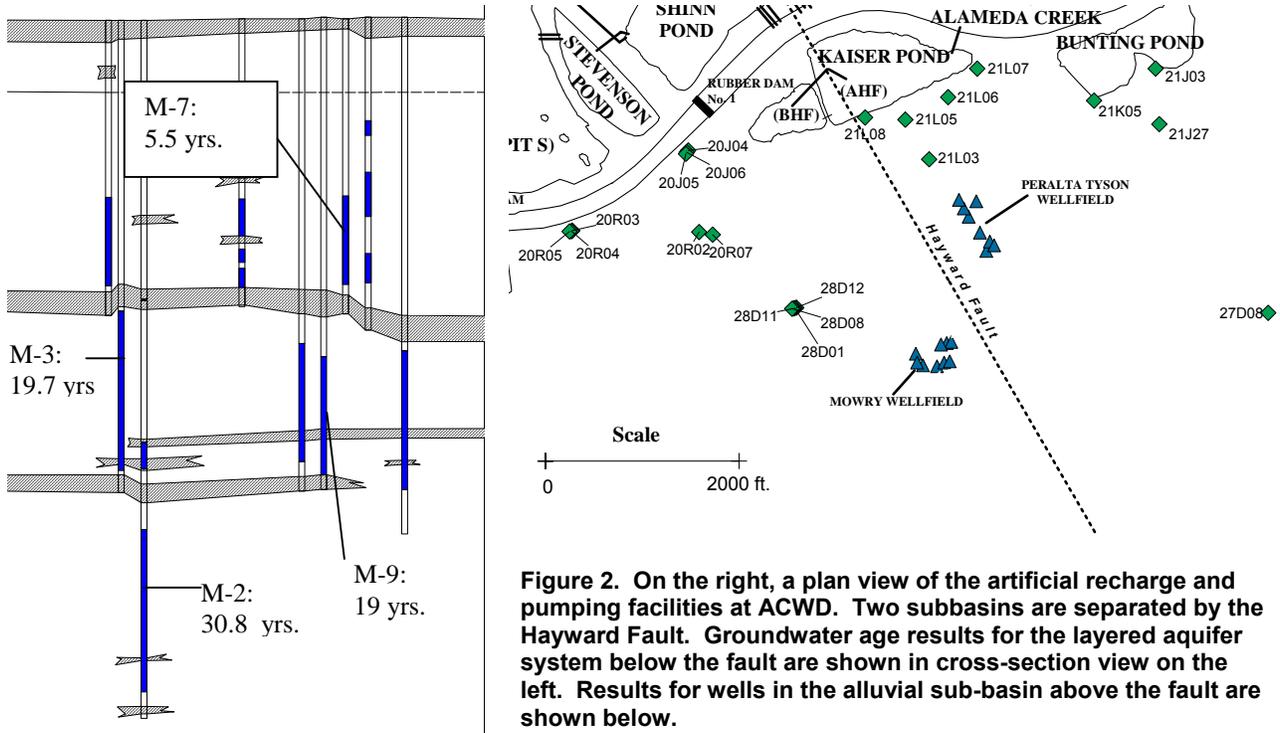
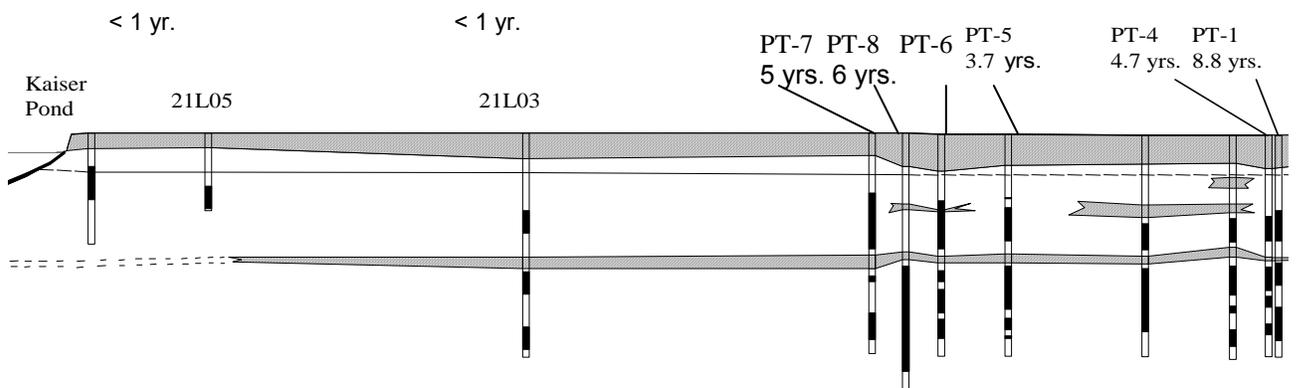


Figure 2. On the right, a plan view of the artificial recharge and pumping facilities at ACWD. Two subbasins are separated by the Hayward Fault. Groundwater age results for the layered aquifer system below the fault are shown in cross-section view on the left. Results for wells in the alluvial sub-basin above the fault are shown below.



The groundwater basin comprises alluvial deposits of the Quaternary period. Between periods of alluvial deposition, sea levels in San Francisco Bay rose and fine-grained sediment settled out to form aquicludes, separating the sands and gravels into distinct aquifer layers. The Hayward Fault, part of the San Andreas system, runs in a general north-south direction in the area, and hydraulically divides the groundwater basin into two sub-basins: the "Above Hayward Fault" (AHF) and "Below Hayward Fault" (BHF) sub-basins on the east and west side of the Hayward Fault, respectively (Fig. 2). About 10^{10} L of municipal pumping takes place in the two wellfields shown. Low permeability layers in the BHF sub-basin result in stratified groundwater, with mean ages of roughly 5, 20, and 30 years for the shallow, middle, and deep aquifers, respectively. Above the Hayward fault, groundwater flow is unimpeded, and wells produce a large volume of young groundwater with a mean age of 5 years.

Stable Isotopes as Tracers of Recharge Source and Evaporation

The minor stable isotopes of water molecules ^2H (deuterium, denoted as D) and ^{18}O vary in precipitation as a function of temperature, elevation and latitude (Craig, 1961; Ingraham & Taylor, 1991). In the Western U.S., extreme changes in elevation occur over relatively short distances. The net effect of isotopic fractionation during evaporation and condensation is that surface water from mountain watersheds has a significantly lower abundance of ^{18}O and D than coastal water (Fig. 3). The abundance of these isotopes in groundwater provides a fingerprint of the origin of the source water.

$\delta^{18}\text{O}$ in precipitation varies from approximately -4‰ along the Pacific coast to -17‰ in e.g., the Sierra Nevada Mountains and in the Colorado River Basin. Imported water used to supplement water supplies in areas of high water demand nearly always comes from colder and/or higher elevation sources, and has a distinctly lighter $\delta^{18}\text{O}$ signature than local water from within the water-poor watershed. Oxygen isotopes in groundwater thus provide a fingerprint that identifies the source water location.

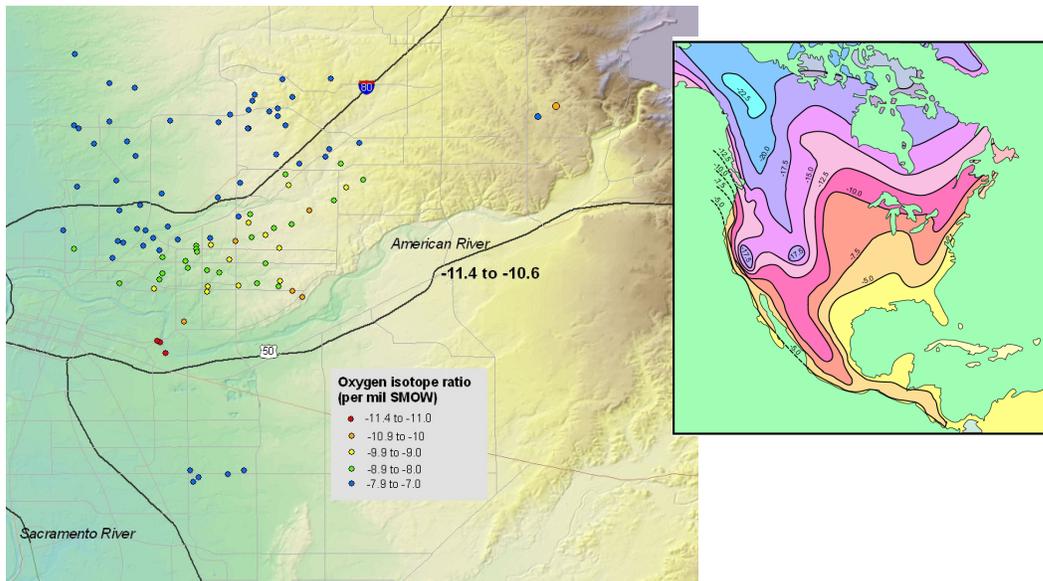


Figure 3. Oxygen isotope observations in Sacramento area drinking water wells. Inset it displays tight contours in $\delta^{18}\text{O}$ and lighter, depleted values at high elevations and latitudes. (after Taylor, 1974)

The oxygen isotope values ($\delta^{18}\text{O}$) delineate regions where groundwater is influenced by recharge of isotopically lighter (^{18}O depleted) American River water and other areas where natural recharge introduces isotopically heavier (^{18}O enriched) local water. Wells from the northern-most part of the Sacramento suburban area have an isotopic signature that is indicative of a local water source. The zone of influence of American River water extends from the areas adjacent to the river, where wells produce 100% recently recharged river water northward to Interstate 80. Local precipitation in the Sacramento area has a $\delta^{18}\text{O}$ value that averages approximately -7.5‰ .

Several geochemical methods have been used to determine groundwater recharge rates including environmental tracers such as stable isotopes of oxygen and hydrogen and solute profiles. Solomon et al., (1996) determine recharge rates using tritium-helium groundwater ages in an area of nearly vertical recharge, and discuss in detail the limitations of the method with regard to dispersive effects of mixing and molecular diffusion, and with regard to complications posed by samples that come from near and before the tritium bomb pulse peak. In nested monitoring wells adjacent to the American river (Fig. 4), all samples are post bomb peak, and the other isotopic and chemical tracers suggest that mixing with non-river sources is minimal. Area 3 is an especially good profile for the purpose of estimating the long-term recharge rate, given the steadily increasing age and consistent $\delta^{18}\text{O}$ values that indicate a pure river source. A vertical recharge rate is calculated using a simple distance/time formula, and a recharge rate of 5.7 ft/yr (1.7 m/yr) is determined for the shallow zone to the deep zone. The rates determined here are estimates of the bulk, long-term recharge rate, and considerable variation is expected on daily and seasonal time scales. A large depression in groundwater levels to the north of the American River and groundwater production near the American River induce recharge at a higher rate than in the natural system. Away from the river, given the mean annual rainfall in the Sacramento area (460 mm/yr) and high evapotranspiration rate for the Central Valley climate (65%), a recharge rate about 10 times lower than the rates calculated for river recharge is expected.

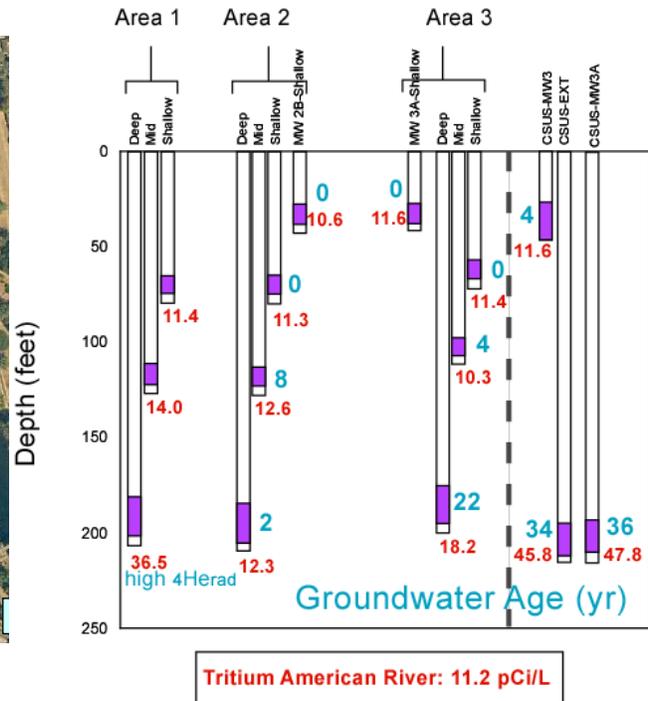
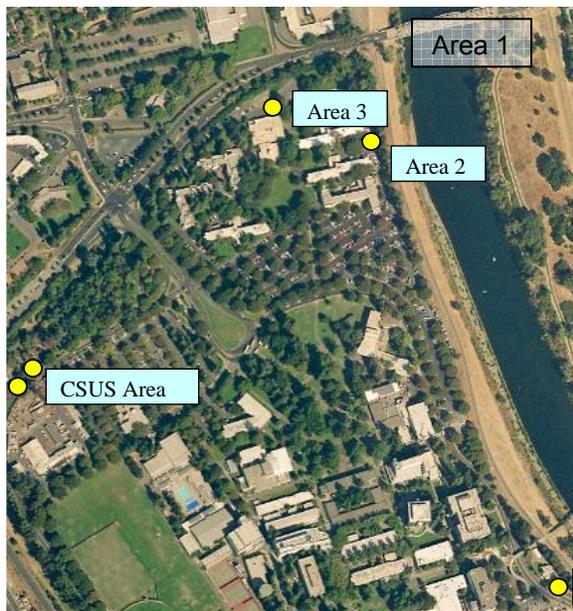


Figure 4. Study area adjacent to the American River in Sacramento, CA is shown on the left, with locations of well clusters as indicated. A slurry wall between the river and wells is apparently not effective in Area 2, where young water reaches to a depth of 200 ft (61m) (right schematic cross section with well screens shaded). Tritium concentrations and calculated tritium-helium groundwater ages show zero ages in the shallow section and increasing age and tritium concentration with depth at all areas except Area 2. Recharge rates are calculated from ages.

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LOWERING BARRIERS TO PUBLIC COMMUNICATION WITH 3D GROUNDWATER MAPPING AT ALBERTA GEOLOGICAL SURVEY: EXAMPLES FROM CANADA'S OIL SANDS AREAS.

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The Province of Alberta, Canada, has recently embarked on a watershed-focused, community-empowered approach to management of its surface-water and groundwater resources. The increased involvement of non-scientists in the resource-management process means that scientific agencies and private-sector consultants face significant challenges when communicating with policy makers in advisory bodies.

There are serious challenges facing hydrogeologists communicating with the public:

- Hydrogeologists need to re-attain public recognition and acceptance that specialized scientific knowledge has high value in the resource-management process and not just high cost. We need to recognize and adapt our communication strategies to new decision-making processes that are more inclusive. Inclusive processes can be more legalistic, emotive and value-laden while being proportionally less scientific or technical in nature.
- Hydrogeologists need to accurately and respectfully convey concepts about complex processes operating underground over long periods of time to persons with only general levels of science education.
- Hydrogeologists need to capture and convey the degree of uncertainty in hydrogeological mapping and forecasting without losing credibility with the lay public and decision makers.

At the Alberta Geological Survey (AGS), we are using three-dimensional (3D) mapping techniques to address these challenges. Experience has shown us that new workplace solutions are needed to facilitate this change, particularly in the areas of data management, gridding, and public presentation. First we will highlight how specific data-management and data-capture initiatives have helped us build the foundation for 3D modeling. Second, we will discuss how we give geological interpretation to grids in ways that help transfer geological skills from flat paper to 3D computer images. Lastly, we will show how we add more processing to lower the barriers to public understanding of these images.

DATA MANAGEMENT

Three-dimensional mapping requires a more sophisticated data-management infrastructure than 2D mapping. Two areas of strong growth driven by the need for 3D mapping are the adaptation of relational database technology and the digitization of paper legacy-data.

Adaptation of Relational Databases

The biggest single infrastructural change in AGS' groundwater studies has been the transition from ASCII flat-files and spreadsheets to relational databases. This change has facilitated 3D mapping in several ways. First, relational databases allow us to rapidly query and blend very different data types based on a range of spatial or temporal relationships. The downside to this adaptation has been the increased stress on geologists and information professionals to maintain productivity while the platform, software, and processes continually change.

Digitizing Paper Legacy-Data

Like many geological surveys, AGS and its partner agencies in the provincial government have a huge legacy of paper files. Although these files are useful, they cannot be used directly to facilitate 3D mapping since data are not accessible in digital form. As an organization, AGS has therefore put substantial resources into sorting and organizing its paper data legacy, creating a searchable metadata catalogue of worthy legacy items. This system helps locate paper records, after which it is left to projects to digitize records as needs arise. In parallel to this process, the AGS groundwater program has supported digital capture of several key parts of the Alberta government groundwater-data legacy. This includes digitization and geospatial assignment of spring records, lake-bottom bathymetries and water-well petrophysical logs. The latter have been voluntarily placed on file with government agencies over the past several decades but are underused due to their present format. When digitization is

completed, these data sets can be blended with digital elevation models, water-well lithology logs and hydrographs to dramatically enhance 3D groundwater mapping in the province.

GRIDDING

True 3D modeling involving generation and characterization of bounded geological bodies is not done routinely at AGS. This is mainly because our processes and information-management infrastructure cannot yet support it. Though we continue to evolve to that goal, we remain in what is often termed a “2.5D” work world. In this sense, we represent regional geological bounding surfaces by 2D grids in 3D space. Scalar properties like permeability and porosity, or categorical classifications like lithology or genetic units, are represented by grid-block assignments or zonation on the grids. The three-dimensional extent of these properties is implied to exist for the vertical distance between offset 2D grids rather than being explicitly defined by point values or continuous definition in voxels.

Nevertheless, working in a 2.5D geological modeling paradigm actually is effective for two reasons. First, it is relatively easy to access 2D grid processes in common desktop geological or GIS software. Second, many regional stratigraphic concepts work well in a bounding-surface hierarchy in which lack of true 3D rendering or definition is not fatal. Indeed, using grids enables regional stratigraphic modeling in a geotemporal as well as a geospatial framework.

PUBLIC PRESENTATIONS

The primary driver towards 3D mapping and modeling at AGS is to facilitate public and stakeholder understanding. Three-dimensional mapping creates an extra burden on geoscientists to learn new tools and processes. The payoff comes in renewed public interest in our work. As a secondary motive, we also gain more insight into hidden geological relationships through the extra processing. At AGS, we have enhanced our use 3D maps and models in three ways to engage our stakeholders and lower barriers to understanding.

Use of Animation

We use animation in two main ways. Like many others before us, we have discovered that 3D models on computer or projection screens are not easily understood in a casual glance by lay people. The use of animation and lighting effects to spin, fly-through, shadow and otherwise render the static 3D models in more dynamic ways is not just embellishment, but are critical for the lay person to recognize the surface or model they are looking at onscreen. This is especially true in a public presentation setting where they are engaged for mere minutes or seconds. Second, we also use animation in 2D and 3D to show the effect of time.

Use of Familiar Visual Idioms

Though not strictly a 3D technique, we are finding success with applying familiar visual idioms to our models to lower the barriers to the public to access our information. A prime example is the use of faux or real hand-coloring of 3D block diagrams instead of complex graphical fills (e.g., sand stipple or limestone blocks) for public presentation. Although the same geological information is contained in these diagrams, use of a very familiar, even childlike, visual graphical idiom removes the need for the casual or lay viewer to interpret unfamiliar graphical patterns and colors before receiving our geological message. An example is shown in Figure 1 below.

Use of tactile models

Before 3D rendering and visualization tools became available with desktop computers, geologists often made plaster or clay models of geological models to explain 3D geological relationships to non-scientists otherwise unable to decipher complex geological maps and cross-sections. At AGS we have come full-circle; using 3D printing technology to render 3D digital geological maps as colorful, 3D, scale models for the non-scientist. We find that having a model in hand is extremely helpful in lowering the barrier of entry into understanding our technical presentations. Interestingly, we have found that geologists’ reaction can be quite muted to the tactile models – in contrast to the typically enthusiastic reaction of the lay persons we are striving to reach.

SUMMARY

At Alberta Geological Survey, we have invested extensively in creating digital data sets and growing our capabilities to do geoscience in a digital world and to create 3D renderings of subsurface geology for our stakeholders. The biggest payoff and greatest motivation to doing this work is the real gain in public understanding

and support for our ongoing activities. We must learn to appreciate that the human brain is foremost a powerful visual processing instrument. With the right three-dimensional, colorful, dynamic images, the public will see and understand geological relationships rapidly with little prior training. But if the imagery is not done correctly, it will not succeed. Therefore, much effort needs to be spent to lower all possible barriers to understanding the 3D imagery so that the extra work involved in its creation pays off.

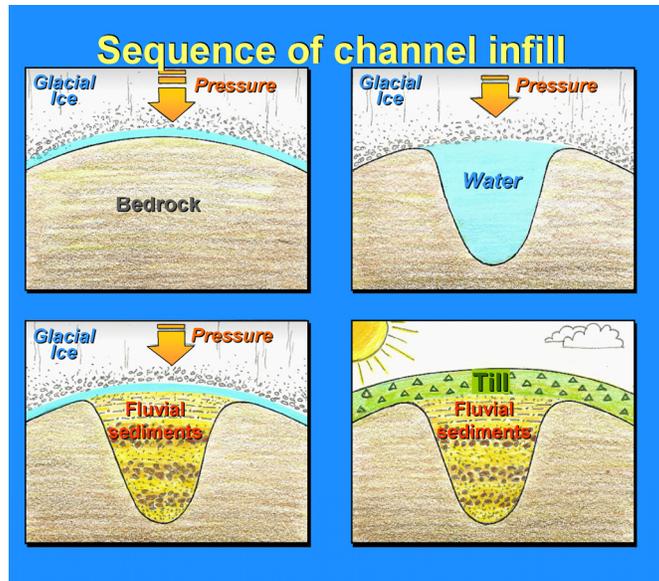


Figure 1. An example of the use of familiar visual idioms to communicate geology to lay audiences.

THE ROLE OF GEOPHYSICS IN 3D MAPPING

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INTRODUCTION

There is an increasing need for three-dimensional (3D) geological information on shallow deposits in order to assess or protect critical water resources, and to address other environmental questions such as hazard or waste disposal issues. This presents the geological community with a particularly challenging task, as data on the third dimension (depth) are generally sparse. Information on the subsurface can come only from (1) borehole logs, (2) geophysical surveys, or (3) projection of surface mapping. All these methods have important roles to play in advancing our understanding of the third dimension; however the aim of this paper is to consider specifically the role of geophysics. Geophysics can be an extremely powerful tool in 3D mapping, and its effectiveness can be increased when some simple questions are first considered, about why, what, where, when and how geophysics should be used. These questions will be addressed in a general sense in this paper, using examples taken from near-surface or “shallow” geophysical surveys carried out primarily in glacial environments. However, the concepts apply in general for all geophysical surveys, including borehole and airborne methods, other geological settings, and different scales.

The reader is referred to papers from previous workshops which provide an overview of the different geophysical techniques that are available for mapping the shallow subsurface (Pugin and Larson, 2002), and a discussion of the utility of geophysical borehole logs (Hunter, 2004).

WHY USE GEOPHYSICS?

Ideally, a geologist would like to “identify” and “map” subsurface sediments in the same way they can “identify” units and “map” structure within an outcrop. However, subsurface deposits can usually only be physically examined in core samples retrieved by drilling. These provide extremely valuable information on the nature of the material, but the samples are small and understanding their depositional context, stratigraphic relationships, lateral extent and variability can be difficult. In contrast, geophysical surveys in themselves cannot directly “identify” the subsurface materials; instead the power of geophysical data is the context it can provide on the subsurface architecture, stratigraphic relationships, and variation in materials. Thus, in a simplistic sense, drill core can be used to “identify” subsurface materials, **whereas geophysics can provide some of the information required to “map” those materials in subsurface space.** This role can be hugely important in developing or testing conceptual 3D geological models.

Geophysical surveys provide information about the magnitudes and variation of the physical properties of the subsurface. Some specific applications include: (1) mapping target horizons or units (e.g. bedrock depth/topography, water table, etc), (2) providing information on subsurface architecture and its complexity (e.g. deltaic structures, buried valleys, existence of clay units within sands), and (3) identifying subsurface anomalies (e.g. contaminant plumes, salt water intrusion).

An example is shown in Figure 1, which is a short (<1 km) shallow seismic reflection profile that demonstrates the value of geophysics in “mapping” complex subsurface stratigraphy and architecture. In this case, the borehole (drilled prior to the geophysical survey) only sampled two of at least six stratigraphic units identifiable on the seismic section. Two units likely to be of considerable interest from a groundwater perspective (a thick discontinuous “sand” unit at 40-80 m depth, and the “buried esker?” within the bedrock valley) were not identified by the drilling. The section also shows that the upper clay unit is highly variable in thickness and is locally considerably thinner than indicated by the borehole. If the clay was considered important in source water protection, such information on the local variability of its thickness would be extremely important. This survey, which could be carried out for less than the cost of a single cored drillhole, provides critical insight into the complex subsurface architecture in this glacial environment, and into the depositional context and stratigraphic relationships of buried units.

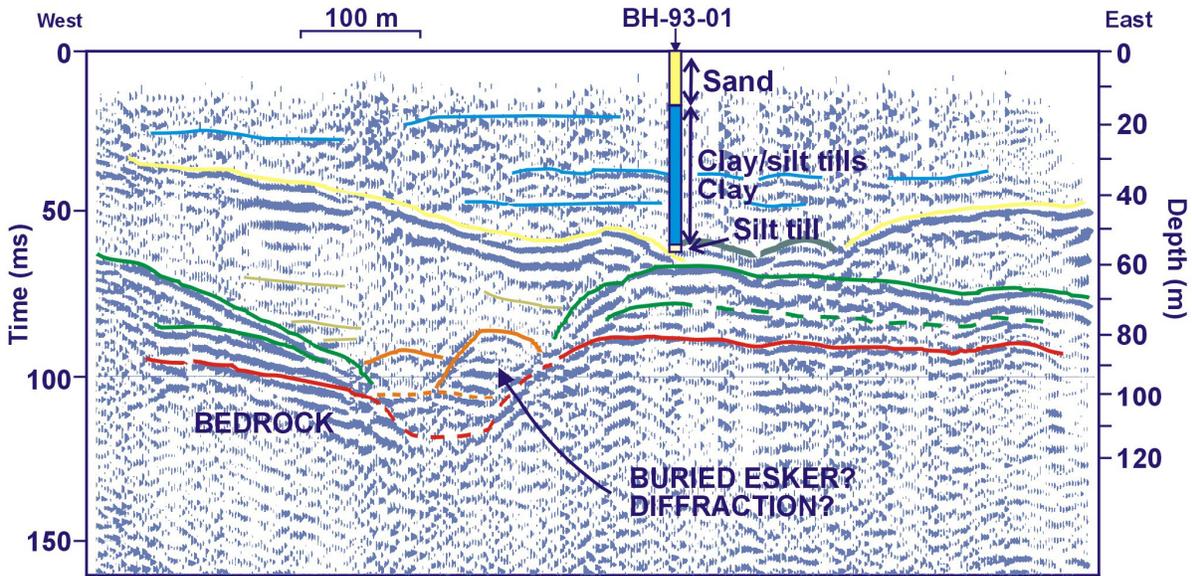


Figure 1. Shallow seismic reflection profile from the Waterloo Moraine area in southern Ontario, Canada, showing the complex subsurface architecture of glacial deposits and the underlying bedrock surface to depths of ~100 m. If the information from the geophysics had been available prior to drilling, the borehole could have been sited so as to intercept and identify more stratigraphic units.

WHAT CAN GEOPHYSICS DO, AND WHAT GEOPHYSICS?

Different types of geophysical surveys measure different physical properties of the subsurface: e.g. seismic methods respond to variations in the seismic velocities of subsurface materials, electrical methods depend on the resistivity or conductivity of subsurface materials (including pore waters), gravity methods respond to variations in density, etc. Thus, **geophysics requires subsurface targets to be characterized by a physical property that contrasts significantly with its surroundings**. The geophysical method(s) used must be chosen based on an understanding or estimate of this physical property for the target and its environment, as well as a clear understanding of the capabilities of the geophysical method(s). The contrast in properties must also produce a signal that is measurable at the ground surface (or other measurement location). In general, deeper targets must be larger or contrast more significantly with their surroundings to be observed.

Figure 2 presents an example of a ground penetrating radar (GPR) survey that was used to map the depth to water table in a surface sand unit. In this case the shallow water table is readily measured by GPR as it is in a resistive material and provides a strong dielectric contrast with the overlying dry sand.

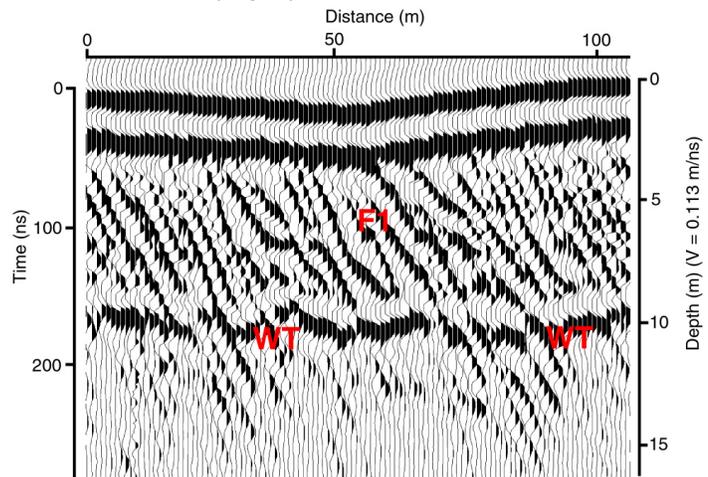


Figure 2. Ground penetrating radar section from the Oak Ridges Moraine area in southern Ontario, Canada, showing details of foreset bedding (F1) in a surface sand unit, and clearly delineating the water table (WT) as a large-amplitude, flat-lying reflection at a depth of ~9 m. Signal penetration is limited to ~15 m.

WHAT CAN GEOPHYSICS NOT DO?

Just as it is important to understand the potential of geophysics, it is equally important to fully understand its limitations. **Geophysical surveys all have an inherent limitation on resolution, which depends on the method, instrumentation and survey parameters being used, and on the particular geological setting of the survey area.** For example, GPR surveys (e.g. Fig.2) can provide resolution on the order of cm to 10s of cm in shallow sands and gravels, but the depth of signal penetration is limited to a few metres, and in conductive materials (e.g. clays) may be essentially zero. Using lower frequency antennas will usually increase the depth of signal penetration to a few tens of metres, but with a corresponding decrease in vertical resolution. Data from electrical resistivity surveys can be used to map electrical properties to greater depths even in conductive sediments (e.g. Fig. 3), but as these methods measure average electrical properties of the subsurface the resolution is quite different from that achieved with GPR. It is important to realize that **no single survey can map all depths and/or targets!**

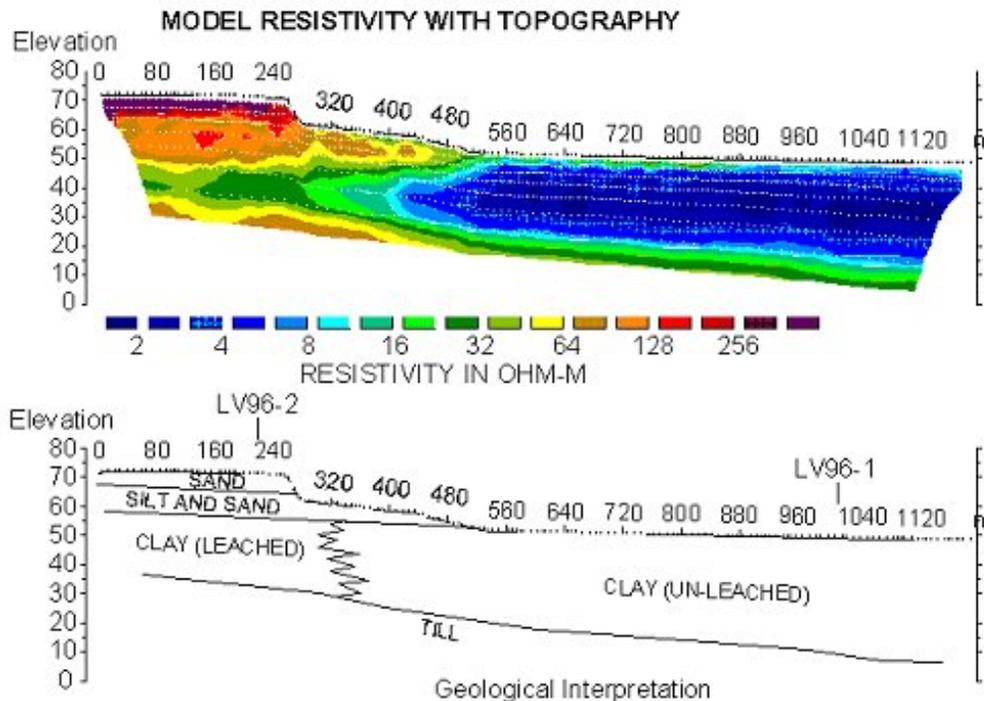
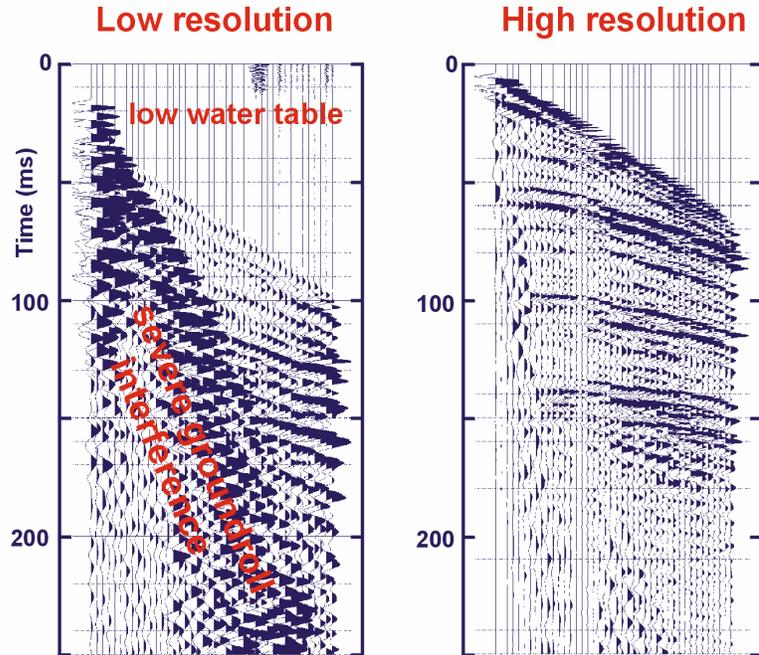


Figure 3. Electrical resistivity section across a slope in eastern Ontario delineating the contrast between very low resistivity saline clays in the channel floor, and more resistive surficial sands and leached (fresh porewater) clays beneath the adjacent terrace. This method can measure the apparent resistivity to depths of tens of metres below ground surface, but clearly does not provide the high resolution of the shallow subsurface that is shown in Fig. 2.

WHERE SHOULD GEOPHYSICS BE USED?

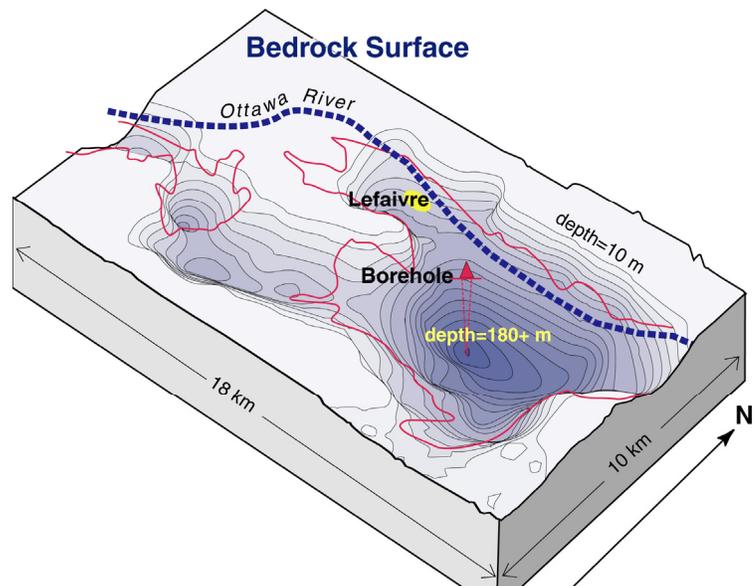
The effectiveness of geophysical surveys can be maximized if thought is given to where the surveys are carried out. Clearly, geophysical information can be critical where subsurface architecture and stratigraphy is complex (e.g. in many glacial terrains – see Fig.1), or where the target is the boundaries or limits of a subsurface unit (e.g. saline groundwater – see Fig. 3). However, in order to be most effective, **geophysical surveys should be conducted in areas where good signal-to-noise data can be acquired** or there is a risk of wasting much effort in collecting data that are of marginal use. **These areas should be determined by a testing phase carried out early in the investigation** to identify and refine the optimum geophysical method(s) to use, the data acquisition parameters and the survey locations. Figure 4 displays an example of two seismic reflection records acquired within a few hundred metres of each other. Different surface conditions at the two sites result in a very significant difference in data quality. A testing program can be used to 1) ensure that the geophysical technique chosen is capable of detecting the target, 2) identify variations in data quality within the survey area due to geological or cultural conditions, and therefore allow optimum sites for follow-up surveys to be determined, and 3) possibly identify anomalies that warrant further investigation in the follow-up surveys.

Figure 4: Two seismic reflection field records obtained only a few hundred m apart. Dry surface materials and a low water table at the first site (left) result in low frequency reflection signals and strong ground roll interference. Damp surface sediments at the second site (right) improve the ground coupling of the source signal and result in much higher resolution reflection data. A testing program helps identify optimum sites or conditions for a follow-up surveys.



A testing program (i.e. a series of site surveys) can also be a means of mapping vertical and lateral variations in a target horizon over a regional area. An example is shown in Figure 5 where ~ 50 seismic reflection test sites were used to map the depth to bedrock over a 180 sq. km area underlain by a deep bedrock basin. In this case, the Paleozoic bedrock surface beneath a thick sequence of marine sediments and glacial deposits produced an recognizable seismic reflection. The depth to bedrock in the centre of the basin (~180 m) was confirmed by drilling.

Figure 5. Depth to bedrock determined in a region east of Ottawa, ON, from a series of ~50 seismic reflection test sites. The red line is the outline on the ground surface of slightly hummocky topography, which is the only visible expression of this subsurface feature. Information on the vertical and lateral variation of a target horizon can often be effectively and efficiently produced using geophysics.



WHEN SHOULD GEOPHYSICS BE USED?

Geophysics should be used when it has been ascertained that the target horizons and/or structure are characterized by a significant contrast in physical properties that is measurable at the surface using the geophysical method(s) chosen. This requires 1) a discussion with the geophysicist about the goals of the survey and his/her judgment of the potential success of various geophysical techniques, and 2) a testing phase, prior to a commitment to a complete survey, to ensure that the data quality obtained at the site is adequate to meet the survey targets. In

general, the most effective use of geophysics is early in a project, so that it can be used to 1) check or develop hypotheses, 2) verify or refine geological models, and 3) identify drilling targets. Using the results of geophysical surveys to identify borehole sites can be extremely important, as it allows drillholes to be judiciously located to identify anomalies and intercept as many stratigraphic units as possible (e.g. Fig. 1).

HOW SHOULD GEOPHYSICS BE USED?

Geophysics should be used to provide subsurface architecture (lateral and vertical context) **in conjunction with boreholes or other information that can be used to verify the results**. This ensures that the geophysical results can be interpreted in a way that is clear and meaningful to the geologist or other project participants. Once an understanding of the physical response of units within the survey area has been acquired through some verified geophysical results, additional geophysical surveys may be confidently interpreted without the same level of verification. Additionally, **the effectiveness of geophysics can be enhanced when there is strong collaboration between geologist/hydrogeologist and geophysicist from the planning through the interpretation phase**. The different perspectives of these various experts can together provide an improved insight into the third dimension.

SUMMARY

When used well, geophysics can play an extremely important role in 3D mapping. It has the potential to provide a structural context on the subsurface architecture, stratigraphic relationships or variation of materials.

In order for geophysics to be effective, three basic conditions must be met:

1. The measured physical property of the target horizons or units must contrast significantly from the surrounding material.
2. Data from the target depth must be sufficient in amplitude and signal-to-noise ratio to be interpretable.
3. The resolution of the methodology used and of the recorded signal must allow appropriate definition of the target (depends on signal characteristics and on depth and size of target).

The following are simple recommendations that will help ensure geophysics can be effectively integrated into a 3D mapping project:

1. Involve geophysicist(s), geologist(s) and hydrogeologist(s) in identifying the targets of geophysical surveys and planning the geophysical program. Be sure all participants understand the potential and limitations (including resolution) of the geophysical survey(s) chosen.
2. Conduct tests to ensure that the planned geophysical survey is capable of mapping/identifying the target horizons/structure. Use these tests to identify the optimum areas/times/parameters for surveying so that data with as high a resolution as possible can be obtained.
3. Plan to acquire borehole or other information that can be used to verify the geophysical results.
4. Involve the geophysicist(s), geologist(s) and hydrogeologist(s) in the final assessment and interpretation of results.

One final consideration: The subsurface is generally complex, and geophysics will undoubtedly bring up new questions/insights that will challenge or require refinements/revisions to any preconceived 3D model. Be prepared for this!

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FROM GEOLOGICAL TO GROUNDWATER FLOW MODELS: AN EXAMPLE OF INTER-OPERABILITY FOR SEMI-REGULAR GRIDS

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ABSTRACT

Integrating geologic information into hydrogeologic numerical models is by no means a straightforward operation. This is especially true for finite element modeling which generally requires that the geological information be integrated into grids that are generally irregular in the horizontal (i, j) direction and regular in the vertical (k) direction. Semi-regular grids of this type are still rarely supported by geological modeling packages and the data structure can vary significantly between softwares. Nevertheless, workable solutions exist for some software packages. Here we present a solution that allows the properties of a gOcad[®] geomodel to be transferred to a semi-regular grid built in GMS[®], a commonly used pre-processor for groundwater flow modeling applications. The transfer is achieved first by building in gOcad a “twin grid” that has the same mesh structure as the original GMS grid. This is done using the research plug-in GridLab developed by the gOcad Research Group. Once the properties of the geomodel are transferred to the twin grid, cell or element number correspondences and property transfer to the original GMS grid is achieved using the database system Access[®]. ASCII file format is used for most data exchange between softwares. The time required to go through the procedure is on the order of minutes, even for large grids, making it a practical solution for the lasting problem of property transfer from geological to hydrogeological models, at least until more convenient and built-in interfaces are developed.

INTRODUCTION

Technological developments during the last decade have allowed for the construction of computer-based 3D geological models in parallel with more sophisticated process-based modeling software (e.g. for groundwater flow modeling, contaminant transport modeling). The usefulness of 3D geological models as stratigraphic data providers in process-based modeling is obvious, but the path toward full inter-operability between the different systems and applications is jammed with stumbling blocks. The central challenge is to be able to transfer the geologic information (e.g. lithofacies) from a geological model built in a particular system to various 3D grids used by other systems. This is especially true for the transfer of data to semi-regular grids, i.e. grids that are irregular in the areal (i, j) direction but regular in the vertical (k) direction. Such grids are increasingly used in groundwater flow modeling, especially grids consisting of prismatic cells. They allow for a more complex and flexible representation of the stratigraphic architecture than regular grids while offering substantial benefits over fully unstructured grids (made of tetrahedral cells) which require much more computing memory and are rarely needed in process-based modeling. However, few geomodeling packages have the capability of discretizing a geological model into a semi-regular grid. Furthermore, the data structure of such a grid is more likely to be quite different from one software to another thus resulting in poor inter-operability with groundwater flow modeling systems. Nevertheless, simple solutions can be sought to improve significantly this inter-operability and to allow the direct transfer of geological properties from geological models to semi-regular grids compatible with the latest generation of flow simulators. The solution proposed herein allows the properties of a gOcad[®] geomodel to be transferred to a semi-regular grid built in GMS[®], a commonly-used pre-processor for groundwater flow modeling applications.

THE PROPOSED SOLUTION

A typical 3D geological model built through gOcad[®] is primarily defined by a series of interlocking discontinuous triangulated surfaces representing the boundaries of geological objects (Fig. 1a). The space between boundaries may be consistently partitioned to describe and represent the geological objects (Fig. 1b). However, in many modeling applications, further discretization is needed. In gOcad[®], such discretization usually takes the form of a regular grid whose cells are hexahedral in shape (Fig. 1c, 1d). Other types of discretization are possible, the most interesting one for hydrogeological applications is generated using a research plug-in (GridLab) developed by the gOcad Research Group (Grosse et al. 2003). The 3D grid is generated by extruding a 2D triangular mesh along a field of pillars oriented in the vertical dimension to generate columns of 3D prismatic cells (Fig. 2). The data structure is highly flexible allowing properties to be assigned either to the grid's cells, cell faces, edges or nodes depending on the application. In finite element modeling, the properties need to be attached to the grid cells (or elements). Also, because the resulting grid has to be a replica of the grid that will be used by the flow simulator, the triangulated surfaces must share the same horizontal mesh structure as the grid of the hydrogeological model. Therefore, even if

these surfaces may require geometric information contained in the geological model, it is easier to use a pre-processor for groundwater flow applications to generate them. In this work, the software *GMS*[®] was chosen to achieve this task. Software interplay is facilitated because of similarities between *GMS* and *gOcad* file formats for triangulated surfaces. Hydrostratigraphic information (e.g. generalized geometry of aquifers and aquitards) can thus be quickly transferred from *gOcad* to *GMS* to generate the grid of the flow model. Surfaces containing the horizontal grid structure can then be transferred back to *gOcad* to generate a replica of the original *GMS* 3D grid. It is through that “twin grid” or replica that the property transfer (from the geological model to the semi-regular grid) will take place using standard property transfer tools available in *gOcad*. However, the data structure of the replica (Fig. 2a) is different from the data structure of the original grid. In the replica, the basic element is a polyhedron defined by 5 polygons, which are in turn defined by their edges which are connected by georeferenced nodes, whereas in the original grid the polyhedron (or element) is only defined by its 6 connected nodes (and associated coordinates). Also, both element and node numbers are ordered differently in the two grids. Lastly, the data structure of the replica is more complex. Extracting the coordinates of the 6 connected nodes of a cell is not straightforward. A solution was developed using the *Microsoft Access*[®] to partition into different tables the data structures of the different grids. The goal is to identify, by going through the data structure, the smallest set of coordinates unique to each polyhedron in the “twin grid”, find out to which original element each set corresponds, and then transfer the geological property assigned to each “twin” polyhedron to the corresponding original element of the hydrogeological model. Fortunately, this can be achieved in a few steps (see below). Once this is done, visualization of the new *GMS* grid can be used for quality control.

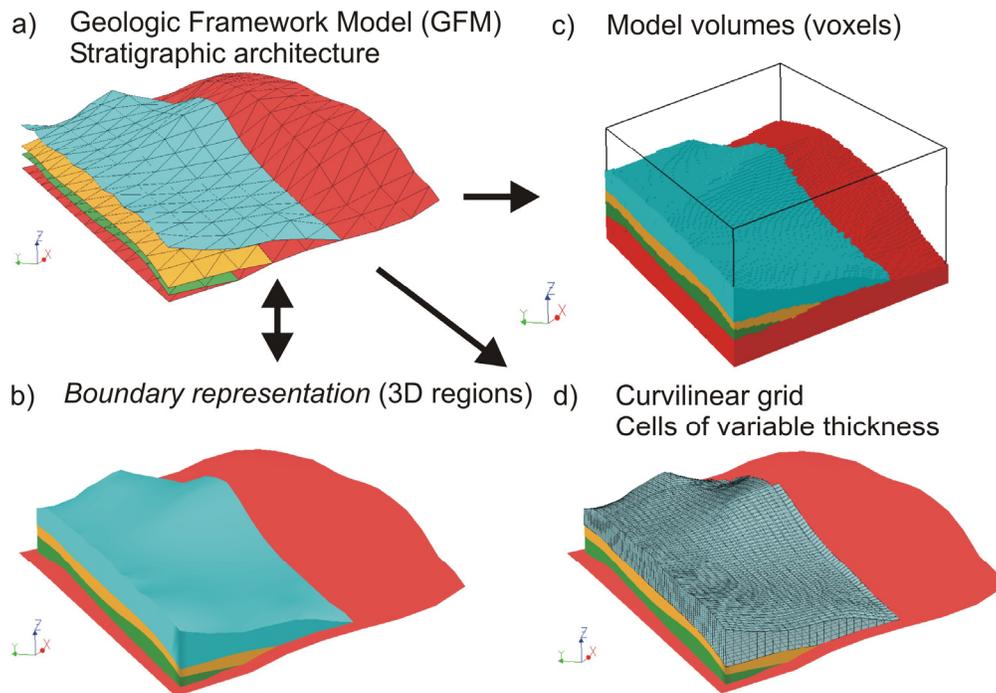


Fig. 1. The “gOcad” approach (cf. Mallet 2002; Caumon et al., 2004). a) The stratigraphic architecture of a region is primarily defined by interlocking surfaces. b) A boundary representation or b-rep defines solids by their bounding surfaces, providing an efficient volume representation. c) and d) Two types of regular grids supported by the software *gOcad* whose cells have an hexahedral shape (adapted from Ross 2004).

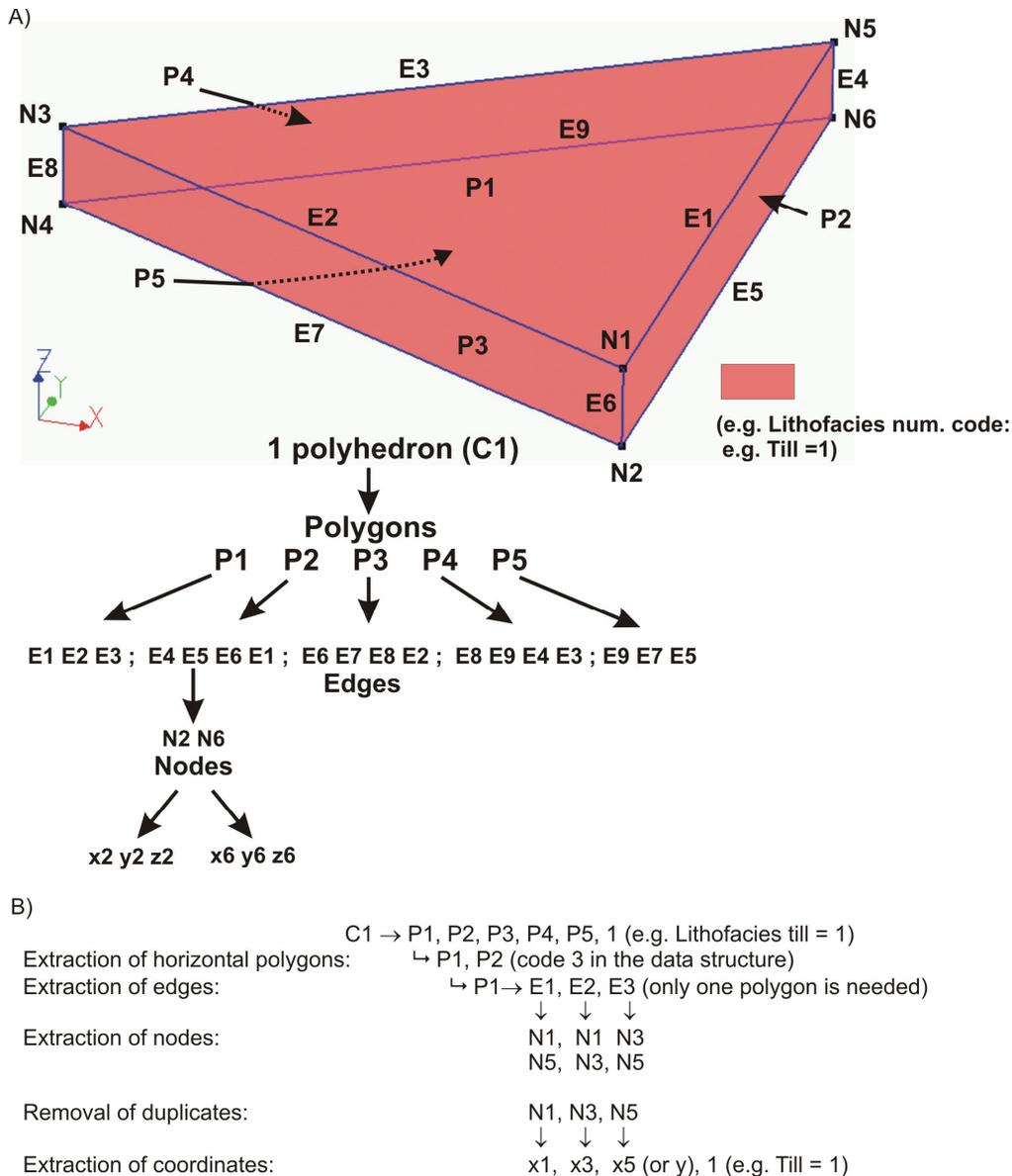


Fig. 2. a) A grid cell (C1) and its data structure as it is designed by the GridLab plug-in. Properties can be assigned to the polyhedron (cell) as well as to its polygons, edges and nodes. b) Extraction of the set of X or Y coordinates associated to the cell (C1) through database queries.

In Fig. 2, the horizontal polygons of the cell C1 are P1 and P5. Since both polygons are defined by the same set of XY pairs, only P1 will be used. This polygon is defined by edges E1, E2 and E3. These edges are in turn connected by nodes N1, N3 and N5. Finally, this set of nodes is defined by a set of XY coordinates which are associated to C1, but also to any other superimposed cell. This is why the procedure has to be applied layer-by-layer. Using the Z values to differentiate superimposed cells is, however, possible but it would not necessarily simplify the procedure. Also, by working layer-by-layer, the user can better follow the procedure steps and detect any problems more easily. Therefore, the next step is to create a list of gOcad cell numbers (C1, C2, ..., Cn) and a list of GMS element numbers for each layer along with their associated set of either X or Y coordinates (there is no need to keep the pair of XY coordinates at this point). Through a last database query in Access®, a correspondence is made between gOcad cells and GMS element numbers (Element1, Element2, ..., Elementn) based on their associated set of X or Y coordinates. At the same time, the geological information (e.g. a lithofacies numeric code; Till=1, Aeolian sand = 10) attached to each cell in the “twin grid” is transferred to its corresponding element in the original grid. It is worth mentioning that, once the database structure and queries are created, all the properties of a “twin grid” can be transferred to its original counterpart in just a few minutes.

Once transferred, the numeric value corresponding to a specific lithofacies (e.g. Till = 1, Aeolian sand = 10) can be translated into a hydrogeologic property for modeling purposes (e.g. hydraulic conductivity, porosity). So far, this procedure has only been used to transfer geological information from gOcad to GMS, but it may also work with other pre-processors or flow simulators that can handle ASCII files through import/export filters.

CONCLUSION

The above procedure is one workable solution to the lasting problem of data transfer between geological and hydrogeological modeling packages. Yet, there is still a need for a more convenient, user-friendly interface linking geomodeling packages to groundwater flow modeling software. The solution presented above should thus remain a temporary solution until full inter-operability is achieved through software development. In fact, the future use of 3D geological models in hydrogeology relies on a large part on the successful development of such an interface.

ACKNOWLEDGMENTS

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SEDIMENT ARCHITECTURE AND COMPOSITION OF THE WATERLOO MORAINE, SOUTHERN ONTARIO: EMERGING INSIGHTS

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INTRODUCTION

Moraines in southern Ontario have been classified as either till or kame-dominated and related to specific genetic processes (Fig. 1; Chapman and Putnam, 1943; Barnett, 1992). Few studies of moraine sediment composition have been completed, and, consequently, understanding of these moraines remains incomplete. The paucity of work, other than stratigraphic studies, on moraines in southern Ontario is illustrated by the extensively studied Waterloo moraine (e.g. Karrow and Paloschi, 1996).

Many moraines in Ontario are important areas of groundwater recharge. Moraine topography and structure controls the transmission of water from surface to groundwater and regional aquifers. An improved understanding of moraines in southern Ontario is of particular interest due to increased concern over source water protection (TEC, 2004). The Waterloo Moraine provides ~60 % of the water supply to Waterloo region (Frind et al., 2002). It is the focus of short term artificial recharge and storage (Wootton et al., 1997), is the site of municipal landfills, has increasing urban encroachment (Sanderson, 1995), and is the headwaters for many stream in the area. Thus, improved information on sediment extent, composition and variability is needed to sustain these vital watershed activities. One, well developed, and little-applied research method in southern Ontario moraines, is sedimentological analogue studies of outcrop and subsurface core for improved understanding of reservoir - aquifer geometry and character (e.g. North and Prosser, 1993; Galloway and Hobday, 1996)

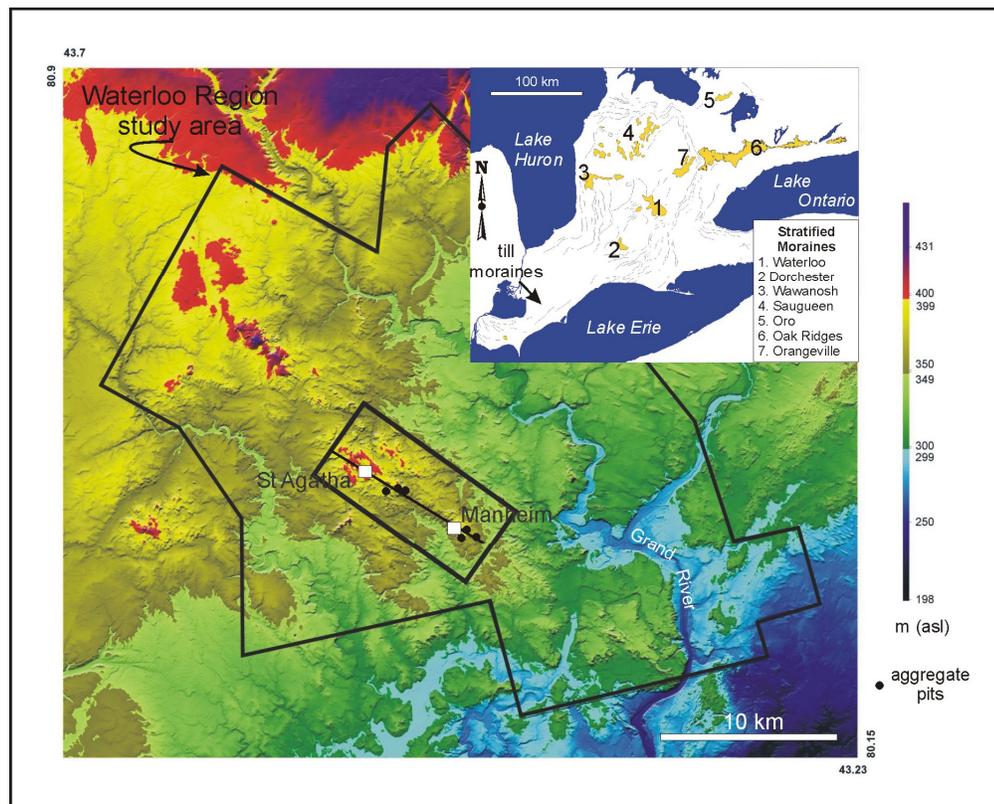


Figure 1. DEM of the Regional Municipality of Waterloo highlighting the location of the study area (black rectangle) and cross-section displayed in Figure 2. Inset map displays the location of till and stratified moraines of southern Ontario.

Paper Objective: This paper focuses on a southeast-northwest transect, from near Manheim toward St

Agatha, of the central core of the Waterloo moraine. This transect provides an initial stratigraphic framework of exposed moraine sediment in six aggregate pits of ~20 m depth and a number of boreholes that have complete penetration of the moraine sediment. This context provides an opportunity to extend the aquifer analogue studies of the unsaturated, near surface, to depth in the saturated zone.

Study Area: The Waterloo Moraine is a prominent topographic feature with an elevation of 400 m asl and a relief of ~50 m (Fig. 1). It consists of a main southeast-northwest elongate ridge (Bajc & Karrow, 2004) and a number of associated ridges that are orientated radially to the main moraine (Karrow, 1993). Associated ridges, informally named spurs, are from south to north referred to as the Washington, Phillipsburg, Crosshill and, Hawkesville spurs. To the west, two sand and gravel moraines; the Easthope and Wellesley have ambiguous relationships to the moraine. Stratigraphically, the moraine overlies Catfish Creek and lower Maryhill till (Bajc et al., 2004). The surficial geology consists primarily of fine sand, silt and silt-sand to clay-silt diamictons. The diamictons have been correlated with Maryhill, Tavistock, and Port Stanley tills (Karrow, 1993).

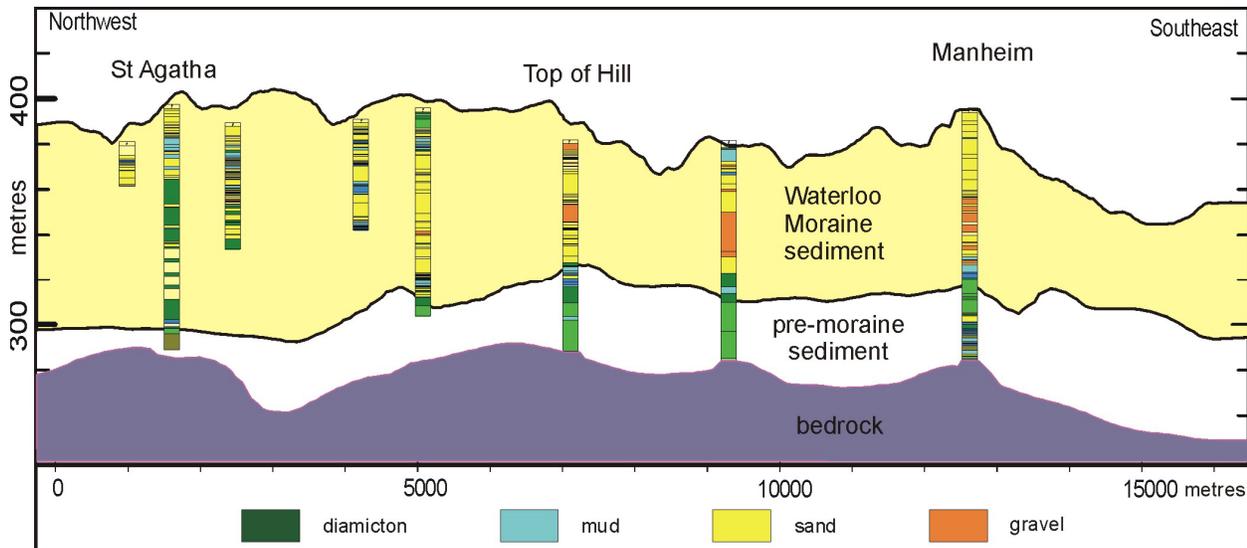


Figure 2. Waterloo Moraine cross-section from Manheim to Saint Agatha displays the transition from coarse to fine sediment texture (right to left) in selected borehole logs. Note small number of fining upward trends in borehole logs. Base is commonly underlain by diamicton, Maryhill Till or catfish Creek Till.

SEDIMENTOLOGY

Transect stratigraphy: The gross stratigraphic architecture of the moraine is being mapped in subsurface as part of a regional 3D stratigraphic modeling program using Viewlog software (Fig. 2; Bajc and Newton, this vol). Within this framework, spatial variations in sediment texture can be identified. From east to west, sediment texture fines from sand and gravel to mud and muddy diamicton, and bed thickness decreases (Fig. 2).

Shallow stratigraphy: Vertical sections examined in a number of 20 m deep aggregate pits indicate a two-fold fining upward depositional succession. The lower interval is > 10 m thick and is predominantly cross-bedded gravel deposits capped by a fine-grained muddy diamicton. The upper 5-10 m of the succession is predominantly medium to fine sand with a distinct upward-fining trend. More proximally, to the southeast, this succession can be dominated by gravel deposits with extensive cut and fill structures and metre-scale deformation features.

Sediment Facies: Sediment facies can be assigned to either esker or subaqueous fan depositional environments based on sediment facies associations. Esker sediment is characterized by cross-bedded gravel and sands with bimodal cobble gravel, openwork gravel, and polymodal gravel. In contrast, subaqueous fan sediment is more commonly polymodal gravel to sand with abundant climbing, cross-stratification, steep-walled scours, and antidune cross-stratification.

Sediment Facies Associations: Several of sediment facies associations have implications for ground water flow. Three examples are large gravel cross-beds, transverse bars, and steep-walled scours. Large cross-beds are formed of three distinct facies, openwork gravel, bimodal gravel, and polymodal gravel. These three facies

form systematic arrangements along 1-2 m high foresets with bimodal gravel at the base, overlain by open-work gravel and with polymodal gravel forming the upper portions of the foresets. Openwork gravel beds can be up to 0.5 m thick and extent 1.0 m up dip and 2.0 m along strike. Figure 3 illustrates the facies distribution within a 30 m² area of an aggregate pit section. The section is approximately transverse to flow.

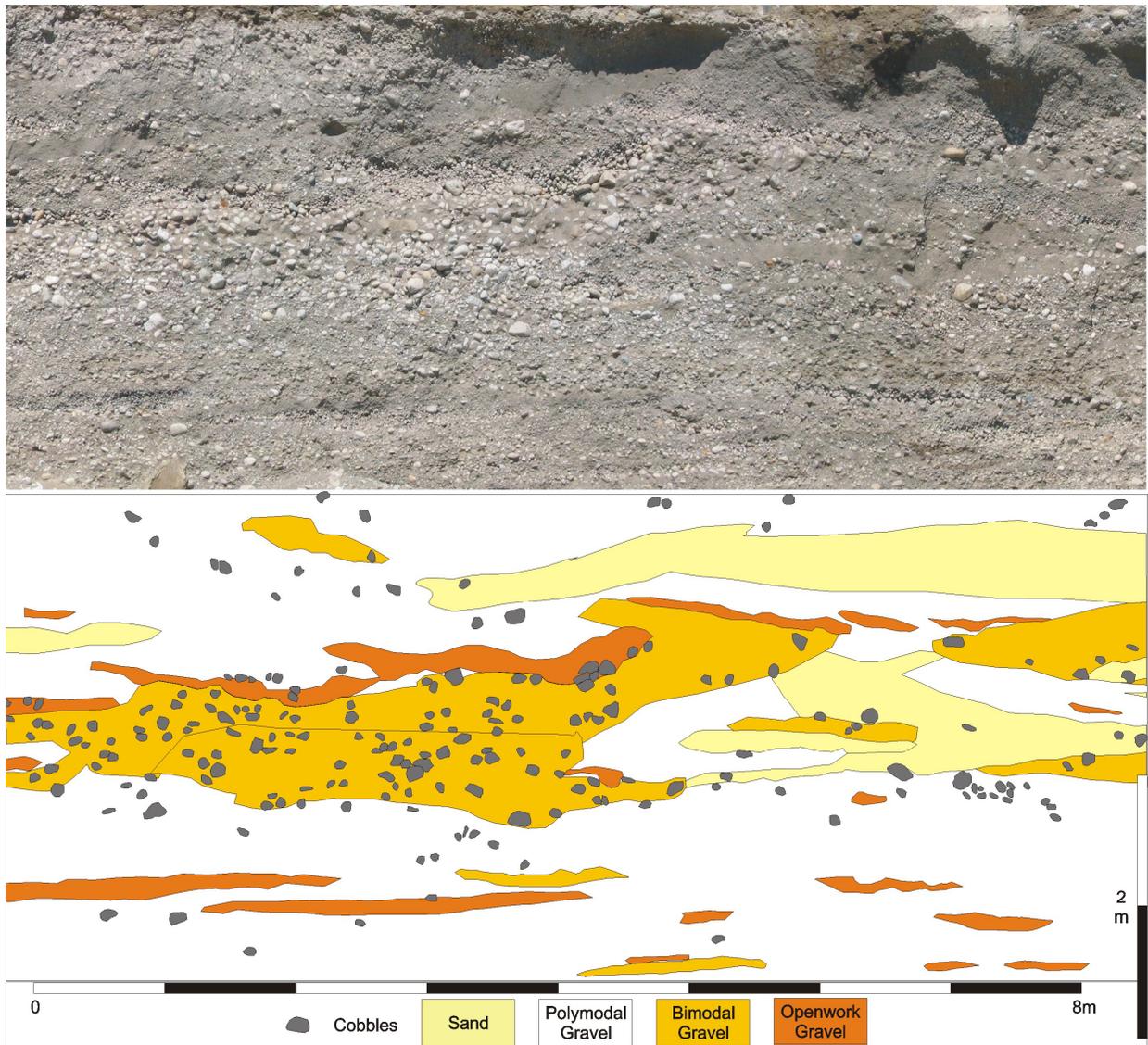


Figure 3. Photo mosaic and line drawing of part of a gravel aggregate pit wall in the Waterloo Moraine. Note the distribution of sediment facies, and vertical changes in relative unit sizes. Area of photo is ~30 m².

HYDROGEOLOGICAL IMPLICATIONS

The stratigraphic architecture of the moraine is dominated by a small number of fining upward sedimentary cycles. The main moraine body has a well defined proximal to distal transition from southeast to northwest and a shift in sediment facies from predominantly sand and gravel to silt and diamicton. Upward fining cycles of gravel and sand can be abruptly overlain by mud rich units of 1-3 m thickness. These units are laterally continuous for 100's metres and in the absence of erosional windows are aquitards. The continuity of these horizons beyond the scale of pit exposure remains poorly defined, however, based on depositional models such horizons could be laterally continuous at a basin wide scale (> 1000 m). Horizontal compartmentalization of the moraine has also been documented in the Manheim area (Duckworth, 1983). Within gravel and sand units aquifer heterogeneity is controlled by sediment facies. A particular example of this control is the arrangement of facies in large gravel dune-scale cross-beds. The arrangement of open-work gravel of pebble and cobble calibre with bimodal sand and cobble

provide the potential for high transmissivity flow units with complex geometries having widths > 50 m and lengths of 100's to 1000's of metres. Gravel units of this nature could be expected to have hydraulic conductivities of 1 to 10⁻⁴ ms⁻¹ (values from Freeze, 1979). Trends in hydraulic conductivity could be strongly aligned parallel to the paleoflow direction of the respective depositional units.

SUMMARY

An improved understanding of the sedimentology of the Waterloo Moraine will provide insight into the hydrostratigraphic architecture of the moraine, the distribution and extent of the major depositional environments and consequently the arrangement of sediment facies and structures that control fluid flow. Current work suggests that moraine sediment in the unsaturated, near surface, is an appropriate analogue for the deeper, saturated portion of the moraine. This conceptual understanding of the distribution, scale, and connectivity of high conductivity units has important implications for studies concerned with source water protection.

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INCORPORATION OF GROUNDWATER FLOW INTO TRADITIONAL SENSITIVITY ANALYSIS OF A SOUTHEAST COASTAL PLAIN LAYERED AQUIFER SYSTEM

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INTRODUCTION

In 1993 the U.S. Environmental Protection Agency (USEPA, 1993) defined aquifer sensitivity/contamination potential as “a measure of the ease with which a contaminant applied on or near the land surface can migrate to an aquifer.” The U.S. EPA went further in describing groundwater contamination potential by stating that it is a function of the intrinsic characteristics of both geologic materials comprising the aquifer as well as overlying saturated and unsaturated materials. Finally, the U.S. EPA noted that aquifer sensitivity, or contamination potential, is “independent of land use and the types of contaminants introduced.” During the ensuing 12 years since the US EPA’s proclamation, there has been steady effort nationwide to assess the susceptibility of water-bearing geologic units according to its definition.

U.S. EPA’s definition of contamination potential implies that land areas can be segregated into mappable units according to some differential measure of contamination potential. In other words, the relative variation in groundwater contamination potential over a geographic area can be deduced and mapped by applying some methodology that integrates certain spatially varying geologic and hydrogeologic criteria pertaining to the “ease with which a contaminant applied on or near the land surface can migrate to an aquifer.” Geographic information system (GIS) technology is a virtual prerequisite for contamination potential mapping and has made large-scale, complex aquifer sensitivity analyses feasible.

We applied three-dimensional (3D) geologic mapping to evaluate the spatial variation in aquifer sensitivity based on the textural character of materials, their thicknesses, and lateral extents. This approach is implemented through the creation of a stack-unit geologic map. Stack-unit geologic mapping is a technique whereby the successions of geologic materials (or variations within materials) are shown in their order of occurrence (from top to bottom) to a specified depth or boundary (Berg and Kempton 1988). The stack-unit mapping approach to contamination potential assessment has been successfully applied in a number of cases, particularly in the Midwest (e.g., Berg and Kempton, 1988; Berg, 1994; Fleming, 1994; Keefer, 1995). Rine et al. (1998) successfully applied the stack-unit mapping technique to contamination potential assessment of a portion of the U.S. Department of Energy’s Savannah River Site in South Carolina.

Experience has shown that aquifer sensitivity maps based on the 3D stack-unit maps of geologic frameworks contribute significantly to environmental protection, natural resources planning, “hot-spot” identification, emergency response, and economic development. However, as valuable a planning tool as these maps are, they are deficient in one important aspect. They do not incorporate, or consider, the hydrodynamics of groundwater flow, and hence solute transport, through the geologic framework. The purpose of this paper is to show the results of our recent efforts to incorporate the groundwater flow system into the stack-unit mapping-based assessment of aquifer sensitivity. The test area to conduct this assessment was at the Marine Corps Air Station at Beaufort, South Carolina (MCAS-Beaufort). We demonstrate the added value of incorporating the dynamics of groundwater flow into the traditional stack-unit map derived aquifer sensitivity analysis.

BACKGROUND

A multi-year geologic/hydrogeologic study of the MCAS-Beaufort focused on the determination of aquifer sensitivity throughout the geographic extent of this military base. MCAS-Beaufort covers 22 km² 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). MCAS-Beaufort is located in 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 determination of aquifer sensitivity focused 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 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. For purposes of our

study, we referred 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 MCAS.

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 the characterization work at the MCAS-Beaufort, we determined that the Hawthorn Formation is relatively thin (i.e., 1 to 2 m in thickness) where present. Although its presence varies significantly across 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. Figure 1 displays the top six hydrostratigraphic units included in the MCAS-Beaufort study of aquifer sensitivity. The middle confining unit is shown only for completeness and is not directly incorporated into the aquifer sensitivity analysis. The water table typically occurs within 2 to 3 meters of land surface. 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 zone.

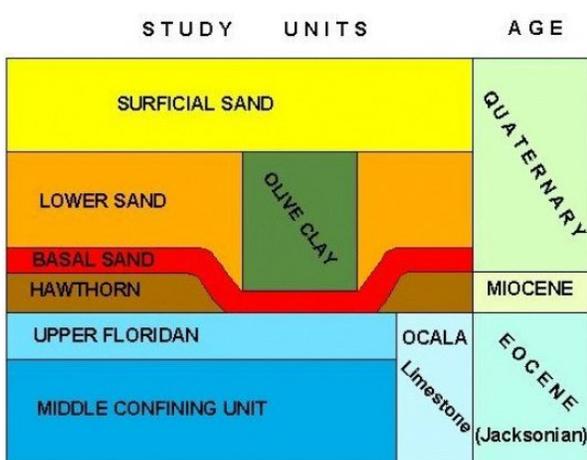


Figure 1. Hydrostratigraphy of the MCAS-Beaufort.

because the machine-drawn maps commonly were not geologically plausible. Thickness contours were eventually simplified enough to retain the character of the unit but reduce the complexity of the combined stack-unit map. The resulting MCAS-Beaufort aquifer sensitivity map shown in Figure 2 is more appropriately called a “geologic” sensitivity map because it was constructed from geologic information. Soil organic carbon content and hydrologic group were also considered so that the geologic sensitivity analysis could better assess water/contaminant movement to the saturated zone in the upper 1-2 m. This model does not include groundwater flow dynamics.

GEOLOGIC SENSITIVITY MAPPING AT MCAS-BEAUFORT

We performed an aquifer sensitivity assessment for the MCAS-Beaufort based on integration of historic data pertaining to hydrogeology in the area, new high resolution reflection seismic profiles, new vertical electric soundings, and core analysis from a series of new boreholes constructed throughout the MCAS. Elevations from vertically adjacent upper surfaces were “machine-subtracted” to create six isopach (i.e., thickness) maps for the hydrostratigraphic units shown in Figure 1. For example, the isopach map of the Surficial Sand unit was produced by subtracting elevations of the Lower Sand / Olive Clay top contour map from the Digital Line Graph (DLG) of the land surface. Final isopach maps of each unit were made by interpretative-redrawing of machine-drawn maps

3D GEOLOGIC MODEL AND RESULTING GROUNDWATER FLOW MODEL

The stack-unit map of MCAS-Beaufort was translated into a fully 3D geologic model of the MCAS-Beaufort study area (Figure 3) which became the basis for development of a high resolution, finite-difference groundwater flow and pathline analysis model of the MCAS-Beaufort. Following rigorous groundwater flow model calibration to a range of observed groundwater levels across MCAS-Beaufort, a dense ensemble of 3D groundwater pathlines was constructed over the entire 22 km² area of the MCAS and incorporated into a SQL database and GIS. Pathlines from any selected area on the base, within a 100 ft grid resolution, can be instantly displayed with their 3D representation on the aerial photo of the MCAS (Figure 4) or in cross section. Particularly, cross sectional displays show the potential contaminant as it moves through the 3D geology at various rates from any point on the site to eventual discharge areas.

The groundwater model was also used to determine areas throughout MCAS-Beaufort with rapid (i.e., less than 10 years and less than 25 years) travel times from the water table to the top of the Upper Floridan Aquifer. These areas were overlain on the MCAS-Beaufort geologic sensitivity map to add consideration of the dynamics of groundwater flow to the traditional aquifer sensitivity mapping. Figure 5 displays the composite MCAS-Beaufort geologic sensitivity groundwater flow dynamics map.

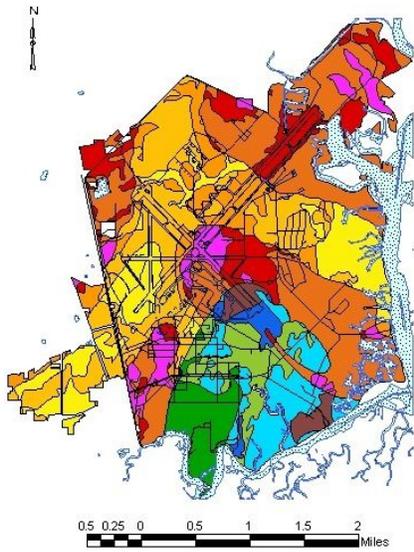


Figure 2. MCAS-Beaufort aquifer sensitivity map (Red = high; Green = low).

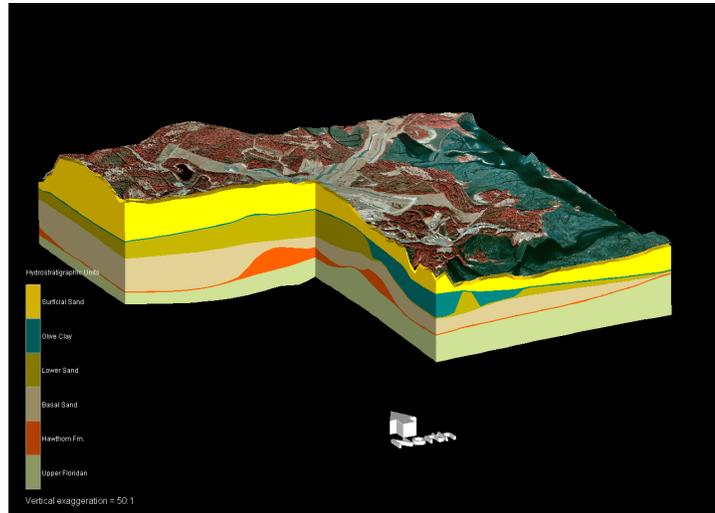


Figure 3. Geologic model of MCAS-Beaufort.

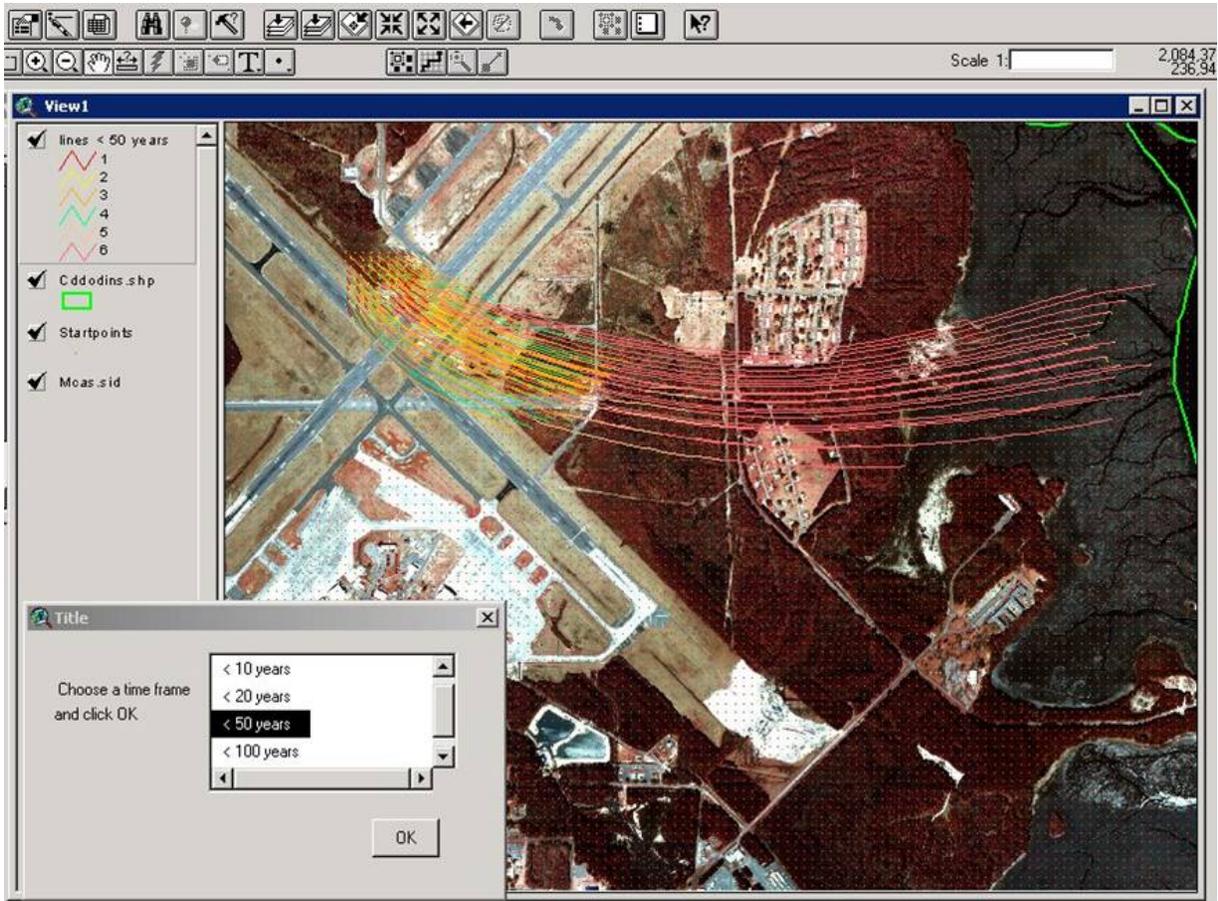


Figure 4. Example GIS projection of selected MCAS-Beaufort groundwater pathlines.

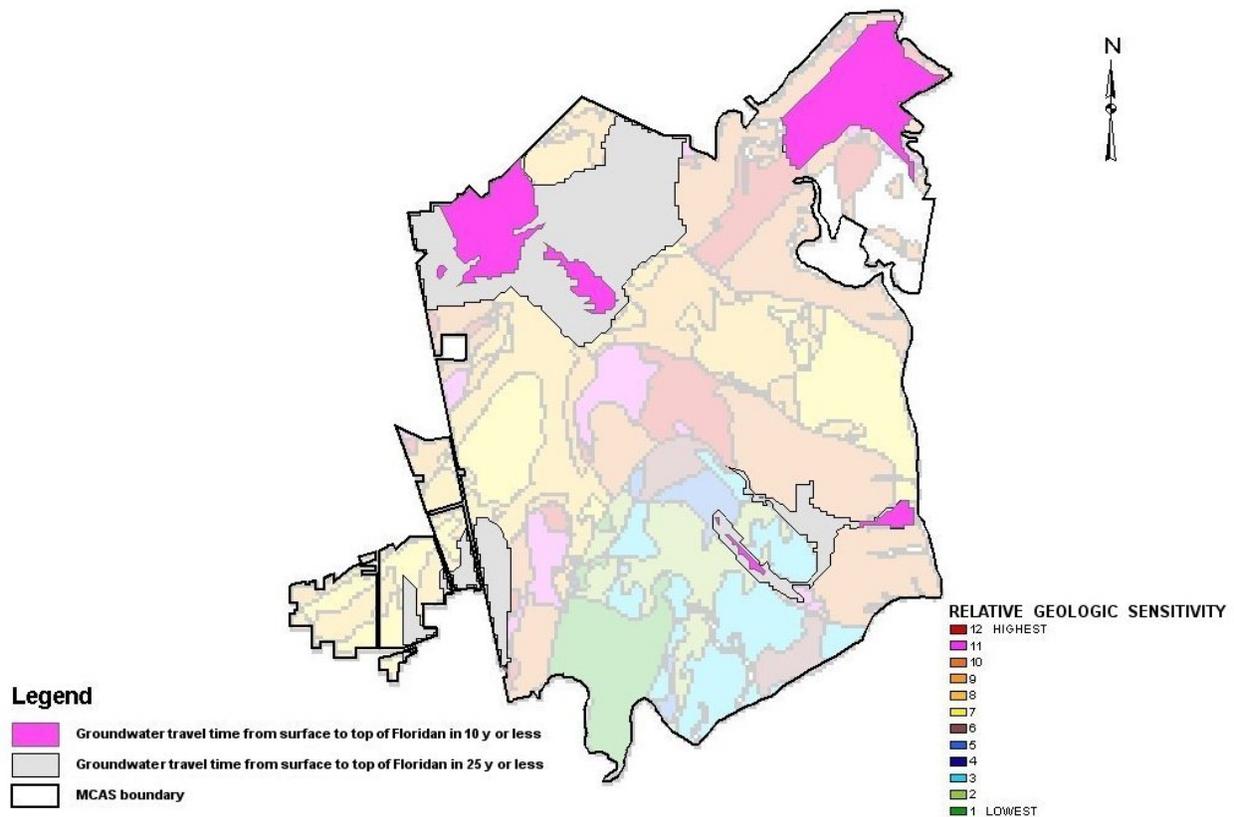


Figure 5. Composite MCAS-Beaufort geology and groundwater flow sensitivity.

CONCLUSIONS

We believe that through the integrated assessment of geologic sensitivity and groundwater flow dynamics that a more representative appraisal of overall aquifer sensitivity is obtained. Three-dimensional geologic mapping not only formed the basis for geologic sensitivity analysis but provided an internally consistent foundation for development of the groundwater flow/pathline model. More informed decision making pertaining to land use, economic development, groundwater protection, intelligent monitoring, and emergency response results from the integrated assessment of geologic sensitivity and groundwater flow dynamics.

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GEOLOGICAL FRAMEWORKS IN SUPPORT OF SOURCE WATER PROTECTION IN ONTARIO

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SOURCE WATER PROTECTION

Following the fatal contamination of municipal water wells in Walkerton, Ontario the provincial government plans to protect source water in all watersheds (Fig. 1). The priority is to control land use and to engineer current well-head and stream/lake intake areas using a multi-barrier approach under the precautionary principle. A Technical Experts Committee (TEC, 2004) identified several guiding principles for carrying out source water protection (SWP):

- adopt a watershed-based approach (while addressing extra-watershed implications)
- develop free and open data / information sharing
- apply sound science as the basis for risk assessment
- assess uncertainty
- continue to renew and improve watershed plans
- commit to ongoing research in support of source protection plans (applied research and sharing of 'lessons learned')

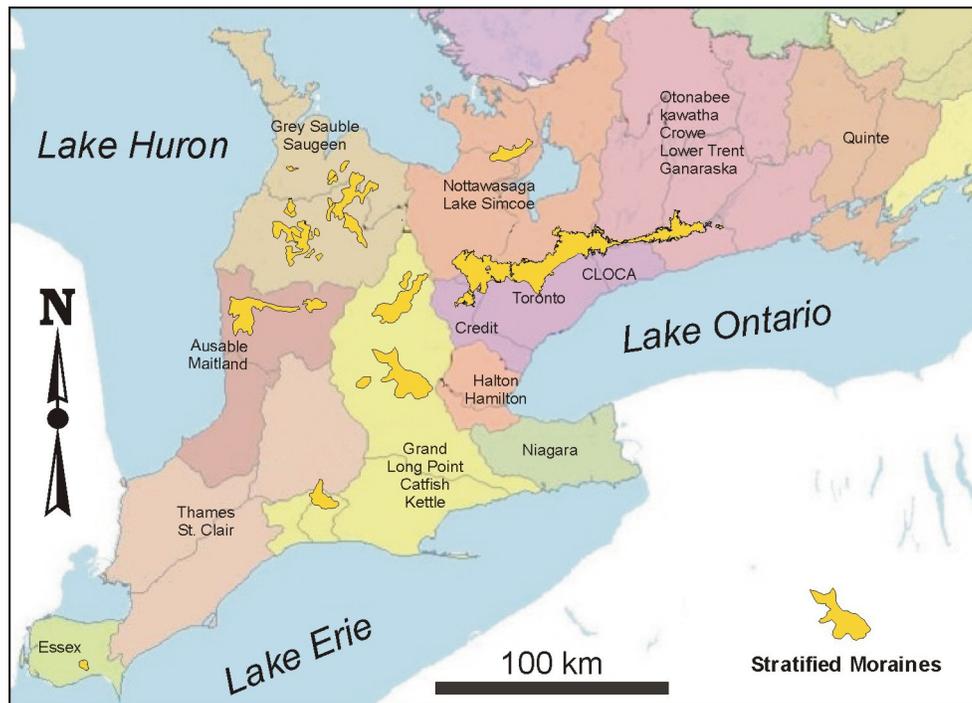


Figure 1. Watershed or proposed jurisdictional boundaries for planned implementation of source water protection in Ontario (base map from Ontario Ministry of Natural Resources, moraines modified from Barnett et al., 1991)

Of fundamental importance from a geoscience point of view is: how can one protect source water? In considering groundwater and linked surface water resources, a key issue in watershed protection is the recognition and evaluation of sensitive hydrogeological terrains such as recharge areas, preferential pathways and discharge areas. To adequately assess flow systems from 'source to tap' requires a geological framework developed using a basin analysis principle.

GEOLOGICAL FRAMEWORK

In adopting guidance from principles proposed by TEC (2004), it is prudent to consider 'lesson learned' with

respect to developing a watershed-scale geological framework. Key lessons cited in advancing regional hydrogeological frameworks (e.g. Sharpe et al., 2002) include the development of a fundamental database, as well as geologic and hydrogeologic models within a basin analysis context (Fig. 1). Basin analysis provides a procedural structure for regional hydrogeological analysis that integrates data from a variety of sources and scales of investigations (Miall, 2000). It is particularly appropriate for groundwater studies in geological environments where variability and flow systems occur on a number of scales (Koltermann and Gorelick, 1996). The basin analysis approach emphasizes geological analysis in developing conceptual and predictive models in order to characterise lithology, stratigraphy and structure as it controls regional groundwater flow. By directly linking geological setting and basin history to aquifer-aquitard properties, this approach strives to develop more plausible hydrogeological models at watershed scales.

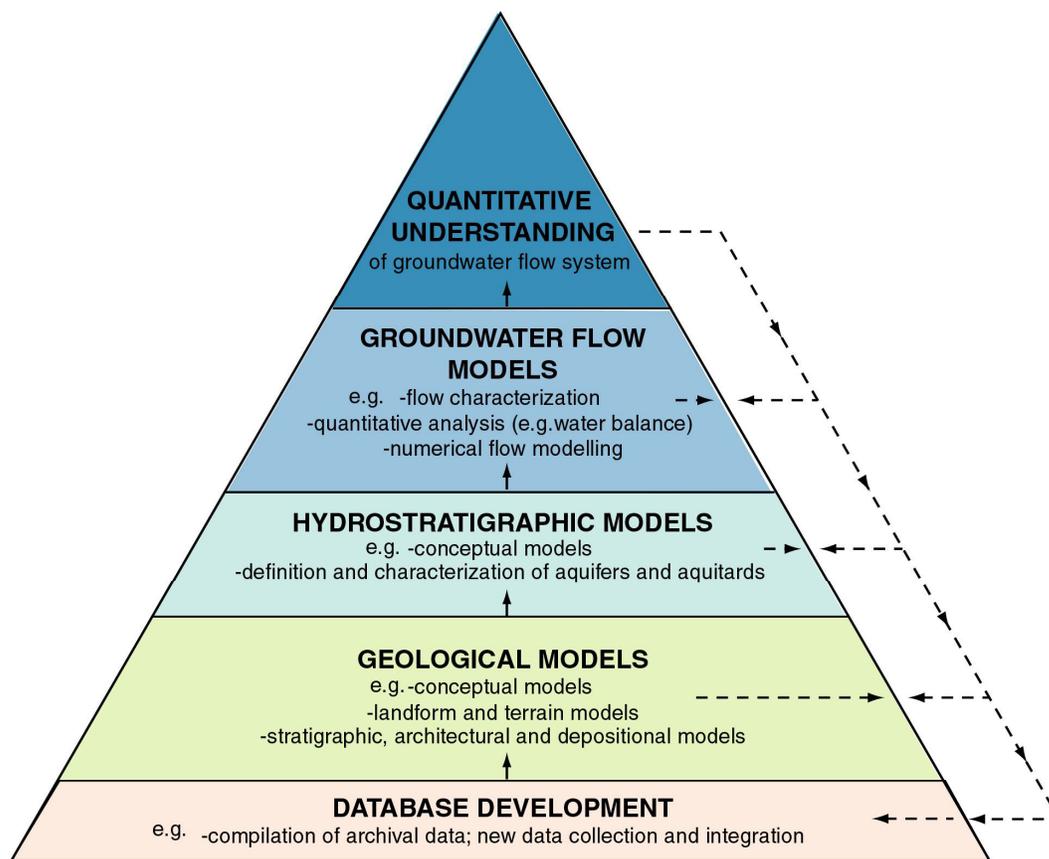


Figure 2. Simplified basin analysis approach used for regional hydrogeology analysis. The approach leads progressively from data base development early in a study (base) to quantitative understanding of groundwater flow systems as the study matures (top) (Sharpe et al., 2002).

In practical terms, source protection of groundwater supplies requires a viable 3D geological model to anchor the basin analysis approach. Recent groundwater problems in Waterloo region (e.g. aquifer closure, artificial recharge, new supply) can be linked to the lack of a robust 3D conceptual and geological model of the Waterloo Moraine (Bajc and Newton, this volume; Russell et al., this volume), despite the years of reliance on groundwater supplies and the long history of hydrogeological study and analysis.

A brief review of the significance of database, geological and hydrogeological models to source water protection precedes a proposal to commence strategic use of basin analysis principles on stratified moraines.

Databases

A relational database that integrates all stratigraphic and terrain data is fundamental to the planning, construction and implementation of a dynamic 3D geological model (Logan et al., in press). It is recommended that this includes a stratigraphic database component which allows the integration of data of unequal quality and permits

interpretation based on evolving geological knowledge. It should also contain linked physical property data such as lithology, grain-size, hydrochemistry, and geophysical signatures. A stratigraphic database is best developed using a training framework of manually-coded, high-quality data. Such a database design, when set within an appropriate conceptual framework and based on field-based geological rules (Logan et al., in press), allows automated interpretation and coding of large numbers of low-quality water well records that are the core dataset for watershed-scale, source water protection.

Geologic models

The contribution of geological knowledge becomes increasingly valuable as source water assessment moves from site to watershed scales. A key element in building a 3D model is a sound conceptual geological model. The lack of regional conceptual geological knowledge in recent Superfund hydrogeological studies, for instance, was cited as a serious and costly shortcoming (LeGrand and Rosen, 1998). Seamless geological mapping (Ontario Geological Survey, 2003) fosters the development of first-order conceptual models and provides the foundation for 3D modeling. It also helps to limit the effect of deficiencies in data coverage and data quality often encountered in watershed scale models.

Accurate stratigraphic interpretation of borehole logs and other subsurface information, essential to constructing a viable 3D model, requires geological context best supplied by seamless mapping linked to a reliable conceptual framework. In areas with a geological knowledge base, a primary task is to assess the validity of existing conceptual geological models and continue to test and assess their reality. In glaciated terrain, this analysis is carried out in the context of available/ evolving glacial process and landform-sediment models, such as the till/stratified moraine models discussed below.

Hydrogeological models

In the context of watershed-scale SWP, hydrogeological models need to be able to assess the role and threat of preferential flow paths as a least-risk objective. Because geologists endeavor to understand the geological system by mapping and developing process-based conceptual models, such as sedimentary facies or event-stratigraphic models of a basin (e.g. Walker, 1992), they are more apt, for example, to identify erosional breaches in aquitards or consider pipe flow in karst aquifers as the critical factors in constructing a hydrogeological model for SWP in a watershed. Hydrogeologists commonly attempt to mathematically model flow systems based on digital geometries developed mainly from water well records. Water well records are not sufficient to generate reliable conceptual models (Russell et al., 1998), particularly ones that could identify such preferential structures. In addition, without the support of a broader geological knowledge base, water-well-based models run the risk of under-estimating these heterogeneities in watershed assessments. Furthermore, due to the mandate of honouring the precautionary principle to SWP, it can be argued that a plausible and testable conceptual geological model is more important to source water resource management and protection than rendering a numerical hydrogeological model. This is illustrated as follows: it is one thing to show karst conduits in a conceptual model; it is quite another enterprise to accurately map these conduits to support a realistic numerical flow model that accurately estimates groundwater flow paths. Consequently, additional numerical techniques such as geostatistical methods (e.g. Desbarats et al., 2001; Weissmann, this volume) and probability mapping, are needed to quantify uncertainty in the 3D model and in the related SWP risk assessment.

A conceptual stratigraphic model is a distillation of geological observations and knowledge that provides a stratigraphic framework, and is a sound basis, for subsequent hydrogeological model development. This requires a strategic plan, in addition to the resources and time to adequately develop the model. The following case study uses stratified moraines in southern Ontario to point out a viable strategy to develop a geological framework, even if a full basin analysis of the area (e.g. complement of high-quality, basin-wide data) is not feasible.

MORAINES AND SOURCE WATER PROTECTION

A preliminary geoscience approach to SWP in Ontario focuses on sensitive hydrogeological terrains, e.g. moraines. High recharge areas such as moraine landscapes are situated at the top of the groundwater flow system. The sedimentary properties of moraines control flow paths of a significant percentage of the watershed recharge, and consequently, have long-term implications for source water protection. Effective planning efforts require reliable information on moraine extent, composition, and structure because these factors determine groundwater flow in local and regional systems. An improved understanding of surface water-groundwater flow system interaction in moraine areas is supported by modeling three-dimensional geological data (e.g. Logan et al., in press). Knowledge of the geological framework can provide valuable information for source water management, particularly through identification of preferential flow paths (e.g. tunnel channels) from surface recharge to deep aquifer systems (TEC, 2004).

The Oak Ridges Moraine (ORM), for example, forms the principal recharge area for groundwater flow to more than 30 watersheds in the Greater Toronto Area (GTA). Furthermore, ORM supplies flow to extensive buried valley aquifers (Russell et al., 2004) used for municipal drinking water supply and that have inter-watershed connection. ORM also discharges abundant water to streams, supports watershed ecosystems, and supplies domestic wells (Sibul et al., 1977). Recent groundwater modeling in the ORM area has clearly been improved by the use of new information on sediment distribution, facies and spatial variability (Holysh et al., 2004; Wexler, this volume). In most moraines, however, there is little primary data to support three-dimensional characterization except low-resolution provincial water well records. Hence, application of principles used to assess the sedimentary and stratigraphic architecture of the ORM may provide lessons for the study of moraines in other watersheds.

Moraines types in southern Ontario

Moraines are common landforms across Ontario (Barnett et al., 1991). They have been described as either till or kame moraines (Chapman and Putnam, 1943; Fig. 1), with little sedimentological description of the internal composition and geometry of these strategic landforms (Barnett et al., 1998; Russell et al., this volume). Kame or stratified moraines are composed of gravel, sand, and silt, deposited at the margin of inactive ice. Till moraines are mapped as massive sediment bodies and thought to be deposited by advancing ice. It is increasingly apparent, however, that many so-called till moraines are also stratified, and that our understanding of most moraines in southern Ontario is poorly developed, particularly in the subsurface and with respect to aquifer characterization. From present knowledge, a conceptual model of till moraines would imply few preferential pathways to underlying aquifers. A conceptual model of stratified moraines, however, if analogous to the Oak Ridges and Waterloo moraines, would be expected to have, highly conductive pathways.

Reliable data to devise or revise conceptual models

To apply sound science as the basis for risk assessment of SWP will require the acquisition of reliable data to map and model travel times for groundwater flow within many watersheds. Such data may exist or be available through open information sharing (e.g. Grand River Conservation Authority). In many cases, however, new data will need to be collected to reduce data uncertainty in flow path analysis, including refining estimates of travel times. In most cases, archival data lacks the resolution, and reliability to adequately document preferred flow paths. Thus, a central need is strategic data collection to better understand the geological history of the basin and develop conceptual models for watersheds analysis.

Conceptual models of moraine composition and structure need to be documented and revised using high-quality geophysical, sedimentologic, and chemical data. In this respect, recent work on the Oak Ridges Moraine and Waterloo moraines (e.g. Sharpe et al., 2002; Bajc and Karrow, 2004) highlights the disparity that exists between the knowledge of these landforms and other moraines in southern Ontario (Karrow, 1996). The ORM is one of few systematic studies completed on sediment architecture and distribution along with accompanying predictive depositional models (Russell et al., 2003). To provide the level of certainty expected of source water protection will require focused, high-quality data collection and strategic study of moraines and related eskers in southern Ontario. To generate a 3D model (e.g. Logan et al., in press), requires similar methodologies to those tested and documented in the Oak Ridges Moraine (Sharpe et al., 2002). To implement this process, a strategic study of moraine sedimentology, using available exposures, will enable the mapping of sediment facies and sediment facies assemblages. This will allow a preliminary assessment of sediment packages with respect to regional conceptual models (e.g. Sharpe et al., 2004; Karrow and Paloschi, 1993). It would also afford an evaluation of data and knowledge gaps to permit revision of moraine models in key watersheds.

THE STRATEGIC APPROACH

It is probable that subsurface geological uncertainty is a fundamental limitation of source water protection. As part of the need to continually improve watershed knowledge, assessment, and protection, strategic new data collection of targeted areas, such as moraines, is necessary. A prime goal is re-assessment and improved understanding of geological history to re-cast formative conceptual models and to improve their predictive capabilities. This approach will allow Conservation Authorities and other vested parties to develop more sophisticated modeling approaches to reduce uncertainty and risk in source water protection planning.

Experience from ORM studies suggest that the most efficient path forward for SWP agencies is to initiate collective research in collaboration with expertise at geological surveys (Ontario Geological Survey, Geological Survey of Canada, United States Geological Survey), and environmental agencies (Ontario Ministry of Environment, Ontario Ministry of Natural Resources, Environment Canada, Conservation Authorities). The goal is to seek opportunities for partnership to undertake strategic geoscience relevant to source water protection by building on and

sharing experience from recent moraine studies in the Oak Ridges and Waterloo areas.

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AQUIFER MAPS FOR COUNTY PLANNERS IN LAKE COUNTY, ILLINOIS: THREE-DIMENSIONAL GEOLOGIC MAPPING, AND AQUIFER SENSITIVITY CLASSIFICATION FOR THE ANTIOCH QUADRANGLE

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INTRODUCTION

Lake County is located in the northeast corner of Illinois (Fig. 1). Adjacent to the Chicago metropolitan area, it contains some of the most rapidly growing communities in the state. Many of these communities rely heavily upon groundwater resources. Accurate maps of the sands and gravels within the thick Quaternary sediments are needed by agencies of local government for infrastructure planning, resource development (potential aquifers, recharge areas, building aggregate, etc.), land use planning, and environmental protection.

Current Illinois State Geological Survey (ISGS) mapping projects in northeastern Illinois (e.g., Central Great Lakes Geologic Mapping Coalition, STATEMAP) are addressing key questions as to the origin and distribution of the glacial deposits and creating products that show the complexity and variability of the succession of materials above bedrock (Barnhardt et al., 2003). To achieve these goals, geologists are using modeling software to integrate water well records, geophysical logs, and borehole data to produce 3-dimensional models and detailed (1:24,000 scale) geologic maps that show the complex geometry of sands and gravels (aquifer materials) and fine-grained sediments (aquitards) in the subsurface.

The county is overlain by a thick (mostly >250ft/80m) succession of Quaternary deposits that resulted from the multiple glacial advances of the last glaciation. Each time glaciers of the Lake Michigan lobe advanced out of and retreated into the Lake Michigan basin a 'layer-cake' of glacial, fluvial, and lacustrine materials was deposited. Because the ice from earlier advances did not completely melt from the area before subsequent ice advanced, the sediment layers were modified by dead-ice sedimentation during deglaciation.



Figure 1. Location Map

THE MODEL

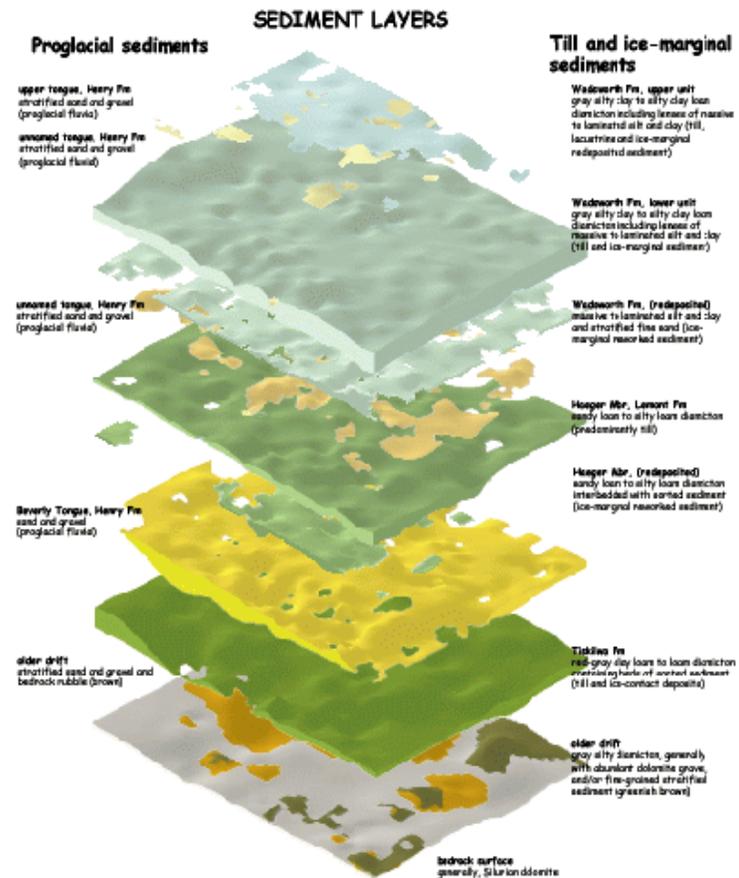
The mapping team acquired, verified, and interpreted drilling records and/or gamma logged the sediments from over 5,000 borings in and around the Antioch Quadrangle. Available water wells and engineering borings (3,036), detailed records from ISGS study-specific drilling (9), natural gamma logs from both new and old boreholes (36), shallow seismic reflection transects (2), and a few outcrop and/or exposure descriptions from gravel pits and construction excavations were reviewed.

The 3-D lithostratigraphic model is based on a selected subset of 352 records, 283 within the quadrangle boundary and an additional 69 records within a 1-mile buffer adjacent to the quadrangle (Hansel, 2005). Wells were selected on the basis of location accuracy, geographic distribution, total depth, and quality of the description of materials found in the well. The hydrostratigraphic model used an additional 110 wells.

For the lithostratigraphic model, the Quaternary materials were grouped into units that represent sediment layers that have a distinct lithology and stratigraphic position and represent different sedimentary environments. The present model includes 11 units (Fig. 2). There are 5 layers of sorted sediment (in shades of yellow) and 6 layers of fine-grained materials (in shades of green). The model displays the geometry and relationships of the sediment layer.

For the hydrostratigraphic model, Quaternary materials were assigned to one of 12 units based on hydrogeologic properties of the materials described and their position in the driller's logs and the static water levels reported in the water-well records. This model will be used to 1) evaluate the aquifer and aquitard units; 2) determine patterns of groundwater flow; and 3) assess both the availability of groundwater and the potential for groundwater contamination.

Figure 2. Lithostratigraphic Model of the Antioch Quadrangle (modified from Hansel, 2005).



AQUIFER RISK MAP

Elevation grids from the lithostratigraphic units were exported to ArcInfo software for visualization and map development. The upper and lower surface grids for each sand and gravel unit (aquifer) were converted to isopachous coverages, coded for elevation, and unioned. Unit thickness was calculated by subtracting the lower elevation from the upper. Similarly, depth-to (cover thickness) distances for each unit were calculated by subtracting the upper surface elevation from land-surface topographic elevations.

The aquifer risk map for each sand and gravel unit (Fig. 3) was produced by joining the unit and depth-to thickness files and coding the polygons using the Aquifer Sensitivity Classification for Illinois (Berg, 2001). This classification scheme includes 6 classes (A through F) of decreasing sensitivity based on the potential for contaminant movement through aquifer materials and their proximity to land surface (Berg et al., 1984). The unit risk maps were unioned into a single coverage. Individual thickness, unit surface elevation, depth-to, and contamination fields were carried into the composite coverage to maintain extractable unit data from the whole.

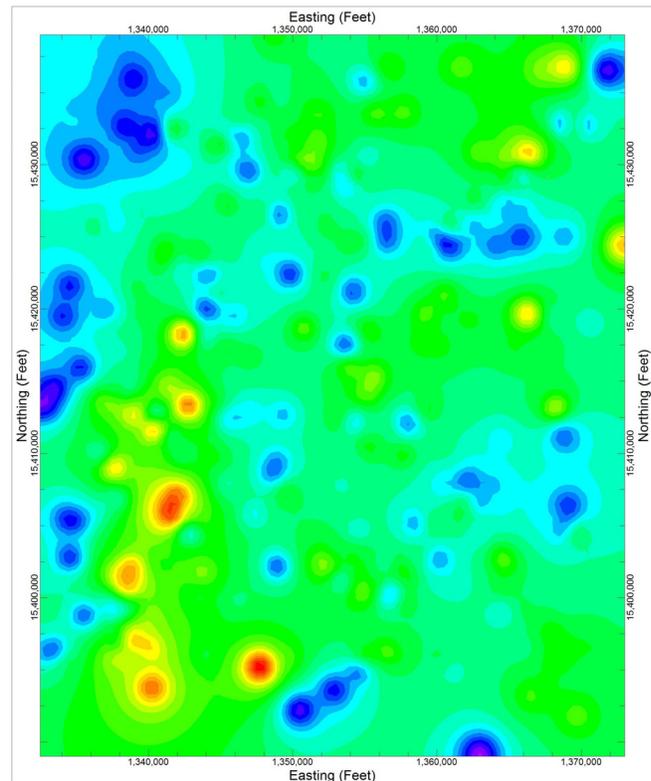
PROXIMITY MAP

This preliminary map displays proximity of 'fairly clean' glaciofluvial materials to land surface (Fig. 4). The map was derived from the hydrostratigraphic model and is an adjunct to the Aquifer Sensitivity Map. It displays some variation in the distribution and geometry of aquifer materials as a result of the different classification of certain sorted sediments on

the basis of their hydrogeologic properties. For example, materials containing the term 'fine sand' were grouped with aquifer materials in the hydro-model but were grouped with fine-grained sediments in the litho-model

The materials from some wells were difficult to categorize because there was insufficient information to determine hydrologic properties. Compound descriptions such as 'gravel and clay', 'silt and sand', 'clay and gravel', etc. were included with fine-grained. However, the potential for water movement within these materials clearly exists.

Figure 4. Proximity of Aquifer Materials to Land Surface Map. The colors represent depth to sand and gravel from land surface. Values increase from magenta (shallow) to red-orange (deep) in 10 foot increments. Distinct color shifts in the image include 30 to 40 feet (dark blue), 110-120 (cyan), 230-240 (yellow), up to 300 to 310 in the thickest areas.



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HOW MUCH DATA IS ENOUGH? DETAILED GEOLOGIC MAPPING NEAR A SUPERFUND SITE, WAUCONDA, ILLINOIS

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Detailed geologic mapping was undertaken in northeastern Illinois to provide officials at state, county, and local agencies a better understanding of Quaternary deposits for environmental, resource, and planning issues. The regional geological framework was developed from mapping in the Wauconda and Grayslake Quadrangles for the National Cooperative Geologic Mapping (STATEMAP) Program (Stumpf *et al.*, 2004; Stumpf, 2004) and the Antioch Quadrangle for the Central Great Lakes Geologic Mapping Coalition (Hansel, 2005) in (Figs. 1 and 2). Specifically, on the Wauconda Quadrangle, officials will use this information to help predict groundwater flow and contaminant potential in the vicinity of a Superfund Site.

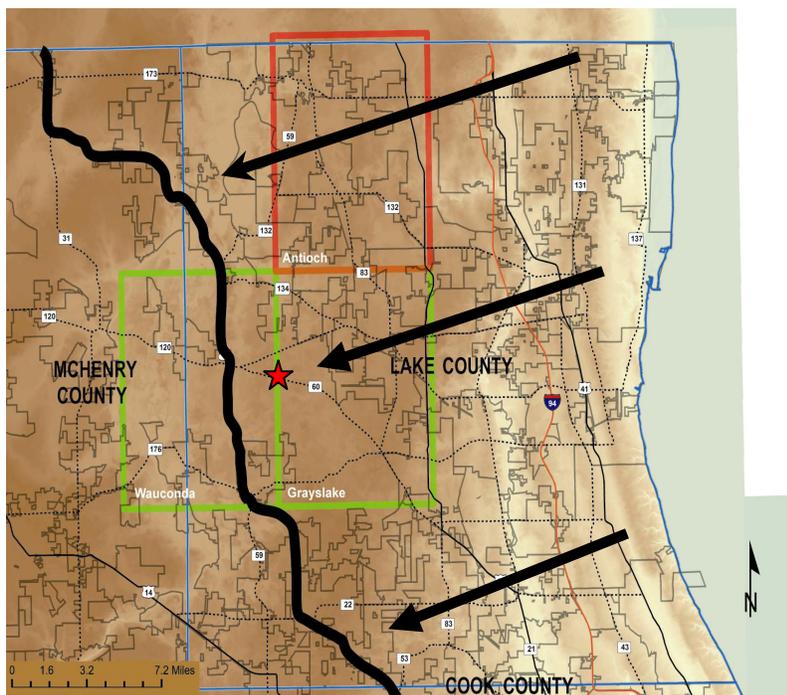


Figure 1. Location of completed geologic mapping areas in northeastern Illinois. The star locates the Wauconda Landfill Superfund Site. The thick black line demarcates the maximum advance of Wadsworth ice westward from the Lake Michigan basin, the last ice advance to cross the area.

BACKGROUND

The Wauconda Landfill is located in western Lake County, Illinois near at the margin of the last glacier advance into the area (Fig. 1).

Quaternary deposits are 100 to 250 feet thick and represent at least three major glacial events that occurred between about 25,000 and 14,000 radiocarbon years before present. Lithologically distinct diamictos interpreted as tills and ice-marginal sediment includes the Tiskilwa, Lemont (Haeger Member), and Wadsworth Formations, all deposited by the Lake Michigan lobe during the three events (Hansel and Johnson, 1996). Proglacial outwash and sandy to silty lake sediment are present between the tills and are classified as tongues of the Henry and Equality Formations, respectively (Figs. 3a and 3b).

Previous surficial geologic mapping in the Wauconda and Grayslake Quadrangles (Stumpf *et al.*, 2004; Stumpf, 2004) identified mostly till at land surface, typically >20 ft thick, overlying sand and gravel. At the landfill, sand and gravel were encountered at the surface, or below <10 ft of till and ice-marginal sediments.

The Wauconda Landfill was used as a sand and gravel pit prior to 1941. In 1951, the site was converted to a sanitary landfill and remained open until 1978. The landfill site is approximately 53 acres, 47 acres of which contains waste that was buried prior to permitting by the Illinois Environmental Protection Agency. The landfill received mostly residential and commercial waste, estimated to be 280,000 tons, of which less than one percent was from industrial sources (USDHH, 1995).

Ongoing studies and monitoring at the landfill since its closure has addressed both surface and groundwater issues. Between 1983 and 1987, studies were completed near the landfill (e.g., WTG/CRA, 1985) to obtain a better understanding of the geology and hydrogeology. Five stratigraphic units were identified: (1) an upper fine-grained unit; (2) an upper aquifer; (3) a middle clay aquitard; (4) a lower aquifer; and (5) dolomite bedrock. Groundwater in the lower aquifer flows towards the southwest, whereas in the upper aquifer flow is northeastward.

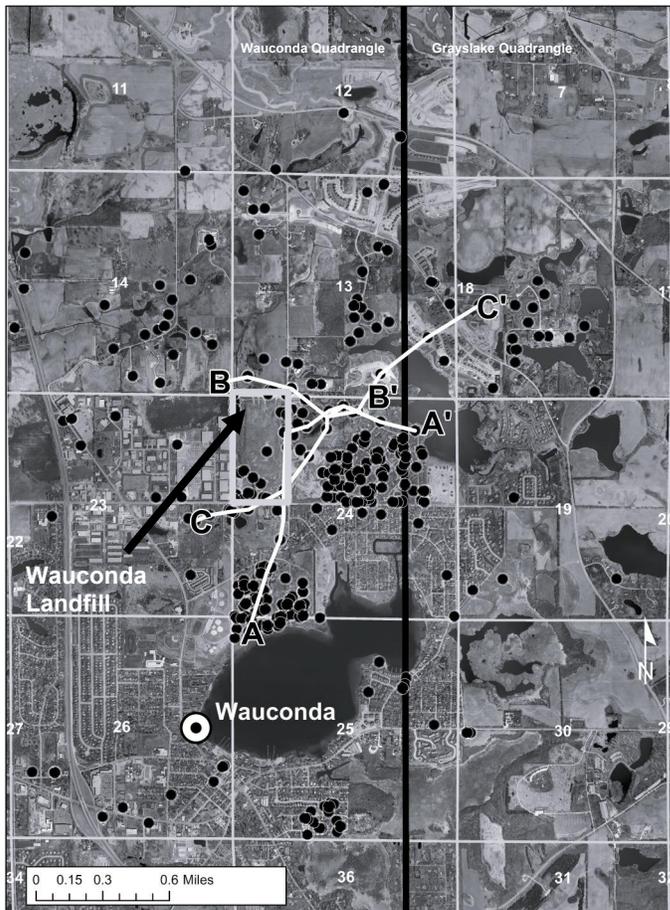


Figure 2. Water wells and stratigraphic borings (dots) within nine-square miles of the Wauconda Landfill. Transects for cross sections shown in figures 4, 5, and 6 are delineated.

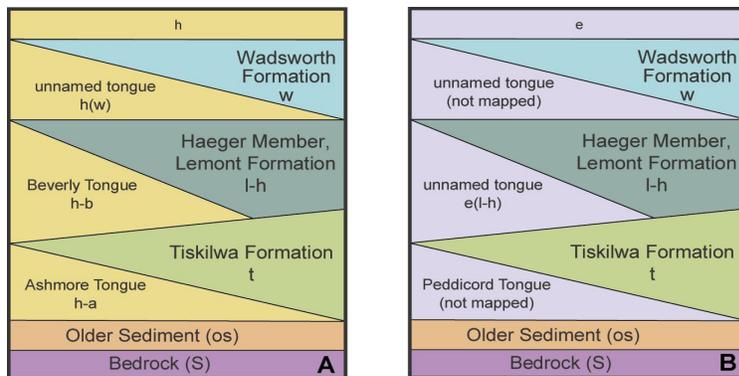


Figure 3. Stratigraphic framework for Lake County displaying intertonguing between A) sand and gravel units of the Henry Formation and B) lacustrine sediments of the Equality Formation with the Wisconsin Episode tills.

Most recently, in 2004, detailed studies at the area have detected vinyl chloride in residential wells to the east of the landfill. Vinyl chloride was found in water of ten private wells, with three having levels above the maximum allowed contaminant concentration of 2 µg/L.

DATABASES

Well and boring databases used to support various site-specific and regional studies near the Wauconda Landfill, have been developed since the early 1980's. The first databases included the records of wells, driller's material descriptions, and surface elevations obtained from county and state agencies. The wells were located in reference to the Public Land Survey System and are generally located within 660 feet of their actual site.

Further studies late in the 1980's (e.g., Conestoga-Rovers, 1987) used new data compiled during the installation of monitoring wells. This data included static water levels, physical properties of the geologic materials, natural gamma ray logs, and water chemistry. The locations of some new and existing borings were measured by land surveyors.

More recently, since 2002, the ISGS as part of STATEMAP projects in the Wauconda and Grayslake Quadrangles, compiled location information, material descriptions, well production, static water levels, and downhole geophysical data. During mapping, it was determined that over 50% of the wells in the ISGS' Geologic Records database within a nine-square mile area of the landfill were incorrectly located. Also, when constructing preliminary cross sections and models, inconsistencies in geology between adjacent data points were identified. To resolve these discrepancies, street addresses for these water wells were cross-referenced with tax parcel and street center line. Some were also relocated using GPS in the field. In 2004, the ISGS received access to data from Conestoga-Rovers and Associates Limited during their study of vinyl chloride contamination. Their database

contains data for wells drilled in subdivisions east and south of the landfill. The wells are located to individual tax parcels and this data were cross-referenced with our database. This final database is continually being updated as new water wells and stratigraphic borings are drilled or as more information on existing borings are obtained. This

includes detailed geologist's descriptions for four new monitoring wells. The ISGS obtained one complete rotasonic core from one of these drill holes.

RESULTS

The Lake County Health Department constructed cross sections to evaluate the subsurface geology during initial studies at the landfill. Drilling records from thirteen wells were used to construct a southwest to northeast cross section (A–A') (Figs. 2 and 4). Later in the 1980's, Conestoga-Rovers and Associates Limited constructed cross sections (e.g., B–B', Figs. 2 and 5) for additional investigations at the landfill. At that time, a database of 142 boring records was available to map the subsurface geology. Both projects identified upper and lower sand and gravel units (aquifers) that are separated by an impermeable unit (aquitard) of sand, silt, and clay. This aquitard appears to pinch out to the east and northeast of the landfill.

Starting in 2002, 289 drilling records were accessed from the ISGS archival well database, and at present 333 records are available. Over 95% of the original records accessed records now have verified locations. Verification was found to be important because mislocated wells can have surface elevations that differ by as much as 50ft from their actual locations.

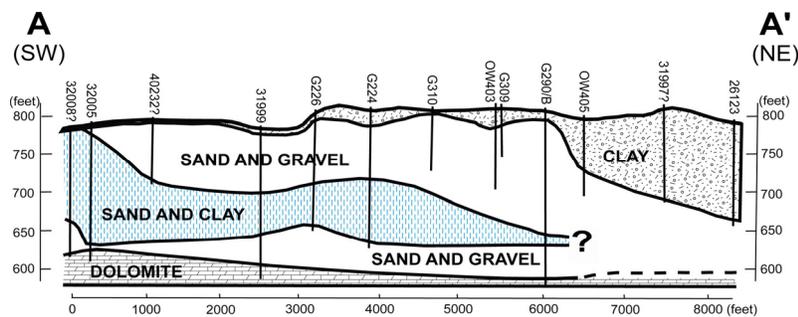


Figure 4. Southwest to northeast cross section across the Wauconda Landfill. The cross section was constructed for an unpublished report by the Lake County Health Department.

A southwest to northeast cross section (C–C', Figs. 2 and 6) was constructed using this data. An evaluation of these records suggests a more complex geology than previously understood, which hence may alter the model for movement of natural and contaminated groundwater. Using the regional geological framework and acquiring more detailed data from continuous core and natural gamma logs, multiple ice-marginal and proglacial facies have been identified (Fig. 6). Resolution of these facies is especially important because they contain significant heterogeneity, and thicken or pinch-out laterally and lie adjacent to materials with different properties that may affect the direction of groundwater flow.

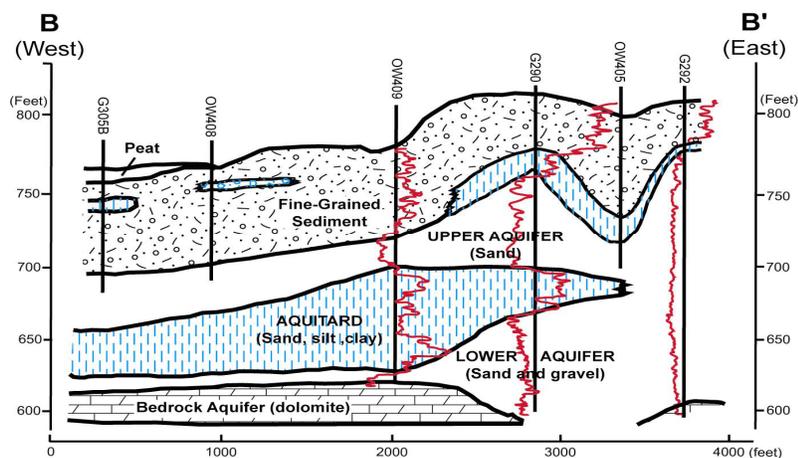


Figure 5. West to east cross section across the Wauconda Landfill constructed by Conestoga-Rovers and Associates Limited for a supplemental feasibility investigation (Conestoga-Rovers, 1987). Natural gamma logs are shown on the geology.

To the east of the landfill, where previously a sand, silt and clay aquitard was predicted to pinch-out, new geologic mapping suggests this unit may extend further east (Figs. 4, 5, and 6). Ice-marginal sediments (silt, sand, clay and diamicton) probably related to Haegar ice advance, in some places separates sand and gravel aquifers of the Henry Formation.

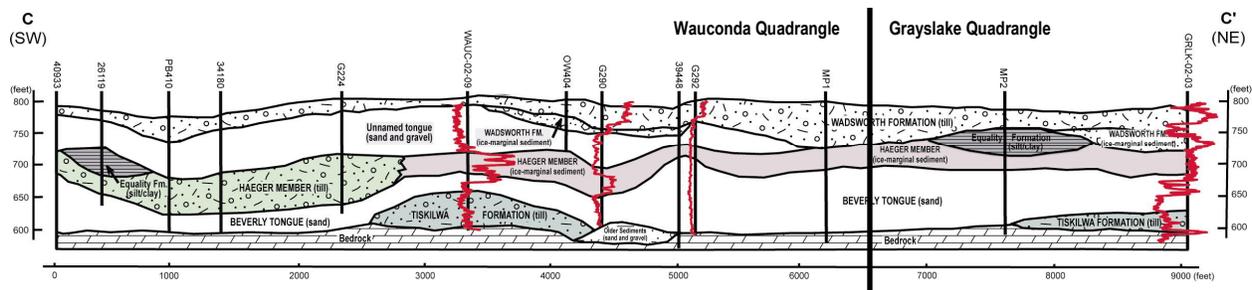


Figure 6. Southwest to northeast cross section across the Wauconda Landfill constructed by the ISGS. The cross section includes wells previously used to construct transects A–A' and B–B', and new, more detailed geologic data. Natural gamma logs are shown on the geology.

RECOMMENDATIONS

Although more data were available for the ISGS mapping, some of the major sedimentary units were resolved with less data in the previous studies. Although, the geometry of some units were delineated only with data collected for the new mapping. This evaluation suggests the amount of data needed generally depends upon the complexity of the geology, data distribution, and the scale of mapping. The acquisition of more detailed data, such as drill core descriptions and natural gamma logs is most important in identifying subtle changes in material properties. With an understanding of the regional geology, the prediction of facies geometries is possible. Verification of boring locations is also necessary.

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USING BOREHOLE DATA AND THREE-DIMENSIONAL MODELS TO MAP THE GROUND-WATER SYSTEM IN THE AMARGOSA DESERT BASIN, NEVADA AND CALIFORNIA

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The ground-water system beneath the Amargosa Desert in southern Nevada and southeastern California (Figure 1) is under increasing demands from agricultural, commercial, and residential users. The Cenozoic basin fill in the Amargosa Desert basin has great lithologic diversity and state of consolidation, and is thus hydrogeologically heterogeneous. However the configuration and continuity of basin-fill aquifers and confining units that underlie the Amargosa Desert are poorly known, leading to difficulties in estimating the available exploitable ground-water resource; understanding and responding to water-level declines created by ground-water withdrawals; and evaluating issues of groundwater quantity and quality. Better prediction of the effects of ground-water development on valued habitats and on the sustainability of water resources can come only from improved understanding of the hydrogeologic system. Knowledge of the geologic framework for the basin-fill aquifer system has been improved by using drill hole data from a 20 km by 90 km area to construct a three-dimensional lithologic model (Figure 2). Lithologic data were reduced to a limited suite of descriptors based on geologic knowledge of the basin and distributed in 3D space using gridding methods. Drill hole data were extrapolated radially from each hole using a cell-based modeling approach where solid model cell nodes were sequentially assigned properties by looking outward horizontally from each borehole in search circles of ever-increasing diameter. Cell dimensions for the modeling were 1000 m in the horizontal dimensions and 10 m in the vertical dimension. The resulting lithologic model portrays a complex system of interfingering coarse- to fine-grained alluvium, playa and palustrine deposits, eolian sands, and interbedded volcanic units (Figure 2). Sixty-six additional boreholes were added in the vicinity of the US Ecology site (Figure 3), a low-level nuclear waste site, to compare the regional model to a more detailed study area. The lithologic models compare well to resistivity data, aeromagnetic data and geologic map data, lending confidence to the interpretation. Lithologic units could not be represented in the model as a stacked stratigraphic sequence because of the complex geology and absence of time markers. Instead, lithologic units were grouped into interpreted genetic classes, such as playa or alluvial fan. Three-dimensional models computed from these interpreted facies data portray the alluvial infilling of a tectonically formed basin that is intermittently internally drained and infrequently the location of regional ground-water discharge.

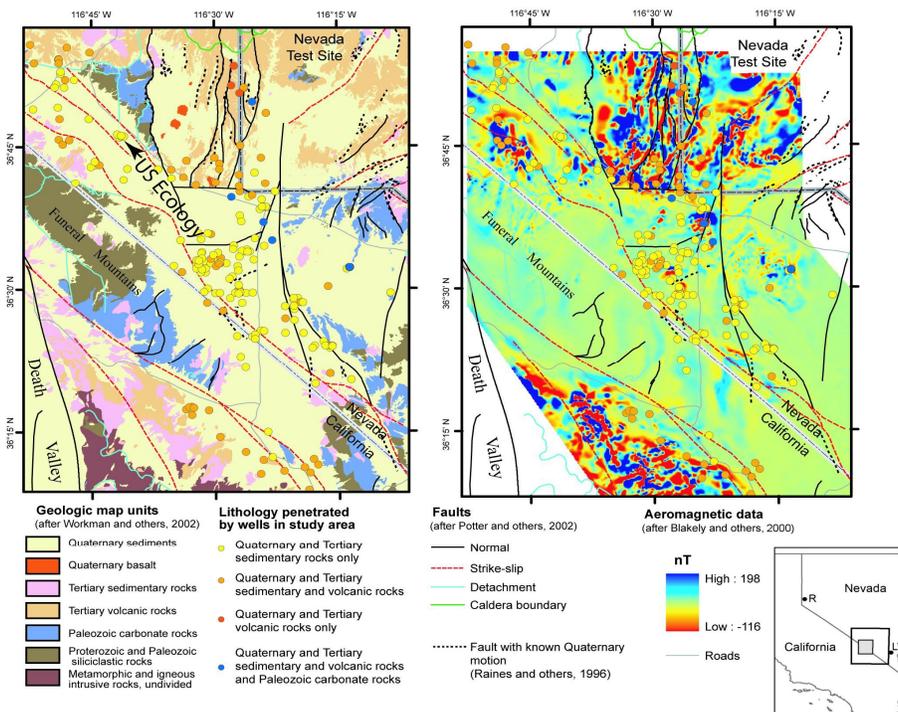


Figure 1. Geologic and aeromagnetic map 1

The Amargosa Desert basin developed in Miocene and Pliocene time as the result of the combined effects of extensional and strike-slip deformation and syntectonic volcanism within the Walker Lane Belt (Stewart, 1988). Normal and strike-slip faults bound uplifted mountain blocks of Proterozoic and Paleozoic rocks and segment basin fill. The basin is bordered by Miocene and Pliocene volcanic fields on the north and south edges of the basin; volcanic rocks associated with these fields create pronounced high-amplitude, short wavelength magnetic anomalies (Blakely et al., 2000). A total of 210 drill holes were selected to characterize the subsurface. Drill holes in the center of the Amargosa Desert basin typically intercept unconsolidated sediment and sedimentary rocks (131 holes; yellow circles); drill holes drilled within or near the two volcanic fields penetrate volcanic rocks or interbedded sedimentary and volcanic rocks (70 holes; orange and dark orange circles); only 9 holes penetrate the entire Cenozoic section and bottom in Paleozoic carbonate rocks (blue circles). Consolidated rocks that fill the deeper parts of the Amargosa Desert basin range in age from Oligocene to Pliocene; younger basalt flows (shown in orange) are also present in the overlying unconsolidated Quaternary section. Consolidated Cenozoic sedimentary rocks (shown in pink) include coarse- to fine-grained sedimentary rocks of variable sorting and bedding characteristics, dominantly fine-grained groundwater discharge and playa deposits and tuffaceous sedimentary rocks and reworked tuffs; Cenozoic volcanic rocks (shown in tan and orange) include welded and nonwelded ash-flow tuffs, basalts, and tephra. Surface exposures of Miocene and older sedimentary rocks are tilted and faulted and these same rocks are likely segmented within the basin by numerous faults. Unconsolidated Quaternary units within the basin (shown in yellow) include coarse- and fine-grained alluvial fan and stream channel deposits, paludal/palustrine spring discharge deposits, and eolian deposits.

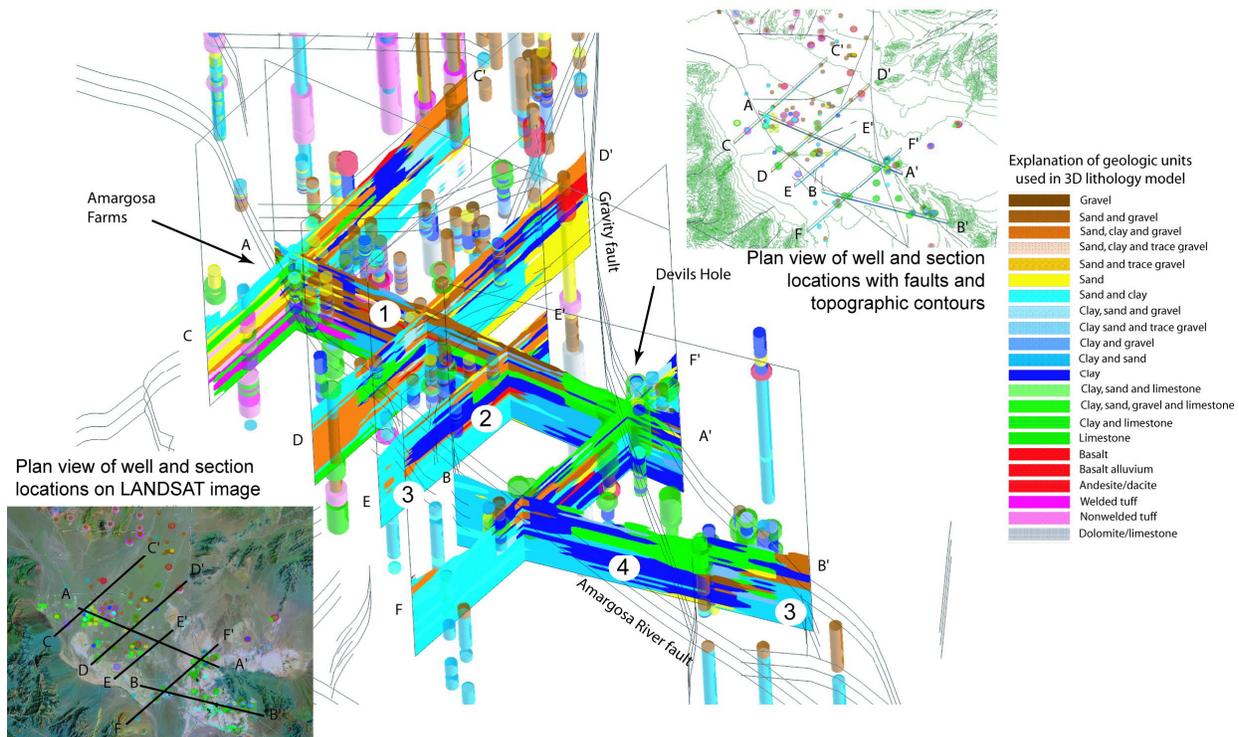


Figure 2. Perspective view of drill hole data and cross sections cut through 3D lithologic model in the central part of the Amargosa Desert basin.

Drill hole lithologic data were interpreted to derive an internally consistent set of geologic units; interpretations were informed by surface mapping data and geologic history of the basin. Drill holes are shown in perspective view as cylinders that are colored according to the interpreted geologic units. Land surface is transparent in this view; boreholes appear to hang in space. Interpreted geologic units were used to generate a 3D lithologic model. The interpolated data in the resulting solid model have the appearance of stratigraphic units, with aspect ratios that emphasize the horizontal dimension over the vertical. Horizontal bedding was assumed and faults were not explicitly included in the model. The cross sections cut through the 3D lithologic model portray the major lithologic variations within the central part of Amargosa Desert basin; the model is shown using the same color scheme used for the geologic units in individual drill holes. The upper surface of the 3D lithologic model is clipped at the topographic surface using a digital elevation model; the base of the model is clipped with the top of pre-Cenozoic

rocks surface as modeled from gravity data (Blakely et al., 1999). The north-central part of the Amargosa Desert basin has a complex layering of primarily alluvial and eolian deposits (labeled 1 in figure), some of these deposits appear to be channels of intermittent rivers. Coarse-grained alluvial deposits and local deposits of continental limestone and spring deposits are capable of supporting large-capacity production wells. These aquifers are part of a complex system of interfingered aquifers and fine-grained confining units that constitute the basin fill. The location and size of buried basalts (labeled 2 in figure) show general agreement with aeromagnetic data and abrupt lithologic transitions generally correspond to interpreted locations of faults in the subsurface (faults are portrayed as series of parallel lines, examples of truncated lithologic units are labeled 3 on figure); these observations lend confidence in the 3D lithologic modeling. The southern part of the basin is filled with an essentially uniform accumulation of fine-grained playa and palustrine deposits (labeled 4 on figure). The broad distribution of these fine-grained discharge deposits in the southern part of the basin preserves the record of an environment much wetter than the modern climate; modern discharge is confined to a considerably smaller area in the vicinity of Ash Meadows (Winograd and Thordarson 1975).

Abundant drill hole, water level and geophysical data permit a more detailed characterization of the US Ecology Site, a low-level nuclear waste disposal site in the northeast part of the Amargosa Desert Basin. Drill hole lithologic data were interpreted and modeled as described for the entire basin, but greater well density allowed for modeling of vertical intervals of 1 m. The water table elevation at the US Ecology site varies from 762 m in the north to 732 m in the southeast. A comparison of modeled lithologic and resistivity data along resistivity line 3 displays general agreement in the portrayal of a sequence of relatively flat lying beds above the modern water table. Color patterns for interpreted lithologic descriptors are the same as those used for the entire basin as described in Figure 2. Sand and gravel have high resistivity, and are displayed in the resistivity data as red and yellows at the top of the sequence. Low resistivity values are generally consistent with the sandy clay layers, shown in blue just above the water table.

A network of vertical north-south and east-west sections cut through the 3D lithology model portray the major lithologic variations at the US Ecology Site. Coarse sand and gravel dominate the shallow subsurface in the northern part of the area (brown and orange, labeled 1); these units thin to the south where predominantly fine-grained playa/palustrine sandy clay occurs high in the section (blue, labeled 2). At depth, a persistent sand interval (yellow, labeled 3) occurs above a thick section of sandy clay (blues and greens in the lower parts of the sections) that contains a welded tuff. This deep, fine-grained sequence defines the presence of a closed basin prior to the establishment of the Amargosa River drainage in this part of the basin, during the time the volcanic rocks were erupting. Fine-grained sands deposited through either eolian processes or fluvial reworking eventually overtopped this playa.

Plan view showing locations of wells used in 3D modeling, resistivity survey lines, elevation of water table and location of sections cut through 3D lithology model

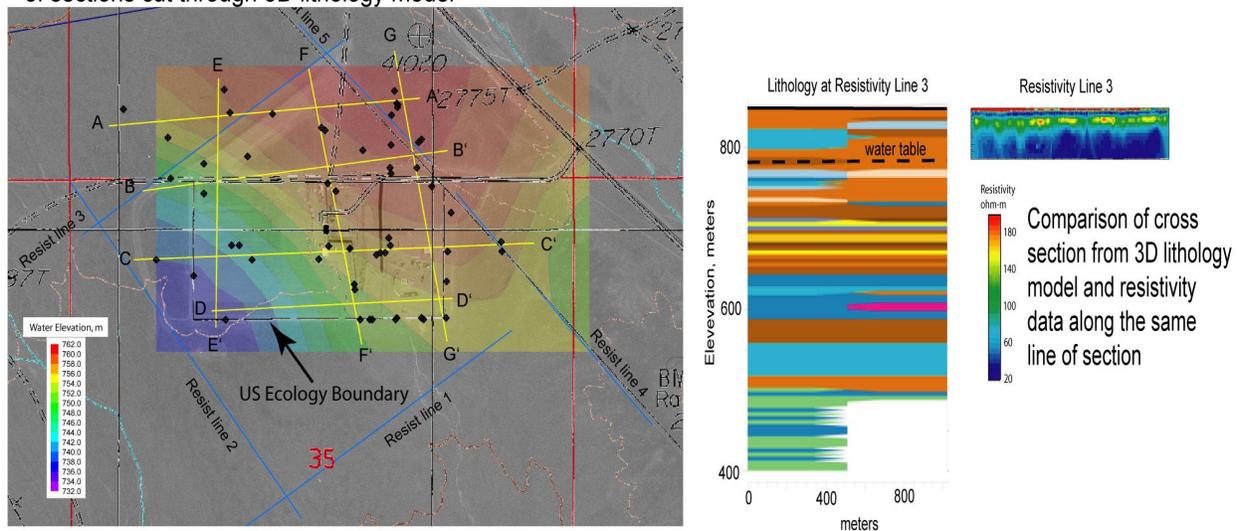


Figure 3. Detailed modeling at US Ecology site.

3D GEOLOGICAL MODELING IN SUPPORT OF GROUND WATER INVENTORY IN THE FARGO-MOORHEAD REGION, MINNESOTA AND NORTH DAKOTA

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ABSTRACT

A three-dimensional (3D) geological model of known and potential aquifers as well as enclosing materials in the Fargo-Moorhead region of North Dakota and Minnesota was required for a current water supply assessment coordinated by U.S. Department of the Interior, Bureau of Reclamation and their partners. A multi-agency team funded by Reclamation therefore compiled, interpreted, and integrated existing geologic mapping at a scale of 1:200,000 for an area (Figure 1) extending from 46 to 47.5 degrees north latitude and from 98 to 95 degrees west longitude, an area 190 km east to west and 170 km north to south. These maps were merged with drillhole data (Figure 2) for 30,000 sites, 60 Quaternary stratigraphic control sites, and new subsurface correlations to produce a 3D geological model extending down to the top of Precambrian rocks, compiled at a scale comparable to that of a 1:500,000 map. This new 3D geology and an accompanying USGS compilation of the quantitative properties of selected major aquifers will provide the framework necessary to conduct subsequent water resource analyses.

To construct the 3D geology, drillhole cross-sections were constructed using ArcView 3.3, ArcGIS 9.0, and custom extensions. Thirty-four regional cross sections were constructed at 5 km spacing. Drillhole logs and surficial geology were displayed along the locus of each cross section to facilitate correlation. Four smaller areas encompassing important aquifers, ranging from 1,300 to 3,200 square km in area, were chosen for more detailed analysis. East-west cross sections were constructed in these areas using 0.5 to 3 km spacing. Creating these cross sections in ArcView allowed sand and till boundaries to be correlated by overlaying shapefiles in the same view window. A series of points for each stratum were extracted from the cross-section shapefile lines and converted into X, Y, & Z values. These points as well as cross-sections scanned and registered in 3D space were then used as the basis for construction of surfaces and volumes in GOCad software (Figure 3). Modeled strata were constructed for a total of 36 lithostratigraphic units (Figure 4), including Quaternary sediments as well as Cretaceous, Ordovician and Precambrian rocks, and these are now being prepared for further application to regional groundwater inventory, to help ensure long-term water supply for the region.

INTRODUCTION

The U.S. Department of the Interior, Bureau of Reclamation (Reclamation), and Garrison Diversion Conservancy are jointly preparing an environmental impact statement (EIS) for the Red River Valley Water Supply Project, which is intended to ensure that the future comprehensive water quality and quantity needs of the Red River Valley are met (Reclamation, 2005). As part of current activity toward these objectives, it was recognized that there is a need to further compile consistent regional information on the capacity of known and potential ground-water sources. In particular, a need to synthesize published quantitative information on currently utilized ground-water sources in Minnesota was identified, to bring compilation of Minnesota data up to a standard similar to that already available for eastern North Dakota. Members of United States Geological Survey (USGS) staff therefore prepared a review on this topic (Rippe et al, 2005). Concurrently, a need for a consistent, broad overview of all confirmed and potential ground-water sources that can presently be identified across the entire region also was recognized. This requirement was fulfilled in the form of geological maps, a 3D computer model, and accompanying documentation meant to facilitate subsequent ground water-related assessment and planning (Thorleifson et al, 2005). The USGS report and the 3D model were commissioned by Reclamation, and were completed in 2005 by a team of agencies coordinated by the Minnesota Geological Survey (MGS).

METHOD

A surficial geology map was prepared to depict the character and distribution of the uppermost geological materials, from the point of view of texture, process, and history. The map shows deposits such as fine-grained Lake Agassiz clay along the Red River, the sandy Sheyenne Delta sediments southwest of Fargo, discontinuous sandy glacial outwash deposits, clay and silt-rich to gravelly tills, and Cretaceous sedimentary rocks such as shale. The Quaternary sediments, consisting of strata related to multiple cycles of glacial advance, retreat, and shifts in ice flow were categorized using standard stratigraphic procedures. A lithostratigraphic database used for the project includes textural and lithologic information for 6,533 sediment samples collected from outcrops, soil-probe borings, power-auger test holes, and rotasonic cores. The textural data include percent sand, silt, and clay. The lithologic data were derived from microscopic examination of the coarse-sand fraction and are presented as percent igneous and metamorphic rocks, carbonate, and shale. Computer-assisted interpretation techniques were used to produce reproducible interpretations of the till datasets. Twenty-four Pleistocene lithostratigraphic units and eight Holocene and Lake Agassiz units were identified for the Fargo-Moorhead study area. A database of drillholes classified on the basis of this new scheme was prepared, as a guide for subsequent 3D modeling. A bedrock geology map also was prepared to depict Cretaceous shale and sandstone that are thick in the west to thin and discontinuous in the east. The Precambrian rocks that underlie the entire study area consist of igneous and metamorphic rocks, commonly altered to clay to a depth of tens of meters. Glacial erosion has stripped this weathering horizon off the Precambrian rocks to a variable degree, although the weathering profile is largely intact where Cretaceous cover is present. A new compilation and interpretation of bedrock surface elevation as well as the elevation of the top of Precambrian igneous and metamorphic rock also was completed, allowing glacial sediment and sedimentary rock thicknesses to be calculated. This mapping in the Minnesota portion of the study area was based on subsurface information from ~11,000 wells in the County Well Index (CWI) database, including 445 wells interpreted to penetrate bedrock. Mapping in North Dakota was based on data compiled by the North Dakota Geological Survey and the North Dakota State Water Commission, including 2,800 wells that terminate within the sediments, and about 1,300 that penetrate bedrock. In the North Dakota portion of the study area, Ordovician Red River Formation carbonate and sandstone of the Winnipeg Formation Black Island Member have previously been inferred to be present between Cretaceous strata and the Precambrian. The 2D mapping was then merged with drillhole data, with the aid of current knowledge on geological processes and history, to produce a 3D depiction of the subsurface geology down to the top of Precambrian igneous and metamorphic rocks.

RESULTS

The greatest level of detail in the 3D model was constructed for four areas where important aquifers were known to occur, including the Hankinson area in southeastern North Dakota, the Fargo area that straddles the North Dakota-Minnesota border, as well as the Pelican River and Pineland areas in Minnesota. In the detail areas, deposits approximately 1 km or larger in horizontal extent are depicted, while for the remainder of the area, geological features approximately 5 km across or greater are depicted. Quantitative descriptions of sand bodies in the detail areas were derived. Current aquifer names were in some cases used, although the focus of the study was to best approximate the boundaries of the sand bodies, without attempting inferences regarding water resource potential. Over 130 sand deposits corresponding to known aquifers and potential aquifers were thus identified and mapped. Portions of twelve buried ice margins at various stratigraphic levels were mapped, suggesting trends that may be useful for future exploration and mapping. For several previously identified aquifers, revised geometry was presented. The work will be an appropriate and essential basis for additional more site-specific work, as well as hydrogeologic characterization of the strata, and analysis of potential water resources that may be utilized to support the future needs of the region.

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Figure 1. Location of the Fargo-Moorhead study area, straddling the North Dakota-Minnesota border

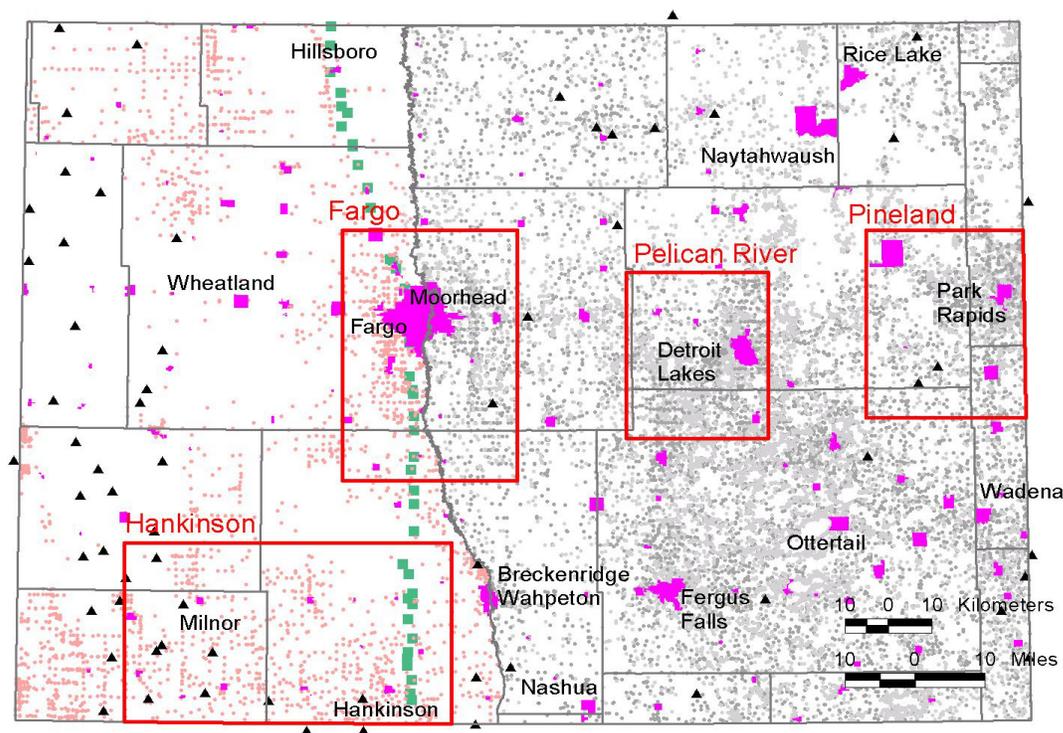


Figure 2. Location of available digital drillhole data; triangles are stratigraphic reference sites; engineering drillhole sites are shown as green squares; North Dakota regional drillhole database sites, mostly water wells, are indicated in a pink color; for Minnesota, east of the Red River, accurately located drillhole sites, mostly water wells, are shown in dark gray, while sites only located to legal survey polygon centroids are shown in light gray

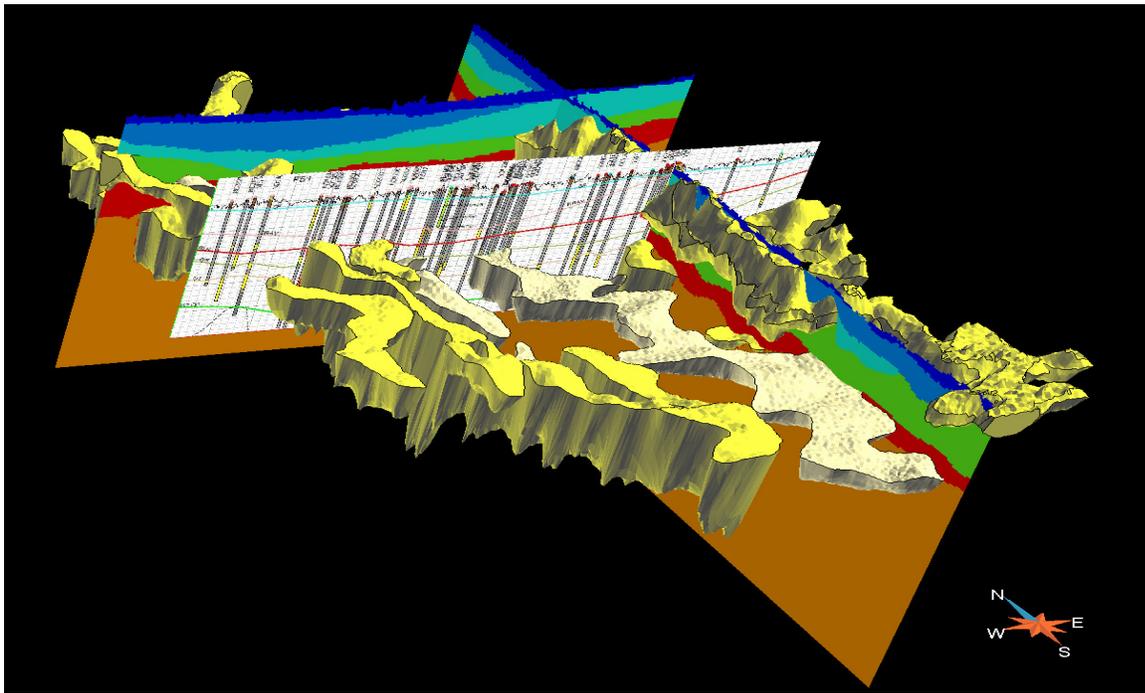


Figure 3. 3D geology was interpreted on cross sections that were scanned in 3D space and utilized to construct 3D solids; this example displays thick glacial lake clay in blue in the Fargo detail area, and a thinner clay cover above a major aquifer in the eastern portion of this detail area, to the right

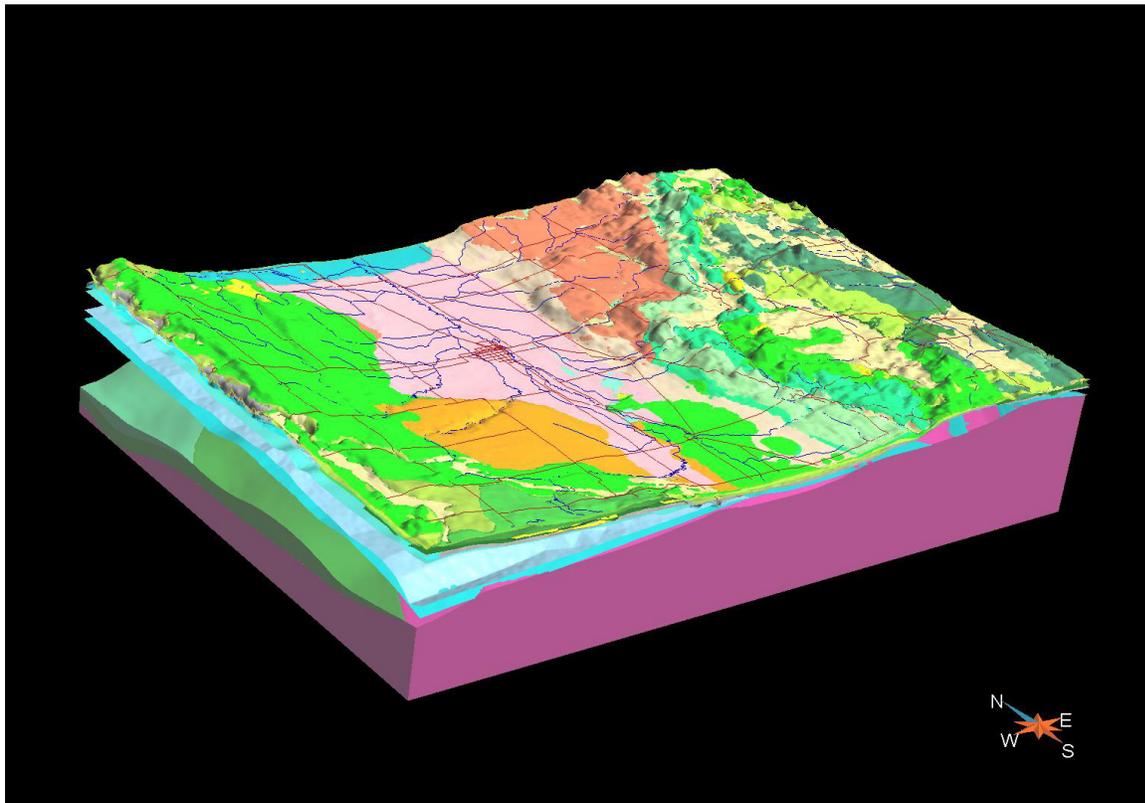


Figure 4. Vertically exaggerated illustration of all strata defined in the Fargo-Moorhead regional 3D model, an area 190 km east to west and 170 km north to south, viewed in 3D from a viewpoint to the southwest; modeled strata range from about 100 m to 300 m in total thickness

COST OF 1:12,000-SCALE GEOLOGIC MAP; \$500,000: COST OF 3D DATA, PRICELESS

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In the Seattle, Washington area (Figure 1), new derivative maps are facilitating planning, engineering, research, and outreach to a greater user population than ever before. This resurgence is due in part to a more informed user base and in part to having more useful map products. Multi-agency collaboration and funding have supported the building of a database of subsurface geologic data, the preparation of new digital geologic maps, and many new derivative maps.

Geologic maps and borehole data are available to partners on agency intranets via interactive programs, to the public over the Internet using ArcIMS, and to onsite visitors using GeoMapNW's computer lab. The new maps and geodatabase provide information such as regional geologic context for subsequent site-specific investigations, extent of fill, thickness of geologic layers, rapid scanning for specific geologic settings, and depth to groundwater, and they also enable quick cross section construction.

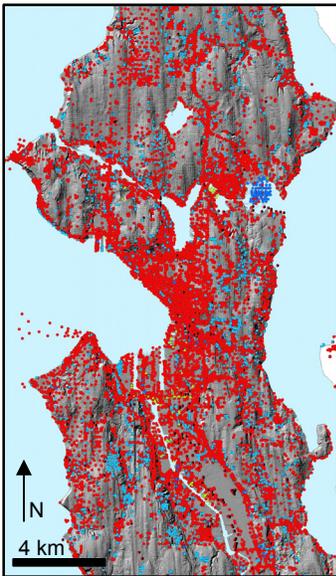


Figure 2. Over 35,000 exploration points, mostly geotechnical borings, in the two-quad Seattle area.

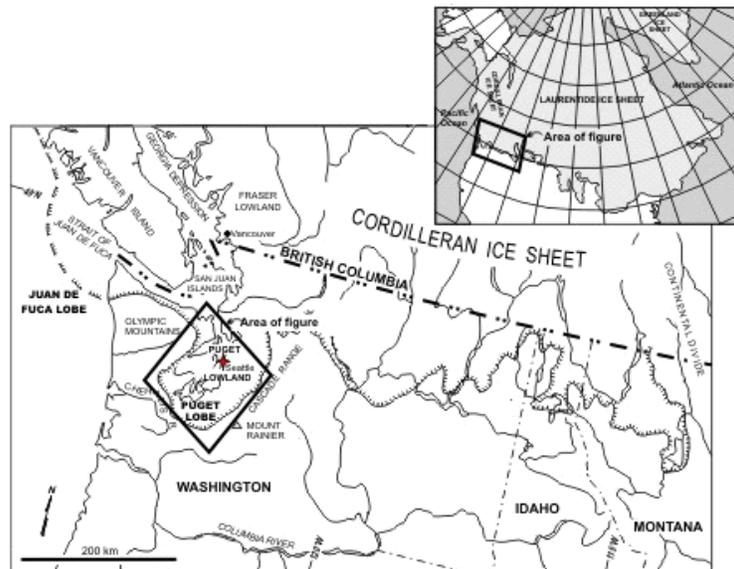


Figure 1. Index map showing position of Seattle in the center of the Puget Lowland.

In Seattle, an area equivalent to about two 7.5' quadrangles was mapped at a scale of 1:12,000 utilizing new field work and data from more than 35,000 exploration points (Figure 2). Differences between the former geologic map (Waldron et al., 1962) and the new map (Figure 3; Troost et al., 2005) include:

- 3 to 4 times more geologic polygons mapped,
- 15 to 25 % more sandy material mapped at the surface, and more widely distributed,
- 25% less till or other fine-grained material at the surface,
- 10% more land surface mapped,
- 3 to 4 times the level of detail,
- better delineation of weak ground areas,
- display of data points used in making the map, and
- full public access to the subsurface data by all users over the Internet (Figure 4).

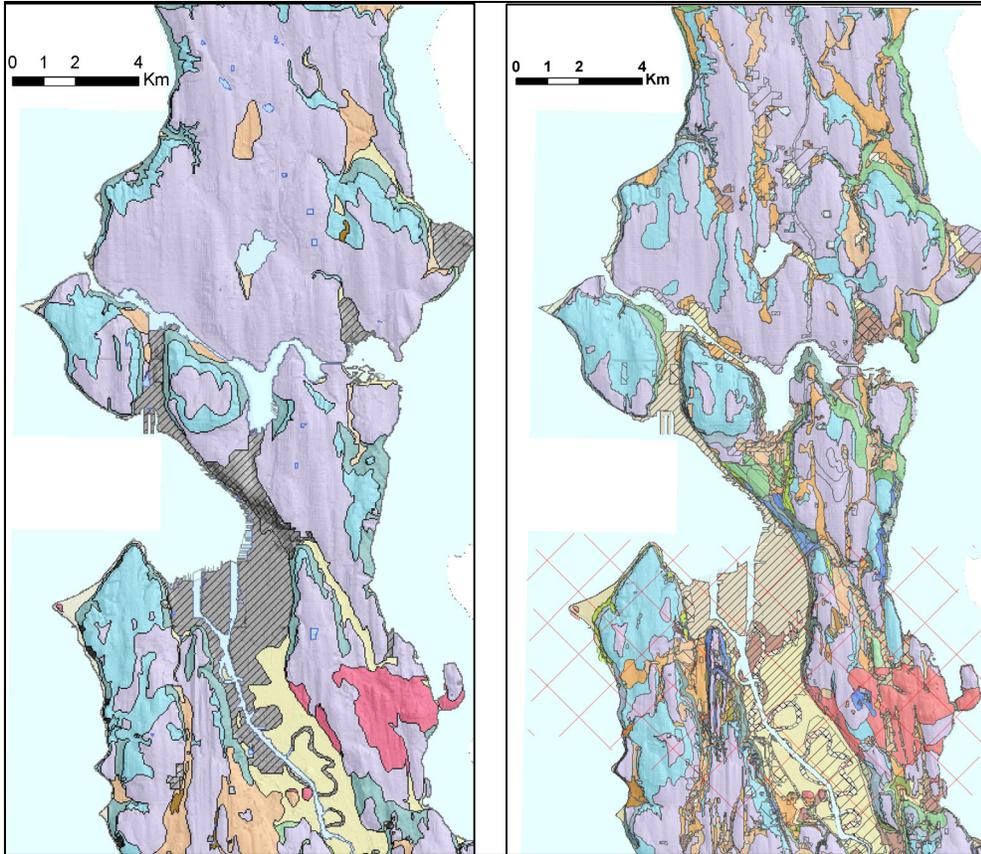


Figure 3. Geologic map of Seattle from Waldron and others (1962; left), and from Trost and others (2005, right).

Two of the most useful derivative maps are: 1) potentially infiltrative soils and 2) the depth to glacially overridden material. Since the new geologic map of Seattle recognizes twice as much land area with high infiltration potential than previously mapped in the City, this new map provides the critical base for evaluating concerns for storm-water runoff and contamination (Figure 5). The surface of glacially overridden materials, combined with the depth to bedrock and ground topography, allows easy creation of a simple but defensible seismic-velocity model of the Seattle area, now being used to generate earthquake ground-motion models and to evaluate liquefaction potential in greater detail than ever before.

Figure 4. Web interface for accessing downhole data. Selecting a borehole displays both a scan and a tabular listing of subsurface layers and meta data.

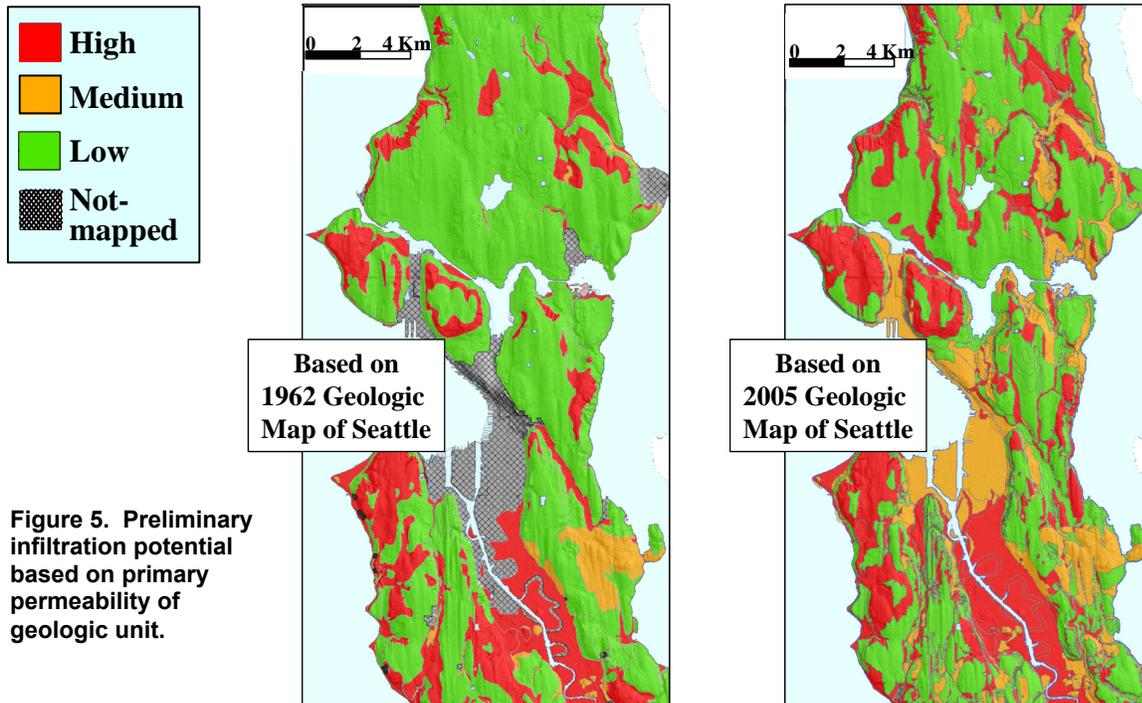


Figure 5. Preliminary infiltration potential based on primary permeability of geologic unit.

Through collaboration with this mapping project, hundreds of planners and engineers are being kept abreast of current research and geologic findings. Yet *local* costs are substantial: a detailed, digital, USGS-published 7.5' geologic quadrangle map based on new field work and a subsurface database averages \$250k at 1:24,000-scale and about twice that amount at 1:12,000 scale. Derivative maps are not nearly as expensive, but they too add an incremental expense, being only as good as their base maps. In an urban area such as Seattle, the cost of detailed geologic mapping and a subsurface database could be expressed with population density, with rates like for \$1.75 to \$2.00 per person (Table 1). Another way to look at the costs is by data density; in an urban area with geologic hazards, geotechnical data may be plentiful. In Seattle, the database averages 350 boreholes per square mile, with a mapping cost of \$ 28.50 per borehole. The costs provided in Table 1 are averages for the Puget Lowland area of Washington, and not just relevant to the Seattle quadrangles.

Table 1. Cost comparisons.

Comparison	Quantity	Rate
Cost of 1:12,000-scale geologic map of Seattle with subsurface database	2 Quads	\$500,000/quad
Cost per square mile	100 square miles	\$10,000
Cost per person	Population: 575,000	\$1.75
Cost per household	260,000 Households	\$3.85
Cost per data point	35,000 data points	\$28.57
Data points per square mile		350
Average distance between data points	feet	800
Max and min point spacing	feet	2000 and 1

One way to evaluate the value of detailed mapping and 3D data is by comparison to the amount of money that will be saved as a result of having detailed geology. For the cost of one detailed geologic map and subsurface

database, one could alternatively acquire the items in one line of Table 2. Over the lifetime of the map, for example, the cost of a detailed geologic map and database could be offset if the map and database were used to eliminate the need for 5 large infiltration ponds by identifying promising areas for local on-site infiltration, or if it saved a municipality the need to engage in one less lawsuit.

How can we quantify the benefits to our funders of having better geologic data and better educated clients to work with? Ultimately, are these new geologic products worth their cost?

Table 2. Equivalent cost of one 7.5 x 15', 1:12-000-scale geologic map and database.

Number	Item (each line represents approximately \$500,000)
2	Stream habitat restoration projects
2	Contaminant investigation studies (i.e. Remedial Investigation or addenda)
2	Reconnaissance level route selection studies (tunnels, major utility line work, etc)
5	Large infiltration ponds
5	Municipal water or reinjection wells
3	Groundwater models
3	Planning level siting for critical facilities, avoiding geologically hazardous areas
10	First-order groundwater level reconnaissance
2	Evaluation of critical areas delineations
0.2	Litigation regarding landslide-prone area based on old geologic mapping
priceless	Time savings for City Engineers not having to go to hard copy archives to find subsurface information from adjacent or nearby projects; time savings for consultants to gather more detailed background information about project site by reviewing readily accessible subsurface data and detailed geologic map; improved geologic understanding

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APPLICATION OF TRANSITION PROBABILITY GEOSTATISTICS IN A DETAILED STRATIGRAPHIC FRAMEWORK

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Heterogeneity of hydraulic properties at multiple scales in an alluvial aquifer is largely controlled by the distribution of facies. Therefore, we require quantified stratigraphic and sedimentologic models in order to incorporate this spatial variability of hydraulic properties into groundwater flow and contaminant transport simulations. Our approach uses sequence stratigraphic concepts, developed for the fluvial fan continental setting to (1) delineate large-scale stratigraphic units in the alluvial aquifer, (2) predict overall facies patterns in the aquifer, and (3) guide development of appropriate Markov chain models used in transition probability geostatistics. After geostatistical simulation, our results are used in groundwater models to estimate groundwater age distributions, evaluate remediation strategies, and model aquifer hydraulic tests in a heterogeneous setting. To illustrate and provide a “how-to” guide to this approach, I use examples from the Kings River fluvial fan, located southeast of Fresno, California (Figure 1).

Initially, we assessed and developed the sequence stratigraphic concepts for the Kings River fluvial fan (Weissmann et al., 2002a). We use the term ‘fluvial fan’ to distinguish fans dominated by deposits of perennial streams from those dominated by debris flow or sheet flood processes. Depositional patterns on the fluvial fan formed in response to Pleistocene glacial cyclicity in the Sierra Nevada (Figure 2). These glacial cycles produced at least four unconformity-bounded sequences within the alluvial basin fill (Figure 3). In this context, we identified three deposit types – open fan (consisting of coarse-grained channel deposits held within finer-grained floodplain deposits), incised valley fill (dominated by very coarse-grained channel fill deposits), and pre-glacial Pliocene deposits (similar to open-fan deposits, however numerous paleosols are present in this unit) – that are held within the sequences. Relatively mature paleosols bound each of these sequences, thus we could define the large-scale sequence geometries through correlation of these paleosols (Figure 4).

We use this stratigraphic framework to develop Markov chain models specific to each deposit type. We take the following steps to develop and apply the Markov chain models of spatial variability (Weissmann and Fogg, 1999):

1. Classify core, geophysical well log, and drillers’ lithologic log data into hydrofacies categories;
2. Measure vertical transition probability from core or geophysical well log data within each stratigraphic unit or deposit type and visually match a Markov chain model to these measured results.
3. Estimate lateral Markov chain models for each deposit type based on:
 - a. estimated facies mean lengths from geologic mapping, geophysical surveys, conceptual models, and/or outcrop analogs (Figure 5);
 - b. estimated embedded transition probabilities for facies juxtaposition tendencies from application of Walther’s Law, geologic mapping, conceptual geological models, and/or outcrop analogs (Figure 4).
4. Simulate each sequence separately using conditioning data from that sequence, then combine all individual sequence realizations into a final realization (Figure 6).

Stratigraphically-based geostatistical simulation using this approach has several advantages over non-stratigraphic approaches. First, the sequence boundaries are marked by unconformities, therefore facies that exist on one side of the unconformity do not correlate to facies on the other side of the unconformity. Thus, correlation across the unconformity (in both model development and simulation) is avoided using this approach. Second, geostatistical simulation assumes stationarity (e.g., statistical homogeneity across the modeled region). By dividing the section into these stratigraphic units, different statistics (e.g., the Markov chain model) of different units are honored. For example, the coarse-grained dominated incised valley fill deposits have a much higher proportion of sand and gravel than the open-fan deposits. By deterministically modeling the distribution of these large-scale units, we separate their simulation and honor this difference in facies proportions and geometries. Finally, facies distributions can be predicted based on position within a sequence, thus allowing use of the sequence stratigraphic conceptual model in a quantitative way. This approach allows geologists to quantify their conceptual geologic interpretations and formulate realizations of the subsurface heterogeneity that appear to reasonably reflect the complex stratigraphic character of alluvial aquifers.

Upon compilation of multiple realizations for the study site, we readily incorporate the facies distributions into groundwater models by assigning hydraulic properties (e.g., hydraulic conductivity, storativity, dispersivity, etc) to each facies type. To date, we have used these realizations of the Kings River fluvial fan to investigate the distribution of groundwater ages to a well (Weissmann et al., 2002b), the influence of incised valley fill deposits on overall

hydrodynamics of the regional flow system (Weissmann et al., 2004), the migration of nitrates through the vadose zone (Harter et al., 2005), and susceptibility of aquifers to contamination (watch for Zhang et al., in the near future).

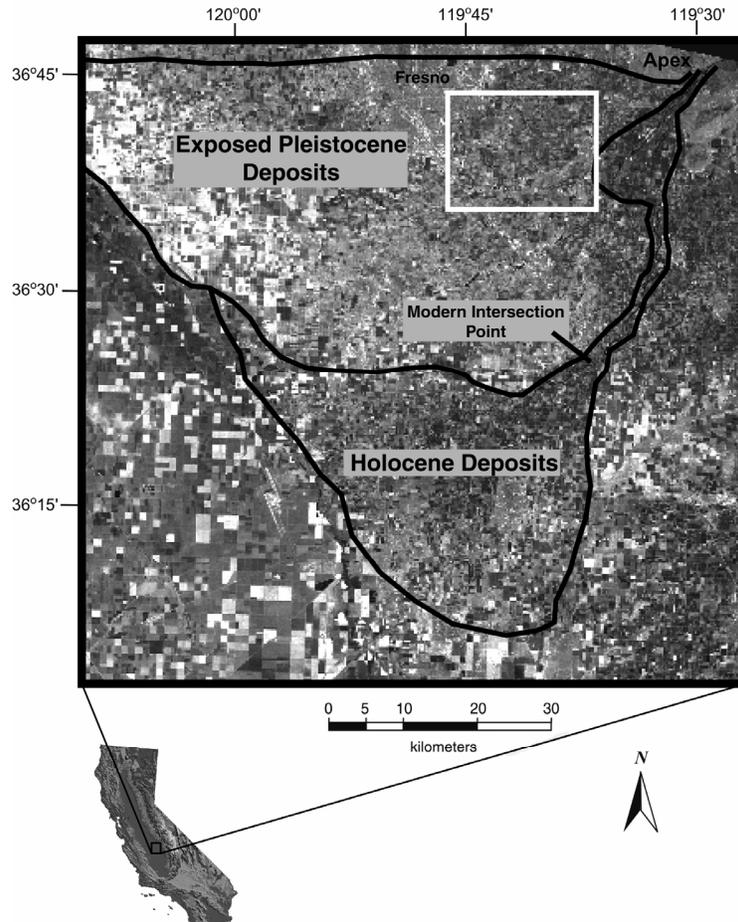


Figure 1. Satellite image and location map of the Kings River fluvial fan. From Weissmann et al. (2004).

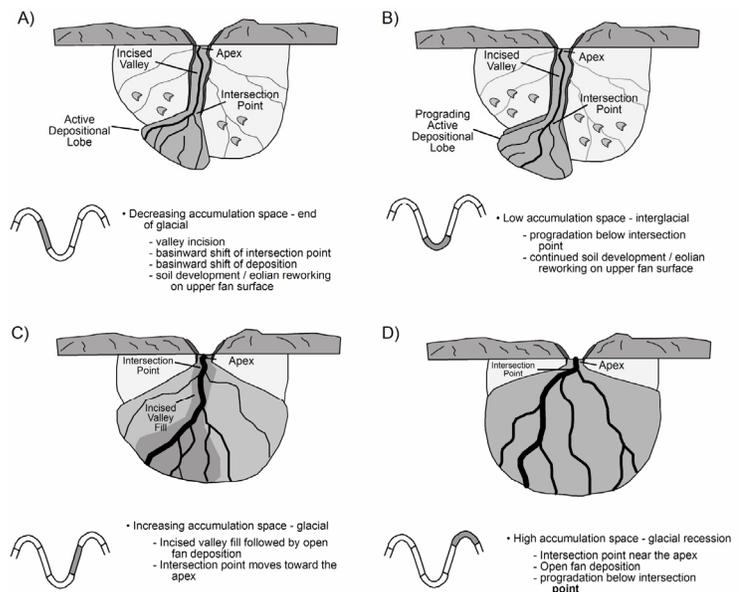
Figure 2. Sequence stratigraphic cycles on the Kings River fluvial fan are developed from changes in sediment supply to discharge ratios due to cycles of outwash from glaciers in the Sierra Nevada. Darker shading indicates active areas of the alluvial fan.

A) incision into the fan during the transition from glacial to interglacial climates.

B) Interglacial climate morphology.

C) Morphology at the beginning of significant glacial outwash.

D) morphology during periods of significant glacial outwash. Figure from Weissmann, et al. (2002a).



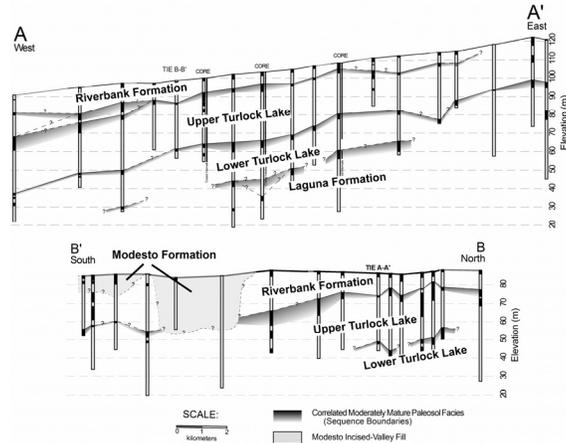


Figure 3. Cross sections through the upper Kings River Alluvial Fan. Section A-A' is parallel to depositional dip, and section B-B' is parallel to depositional strike. From Weissmann, et al. (2002a)

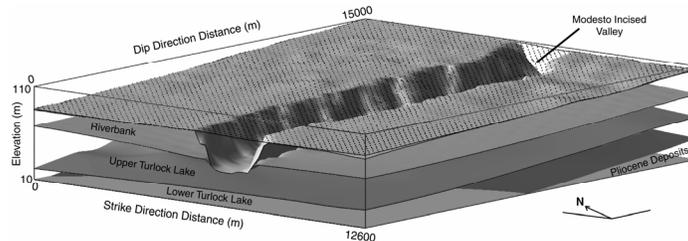


Figure 4. Modeled sequence bounding surfaces through the study site (from Weissmann et al. (2004).

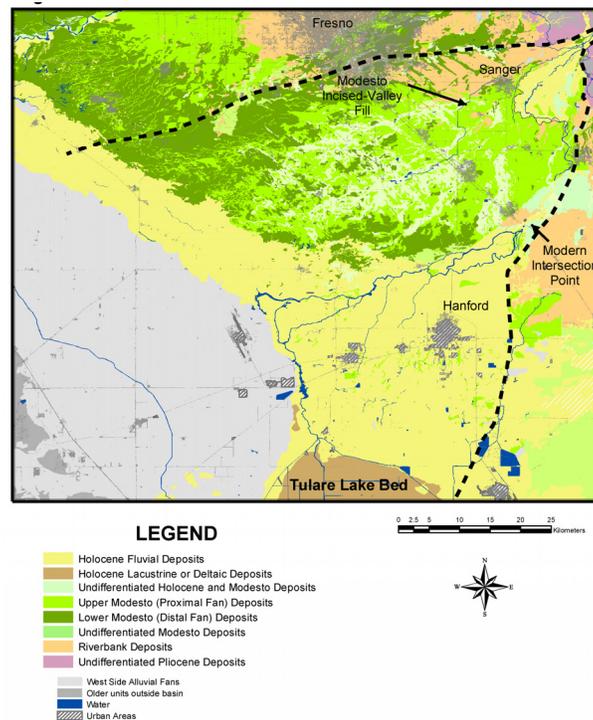


Figure 5: Soil map of the Kings River fluvial fan showing the generalized distribution of facies on the fan surface. C-horizon textures were used to develop this facies map (see Weissmann et al., 1999, 2002a, for further discussion). The facies distribution on this map were used to measure lateral transition probabilities. These were slightly modified to account for preservation potential and incorporated into the lateral Markov chain models for open-fan deposits (Weissmann et al., 1999). Map from Weissmann et al. (2005).

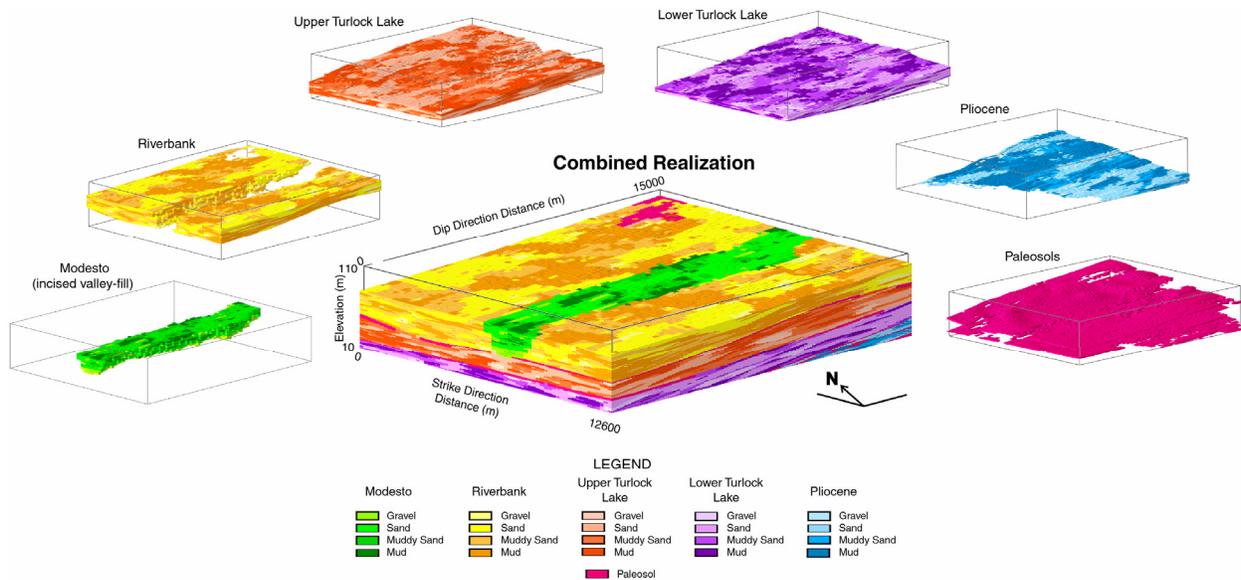


Figure 6. Compiled realization for the Kings River fluvial fan study area (From Weissmann et al., 2004).

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REGIONAL GROUNDWATER FLOW MODELING IN THE OAK RIDGES MORaine AREA: BUILDING ON THE 3D GEOLOGIC MODEL

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With more powerful computers and better software for data visualization, management, and analysis, it has become possible to build detailed 3D geologic models and then incorporate all the complexity and spatial variability in stratigraphy and hydraulic properties within high-resolution numerical models. This became a primary objective in developing a regional model for the Oak Ridges Moraine area in southern Ontario. Including the local variation in stratigraphy and aquifer properties along with better characterization of the surface water system led to a model that was much more representative of the flow system.

Extensive data were compiled, analyzed and synthesized to create a regional-scale model covering the entire Oak Ridges Moraine (ORM) area. The model built on a conceptual understanding of the geologic framework and depositional history of the ORM (Sharpe et al., 2002). Further refinement was done to subdivide the "Lower Deposits" defined by Sharpe et al. into aquifer and aquitard units. Refinement was a time-consuming task, requiring the analysis of individual well logs. The refined hydrostratigraphic model became the basis of the sub-regional-scale "Core Model" covering a 55-km wide area between Lake Simcoe and Lake Ontario. Methods were developed to use lithologic data from the large volume of water well records to supplement aquifer testing data and develop maps of hydraulic conductivity. The hydraulic conductivity distribution obtained conformed well to our understanding of depositional processes in the ORM. It also correlated well with variation in hydraulic gradients. Limits in the data and in our knowledge of the depositional processes, however, make it difficult to see clear trends in the spatial distribution of properties in the lower units.

Spatial variation in groundwater recharge was estimated using climate, surficial geology, topography, and land use data. Better mapping of properties within the shallow system could lead to improved representation of recharge, runoff and ET. Streambed properties were estimated based on surficial geology and stratigraphy. It is suspected that more data on the local-scale stratigraphy within the stream valleys would help improve the match between simulated and measured spatial distributions in flow.

The refined geologic model, with 100-m cell size, has now been extended to the east and west. New conceptual models were developed to handle the transition from a bedrock flow system of the Niagara Escarpment in the west to the overburden aquifer dominated flow system to the east. The conceptual models will be tested as the numerical model is developed for these areas.

The process of model construction helped us focus on the gaps and biases in the available data. Much effort was invested in using our conceptual understanding of depositional and erosional processes to bridge these gaps and guide the construction of the hydrostratigraphic and numerical models. The continued success of the project is attributed to four guiding principles: 1) a focus on data; 2) incorporation of geological interpretation, along with other data sources, into the geological analyses; 3) a strong emphasis on understanding the link between the groundwater and surface water systems; and 4) an effective blending of a regional-scale approach with sufficient resolution and detail for local-scale analyses.

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