THREE-DIMENSIONAL GEOLOGICAL MAPPING

WORKSHOP EXTENDED ABSTRACTS

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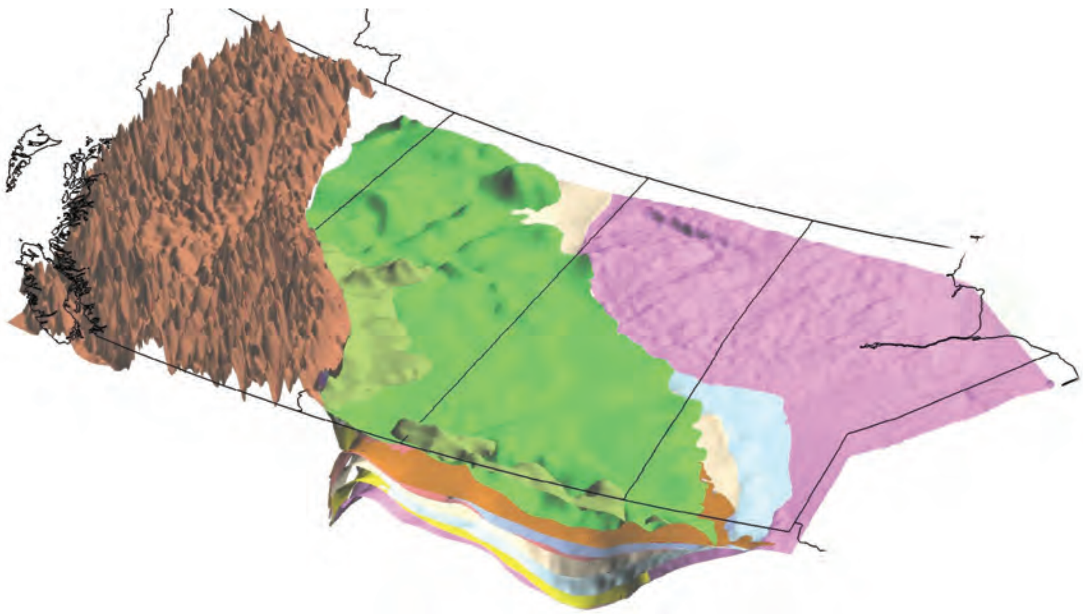
Conveners:

Richard C. Berg, Illinois State Geological Survey
Hazen A.J. Russell, Geological Survey of Canada
L. Harvey Thorleifson, Minnesota Geological Survey



ISGS Open File Series 2009-4

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Institute of Natural Resource Sustainability
William W. Shilts, Executive Director
ILLINOIS STATE GEOLOGICAL SURVEY
E. Donald McKay III, Interim Director
615 East Peabody Drive
Champaign, Illinois 61820-6964
217-333-4747
www.isgs.illinois.edu

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Finally, we thank all of our presenters and their respective funding agencies and sources for making this workshop a success.

INTRODUCTION — THREE-DIMENSIONAL GEOLOGICAL MAPPING: AN INTERNATIONAL PERSPECTIVE

Richard C. Berg[1], Hazen A.J. Russell[2], and L. Harvey Thorleifson[3]

[1]Illinois State Geological Survey, Institute of Natural Resource Sustainability, [2]Geological Survey of Canada, and [3]Minnesota Geological Survey

INTRODUCTION

This is the sixth in a series of workshops on three-dimensional (3-D) geological mapping that began in 2001 and has been conducted every 1.5 to 2 years at Geological Society of America meetings and at an annual meeting of the Geological Association of Canada. The workshops have focused on the development of techniques for 3-D geological mapping of surficial and shallow bedrock mainly for purposes of using 3-D maps and models for specific interpretive outcomes. The workshops have emphasized (1) the need for high-quality subsurface geologic information, (2) procedures for dealing with large data sets and management of that data, and (3) most importantly, that the better and more precise the geologic model, the better is its predictive capabilities, and therefore, the more improved are subsequent derivative maps and models, including 3-D hydrogeologic groundwater models.

The previous five workshops, as well as the present workshop, have maintained a format that has intermixed overarching issues (such as basin analysis, contributions of geophysics and groundwater data to 3-D geologic models, and Web delivery of information) with political and economic realities of national and state/provincial-wide commitments to mapping with specific regional and site-specific case study examples. The primary emphasis of the workshops has been directed towards 3-D applications that help address hydrogeological considerations. However, to achieve an "outside the box" perspective, workshop organizers have also included key presentations from the oil industry and the engineering and/or consulting community.

With each successive workshop, there have been remarkable advancements in technology, and in turn, continually improved ability to visualize 3-D geological information. This has resulted in improved conceptualization and understanding of often complex geology by the geologists and hydrogeologists who have developed the information. Moreover, these technological advancements have provided tools that now allow stakeholders and the user community to better comprehend subsurface geology. While a 2-D multi-colored map can portray various geologic materials and/or their interpreted derivative products on a flat 2-D map, the 3-D map or model provides even the most novice user an opportunity to look within the Earth, rotate and tilt a block of information, strip away and add layers, show data at various depths, etc., and in so doing provide a degree of comprehension of geology that was previously impossible to achieve. And with better comprehension comes a better understanding and communication of the importance of geology in dealing with various land- and water-use issues. Where are aquifers, how thick are they, how are they distributed, how easily are they being recharged, and what is their potential for contamination? What near-surface materials are most susceptible to landsliding, slumping, or liquefaction from earthquake shaking? Where are sand and gravel or shallow bedrock aggregate resources for infrastructure development?

CURRENT WORKSHOP

All of our workshops, including this one, provide the opportunity for participants to share their experiences and ideas and to discuss various aspects, protocols, and applications associated with 3-D mapping and modeling. As these workshops have expanded to include more international participants and attendees, it has been obvious that regardless of nation or continent, there remains a very consistent and urgent need for developing 3-D geologic information to address critical land- and water-use issues. This sixth workshop builds on the previous five workshops (Berg and Thorleifson, 2001; Thorleifson and Berg, 2002; Berg et al., 2004, Russell et al., 2005, and Thorleifson et al. 2007), but includes a broader international perspective with presentations from France, Germany, and Australia, in addition to those from the United States, Canada, the United Kingdom, and The Netherlands. Also emphasized is the delivery of information via the Web, as well as various other innovations for map comprehension and data management.

There are 15 presentations in this workshop. The talk by Jackson discusses ways in which geoscience modellers can make a difference within their own geoscience community and ways for them to expand their interactions beyond their jurisdictional boundaries. It also discusses OneGeology, which is a multi-national geological survey initiative to make geological map data accessible on the Web, and it emphasizes that “hot button” geological issues are not constrained by political boundaries and therefore must be dealt with on a transnational basis. A related presentation by Kessler from the British Geological Survey discusses Geological Survey organizations’ initial emphasis on finding construction materials, minerals, and hydrocarbons. He evaluates the next stage in their evolution, which sees them opening up their information and transdisciplinary integration within the wider “modeling” community including the social and economic disciplines. He mentions that geological and groundwater models are a means to an end and not an end in themselves, but rather parts of a jigsaw puzzle of data and models needed by decision makers to respond to the pressing human and environmental questions in today’s changing world.

National perspectives of 3-D mapping and modeling are the focus of five presentations from the United State, France, Germany, The Netherlands, and Australia:

1. McKay calls for a need for high quality 3-D geologic information and concludes that in the U.S., federal and state mapping programs fall far short of meeting the country’s pressing societal needs for the information. Regional mapping coalitions, such as the Great Lakes Geologic Mapping Coalition, can accelerate the effectiveness of mapping, and new software and hardware can fill gaps in available computing and analysis tools and enable optimum quality in 3-D geologic interpretations and modeling.

2. Truffert of the French Geological Survey mentions that European Geological Surveys have a core mission to describe the solid Earth’s subsurface, and that 3-D geological models have aided the interpretation of Geosciences and have grown in a progressive way for almost 20 years. She provides an example of 3-D mapping of a karst aquifer system in Switzerland.

3. Willscher discusses 3-D mapping at the German Federal Institute for Geosciences and Natural Resources (BGR), where they regard 3-D structure model development as a standard operating procedure that guarantees spatial consistency for geological and hydrogeological information. She provides two examples of 3-D modeling from a salt dome in northern Germany and from Dhaka City, Bangladesh.

4. Stafleu mentions that The Geological Survey of the Netherlands is constructing a 3-D geological property model of the upper 50 meters of the Dutch subsurface primarily to address groundwater extraction and infrastructural issues. Following the completion of a model of the Zeeland province, the province of Zuid-Holland, including the major cities of Rotterdam and The Hague, is now the focus.

5. Gill talks about water shortages, being common in Australia, as a driving force for using 3-D mapping and hydrogeology to improve the quantification and the management of groundwater resources. There is a three- year study to develop and test the capability of new hydrogeology tools in three study areas in Victoria, and several investigations in other parts of Australia are conducting closely related work.

Overarching presentations on the connections between geophysics and 3-D modeling, links between groundwater and 3-D modeling, and a geostatistical approach to 3-D modeling are the focus of three presentations.

1. Wiederhold discusses the contributions of geophysics to geological models based on studies of the North European Basin in Belgium, The Netherlands, and parts of Germany, Denmark, and Poland. Here, geophysical measurements are an important tool for constructing geological models because complex Quaternary and Tertiary deposits are often disturbed by glacial tectonics and uplift of salt domes. “Walls” of geophysical profiles provide meaningful perspectives to unravel geological complexities.

2. Faunt discusses the increasing popularity of developing 3-D geologic models to define hydraulic properties for groundwater flow models. She describes how two different geologic provinces are represented in 3-D models and she provides examples of how geologic principles are used to help constrain model simulations. Case studies on groundwater availability in the Central Valley of California and the Death Valley regional groundwater flow system show geology being used as the framework for groundwater flow models.

3. Phelps discusses the multi-point geostatistical approach for mapping locally complex geologic units in 3-D, whereby many alternative maps can be created that conform to known geology and expected geometry of

geologic units. Maps can incorporate significant geologic characteristics and provide estimates of regional geologic variability leading to uncertainty estimates for process models (flow and transport). Multi-point geostatistics can be used to map geologically complex 3-D units that otherwise could not be mapped in detail.

Web availability of geological information is the focus of three presentations:

1. Turner mentions that many modeling difficulties have been largely overcome by using new software and techniques and, importantly, by understanding clients' needs. Second-generation Internet, or Web 2.0, technologies and hosted services that facilitate communication among online groups belonging to Web-based communities, and client- and Web-based 2-D and 3-D visualization systems such as Google Earth and Google Maps can assist participants engaged in societal decision-making exercises.

2. Sharpe discusses online access to Canadian groundwater information through a groundwater information network (GIN). Groundwater information is provided via Open Geospatial Consortium-compliant Web services and Groundwater Markup Language. GIN serves a range of client applications, and there is a portal for 2-D and 3-D map interrogation, visualization, and statistical reporting of user selected data.

3. Thorleifson discusses a geological survey agenda for developing vertically georeferenced, Web-optimized subsurface information. These agencies have made considerable progress making standard information products Web-accessible, but the process of Web optimization, including vertically georeferencing of map content and optimizing it for zoom, browse, and query, is in its infancy. He emphasizes that users increasingly will demand that geologic map information be quickly and efficiently obtained via the Web, and this has caused and will cause all geological surveys to assess how quickly they can respond to this need.

A large regional case study of 3-D modeling is presented by Keller, who cites increasing demands for groundwater and hydrocarbons as the two main drivers for 3-D modeling. The first model covered the Winnipeg area of southeastern Manitoba and then extended north to include the Lake Winnipeg basin and west to complete the southern Manitoba Phanerozoic terrane. A regional scale model was recently created covering Manitoba, Saskatchewan, and Alberta, and future modeling will include Minnesota and North Dakota to produce a Red River Valley 3-D geological model. Last is a planned 3-D model of the Hudson Bay Lowland area of northern Manitoba.

CONCLUSIONS

Basic 3-D geological information is critical for addressing many of geoscience's "hot button" international issues such as global climate change (including sea level rise), water resources and allocations (closely allied with global warming), and earth hazards. Unfortunately, as these issues have gained prominence, there has not been a universal world-wide upswing in providing commensurate and additional geological information that is the solid underpinning that addresses many aspects of the hot topic issues in the first place. However, once we place geologic information within a 3-D perspective, we immediately achieve improved understanding of the geologic setting for decision makers, and by default, the information becomes more relevant to the general public. But we must also couple our improved geologic understanding with an efficient procedure for delivering that information to users via the Web or other delivery systems. All of this is essential to address, in a timely fashion, many of our global, national, state/provincial/regional, and municipal land- and water-use issues. The message must be clear if we expect to achieve a global commitment for 3-D geologic mapping activities.

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TROY VALLEY GLACIAL AQUIFER: 3D HYDROSTRATIGRAPHIC MODEL AIDING WATER MANAGEMENT IN SOUTHEASTERN WISCONSIN, USA

Kallina M. Dunkle[1], David M. Mickelson[1], Mary P. Anderson[1], and Michael N. Fienen[2]

[1]Department of Geoscience, University of Wisconsin-Madison, USA, [2]USGS Wisconsin Water Science Center, USA
dunkle@wisc.edu

INTRODUCTION

Glacial deposits in the Troy Valley (Figure 1), a buried bedrock valley, could be a source of groundwater for municipalities in southeastern Wisconsin. However, municipal pumping may divert significant amounts of water from lakes, streams, and wetlands. Three-dimensional hydrostratigraphic and groundwater flow models were constructed to determine the effects of pumping four recently installed municipal wells near Lake Beulah and Vernon Marsh (Figure 1). The 3D hydrostratigraphic model was produced using Rockworks^{TM} v. 2006 software and imported into a regional 3D groundwater flow model using the computer code MODFLOW.

GEOLOGIC DATA AND INTERPRETATION

Well data were obtained from several sources, including the Wisconsin Geological and Natural History Survey (WGNHS) WiscLith Database and the Well Construction Report (WCR) Database. These databases include information on almost 12,000 wells that were drilled within the Troy buried valley. However, most of these well logs do not have surface elevation data. The Walworth and Waukesha County databases contain almost 2,000 wells that have elevation data that were checked for location accuracy. Most well locations are accurate to within either 100 or 250 ft (WGNHS personal communication, 2007). Additional well and test boring data were obtained from the local consulting firms of Ruekert-Mielke, Inc and Layne, Inc (personal communication, 2007). These data have more accurate locations, including elevations, and usually a geologist was present who logged the deposits during drilling.

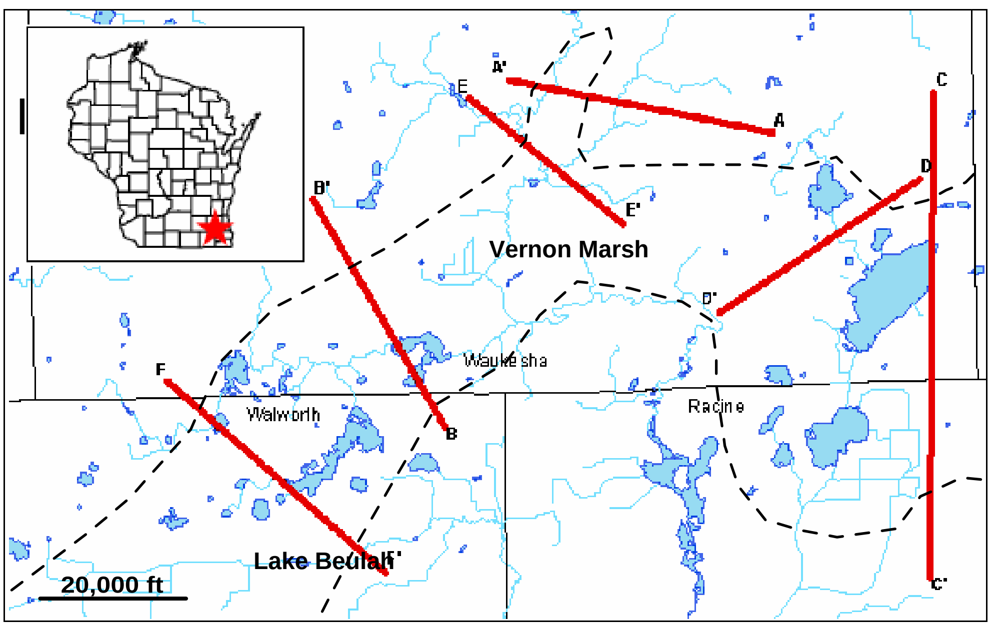

Figure 1. Map showing location of study area in southeastern Wisconsin. Dashed line shows approximate extent of the Troy Valley. Solid red lines mark locations of cross sections. Note the numerous surface water features, especially Lake Beulah and Vernon Marsh.

Initial interpretations of the geology were done with six cross sections, mostly perpendicular to the axis of the Troy Valley, constructed in cooperation with geologists at Ruekert-Mielke, Inc. In constructing the cross sections, drill holes completed by Ruekert-Mielke, Inc. were used because these data are likely more reliable than those from the WCR Database. However, some WCR wells were used to fill in gaps in the cross sections. The cross sections were drawn by hand using a combination of well or boring logs, topographic maps, and depth-to-bedrock maps. The cross sections show two glacial deposit units, a fine-grained unit that contains all lacustrine, till, and fine sand deposits, and a coarse-grained unit that contains coarser sand and gravel.

The driller's descriptions on the over 12,000 well construction reports were separated into four hydrofacies: (1) fine-grained till and lacustrine deposits such as clay and silt, (2) mainly silty and sandy till and deposits of intermediate composition, (3) sand, and (4) gravel deposits. Because most drillers lack formal geologic training, some logs were written up after well completion rather than onsite, and often subtle differences in sediment are not reflected in cuttings, the quality of these data varies considerably. For example, terms such as "hardpan" usually refer to glacial till, but so can stoney clay or clayey gravel, among other designations. Considerable effort was made to be consistent and as accurate as possible in transforming the driller's descriptions into geologic categories (Table 1).

Table 1. Units in drillers' descriptions that are included in each of the hydrofacies and their corresponding hydraulic conductivity values selected for use in the hydrostratigraphic model.

Hydrofacies 1	**Hydrofacies 2**			**Hydrofacies 3**	**Hydrofacies 4**
clay	hardpan	silty sand	muck sand and gravel	sand	sand and gravel
silty clay	clayey gravel	fine sand and gravel	silty gravel	coarse sand	gravel and boulders
sand, clay	clay and gravel	sand and silt with till	peat	medium sand	fine gravel
silty clay	sand gravel and clay	drift silt sand gravel	top soil and peat	water bearing sand	rubble
clay, sand	clay and stones	clay gravel and silt	clay and peat	blow sand	sand, fine gravel
sandy clay	fine sand	gravel muddy	black muck	quick sand	broken rock
surface clay	clay and cobbles	silty sand and gravel	peat moss	drift sand	boulder
puddle clay	clay and broken rock	muddy sand and gravel	muck	heaving sand	gravel
drift silt sand clay	stoney clay	muck sand	marsh mud		
	Initial Hydraulic Conductivity (cm/s)				
10^{-8}	10^{-5}			10^{-2}	10^{-1}

Literature values of hydraulic conductivity were assigned to each of the four hydrofacies (Table 1) relying on measurements of glacial deposits from North America (Stephenson *et al.*, 1988), as well as studies in southern Wisconsin (Simpkins *et al.*, 1990; Anderson *et al.*, 1999). Field-derived values of hydraulic conductivity were used rather than laboratory-derived values to better account for features such as weathering horizons and fractures.

HYDROSTRATIGRAPHIC MODEL CONSTRUCTION

The software Rockworks™ v. 2006 was selected to construct the hydrostratigraphic model because it could import the assembled well data, export those data in a format that could be imported into the groundwater model, was inexpensive, fairly easy to use, and creates and displays a 3D model. The well data (1,863 wells) from the WGNHS that had been checked for location accuracy were imported into Rockworks™ using the software's Excel™ template. The wells were then displayed as cylinders in 3D space to determine if any trends existed in the deposits. The most noticeable feature was the abundance of hydrofacies 1 (lacustrine silt and clay) on the eastern edge of Waukesha County, which was the uppermost unit in almost all of the wells in that region. Visualizing the raw data in 3D was a useful way to develop a general sense of the geology in the region, before allowing Rockworks™ to create a solid model (i.e., a block diagram of the deposits).

Since our final goal was a hydrostratigraphic model with nodes having the same lateral spacing as the groundwater model, a 400 by 400 ft grid spacing was used, creating 339 nodes in the x direction and 251 in the y, for a total of 85,089 nodes per layer. The final grid spacing in the z direction is 10 ft, creating 69 layers. This fine vertical spacing also allows for easier import into the groundwater model.

Only the well data from unconsolidated sediment were used to construct the solid model. All bedrock data were removed from the initial data that had been imported so that only the valley fill would be interpolated. This was necessary because an intermediate hydraulic conductivity zone that does not exist would have been created by the software had the bedrock been kept in the data set. Literature values of hydraulic conductivity (K) were entered into the model as the natural logarithm of K (ln K) due to the large order of magnitude difference between units. Using ln K allows for more accurate interpolations because the differences are equalized across orders of magnitude. The midpoint elevations of each unit in a well were used for the z direction locations. For example, if till was located between 770 and 830 feet, then an elevation of 800 ft was used as the z location. This was done because point, not continuous data, are needed in order to create a solid model.

The method of interpolation used in the solid modeling was Inverse-Distance with Weighting. A node was assigned a value (for this study, the ln K) based on a weighted average of neighboring data points. These interpolated values were determined by the following equation: $G_{node} = \Sigma(G_{point}/d^n) / \Sigma(1/d^n)$ where G is the value, d is the inverse of a point's distance from the node that is being solved for, and n is an exponent. This allowed for the closest points to have the greatest effect on the node's final value, with higher n values causing less influence from more distant points. More weight can be added either horizontally or vertically, by assigning different n values for each. This means that a larger n value assigned to a direction will cause that direction to have less weight in determining a node's value.

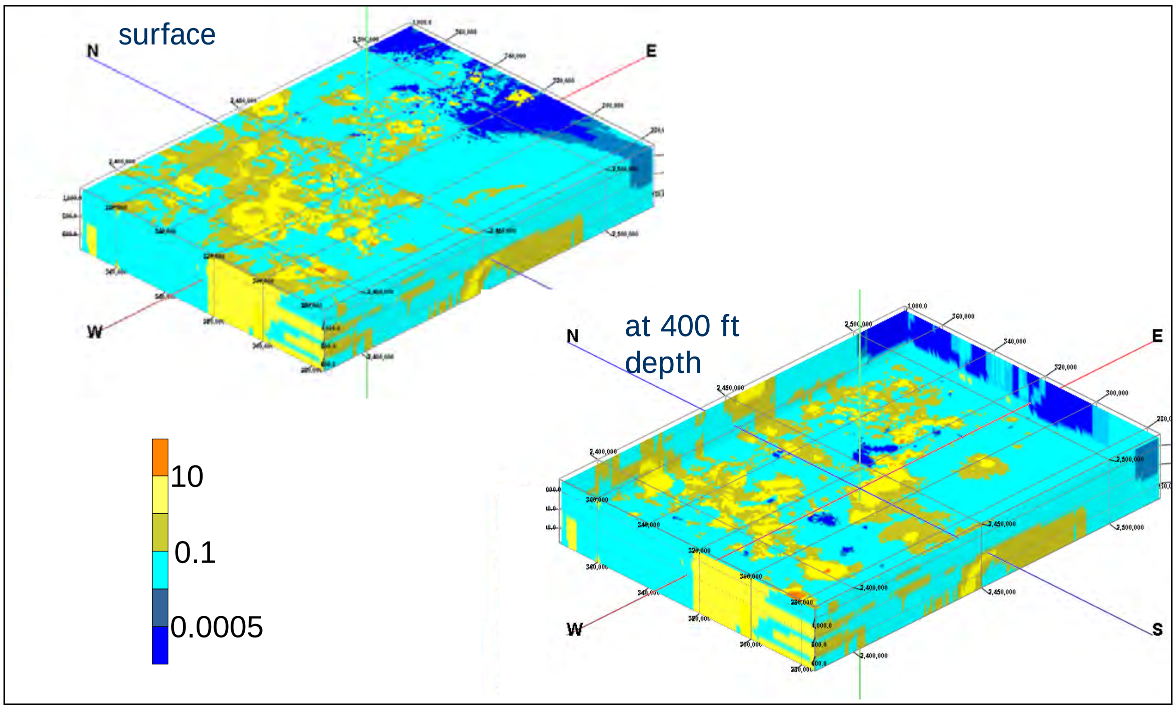

Figure 2. 1-30 Horizontal-Vertical Model results displayed at the (a) surface and at (b) 400 ft depth. Note that hydrofacies 1 is present in the eastern part of the surface layer, as seen in the raw data. The scale indicates values of hydraulic conductivity in ft/day.

Eleven models with different horizontal verses vertical weighting were run. The initial Rockworks™ setting of 2-2 horizontal-vertical weighting was run as a base case. Because the horizontal weighting equals the vertical, there is no preferential weighting in a specific direction. The selection of 2-2 was arbitrary. A model of 1-1 or 100-100, would have given the same horizontal and vertical weighting, but with slightly different results since the number itself indicates how much influence points farther away have on a node, with larger numbers causing less influence from more distant points. The 2-2 model did not produce the surface hydrofacies 1 deposits that are seen in the raw well data. Also, the model showed vertical tubes of sand and gravel, which does not make geologic sense. Therefore, all subsequent models were selected with more weighting in the horizontal direction to reduce this effect. Initial comparisons of the models eliminated all but two because they either still showed areas with vertical tubes, did not show the surface clay (hydrofacies 1) seen in the raw data, or had continuous horizontal layers of sand, which is inconsistent with the cross sections, which show that the sands are not well connected laterally. The final selection of a hydrostratigraphic model was based on which was most geologically reasonable and best matched the six cross sections. The model with horizontal to vertical weighting of 1-30 (Figure 2) was selected and imported into the groundwater flow model.

GROUNDWATER FLOW MODELS

A regional steady-state 3D groundwater flow model, based on the computer code MODFLOW (McDonald & Harbaugh, 1988) was created. Calibration of the regional model was performed using both the inverse code PEST (Doherty, 2004) and manual calibration. The calibrated regional model was run with the addition of four recently installed pumping wells, in order to determine the effects of these wells on groundwater heads and surface water features at steady-state. Then two local scale models encompassing Lake Beulah and Vernon Marsh were created using telescopic mesh refinement and the calibrated regional model. In the local scale models, MODFLOW's Lake Package (Merritt & Konikow, 2000) and Stream Flow Routing Package (Prudic *et al.*, 2004) were used so that effects of pumping on surface water levels could be assessed. The groundwater flow modeling included an uncertainty analysis to test the effect of hydraulic conductivity values and pumping rates.

RESULTS

Results from the regional and local scale groundwater models showed that pumping in the Troy Valley near Vernon Marsh and Lake Beulah will reduce groundwater heads and groundwater flow to surface water features near the pumping wells. The simulation shows the maximum possible impact under the assumptions used in the model, because the results of the predictive simulation were influenced by the fixed flux boundary conditions. Under field conditions, the wells will induce more water to flow into the area than is allowed by the fixed flux boundary conditions. Under fixed flux boundary conditions, an average 18% reduction in groundwater inflow in the northern section of Vernon Marsh and an average of 20% reduction in groundwater flow to Lake Beulah, where groundwater supplies 30% and 20%, respectively, of the total water inflow to these surface water features. Additionally, flow reverses in reaches of the Fox River north of Vernon Marsh and in the southern portion of Lake Beulah. Sensitivity tests on the lateral boundary conditions of the regional model showed that the impacts will be less when more water is allowed to flow through the boundaries.

The hydraulic conductivity of the glacial deposits can significantly affect the predicted heads under pumping conditions, depending on the location within the modeled area. The uncertainty analysis indicated that heads near Lake Beulah could vary over 4 ft and heads near Vernon Marsh could vary over 13 ft with varying hydraulic conductivities of the glacial deposits. Finally, the use of inverse distance weighting to interpolate the spatial distribution of the glacial deposits in a three-dimensional hydrostratigraphic model produced geologically reasonable results. This was evident in the calibrated regional groundwater flow model, which accurately represented the water table and had a good fit to the calibration targets.

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APPLICATION OF THREE-DIMENSIONAL GEOLOGIC MODELS IN DEVELOPING GROUNDWATER-FLOW MODELS

Claudia C. Faunt, Donald Sweetkind, and Randall T. Hanson

U.S. Geological Survey, USA ccfaunt@usgs.gov

INTRODUCTION

Three-dimensional (3D) geologic models have been used to define the geologic framework of complex regional aquifer systems. These models define the stratigraphy and structure of lithologic units using data points defined by surface contacts, drill-hole data, and (or) geophysical data. Where data are missing, data points are derived from known data points on the basis of geologic principles. In recent years, 3D geologic models have been used to define the model domain and hydraulic properties of regional 3D groundwater-flow models. This paper illustrates how 3D geologic models were used to describe the geologic framework and provide the basis for groundwater-flow simulations of the Central Valley aquifer system in California and the Death Valley regional groundwater flow system (DVRFS) in Nevada and California. The groundwater availability of the Central Valley of California is being assessed as part of the U.S. Geological Survey (USGS) groundwater availability program (Faunt 2009). The Death Valley regional groundwater flow system (DVRFS), which contains the Nevada Test Site and Yucca Mountain, is being studied in cooperation with the Department of Energy (Belcher 2004). The geologic conditions and groundwater use in the Central Valley and the Death Valley regions are quite different, providing an opportunity to compare the 3D geologic modeling approach in two different geohydrologic regimes.

CENTRAL VALLEY

California's Central Valley has been one of the most productive agricultural regions in the world since the 1950s. Most crops are irrigated with surface-water diversions and (or) groundwater pumping. About one-fifth of the Nation's groundwater pumping is from the Central Valley aquifer system. The Central Valley contains many communities, industries, and ecosystems that depend directly or indirectly on groundwater; consequently, the competition for available groundwater resources is intensifying. The objectives of the Central Valley groundwater availability study were to develop an understanding of the groundwater system and to develop modeling tools to quantify the region's water resources, and the human activities and climate variability affecting them so that possible future water-use conflicts could be reduced or avoided. In order to understand the status of the groundwater system, the geologic framework, hydraulic properties, and storage properties of the aquifer system were assessed.

The Central Valley is a large sediment-filled trough between the Coast Ranges and the Sierra Nevada. The valley is filled with sediments of deep marine, shallow-marine, deltaic, and continental origin. Most of the sediments comprising the heavily pumped aquifer system are of continental origin and are derived from the major rivers and their tributaries that drain the adjoining mountains. The hydrologic system in Central Valley is complex, in part, because of the heterogeneous nature of the valley fill. In this study, a texture model was developed to define the hydraulic properties of the valley-fill deposits. Sediment texture was defined as the percentage of coarse-grained sediment within a specified subsurface depth interval (Laudon and Belitz 1991). Although grain shape and sorting are often included as texture characteristics, they were not included as part of the texture classification used in this study. The texture model was developed by compiling and analyzing approximately 8,500 drillers' logs, describing lithologies up to 950 meters (m) below land surface. The lithologic descriptions on the logs were simplified into a binary classification of coarse- and fine-grained sediment. The percentage of coarse-grained sediment was computed for each 15-meter depth interval. Geostatistical techniques (3D kriging) were used to analyze spatial correlations of the percentages of coarse-grained textures using a 1.6 km spatial grid at 15-m depth intervals from land surface down to 700 m below land surface (Figure 1). The texture model reflects estimated regional, spatial, and vertical heterogeneity in the aquifer system. The heterogeneous texture model correlates to sediment source areas, independently mapped geomorphic provinces, and factors affecting the development of alluvial fans--demonstrating the utility of using readily obtained drillers' logs as a source of lithologic information.

The texture model was used to assess the vertical and lateral hydraulic conductivity distribution and the storage property distribution for the 3D numerical groundwater flow model developed for the region. The texture model was upscaled form 15-m depth intervals to a 10-layer groundwater flow model. A method for estimating hydraulic conductivity based on the correlation of percentage of coarse-grained deposits to hydraulic conductivity was developed. The horizontal and vertical hydraulic conductivity estimates for each textural end member are based on the power mean of the hydraulic conductivity of the coarse- and fine-grained end members and the percentage of these end members in each model cell. In the case of the Central Valley properties, the power mean results in a geometric mean in the horizontal direction and averages approaching a harmonic mean in the vertical direction. Initially, only one value of hydraulic conductivity for each of the end members was used. Geomorphic provinces and stratigraphic units were used to subdivide the domain because the details in the hydraulic observations could not all be represented with just two end members.

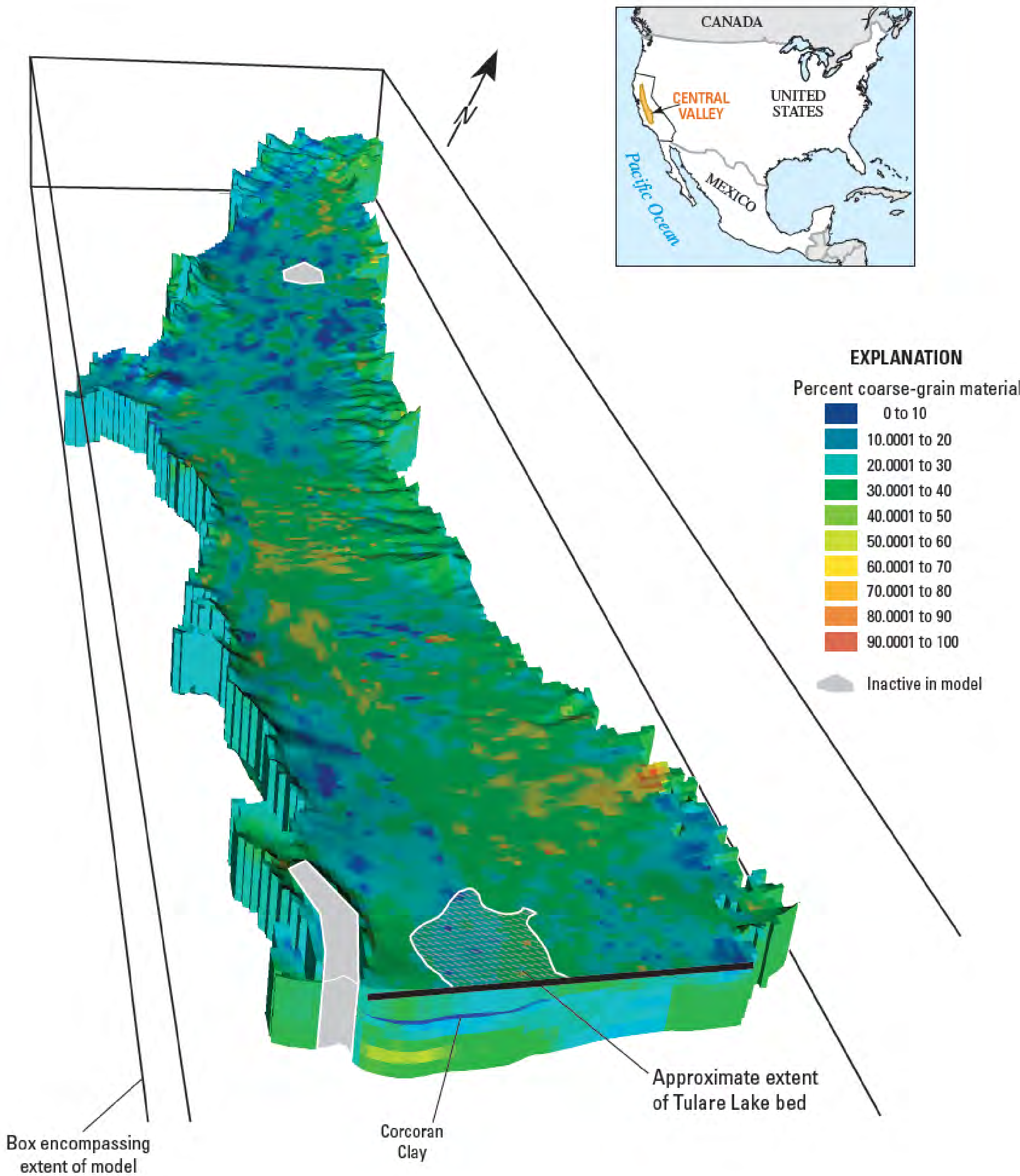

Figure 1. Block diagram of the northern three-fourths of the Central Valley texture model with cutaway in south.

DEATH VALLEY

The DVRFS occupies a scarcely populated desert region in Nevada and California where groundwater is used minimally but is the primary water source. Regional groundwater flow predominantly is through a thick Paleozoic carbonate rock sequence affected by complex geologic structures from regional faulting and fracturing that can enhance or impede flow. Spring flow and evapotranspiration are the dominant groundwater discharge processes. Relative to the Central Valley, small amounts of groundwater are withdrawn for agricultural, commercial, and domestic uses. Interest in the DVRFS is driven by the need to: (1) understand the groundwater flow paths and travel times associated with potential movement of radioactive material from the Nevada Test Site (NTS); (2) characterize the groundwater system in the vicinity of the proposed high-level radioactive waste repository at Yucca Mountain; and (3) address a variety of potential effects of groundwater usage on users down-gradient from the NTS and Yucca Mountain, including the agricultural communities in the Amargosa Desert, Death Valley National Park, and Native American interests (Belcher, 2004).

The DVRFS consists of Precambrian and Paleozoic crystalline and sedimentary rocks, Mesozoic sedimentary rocks, Mesozoic to Cenozoic intrusive rocks, Cenozoic volcanic tuffs and lavas, and late Cenozoic sedimentary deposits. Geologic data from geologic maps, cross sections, and borehole lithologic logs were used to subdivide these rocks or deposits into 27 separate hydrogeologic units (HGUs). A 3D geologic model, referred to here as a hydrogeologic framework model (HFM), was developed to represent the geometry of the HGUs (Figure 2). Approximately 70 regional geologic cross sections, reflecting a consistent interpretation of regional structural style, and approximately 7,000 lithologic contacts between HGUs from borehole information provided the subsurface control for the HFM. Gridded surfaces from other 3D geologic models constructed for the Nevada Test Site (NTS) and Yucca Mountain also were used. The HFM defines regional-scale hydrogeology and structures for thicknesses ranging from 4,000 m to 8,000m. The model has 1,500-m horizontal resolution and variable vertical thickness for the HGUs. Faults thought to be hydrologically significant were used for offsetting HGUs in the HFM.

The HGUs were used to develop the vertical and lateral hydraulic conductivity distribution and the storage-property distribution for the DVRFS 3D numerical groundwater-flow model. Available geohydrologic information indicated that the HGUs needed to be subdivided into zones to better represent the variation in hydraulic properties in individual HGUs resulting from facies changes, different structural provinces, and other types of alterations. A total of about 100 HGUs and related zones were identified in the HFM. The hydraulic conductivity and storage properties of the 27 HGUs and related zones were estimated on the basis of pumping tests, values reported in the literature, and previous models in the area. Initially, the hydraulic properties were lumped into four classes: valley fill aquifer, volcanic rocks, carbonate aquifer, and confining units. The groundwater-flow model has the same 1,500-m horizontal resolution as the HFM; however, the vertical resolution of the two models is different. The groundwater-flow model separated the DVRFS into 16 layers of variable thickness that are parallel to the water table and thicken with depth. The hydraulic properties stored in the HFM were upscaled to the groundwater-flow model by utilizing the HUF Package of MODFLOW (Andermann et al. 2000). As calibration proceeded, the hydraulic conductivity and storage properties assigned to the different classes were modified on the basis of the HGUs and zones in the HFM until simulated hydraulic head and discharge measurements approached measured values.

SUMMARY AND APPLICATION OF 3D GEOLOGIC MODELS IN FLOW MODELS

The application of 3D geologic models for developing and constraining groundwater-flow models was presented for two different geologic settings: (1) Central Valley–an alluvial aquifer system and (2) Death Valley–a carbonate-rock aquifer system. In the alluvial aquifer system, the geologic model was defined utilizing texture information, and in the carbonate rock aquifer system the model was defined using mapped HGUs. Both groundwater-flow models started with a simple set of parameters, representing only the dominant subsurface characteristics represented by the geologic models. In both geologic settings, the use of a small number of parameters at the beginning of the groundwater-flow model calibration allowed for a clear evaluation of gross features of the subsurface. Subsequently, composite scaled sensitivities, and flow and head observation residuals, were used to determine whether the geologic models could be subdivided to produce additional parameters that could be estimated with the available data. In the future, uncertainty in the results of the groundwater-flow model simulations could be reduced by improving on the quality, interpretation, and representation of the 3D geologic model and the spatial variability of material properties within the model.

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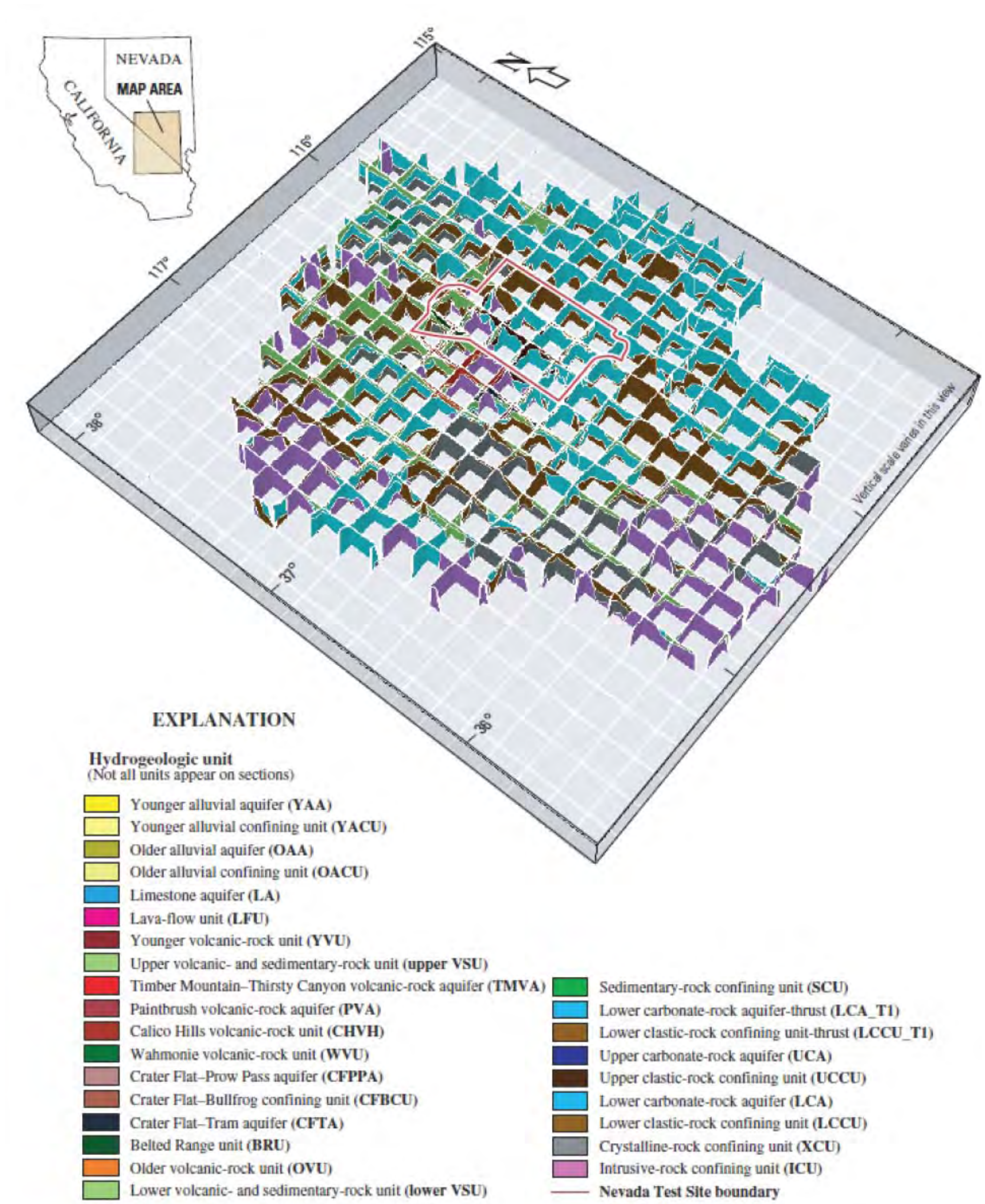

Figure 2. Oblique view of the three-dimensional hydrogeologic framework model for the Death Valley regional flow system. A fence diagram shows the distribution of the hydrogeologic units.

3D DOWN-UNDER — WHAT ARE THE AUSTRALIANS UP TO IN 3D HYDROGEOLOGY

Bruce Gill, Don Cherry, Xiang Cheng, Jon Fawcett, and Mark Reid

Future Farming Systems Research, Department of Primary Industries, Victoria, Australia, Bruce.gill@dpi.vic.gov.au

INTRODUCTION

Water shortage is common in much of Australia. With the vast majority of the continent classed as semi arid (an overall average of 455mm rainfall per year) and the tropical north having monsoonal rains and long dry seasons, groundwater provides an essential buffer for many parts of the country. In recent years though, rainfall has been significantly below average, especially across the south east of the continent, which has affected vast areas of Australia's most important agricultural production region. The Murray Darling Basin, (which occupies 1/7th of the continent) supported average annual consumptive water use of 11,000 GL (to 1997), but last year, had fallen to less than half. This year, heading in to spring, the 22,600 GL of upstream basin storage is sitting at only 23% of capacity.

The increasingly precarious surface water supply situation is placing groundwater resources under greater stress. It is in this environment that 3D hydrogeology developments are gaining attention as a means of improving both the quantification and the management of groundwater resources. While the authors of this extended abstract are working on a three- year study to develop and test the capability of the new hydrogeology tools in three study areas in Victoria, several other groups and organisations in other parts of Australia are carrying out closely related work (Figure 4).

Being aware of the progress being made in 3D hydrogeology in both North America and Europe through this workshop and the 2nd British Geological Survey hosted 2nd International GSI3d conference of September 2008, (Mathers, 2008), it was timely to meet together with scientists undertaking similar work in Australia. To that end, a two-day workshop was held at the Geoscience Australia head office in Canberra on the 31st August and the 1st of September. Over 50 participants watched 23 presentations of a wide range of approaches and case studies from around the country. Demonstrations of 3D visualisations in both the purpose-built visualisation suite and using portable equipment were also included. A compilation of workshop extended abstracts (Gill, 2009) is available from www.ga.gov.au/3DHydro/workshop09/.

VICTORIAN 3D HYDROGEOLOGY PROJECT

The Victorian Geological Survey (now Geoscience Victoria) has been developing a fully attributed 1:250,000 scale 3D model of the whole crust of Victoria, incorporating the onshore and offshore geology since about 2004. Primarily focussed on developing improved understanding of the mineral and hydrocarbon resources of the state, the 3D framework being developed goes deeper than required for groundwater supply needs. Nonetheless, the upper most mapped units in many parts of the state are hydrogeological units and the basement rock generally constrains the base of the groundwater systems of interest. This 3D geology work helped catalyse 3D hydrogeology in Victoria.

Early in the life of the study, a literature review was carried out and completed in January 2009. This identified the growing body of knowledge accumulating overseas and was very helpful in highlighting a range of key learnings as to the potential benefits of 3D hydrogeology, such as:

- the value for building conceptual hydrogeology frameworks upon which more reliable numerical models can be constructed,
- making much better use of all the available data,
- building data sets that conform with national and international standards
- how they can be used to improve comprehension of hydrogeology
- the need to define the uncertainty of the 3D mapping renditions and not over-extend the technology

Another conclusion drawn was that there seemed to be limited documentation of the usage of 3D hydrogeology methods for groundwater resource quantification or examples where applications of visualisations for improving stakeholder comprehension of the resource had been trialled.

Three study areas were selected for 3D hydrogeology mapping on the basis of (i) having significant groundwater resources that are intensively used, (ii) having uncertainties regarding aquifer extent and stream connectivity, (iii) having reasonable data availability, and (iv) requiring management plans to be developed. These areas are called the Southern Campaspe Plains, the Upper Loddon and the Moorabool catchment (Figure 1). The Moorabool area has geology and groundwater systems that are feeding significant quantities of salt to surface water supplies downstream, hence an additional objective is to investigate whether the 3D mapping can help identify the source of the high salt loads.

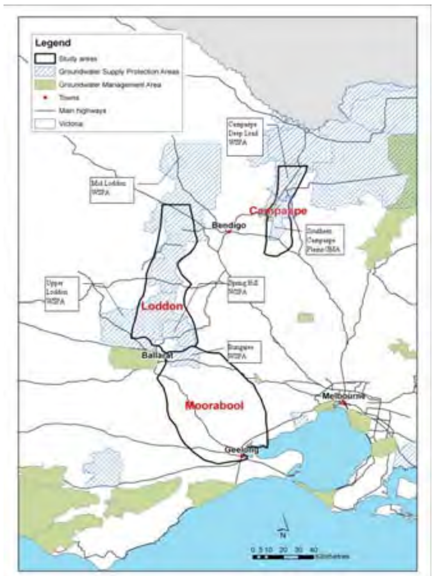

Figure 1. Location plan of the three study areas being used to explore the potential of 3D hydrogeology in Victoria.

The three study areas chosen have varying degrees of data density, data types and data quality. Bore log data, surface geology, and any other relevant information were gathered, including geophysical datasets, groundwater geochemistry, imagery, and previous modeling. This data was transformed into a common projection and stored in a GIS database and dominant hydrogeological surfaces developed from the data.

A key finding early on in assembling the geological data is the value in using the 3D visualisation power available to ensure the data and surfaces built from them are reasonable interpretations. Anomalies in the data such as missing or incorrect coordinates for logs, poor logging data or geological interpretations were worked through to derive 3D models of the study areas. Applying simple visual checks to make sure that a feature ‘looks right’ or fits a known and accepted geological interpretation improved confidence in the models.

3D modeling and visualisations also have been used to corroborate findings from other studies. Figure 2 highlights part of the Upper Loddon study areas, where cross cutting faults (Holdgate et al, 2006) are thought to be responsible for displacements down the valley that controlled the depositional thickness of sands and gravels of the main regional aquifer system that is overlain by Quaternary basalts. Until this time, earlier interpretations had mapped considerably more extensive and continuous alluvial deposits in the area.

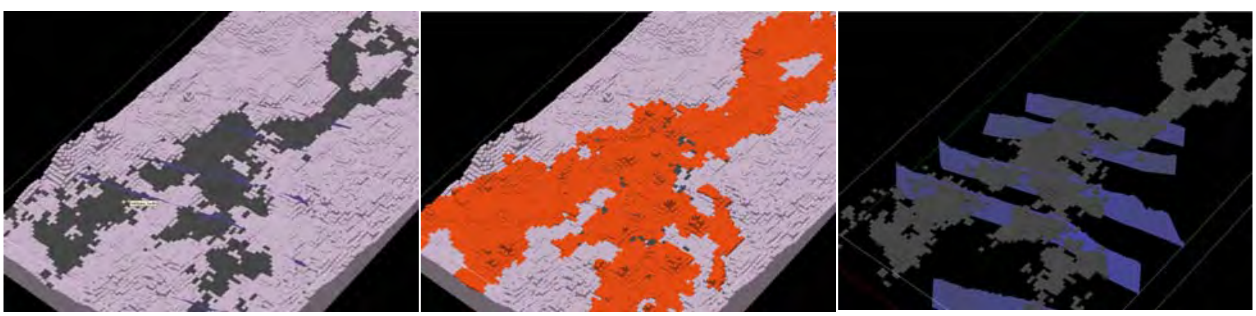

Figure 2. Voxel models showing deep lead aquifer distribution on bedrock (left) Basalt valley-infill (middle) and deep lead with interpreted faults (right) of the Upper Loddon study area.

NUMERICAL MODELING REVIEW

Another investigation undertaken as part of the study has been a review of all the past numerical groundwater models within or surrounding the three study areas. The first major numerical groundwater model covering the Campaspe and Loddon study areas was undertaken in 1990 as part of a coarse scale assessment of the Victorian Riverine Plain groundwater system. Since then, numerous other groundwater modeling studies have been carried out, each seeking to improve understanding of the groundwater systems for a range of reasons, including salinity, land management or water resource issues.

A key finding from the review was that all the models were different in respect to scales, boundaries, modeling approaches, software choices, and in model inputs and outputs. While the results may be considered useful with regard to improving general understanding of the specific systems being studied at the time, they left little of value in terms of legacy data sets or directly comparable results. Each modeling study tended to start from first principles in respect to developing the conceptual models of the groundwater flow systems. Surface geology mapping and available groundwater drilling data were the main inputs for model grid construction, and little, if any, iterative development occurred during successive modeling studies. A key conclusion then is that the building of a state owned 3D geological / hydrogeological data set will greatly improve subsequent numerical groundwater model studies by removing a major source of inefficiency and uncertainty at the conceptual model development stage.

A fundamental requirement of any attempt to define the possible ‘safe’ or ‘sustainable’ annual yield from any defined aquifer or area is to start with as good a geological framework and hydrogeological conceptual model as possible. Not only can logical boundaries and areas be better defined to start with, but whenever any calculations are performed using any of the possible numerical modeling methods, the best geological and hydrogeological framework available will reduce the likelihood of missing important factors and enable the basis for the determination to be clearly understood. The review has highlighted the benefits that completion of a 3D hydrogeological framework would provide as the basis for any future modeling work. Transparency of model conceptual design, repeatability, iterative improvement, and a basis for the projection of model outputs will all be facilitated by the development of 3D hydrogeology mapping.

IMPROVING HYDROGEOLOGICAL CONCEPTUALISATION AND NUMERICAL GROUNDWATER MODEL DESIGN

A recently completed comparison of model grids developed using earlier methods compared to those developed using 3D hydrogeology methods was undertaken in the Upper Loddon study area. The Upper Loddon system is characterised by incised fractured rock valleys in-filled with Tertiary alluvial sands and gravels, overlain by up to 150 metres of Quaternary basalts and scoria. The sands and gravels are considered an important water resource, especially in channelling water further to the north, and earlier interpretations had surmised that the sands and gravels were more extensive than 3D based methods are now showing.

The left hand map in Figure 3 shows the basement rock outcrop (blue) and shades of red indicating thickness of the sands and gravels. This mapping was developed in 2005 (Fawcett et al, 2006), and has subsequently been refined using Gocad and additional data sets. This data includes interpreted faults (Holdgate et al, 2006) and groundwater chemistry data (Hagerty, 2007). The green to pink toned map (top right) is the thickness of the sand and gravel aquifer layer used for a regional scale groundwater model, whereas the map below it shows the same image with the 3D derived sand and gravel isopachs (grey shading) over the top. The contrast in size of the aquifer can clearly be seen and the groundwater resource estimates from models based on these maps would be vastly different.

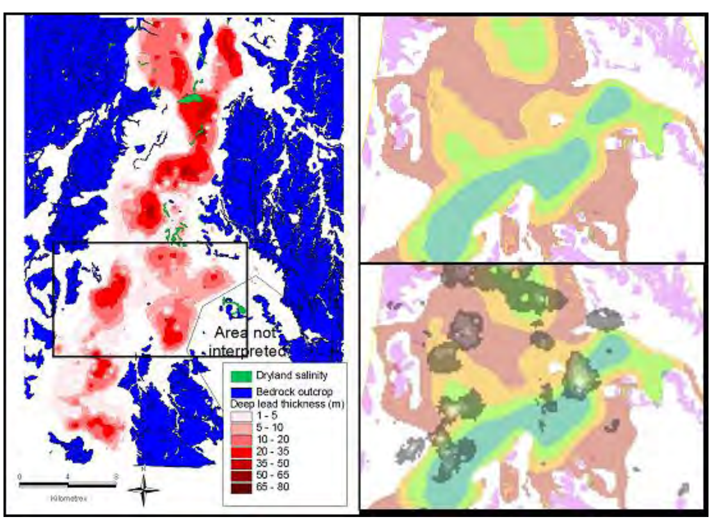

Figure 3. Isopach maps of the sand and gravel alluvial aquifer in the Upper Loddon. The left hand map was derived using 3D modeling methods, while the regional scale model isopach map (top right) was generated from drill logs only. The bottom right maps shows the 3D isopachs (grey) overlain on the regional scale model map.

As an adjunct to the main study, a PhD study is researching the hypothesis “That 3D hydrogeology mapping, resource assessment methods and visualisations can lead to improved groundwater resource management outcomes". Findings from relevant literature highlight that the more successful implementations of groundwater management plans have occurred where there is good cooperation between users and the responsible authority. A key factor in establishing this cooperation is a shared understanding of the resource. Traditional analogue renditions of the subsurface are clearly limited for a lay audience, so using 3D mapping and visualisation technology, the study will investigate how various visualisations may be more or less effective in building understanding of the resource in two of the study areas.

INTERSTATE AND NATIONAL PROJECTS

From a national perspective, 3D hydrogeology is being used to investigate a number of areas of groundwater stress in urban, semi-urban, and agricultural regions. Figure 4 shows the locations of some of these projects and more details and contacts for these and other projects are contained in Gill (2009).

In the Perth Basin of Western Australia, annual rainfall has dropped dramatically in the last 20-30 yrs. Groundwater investigations by the Department of Water (DoW WA) are focussed on gaining a greater understanding of the large groundwater resource of the Perth Basin in order to manage increased demand from the deep aquifers in this basin.

In New South Wales, the University of NSW (UNSW) is investigating the long term impact of surface irrigation, recharge, hydrologic connectivity, and the temporal interactions of ground and surface waters of the Namoi River catchment. Elsewhere in NSW, studies have been using airborne electromagnetic surveys to map subsurface salinity, aquitards and freshwater plumes.

The Queensland University of Technology (QUT) is developing software to model, visualise, and manage groundwater data, as well as exploring the role of groundwater system visualisations as a management tool. Their principal areas of investigation are the heavily utilised groundwater systems in the Condamine River catchment near Toowoomba, west of Brisbane. A semi urban area near Darwin (Howard East) has also been a test area for the Groundwater Visualisation System (GVS) software package they are developing.

Also in Victoria, the state and regional water authority are exploring the use of ArcHydro and are in the process of defining statewide standardised hydrogeological units. The national geoscience research organisation, Geoscience Australia, has a national role and has been involved in several studies, including 3D mapping of the Great Artesian Basin and Murray Darling Basin and development of national hydrogeological mapping protocols.

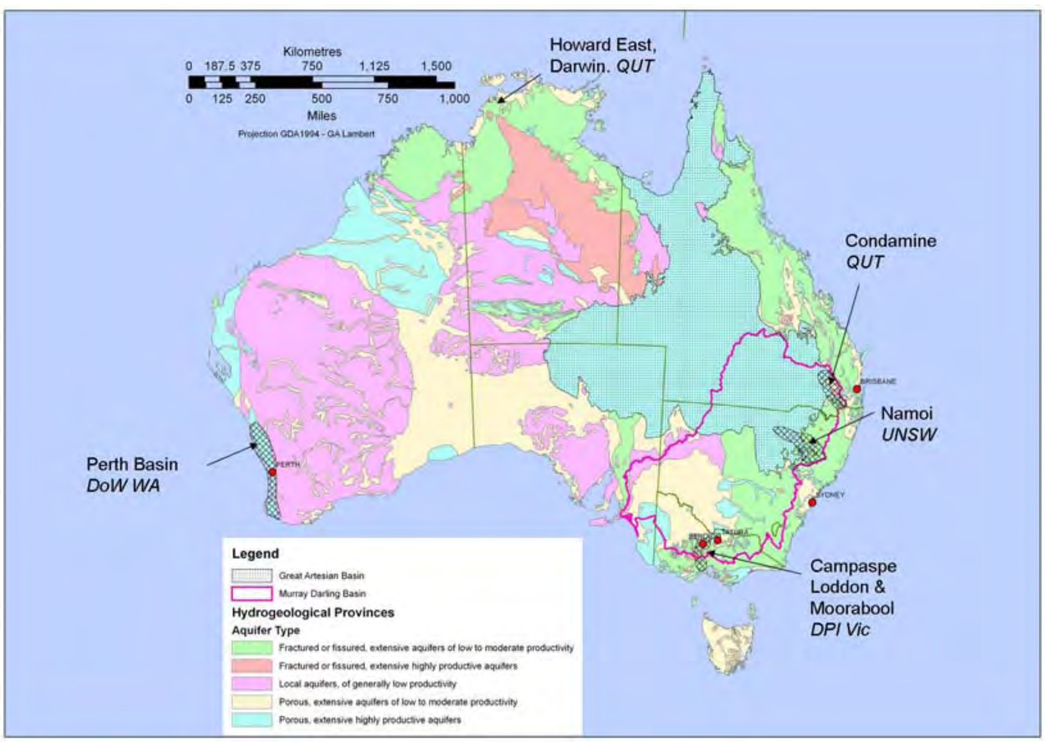

Figure 4. Hydrogeological provinces of Australia with the locations of some current 3D hydrogeology projects indicated.

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MAKE A DIFFERENCE OUTSIDE YOUR OWN BACKYARD

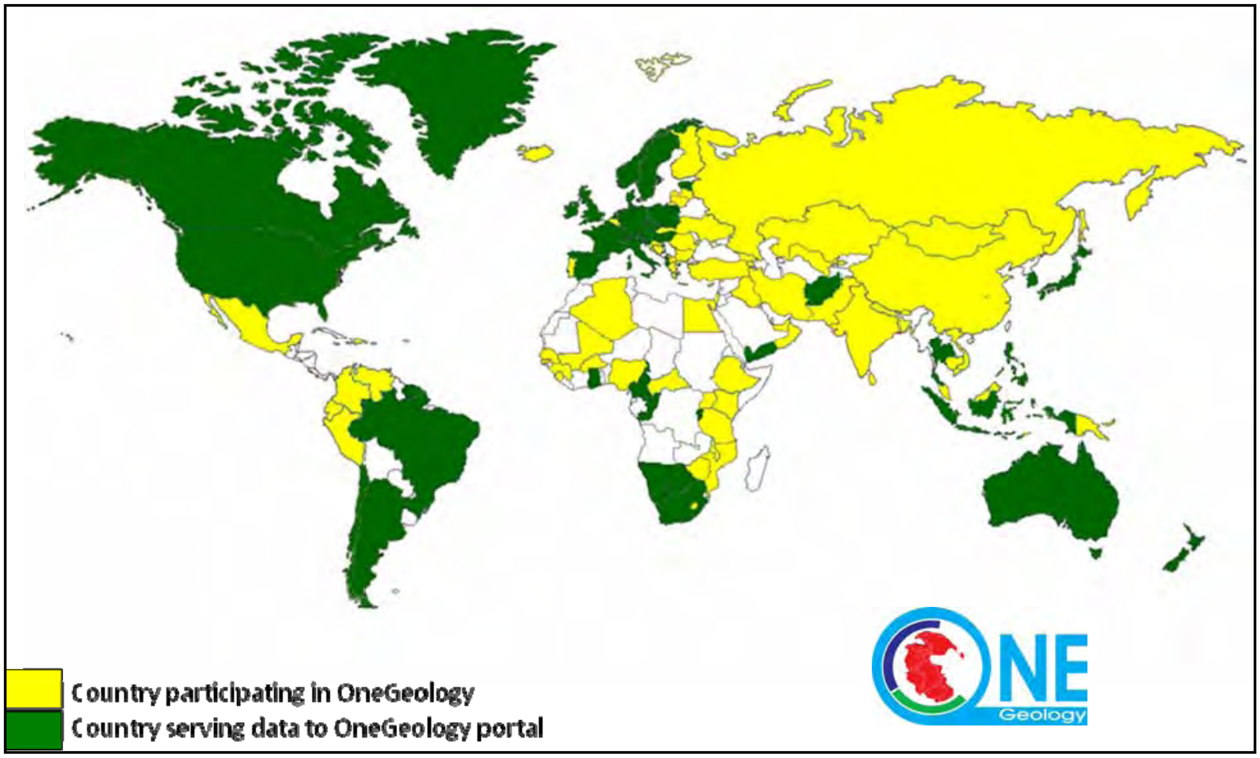
Ian Jackson

British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham, United Kingdom, NG12 5GG, ij@bgs.ac.uk

In this paper "outside your own backyard" is going to be used in two ways. The first refers to geoscience modellers making a difference within our own, geoscience, community. The second way relates to the need for modellers to improve their interactions with the wider world. The paper largely pertains to the work of geological surveys, with which I am most familiar, but some of the points will have relevance beyond.

UNITED BUT DIVERSE

They may already be obvious to some, but the experience of being a part of the OneGeology bandwagon has rammed home a few things in the last 3 years. For those who have not heard of it, OneGeology is a multi-national geological survey initiative to make geological map data Web accessible. It is an initiative that has provided several of us with the opportunity to visit and meet geoscientists and geological surveys in every continent and has given privileged insight into the status of geological information and informatics and the visions of our peers across the globe. And just what has the experience revealed? It can be summarised in a couple of paradoxical words – unity and diversity. Around the world geoscientists share a basic aspiration – to model and describe their multi-



dimensional, multi-parameter domains in a digital multi-dimensional and multi-parameter way. No-one has a monopoly on this aspiration; it is articulated wherever you go, sometimes in a technically sophisticated and complex way, sometimes with basic but elegant simplicity. At the same time, the resources, technology, and support infrastructure to implement this aspiration are much less ubiquitous and there is a huge disparity in the tangible progress made across the planet. Almost equally diverse are the approaches taken to modeling by those who are fortunate to have the wherewithal to do it. The conclusions that follow from these basic observations are the subject of the first part of this paper and a prime basis for the exhortation in the title for us to get outside our own backyards.

YOU ARE NOT ALONE

It is natural to assume that the scientific, technical, and cultural challenges one faces in developing and implementing 3D modeling are unique to you and to push ahead and try to deliver your own solution. It is, however, exceedingly improbable that, at the beginning of the 21st century, this will be the case - somebody somewhere will have struggled with, or will be struggling with your problem. Your piece of bedrock, or surficial, or even anthropogenic, domain and geological geometry is not unique. It is equally improbable that your application or hardware quandary or a similar problem has not been encountered before, and yet how often do we choose to re-invent our own little bespoke wheel? We then defend our "territory" and our own way of doing things, which in the long run only serves to fragment geoscience, not bring it together. We need to find improved ways of sharing experience and solutions. This workshop series has and is making a great contribution, but it needs to be replicated, diversified, and supplemented by other resources – on line and in print. But all these things are no substitute for getting on our bikes and visiting colleagues and seeing and borrowing from what others in the world have to offer.

PUTTING SOMETHING BACK

Around the world there are geoscientists who see the potential of a 3D and 4D digital world and share our vision but do not have the privilege of the resources, or influence, or experiences many of us here at this workshop have. They need help to marshal and win the arguments to make the progress they and their nations so desperately need. While some of us could, and do, supply their organisations with the 3D modeling software and applications, this is perhaps - however attractive and glamorous the application may appear to both recipient and donor - not on its own a sustainable, or responsible, answer. The real pressing need is arguably for assistance in developing basic infrastructure – i.e., a sound information policy foundation, a workable technical and managerial strategy, and well constructed use and business cases (of which more later), in other words an integrated and practical package with appropriate technology; above all assistance which helps avoid and mitigates the pitfalls that we encountered and shortens the length of the digital learning curve. There is a huge appetite for knowledge that we, in the so-called developed world, may consider routine and not particularly special and there are real opportunities to spread that knowledge and add value outside our accustomed territory.

MAKE THE CASE

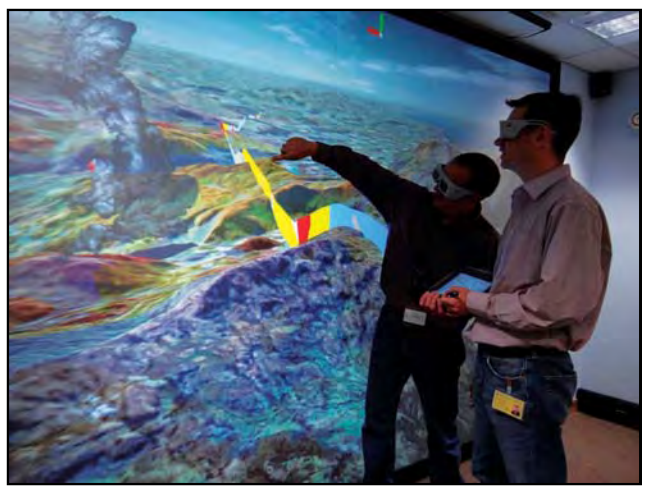
Most geoscientists do not need to be convinced of the capabilities of models to more fully record our understanding of the world beneath our feet. We are know that these models, whether they be 3D or 4D, can better hold and present the interpretation of the diverse evidence we have gathered and can be used to predict geometry or properties at some point in space and perhaps time. But models represent a substantial investment in data and skills acquisition over conventional 2D outputs. Moreover, management and external clients (and some geoscientists) will need to be convinced that the cost-benefit case stacks up. We need to be able to answer the "so what" question that will inevitably come from these sources. How do you explain to an insurance company what benefit a model provides over the standard 2D geo-hazard assessment we provide to them, or to a local authority about the advantages of having information in a minerals plan that derives from more than two dimensions. It is not that the case cannot be made; it is just that too often we fail to make it persuasively, if we make it at all. One of the possible outcomes of this workshop could be a set of use cases and/or cost-benefit cases for 3D models, articulated in language which an intelligent layperson can comprehend. It would be excellent to see examples from groundwater resources and protection, urban planning, radioactive waste disposal, major civil engineering schemes, etc.

ENGAGING WITH THE FLAT EARTH SOCIETY

The dominance of the topographic sector within the increasingly important spatial data infrastructure (SDI) community (and by contrast the relative silence of the geoscientists) means that at times you could be forgiven for thinking that geographic information and spatial data had only two (or at a push 2.5) dimensions. Of the three spatial dimensions, X and Y are very much the principal considerations. If you will excuse the pun, Z has a much lower profile. T = time gets a rare mention and a 5th dimension – uncertainty – little airtime at all. We know that modeling the real world requires us to get to grips with these other dimensions too. To predict the rocks, their properties and how they and the fluids and gases within them move, has required a multi-dimensional approach. On the other hand, the topographic community is much more mature and professional in terms of the organisation, management, interoperability, and dissemination of their data, and there is much we can learn from them. Instead of being snobbish about the geographers, we need to be proactive and explore how the geographic and geological communities might better share their expertise and experience in the future.

THE VIRTUAL WORLD BEYOND

It is a given that to reach outside our backyards we must make the fullest use of the internet. Making basic models available in 3D postscript and other formats is a great start, but inevitably the full modeling workflow, in particular delivery, must be as far as possible Web-enabled …and interactive…..and easy to use….and complying with international spatial data and applications interoperability standards. At the same time, we need to smoothly integrate the seductive game-like developments in visualisation and virtualisation with our 3D models and Web-enable these too and then unashamedly use them to convince the internal doubters and new potential external users of the advantages of a 3D world.



THE WHOLE IS GREATER THAN THE SUM OF ITS PARTS

As with the rocks, the issues that geoscience are central to – natural resource development, hazard mitigation, climate change - show no respect for political boundaries and are often trans-national. Those issues also transcend geoscience because they are multidisciplinary. Our world is shrinking at an accelerating rate too, in a virtual sense at least. These realities and the arguments made in this paper all point one way – that the optimum course of action by our community is not only to take forward the work of our own projects, programmes, and organisations, but to exploit every opportunity to add value by collective action. In other words: to share more and collaborate more, inside and outside our domain. This will depend crucially on those in senior management positions having the confidence to look beyond the expeditious local solution and recognise that it is joined up geoscience modeling that will sustain and have lasting strategic value. In a complex changing world it is multi-disciplinary science that can model and predict the real world that has the best chance of success, and we will be more innovative and ensure that our results can be deployed if we work together.

PROGRESS IN 3D GEOLOGICAL MAPPING IN THE EASTERN PRAIRIES OF CANADA AND THE USA

Greg Keller[1], Gaywood Matile[1], and Harvey Thorleifson[2]

[1]Manitoba Geological Survey, Winnepeg, Manitoba, Canada, [2]Minnesota Geological Survey, St. Paul, Minnesota, greg.keller@gov.mb.ca

INTRODUCTION

Increasing demand for groundwater and hydrocarbons have been the two main drivers for 3D mapping in Manitoba. In order to satisfy these demands, and to broaden our knowledge of the subsurface, the Manitoba Geological Survey has been working toward a provincial 3D model by developing regional and detailed models, as well as protocols and methodologies for model construction. Early in 2000, after years of data compilation, the first of Manitoba's 3D models was built. This hydrostratigraphic model, built with funding from the National Geoscience Mapping Program (NATMAP), covered the 200 km by 230 km Winnipeg area of southeastern Manitoba. Subsequently, Paula Kennedy of the University of Manitoba completed a groundwater-flow model based upon this data, proving its feasibility for groundwater modeling (Kennedy and Woodbury, 2005). The model has since been extended northward to include the Lake Winnipeg basin and is currently being extended westward to complete all of the southern Manitoba Phanerozoic terrane south of 55° North Latitude. The southwest Manitoba model will include bedrock units derived from the recently completed Williston Basin architecture and hydrocarbon potential project 3D model which was funded by the federal (Canada) Targeted Geoscience Initiative (TGI). This cooperative model was created using high quality drill data from both Manitoba and Saskatchewan. A regional scale model was recently created using data from the Atlas of the Western Canadian Sedimentary Basin (WCSB) (Mossop and Shetsen, 1994). It was built using digitized structure contours, and covers Manitoba, Saskatchewan, and Alberta. Future modeling will include further cooperation with both Minnesota and North Dakota in order to produce the Red River Valley 3D geological model. This model will connect the existing Manitoba models with the 3D geological model of groundwater-bearing strata in the Fargo-Moorhead region. Early in 2009, the first step was taken toward this end by creating a cross-border seamless Quaternary map covering the study area. Finally, a new project on the hydrocarbon potential of the Hudson Bay and Foxe basins has been initiated. This project is part of the new Geological Survey of Canada northern Geoscience of Energy and Minerals program (GEM). One of the planned products is a 3D model of the Hudson Bay Lowland (HBL) area of northern Manitoba.

Table 1. Model extents (Figure 1).

Model	**Latitude Range**	**Longitude Range**	**Area**	**Units**
Southeast Manitoba	49° to 51°	-98° to -95°	45 000 km^2 (17 500 mi^2)	14 bedrock units, 17 Quaternary units
Lake Winnipeg	51° to 54°	-100.3° to -95.3°	78 000 km^2 (30 000 mi^2)	8 bedrock units, 24 Quaternary units
TGI Williston Basin	49° to 55.5°	-106° to -96°	494 000 km^2 (190 700 mi^2)	42 bedrock units
WCSB	Manitoba, Saskatchewan and Alberta		2 920 940 km^2 (1 127 780 mi^2)	10 bedrock units (chronostratigraphic)
Southwest Manitoba	49° to 55°	-101.5° to -98°	176 225 km^2 (68 041 mi^2)	Yet to be determined
Red River Valley	45.5° to 51°	-98° to -95°	136 100 km^2 (52 550 mi^2)	Yet to be determined
Hudson Bay Low	~ 54° to ~ 59°	~-97.5° to ~ -89°	190 060 km^2 (73 400 mi^2)	Yet to be determined

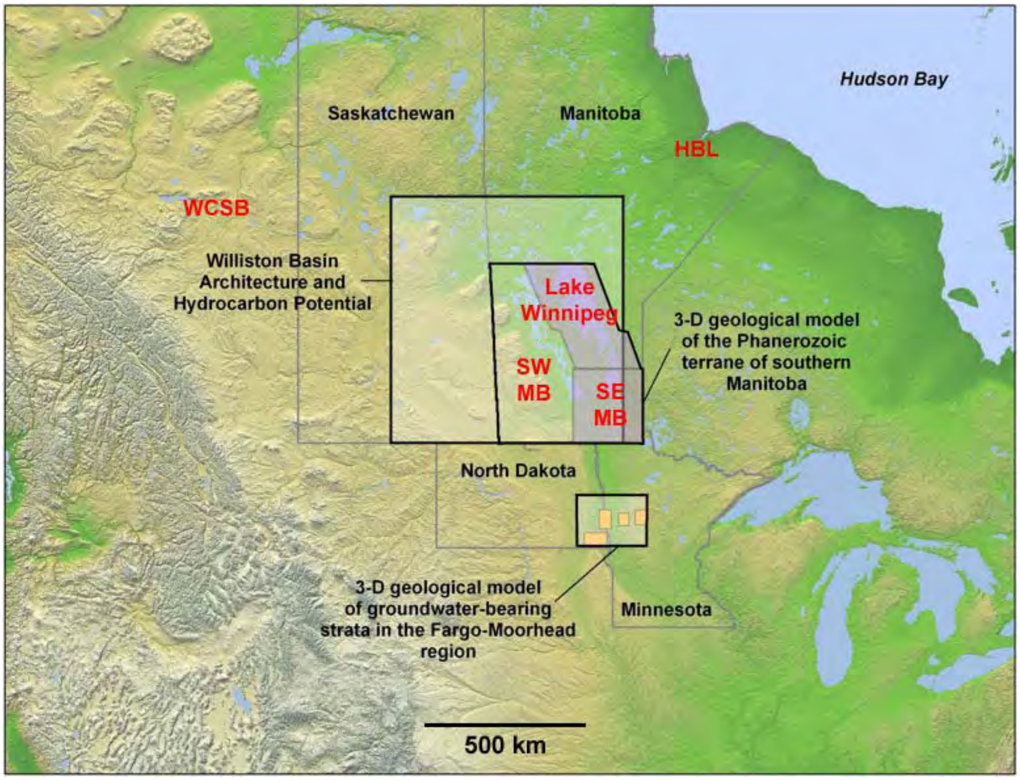


Figure 1. Index map of model areas. Orange blocks indicate areas of higher detail within the Fargo-Moorhead model.

MODEL INPUTS

Many years, in the early stage of this 3D mapping work, were spent building the data infrastructure, and integrating numerous disparate datasets, required for the cross-section method of building the NATMAP southeastern Manitoba model. This is the same methodology we used to create the Lake Winnipeg model and a modified version of which we are using to build the southwestern Manitoba model.

Cross-sections

Cross-sections (Figure 2) are plotted on 42 by 54-inch paper. They represent an east-west transect drawn every 5 km and include all available data within 2.5 km from the line of cross-section. For reference, the cross-sections include two map windows across the top containing bedrock mapped extents and surficial geology polygons with Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) shaded relief and drillhole locations for the area of the cross-section. The cross-section itself comprises an SRTM DEM surface profile and drillhole plots from the Manitoba GWdrill water well database (107 000 drillholes) (Manitoba Water Stewardship, 2007), Manitoba oil and gas well information system database (MOGWIS) (4 400 drillholes), Manitoba Stratigraphic database (4 800 drillholes), TGI Williston Basin formation tops database (9 012 drillholes) (TGI II working group, 2009), Western Canada Sedimentary Basin database (750 drillholes), and 27 rotosonic drillholes which were drilled under the auspices of the Canadian NATMAP program of the early 1990's. The drillholes are colour coded based on lithology for sediments and formation for rock. The cross-sections are drawn (correlated) by hand and the stratigraphy is captured every 5 km. The resultant 5 km grid of predicted stratigraphic points are then input to the Gocad software and built into a 3D model. The glacial stratigraphy is then correlated to the prominent published stratigraphic model in the region (Teller and Fenton (1980) for southeast Manitoba and Klassen (1979) in southwest Manitoba).

ArcMap project file

For reference during the interpretation stage of the cross-sections, an ArcMap project was compiled containing additional map data representing various aspects of a paleogeographic reconstruction for the area based on previous work. For example, the understanding of both glacial retreat and glacial Lake Agassiz factor strongly into the interpretation of the cross-sections and these and other concepts need to be readily available for reference. The map base for the ArcMap project is the surficial geology from Matile and Keller (2007) with shaded-relief from the USGS

(2003). Layers that can be draped on the surficial geology include: glacial ice margins modified from Thorleifson (1996), Elson (1956) and Christiansen (1979), Lake Agassiz shorelines, levels and isobases modified from Thorleifson (1996), pre-glacial drainage from Elson (1956), and the locations of various obscure subsurface data, such as river sections from Klassen (1979) and bedrock outcrops.

<u>Correlation to adjacent regions</u>

Previously interpreted cross-sections from eastern Manitoba are used to correlate to previous 3D mapping and to verify that the interpretation is still valid when taking into account the additional western data. We are also fortunate to have available interpreted cross-sections, depth to bedrock and bedrock geology maps from the Saskatchewan Research Council, Sask Water, Geology and Groundwater Resources of southern Saskatchewan (http://www.swa.ca/WaterManagement/Groundwater.asp?type=Mapping), which we use to correlate our 3D mapping to the Saskatchewan sub-surface geology.

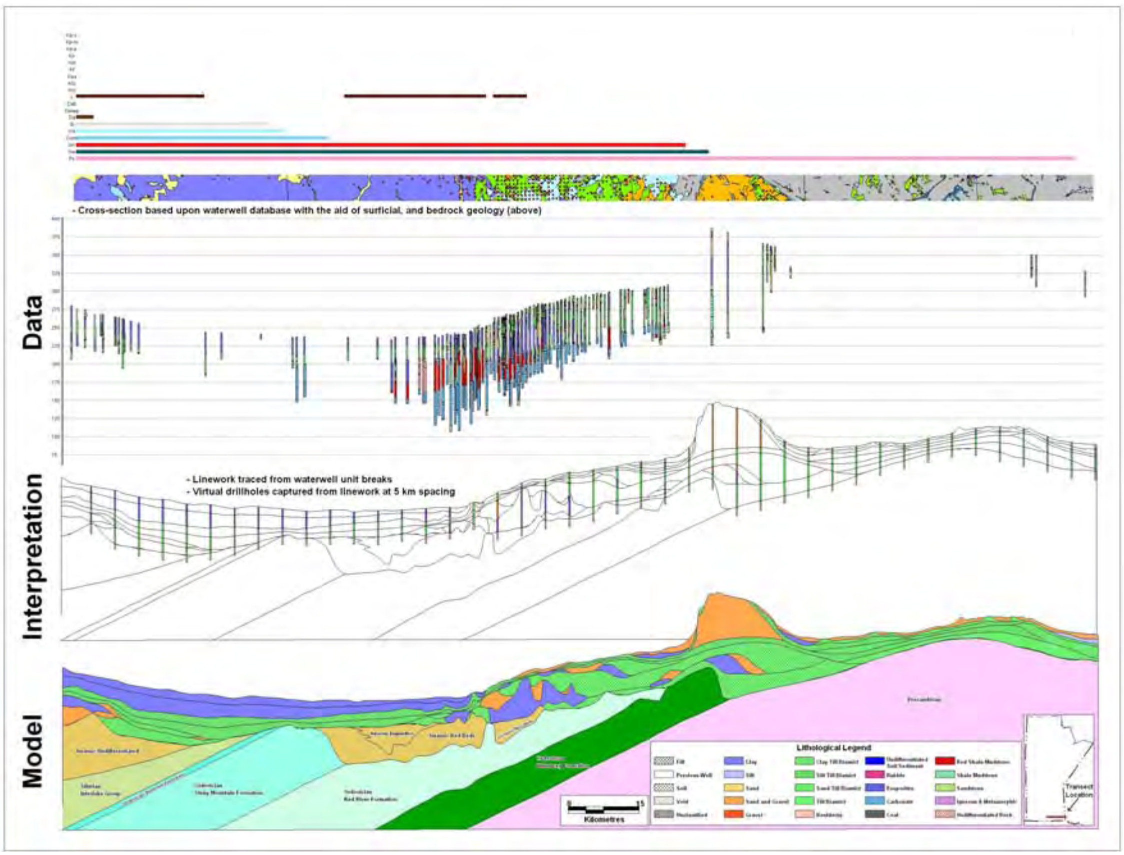


Figure 2. Cross-section methodology of 3D modeling depicting a typical 5 km east-west transect from southeast Manitoba. Depicted at the top are bedrock extent and surficial geology. Below are various iterations of the cross-section and the hand-drawn geological interpretation.

MODEL CONSTRUCTION

To date, three different approaches to 3D mapping have been used based on the nature of the project and the availability of data. The southeast Manitoba model was our first foray into 3D mapping. We used manually interpreted cross-sections to filter datasets with variable data quality. The Lake Winnipeg area used the same approach; however, we had the added luxury of having available to us high quality seismic data from the bottom of Lake Winnipeg. A second approach was used for the TGI Williston Basin project. Again, with the TGI project, we had high quality data and therefore were able to use the data directly for 3D modeling. The issue with the TGI project was limited drillhole data in the fringe areas leading to potential edge issues and occasional flattened escarpments. A third approach was used in the creation of the WCSB model, which was converting a published 2D version of a 3D geological model into a fully 3D digital model. This was achieved by scanning and georectifying unit structure contours and edges and transforming them into 3D point sets. The three approaches are described below.

Southeast Manitoba model

The SE Manitoba 3D Geological model (Figure 3) is based on a 5 km grid of predicted stratigraphy points which were brought into Gocad for modeling. The individual units were modeled from the bottom up, starting with the Precambrian surface. In this methodology, each predicted stratigraphic point contains a measurement for every possible unit in the model. Where a unit does not exist, it is given a zero thickness value. Therefore, there is a 5 km grid of tops for each mapped unit which was used to create a surface for that unit. Unit edges were controlled by pressing the surface being modeled (upper) below the underlying unit where the upper unit does not exist (has a zero thickness value) and then clipping that upper surface with the underlying surface. This methodology gives the geologist considerable control over the unit morphology and the nature of the edge. A surface and a Sgrid (Gocad stratigraphic grid) were created for each of the units in the model.

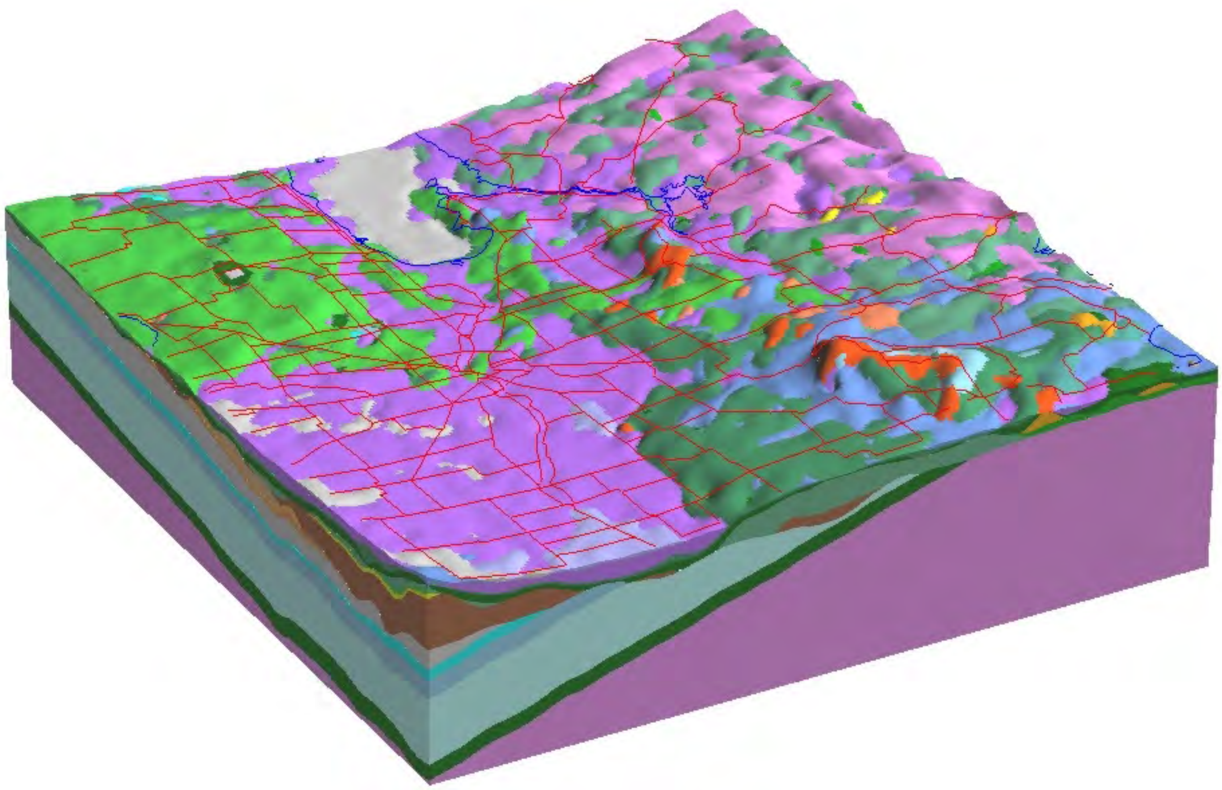


Figure 3. 3D geological model of the Winnipeg region.

TGI model

Whereas the drillhole data of highly variable quality in southeastern Manitoba was screened through the geological interpretation of 5 km transects, drillhole data in the TGI Williston Basin project has been screened at a very high level of consistency by re-picking five to eight deep, stratigraphically significant drillholes per township (10 km by 10 km). This dataset of re-picked formation tops and a new set of formation edges form the basis of the TGI Williston Basin model (Figure 4). The 3D surfaces were constructed using these picked tops from a total of 9012 wells, which includes 5046 wells from Saskatchewan, 2606 wells from Manitoba, 771 wells from North Dakota, and 589 wells from Montana. The North Dakota and Montana wells were included to reduce edge effects and to more easily correlate to the American portion of the Red River Valley 3D model in the future. Although tops for 60 formations were picked in the TGI Williston Basin project, only 42 were selected for modeling. Again, this model is based entirely on the unit tops dataset, and formation edges were defined by forcing the surfaces to conform to the predefined TGI unit edges. Many fringe areas have a low data density, especially those areas close to unit edges. Because of this shortcoming, the expression of the unit edge, especially along escarpments, is not always accurately predicted. No solid model was created.

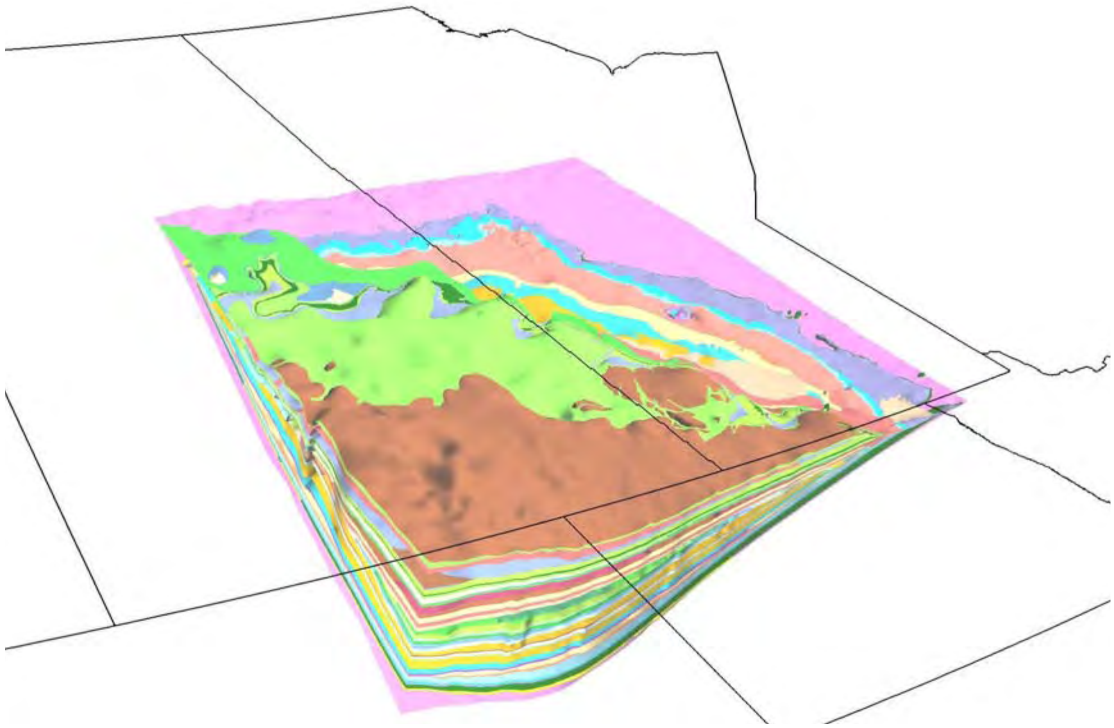


Figure 4. 3D geological model of the TGI Williston Basin region.

WCSB model

The WCSB 3D model (Figure 5) is based entirely on the published structure contours contained in the WCSB Atlas (Mossop and Shetsen, 1994). Structure contours for each geological time period were scanned, digitized, and georectified. The structure contours were then broken into points and given xyz coordinates. The same was done with the published edges for each time period. However, the edges were pressed onto the next older unit to obtain an elevation. This point set, derived from the contours and the unit edges, was then brought into Gocad and a unit surface was created. The surface was then trimmed at the published edge. No solid model was created.

ISSUES

While having a 5 km width of drillholes merged onto a single cross-section does, in data-rich areas, make cross-section interpretation difficult, in data-poor areas, it increases the probability of having some data to aid interpretation. In data-poor areas there is also a tendency to have cross-section parallel ridges due to slight variations in the interpreted unit tops; an issue which is eliminated when using strictly picked drillhole tops. However, w believe that having all available data visible on the cross-section ties together all of the different aspects of the geology, even in data-poor areas and especially in areas of high local relief at ground or rock surface. Drawing unit edges in plan view and then transposing them into 3D (as was done in the TGI model) vertically distorts the edges leading to flattened bedrock escarpments. In the southwest Manitoba model we have the benefit of the high quality TGI dataset, and using the cross-section method allows us to supplement the TGI dataset with predicted stratigraphic points based on extrapolated rock trends onto the interpreted bedrock surface which may or may not correspond to the ground (SRTM) surface. This allows us to tweak the TGI rock surfaces and integrate them with the glacial sediments.

A network of pre-glacial/Tertiary buried valley aquifers has been cut into the bedrock surface in southern Manitoba, but has yet to be systematically mapped in detail. These channels are an important water source in some areas. We have recognized these channels on some of the cross-sections, but not consistently enough to map them with confidence. We assume that they are recognizable only when the channel is orthogonal to the cross-section.

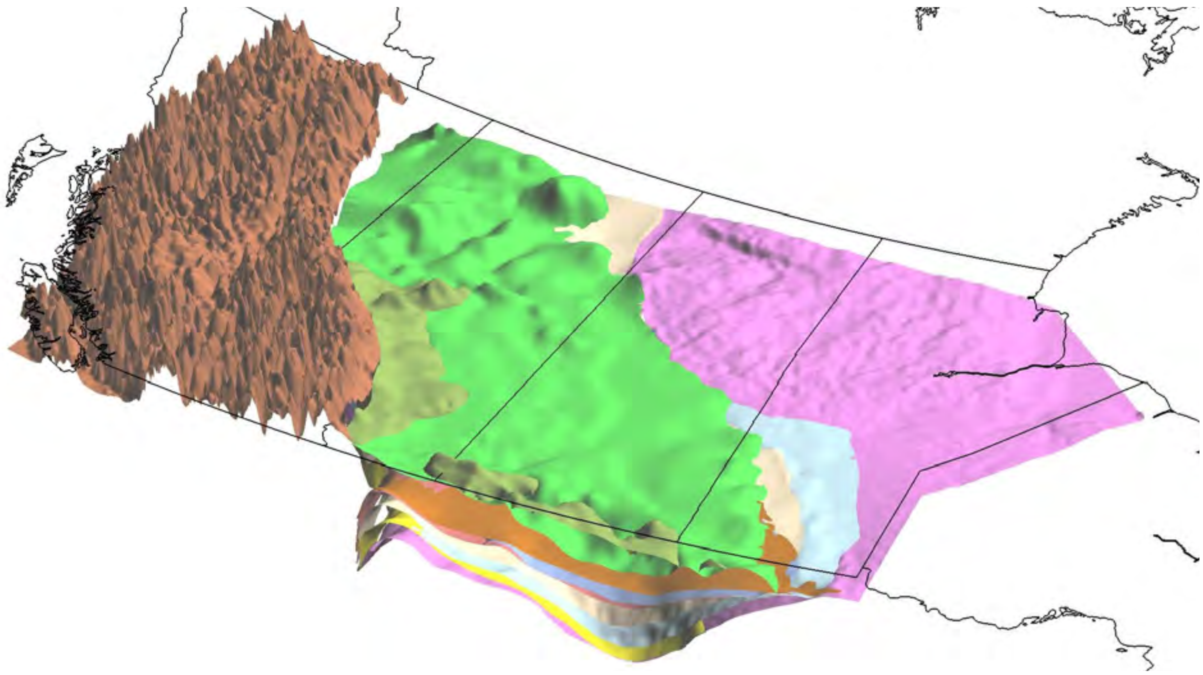


Figure 5. 3D geological model of the WCSB spanning across Manitoba, Saskatchewan, and Alberta.

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BUILDING ON GEOLOGICAL MODELS — THE VISION OF AN ENVIRONMENTAL MODELLING PLATFORM

Holger Kessler[1], Diarmad Campbell[2], Jon Ford[1], Jeremy Giles[1], Andrew Hughes[1], Ian Jackson[1], Denis Peach[1], Simon Price[1], Hans-Georg Sobisch[3], Ricky Terrington[1], and Ben Wood[1]

[1]British Geological Survey, Kingsley Dunham Centre, Nottingham, NG12 5GG, United Kingdom; [2]British Geological Survey, Murchison House, West Mains Road, Edinburgh, EH9 3LA, United Kingdom; [3]INSIGHT GmbH, Hochstadenstr. 1-3, 50674, Köln, Germany, hke@bgs.ac.uk

INTRODUCTION AND BACKGROUND

Geological Survey Organisations (GSOs) were originally founded to produce an inventory of the earth's resources to inform governments and support construction and primary industries. Therefore, their initial emphasis was on finding construction material, metalliferous minerals, and hydrocarbons. Throughout the 20th Century, the focus shifted towards aggregates, water, and more recently to environmental concerns such as waste, reuse of post-industrial contaminated land, climate change, and biodiversity.

Although the external drivers for their existence have changed, the fundamental purpose has not, and this is unlikely to change in the future. Price (1992) summarises the mission of a GSO to "maintain the national geoscience knowledgebase" in order to "ensure the availability of the geoscience information and expertise to promote the wise use of the nation's natural resources and the safety, health and well being of its people" However as many countries move towards knowledge and service driven economies faced with global environmental challenges ,GSOs of the 21st Century will have to continue to evolve, adapt, and in particular change the ways they operate. This is especially true against a background of rapidly advancing geospatial technology.

The GSO's agenda must be to confirm themselves as the natural custodians of the subsurface, not focused on one particular industry or science area, but assisting governments, industry, and the general public to manage the subsurface in an integrated, holistic, and sustainable manner. They must then engage with other organisations to link the understanding of the subsurface with the wider environment, to understand the interaction of the subsurface with the atmosphere, biosphere, and hydrosphere (Figure 1). Last but not least, they have a duty to make their knowledge and information accessible and understandable to the people on behalf of whom the governments act and to whom they are accountable.

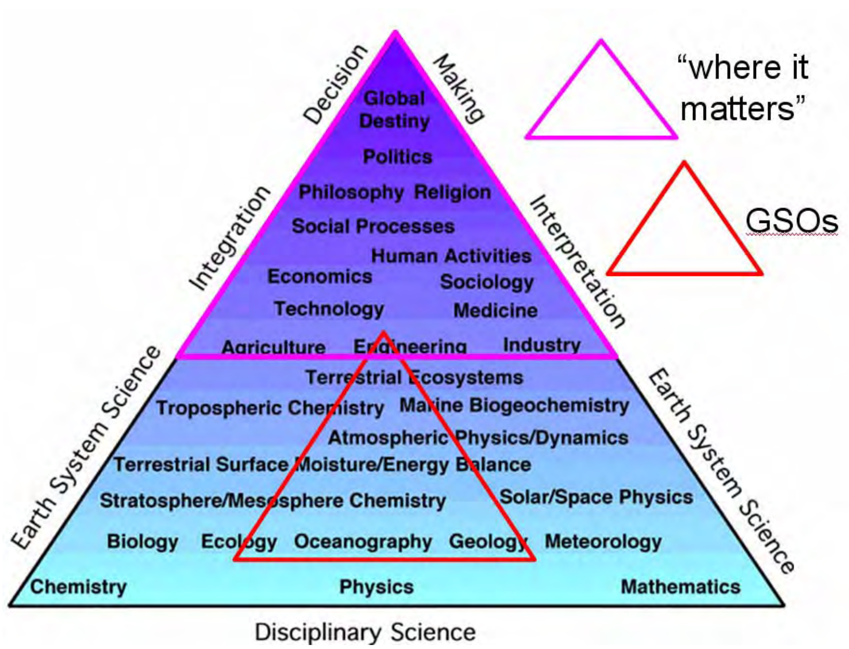

Figure 1. The footprint of GSOs in Whole Earth System Science, modified from Ruzek (2009).

Taking the British Geological Survey (BGS) as an example, this paper will outline the next stage in the evolution of a GSO, which will see the opening up of their information and the transdisciplinary integration of their geological, groundwater and other geoscience models within the wider “modelling” community including the social and economic disciplines. A main part of this mission is the development and deployment of an open Environmental Modelling Platform (EMP) providing ready access to data and knowledge as well as geospatial, conceptual, and numerical models through a subsurface management system akin to Geographic Information Systems in use today.

The urgency of this task, as well as the size of the cultural and technical challenges that need to be accomplished, demand the close co-operation of GSOs amongst themselves as well as strong collaboration with partners in science, industry, and government.

THE ENVIRONMENTAL CHALLENGES AHEAD

Reports by Stern (2006) and the IPCC (2007) have identified the need for urgent action to tackle the causes of climatic and environmental change. Importantly, they emphasize the need to plan for the mitigation of their impacts, and the importance of preparing society to adapt to the consequences of these changes.

Although predictive modelling of atmospheric and marine systems is key to test the understanding of the causes of climate change, the most direct impacts of any change (whether human or natural in cause) will be felt onshore. Earth sciences will play a major role in adapting to these impacts and responding to challenges including:

- The ability to provide clean and affordable drinking water and water for industrial use from ground or surface water
- Managing the risks of flooding from the sea, rivers, rainfall run-off, and groundwater
- The safe disposal, containment, and potential re-use of anthropogenic waste products
- Prediction of ground conditions for major infrastructure projects (e.g., transport, housing, utilities)
- The mitigation of physical hazard such as landslides, subsidence, earthquakes, and tsunamis
- The conservation of land to maintain food production as well as protecting biodiversity
- The sustainable management of ground sourced heating and cooling

These challenges can only be met if solutions are based on sound scientific evidence. Although we have knowledge and understanding of many individual processes in the natural sciences, it is clear that a single science discipline working in isolation is not able to answer these questions or understand their inter-relationships. For example, models of the carbon cycle largely ignore the presence of deep terrestrial carbon and hydrological models rarely deal with groundwater in an adequate way.

THE BGS STRATEGY

In its current 5-year strategy (British Geological Survey, 2009), the BGS recognises the need to share its data, models, and knowledge with the wider science community in order to contribute adequately to resolving the questions set out above. Furthermore, the strategy document states that ‘BGS will develop a more holistic focus on modelling and the prediction of environmental change and its impacts’; effectively moving the survey’s primary activities from mapping and archiving increasingly towards modelling and forecasting to support decision making (Figure 2).

The scientific and organisational challenges to deliver this mission are detailed as follows:

1. Acquire, interpret ,and enhance the UK geoscience knowledge base and make it accessible and interoperable
2. Improve the communication of geoscience knowledge so that it can better support policy and decision-making by government and society
3. Enhance external partnerships to improve the quality, reach, and impact of our science
4. Apply a whole-systems approach to our science and improve understanding of the nature and sustainable use of natural resources and the potential impact of hazards
5. Understand, quantify, and predict the response of the Earth’s ‘zone of human interaction’ to future environmental change
6. Increase the economic impact and relevance of our work

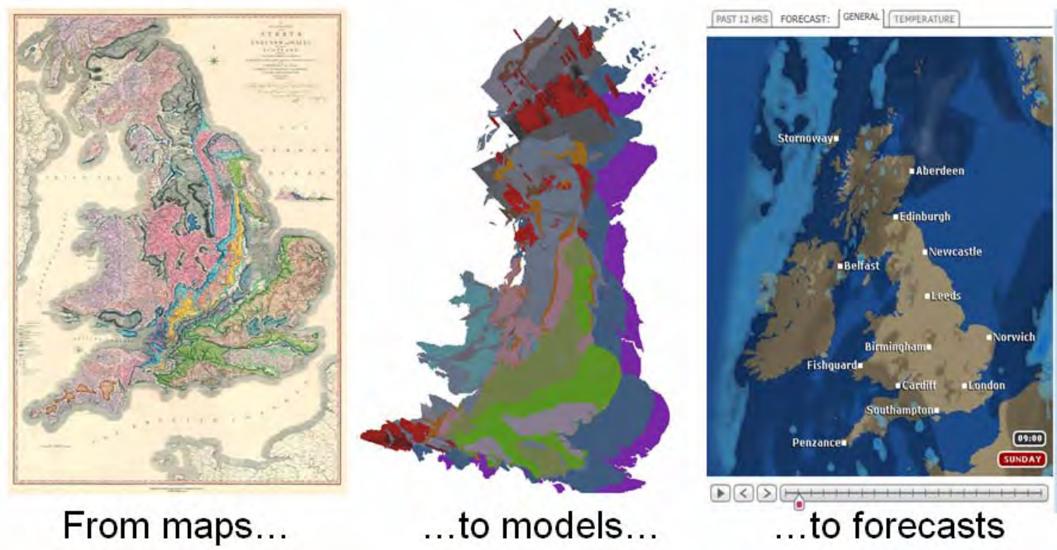

Figure 2. The evolution of a Geological Survey Organisation, including a screenshot of the BBC's weather forecast, © BBC (2009).

A corner stone in delivering the BGS strategy is the development of an open Environmental Modelling Platform (EMP) to provide a data architecture and applications environment that supports the generation and coupling of spatial and process models.

The BGS has established a portfolio of test bed projects including the Thames Basin and Glasgow and Clyde Basin cross-cutting projects to support the development of the EMP. Each of these projects will provide the EMP with real-world data and models together with the key environmental questions affecting each region (see Campbell, 2007; Ford 2008). The aim of the EMP is to facilitate the transdisciplinary integration of this information with socio-economic and wider environmental models to generate predictive responses to these questions. The test bed projects will establish proof of concept for the EMP, and lead to the development of generic and extensible methodologies and systems to deploy the EMP throughout the BGS and make it operational across its territory.

THE ENVIRONMENTAL MODELLING PLATFORM

GSOs increasingly employ advances in Information Technology to better visualise and understand natural systems. Instead of 2-dimensional paper maps and reports, many GSOs now produce 3-dimensional geological framework models and groundwater flow models as their standard output (Figure 3). Additionally, standard routines are emerging to link geological data to groundwater models (Kessler 2007, Hughes 2008)), but still these models are only aimed at solving one specific part of the earth's system, e.g. the flow of groundwater to an abstraction borehole or the availability of water for irrigation. Although the outputs are often impressive in terms of accuracy and visualisation, they are inherently limited in the extent to which they can be used to simulate the response to feedbacks from other models of the earth system, in particular the impact of human actions.

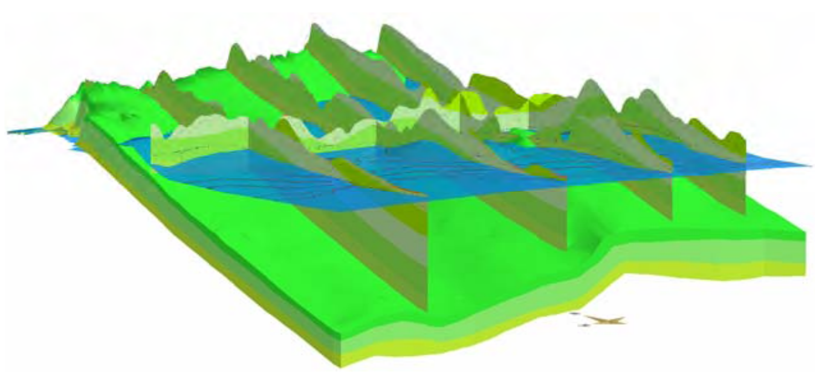

Figure 3. Integrated geological and groundwater models in an area around Brighton, UK (from Hadlow et al 2008).

At the heart of the EMP stands the vision to provide the data standards and applications seamlessly to link data models concepts and numerical simulations concerned with the surface and subsurface (Figure 4). Furthermore, these geoscience models also need to link to socio-economic models such as population growth, urban growth scenarios, or commodity prices.

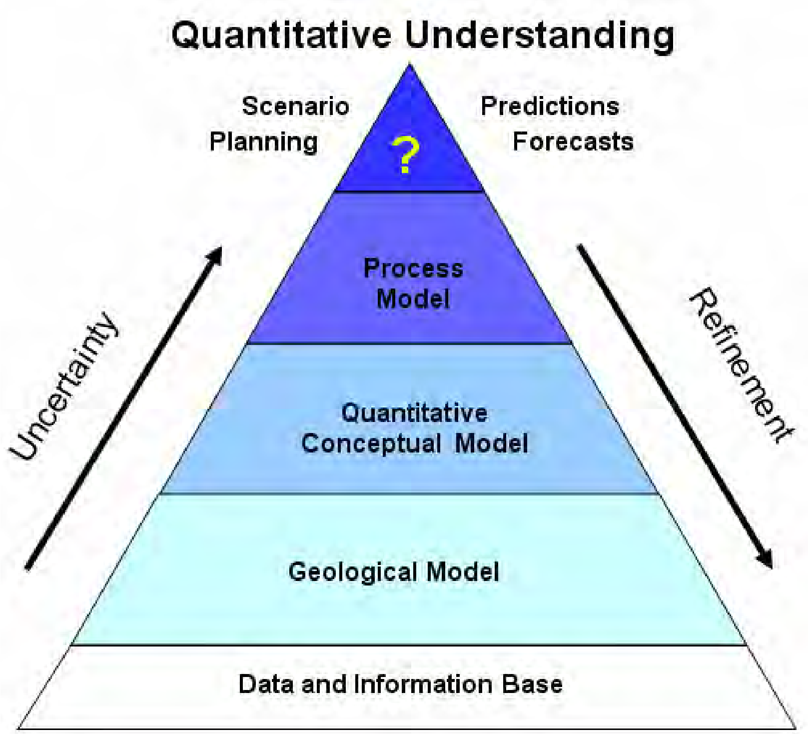

Figure 4. Schematic diagram showing the interrelationships between models and data (modified from Sharp et al 2002).

Problems with linking models arise where data from models from one discipline are incompatible with the other, either in terms of the data format or the scientific concepts and language. The Geological and Hydroscience communities have begun to develop common languages and software standards to overcome these barriers. Two examples of initiatives that are beginning to change the way we interact between science disciplines are OpenMI (Open Model Integration Environment) and GeoSciML (Geoscience Mark-up Language). OpenMI provides a standard interface, which allows models to exchange data with each other and databases on a time step by time step basis as they run. It thus facilitates the modelling of process interactions. The models may come from different developers, represent processes from different domains, be based on different concepts, and have different spatial and temporal resolutions (OpenMI 2009). GeosciML aims to agree a common conceptual data model on the nature and structure of the geoscience information, to which data held in individual databases can be mapped and consequently transferred between applications and users (GeoSciML 2009).

An additional hurdle that needs to be overcome is that the fragmentation of institutions responsible for the monitoring and protection of the environment, and in particular the subsurface, combined with impediments due to copyright restrictions and ownership of data, have together made the strategic and integrated management of the subsurface a virtual impossibility.

THE NEED FOR A SUBSURFACE MANAGEMENT SYSTEM

As discussed, the subsurface is used intensively for a variety of purposes. Historically, human interaction with the subsurface has been limited to the exploitation of resources on which construction and industry depend, such as metals, industrial minerals, building materials, and groundwater. Traditional thematic geological maps and GIS systems suited the need of these individual themes. However, economic development driven by population growth has placed greater demands on the subsurface, including the need to accommodate utilities and telecommunications infrastructure: vital elements of the emerging information economies. Competition for available space will continue to increase in response to the demand for geothermal energy, the need for storage of waste (including CO2), and ongoing construction of road, rail, and sewerage infrastructure. The subsurface is an integral part of the economic system, and its increasingly complex use suggests that a more coordinated approach to its regulation and management is essential, and should be coupled with that of the surface. To provide a basis for the sustainable management of the subsurface, a 3D and 4D understanding of the ground, its existing subsurface installations, land use history, and suitability for future use is critical

Current practice in the management of the subsurface is far from this ideal. Most subsurface interventions are preceded by feasibility studies, predictive modelling or investigations intended to mitigate risks or predict the impacts of the work. However, the complex interactions between the anthropogenic structures and natural processes mean that a holistic impact assessment is often not achievable. A fundamental pre-condition for integrated spatial, volumetric, and temporal planning in the subsurface is knowledge of the distribution of existing infrastructure in the context of the geological succession and its properties. Increasingly, this information is expressed in three-dimensional geological framework models which allow the full complexity of the subsurface to be analysed and predictions made concerning the movement of liquids, gases, and heat and their interaction with buried infrastructure and any planned intervention in the subsurface.

Key to the delivery of the results from the EMP to planners, regulators, and other decision makers is to make the results visible in the context of the real world. There is an identifiable need for a comprehensive 4-dimensional subsurface management system forming the basis for spatial, volumetric, and temporal decision making in the subsurface in the same way as today's GIS systems are used for spatial planning, insurance risk assessment, or emergency planning. It is vital that this system is not developed in isolation from real end-users and also that the system is able to deal with the wide variety of subsurface models that exist in the GSOs across the world. Systems that fulfil parts of this strategy are emerging at several GSOs and examples from the Geological Survey of the Netherlands and the British Geological Survey are shown in Figures 5 and 6. The former shows the dissemination of subsurface data and models via the TNO DinoLOKET Website, while the second shows the integrated visualisation of tunnels and buildings with the geological model.

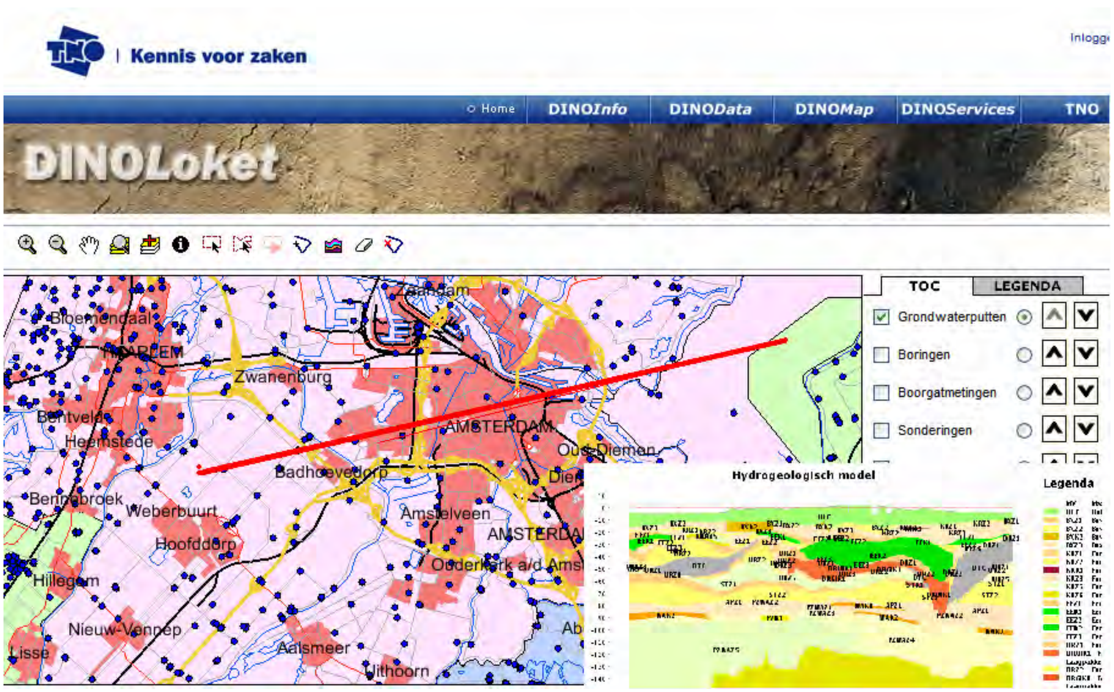

Figure 5. A hydrogeological section through Amsterdam, Netherlands, using the TNO's DINOLoket Web service, TNO (2009).

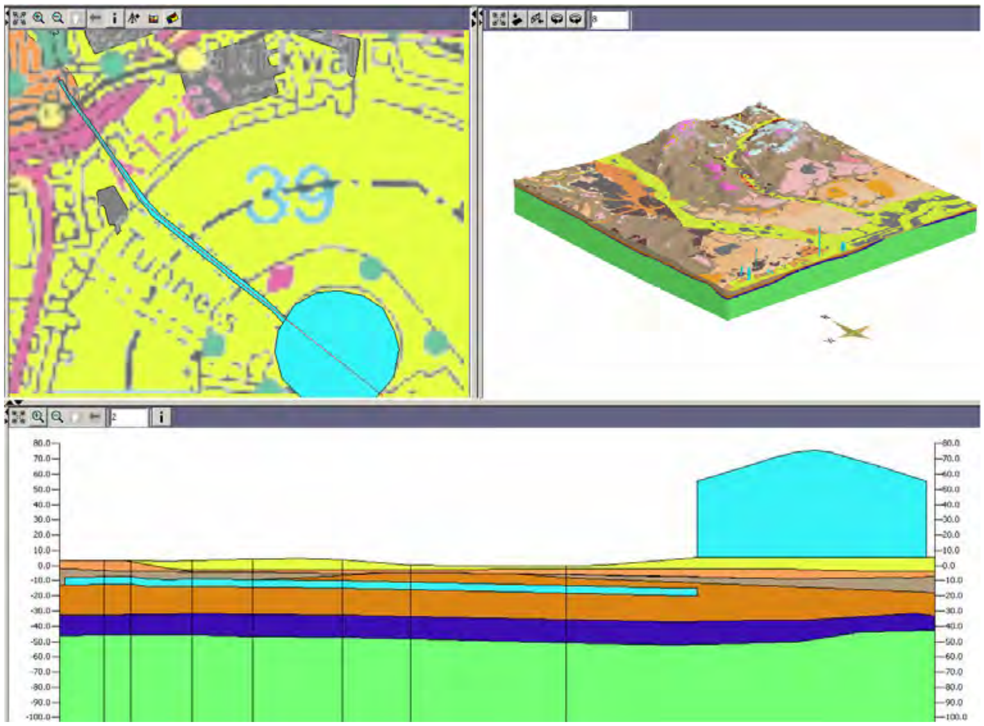

Figure 6. A map and cross-sectional view of the Blackwall Tunnel and Millenium Dome, London displayed in the Subsurface Viewer (Terrington et al, 2009).

CONCLUSIONS

Attributed geological and groundwater models are means to an end, not an end in themselves. They are more parts of a jigsaw of data and models needed by decision makers to respond to the pressing human and environmental questions in today's changing world. Geological Survey Organisations, as the custodians of strategic Earth Science knowledge and information, have to rise to the challenge and leave their traditional comfort zone to interact with the wider science and user community to link up their data and knowledge with others and provide the outcomes in a form that can be used readily by decision makers.

Most importantly, the need for international cooperation between GSOs is crucial whether it is through workshops, joint projects or collaborations using the Internet. As Jackson (2009 this edition) indicates, the geology may be different in each corner of the world, but the global challenges we face as well as the core functions of GSOs are the same in Bangladesh as in The Netherlands. Only if we engage with each other and align our knowledge and resources can we create the momentum needed to build the Environmental Modelling Platform.

As Price (1992) concludes in his paper on the future role of GSOs: "The potential role for national geological surveys is very large, the actual future role will depend … on the leadership displayed by national geological surveys both individually and collectively".

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DO GEOLOGIC MAPPING PROGRAMS IN THE U.S. AS PRESENTLY CONSTITUTED MEET PRESSING SOCIETAL NEEDS?

E. Donald McKay III

Illinois State Geological Survey, Institute of Natural Resource Sustainability, University of Illinois, 615 E. Peabody Dr., Champaign, IL 61820, mckay@isgs.illinois.edu

Is geological mapping in the U.S. being done in the places and using approaches that produce appropriate, timely, geologic information to meet the Nation's most pressing needs? If not, we must refine our methods and accelerate our timetable to make the needed products more relevant and available.

Ongoing federally funded geologic mapping in the United States is producing maps of good quality. Mapping advisory committees at the state level help direct projects into areas where need is significant. Mapping programs are chronically underfunded. Where more conventional geologic mapping is needed, more money would help address map production shortfalls immediately. But, funding is only part of the problem. There are places where conventional maps and conventional approaches to geologic mapping fall short of meeting societal needs. There, the content of a conventional geologic map is simply insufficient to capture the salient geologic features needed to support decisions regarding pressing societal issues. In those locations and situations, mapping methods need to be refined, approaches adjusted, and products tailored to meet the needs of society.

Typically, geologic maps portray surficial geology and represent the best available understanding of the distribution of bedrock units and/or unconsolidated deposits at the ground surface. The geologic map sheet includes a legend, cross sections, and assorted information and data that provide a good deal of important supplemental knowledge. Such maps are very useful and provide sufficient information to address many issues, but they have limitations with respect to informing the user about the subsurface. Surficial geologic maps of flat terrain with few surface outcrop or exposures, e.g. Illinois, are minimally informative about the subsurface, because important subsurface units and structure cannot be inferred or extrapolated from map patterns or observations recorded on the map. Surficial geologic maps of glaciated terrain, for example, typically reveal little about the subsurface, because almost no feature on the glaciated land surface is useful for projecting thickness, continuity, or character of glacial and associated sediments into the subsurface. Strike and dip are useless; depositional units can be highly variable; structural complexity is great; erosion surfaces and other unconformities are common; and facies changes abrupt and unpredictable.

Needs for geologic maps with significant content about the subsurface are particularly acute in or near large cities, where that knowledge is required because (a) growth is fast and concentrated, (b) natural resource demands are large, (c) economic development is rapid, (d) human health and safety issues potentially impact large numbers of people, (e) environmental problems are long-standing and widespread, and (f) consequences of decisions made in ignorance are serious. In these urban and suburban settings, an approach to mapping that provides appropriate subsurface information is needed urgently.

The need for subsurface geologic mapping in the ubiquitous glacial terrain of the Great Lakes states of the upper Midwest is particularly acute and the task of mapping particularly challenging. The Great Lakes region is home to (a) 20% of the U.S. population, more than 80 million people, (b) the rust-belt of industrial centers (present and historic), (c) the corn-belt agricultural breadbasket with its intensively modified land, displaced and damaged ecosystems, large groundwater demand, and nutrient-pesticide load, (d) dependence on groundwater for drinking water supplies, (e) major potential for biofuel production and its associated water consumption, (f) two of the world's megacities (New York and Chicago), and (g) 16 cities of more than a million people (Figure 1). Yet much of the Great Lakes region is not mapped geologically in any fashion at 1:24,000.

Given that virtually the entire eight-state Great Lakes region is underlain by glacial deposits up to 400-m thick, representing multiple episodes of glaciation and interglacial weathering, traditional surficial geologic mapping has severe limitations for collecting and conveying the geologic content needed to address pressing issues of the region, many of which involve aspects of ground- and surface-water resources and protection. The general undermapping of the Great Lakes states is largely due to lack of investment in mapping but also partly a consequence of the ubiquitous glacial cover that makes mapping difficult.

As a consequence of the unique geology of the Great Lakes states, geologists in the region have been pioneers in development of understanding of glacial sedimentation and stratigraphy, paleosols, and Quaternary history, as well as leaders in development of approaches to geologic mapping that capture salient knowledge of the subsurface. Whether called stack-unit, slice-unit, 2½-D, or 3-D mapping, these Midwestern approaches to mapping, refined over the last few decades, have been aimed at portraying the principal characteristics of the shallow subsurface glacial and related geology. Glacial mappers and geophysicists in the region have developed and refined tools and techniques, tested approaches, and learned what it takes and what it costs to map this terrain. They have studied methods that are applied by groups elsewhere, such as in the United Kingdom and The Netherlands, where similar issues have driven development of subsurface mapping along similar paths.

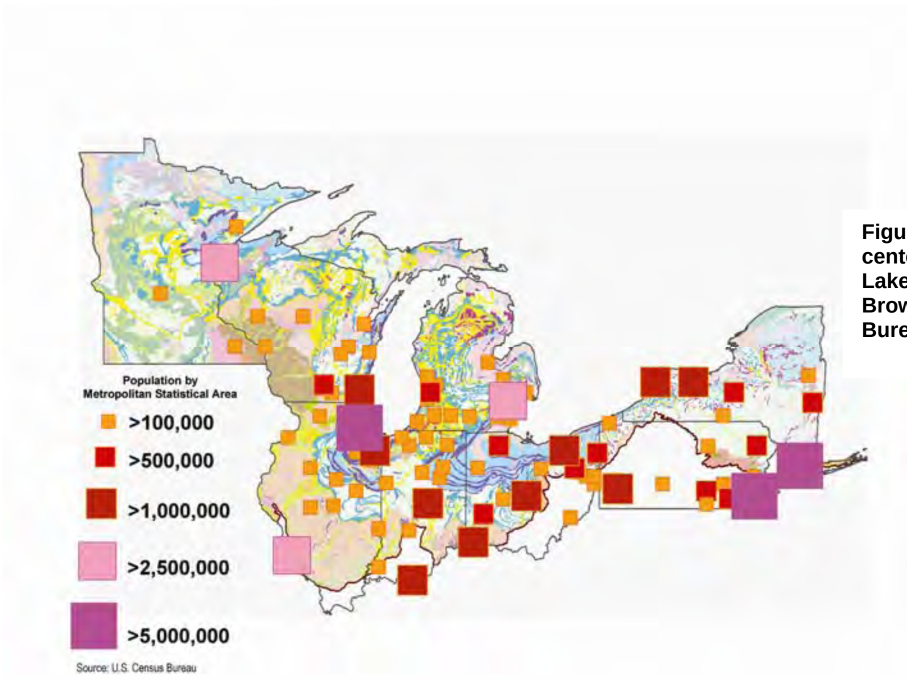

Figure 1. Principal population centers in the glaciated Great Lakes states. Sources: Steve Brown, ISGS, and U.S. Census Bureau.

THE NATIONAL COOPERATIVE GEOLOGIC MAPPING PROGRAM

After having been stagnant for decades, geologic mapping in the United States was reanimated with passage and funding of the National Geologic Mapping Act (NGMA) in 1992. The NGMA created the National Cooperative Geologic Mapping Program (NCGMP) and its components, STATEMAP, FEDMAP, and EDMAP. Under the STATEMAP component, federal funds are matched by state funds and mapping is conducted by state geological surveys in areas determined to be highest priority by state geologic mapping advisory committees. This focus on state-level establishment of priorities ensures that mapping of societal relevance is undertaken and that compatibility with the NCGMP mission "to provide reliable geologic maps and subsurface frameworks (my emphasis) that contribute to sustaining and improving the quality of life and economic vitality of the Nation and mitigating hazardous events and conditions" is maintained.

From somewhat over $1 million in 1993, its first year of funding, the STATEMAP component rose to $3.5 to $4 million between 1996 and 2000 and to $6 to $6.6 million over the past 9 years (Figure 2). In fiscal 2009, STATEMAP funds were distributed among 47 state geological surveys whose federal awards averaged about $145,000. Between 2003 and 2008, 450 to 975 map sheets at a scale of 1:24,000 were funded each year. At the present rate it will take the geological surveys of the nation more than a century to create the first nationwide surficial geologic map coverage at 1:24,000 scale. Given that timeframe and the urgency with which maps are needed everywhere, the NCGMP is underfunded to do basic surficial geologic mapping. It is grossly underfunded to address subsurface mapping where such mapping is needed urgently.

THE GREAT LAKES GEOLOGIC MAPPING COALITION

Cognizant of the challenges of mapping glacial geology and of the needs of Midwestern cities and citizens for subsurface geologic information to support decisions being made daily that affect health, well-being, economy, and environment, and recognizing the inadequacy of NCGMP funding, the geological surveys of Illinois, Indiana, Michigan, and Ohio partnered with the USGS in 1996 to form the Central Great Lakes Geologic Mapping Coalition (CGLGMC) just 3 years after the NCGMP was created. From the outset, the Coalition's goals have been to (a) assess the status of geologic mapping in the region, (b) survey the societal justifications and technical requirements for mapping, and (c) develop means to accelerate mapping to address the most pressing needs.

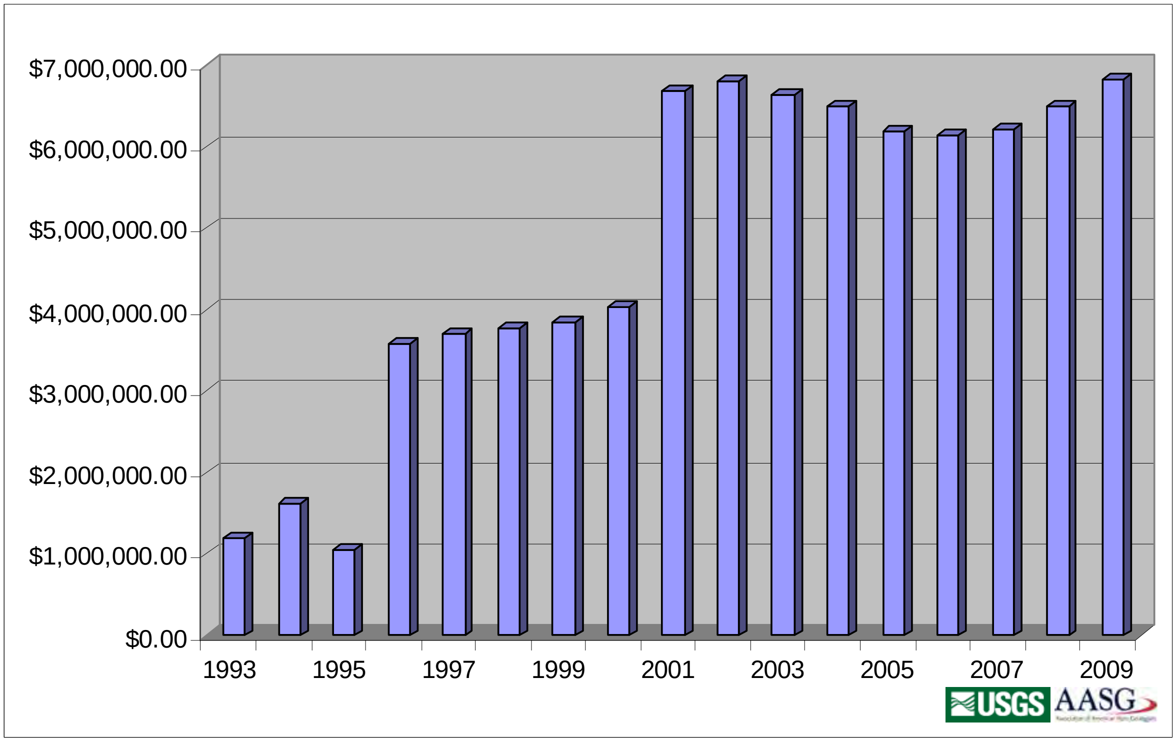

Figure 2. STATEMAP funding 1993 to 2009. Source: Randy Orndorff, USGS - NCGMP.

Beginning in 1996, the Coalition held a series of mapping forums in major cities, to which they invited users of geologic maps in order to hear those users voice their needs for geologic information. The upshot of the Indianapolis, Columbus, Chicago, and Peoria forums, which were attended by more than 1000 stakeholders representing all sectors of map users, was a list of map specifications and needs. Stakeholder advice to the Coalition was to produce (a) detailed large-scale (1:24,000) maps, (b) maps of the distribution, depth, and thickness of aquifer and non-aquifer materials for appropriate management and protection of groundwater, (c) maps of aggregate resource distribution for planning and development, (d) maps for identification of hazardous settings, such as conditions that favored liquefaction, landsliding, or subsidence, and (e) maps that could be used in management or mitigation of contaminated sites and in identification of land capable of safely hosting new waste disposal or industrial sites.

Early in its existence, the Coalition formed a technical team that developed an intersurvey agreement to (a) enhance collaboration, (b) promote sharing of technology, expertise, and data, (c) develop and refine approaches to subsurface "3-D" geologic mapping, and (d) coordinate a 3-year pilot period, wherein they would refine and demonstrate the mapping approach (Berg et al. 1999). The Coalition undertook pilot projects in the four states, organized annual conferences to share findings and techniques, and embarked on joint efforts to raise the awareness of Congress and the Administration regarding the special needs for mapping of portions of Great Lakes states. In 2009, the Coalition added four partners, Minnesota, New York, Pennsylvania, and Wisconsin, becoming the Great Lakes Geologic Mapping Coalition (GLGMC).

THE EVOLVING APPROACH: "3-D GEOLOGIC MAPPING" BECAME 3-D GEOLOGIC MODELING AND MAPPING

Although a misnomer, "3-D geologic mapping" is a phrase that initially communicated and still communicates a concept that has resonated with constituents and with potential supporters of mapping in Congress. In fact, the "3-D" approach to mapping is not a single approach but is tailored by each Survey for its terrain and clients. In Illinois, "3-D mapping" has evolved to include (a) compilation, automation, and interpretation of existing well records, (b) core drilling and shallow seismic reflection, (c) examination of pits, quarries, and exposures, (d) data synthesis and interpretation, and creation of 3-D volume models of lithostratigraphy and lithofacies. Geologic units are delineated in 3-D computer space. 2-D maps, 2-D cross-sections, fence diagrams, and cut-away block views are derived from the

3-D models (Figure 3). This approach is being further refined via acquisition of the Geovisionary 3-D modeling and visualization system. Developed in Britain, Geovisionary is used by the British Geological Survey (BGS) in their geologic mapping and, as there, promises to improve Coalition scientists' ability to view and visualize the relationships among cores, geophysical logs, seismic lines, digital surfaces, and aerial images, thereby enabling improvement of 3-D models and derivative products (Figure 4). This new software-hardware system fills a gap in available computing and analysis tools and will enable highest possible quality and data fidelity in 3-D geologic modeling, interpretations, and mapping.

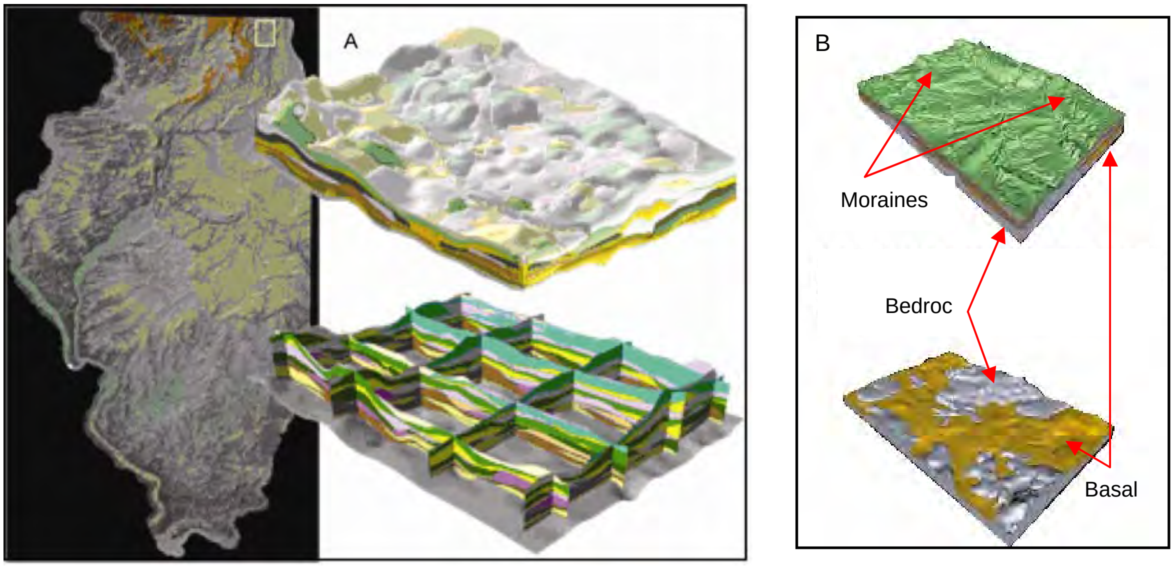

Figure 3. Examples of 3D geologic models of Quaternary deposits in Illinois, including (A) deposits up to 100m thick overlying Paleozoic bedrock in a four 7.5-quadrangle area of Lake County, northeastern Illinois and (B) deposits infilling the Mahomet-Teays Bedrock Valley, Champaign 30x60-minute Quadrangle, east-central Illinois. Sources: Jason Thomason, ISGS, and David Soller, USGS.

NEXT STEPS

After 13 years of collaboration, the geological surveys of the GLGMC have a distance to go. Available shallow geophysics systems do not resolve the detail required; a larger seismic source is needed. Neither geophysics nor drilling capabilities are well distributed among the surveys. Laboratory analytical support is partially in place. Mapping teams are understaffed. Integration of the new, promising 3-D modeling and visualization capabilities into the toolkits of the individual surveys is just beginning and is expensive. Fiscal crises in state governments have hampered progress in some states. Federal funds remain insufficient. In 1999, the 5-member Coalition estimated it would require $11.9 million per year for 14 years to map priority areas of the 4 states, an average of more than $2 million per year per survey. Annual funding in 2009 provided an average of slightly over $90,000 per geological survey participating.

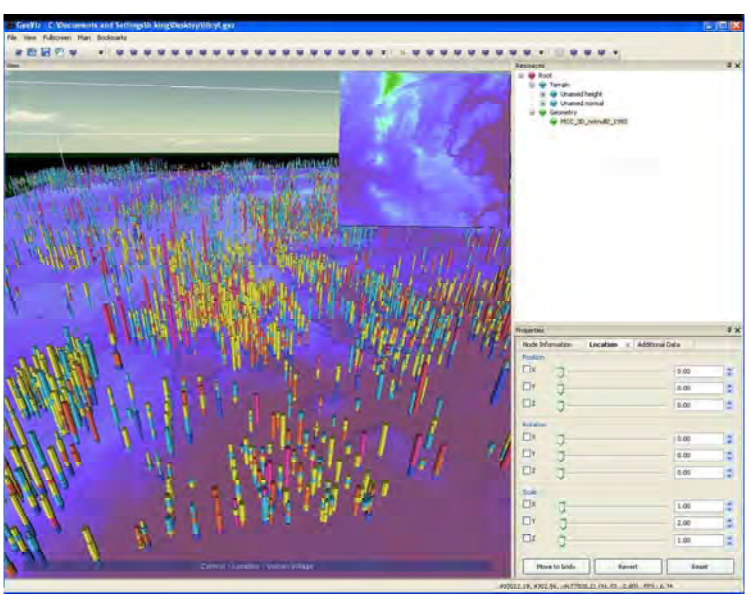

Figure 4. View constructed with GeoVisionary software from borehole records of thousands of wells in Lake County, northeastern Illinois, shows lithotype classification of the glacial

succession as color-coded cylinders. Source: Virtalis Ltd. and D.A. Keefer, ISGS.

CONCLUSION

Supporters of the GLGMC in the USGS, U.S. Department of the Interior, Office of Management and Budget, and Congress recognize the need for accelerated geologic mapping with a “3-D” option, and all have supported requests for additional resources. Stakeholders in the states make their needs known and strongly support the Coalition’s work in communications with Washington. In Washington, the Coalition continues to advocate inclusion of 3-D geologic modeling and mapping as an option for geologic mapping of selected high-need areas in work funded by the NCGMP. In our view, the “3-D” approach completes the array of mapping approaches needed to fulfill the intent of the NGMA and its mission to provide societally relevant geologic maps and subsurface frameworks tailored to the priorities and needs of local areas and stakeholders. Development of the tools to accomplish “3-D modeling and mapping” in glacial terrain has made great progress in delivering the maps and subsurface framework. It is time to ramp up funding of the NCGMP to accelerate both traditional geologic mapping nationwide and 3-D geologic modeling and mapping regionally so that both can be accomplished where they are most needed and that this can be accomplished soon.

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MAPPING LOCALLY COMPLEX GEOLOGIC UNITS IN THREE DIMENSIONS: THE MULTI-POINT GEOSTATISTICAL APPROACH

G. Phelps[1] and A. Boucher[2]

[1]U.S. Geological Survey, Menlo Park, CA 94025, [2]Dept. of Environmental Earth System Science, Stanford University, 450 Serra Mall, Stanford, CA 94305 gphelps@usgs.gov

ABSTRACT

Multi-point geostatistics offers a way to map locally complex geology in three dimensions. The resulting maps are not unique; rather, many alternative maps are created, each conforming to known geology and expected geologic unit shape. The maps can incorporate important geologic characteristics, such as a general change in unit orientation across a basin and vertical continuity between units. The alternative 3D geologic maps, when viewed together, provide estimates of the geologic variability of the region, and can lead directly to estimates of uncertainty for process models that are built upon the 3D geology, such as flow and transport models.

INTRODUCTION

Three-dimensional geologic mapping poses the challenge of having to describe the geology throughout a volume, most of which is not observable. The primary data for 3D mapping are from surface geologic maps. Geophysical data provide additional constraints. Direct observation of the mapped volume, however, is severely limited, such that even when combined, the above data cannot resolve many structural and depositional complexities at the scale of a kilometer, or more.

3D geologic maps are usually simpler than comparable 2D surface geologic maps because of the inability to directly gather data in 3D. When geologic units are occasionally mapped in detail in 3D, their form is determined by the geologist's interpretation, based on a conceptual model of the geology. Many interpretations are possible, but because of the time and difficulty involved in constructing a 3D map, only one, or at best a handful, of interpretations are mapped. This variability at the conceptual level and at the scale of small structures and depositional complexities, is understood implicitly by geologists, but is not explicitly defined or depicted in the mapping. The particular depiction of geologic complexity in a 3D geologic map can have a significant influence on the outcome of process models, causing them to significantly over- or under-predict properties of interest, such as flow and transport. Excluding geologic complexity, or excluding the variability of the geologic complexity, limits the utility of 3D geologic maps. However, if a plausible model of the local geologic complexity can be developed, and some estimate of the variability can be obtained, then these shortcomings can be mitigated.

3D geologic maps need to honor the available data, and also the conceptual model of the geology – that is, what is understood about geologic process, stratigraphic framework, and geologic unit configurations. Indicator simulation, in which variograms are used as models of spatial correlation between geologic units, honors the available data, but not the conceptual model of the geology. Indicator simulation cannot replicate the shape of geologic units faithfully; while the results yield bivariate statistics that maintain both the histogram and the variogram (the proportions of the geologic units are consistent, as is the linear spatial correlation), other relationships, such as unit sinuosity and connectivity, are not maintained. Thus the results preserve some spatial relations, but do not faithfully replicate the continuity observed in geology.

Multi-point geostatistics uses the outcrop patterns in a map of local geology, called a training image (TI), decomposes these patterns into unique pattern elements, and stores the probability of occurrence of each pattern element given other local pattern elements. Elemental shapes seen in the training image are retained and can be re-assembled in various ways with the same probability that they occurred in the training image. By using multi-point geostatistics, local geologic complexity can be assessed and multiple maps can be created, capturing not only an interpretation of the local geologic complexity, but also its variability. The multi-point geostatistical method requires a new approach to geologic mapping, away from the single interpretation and towards multiple interpretations generated by the geologist using algorithms that incorporate the geologists' data and interpretation.

MULTI-POINT GEOSTATISTICS

Multi-point geostatistics is a method for producing simulated patterns on the basis of pattern elements present in a training image. The training image, supplied by the mapper, is deconstructed by recording the identity and spatial relationship of all neighboring points in a specified window. The probabilities of each spatial relationship, in each window across the TI, are recorded and stored. A simulation begins by picking a random point within the study area (or volume) and assigning a geologic unit, chosen on the basis of the probability of finding that unit given the observed data in the surrounding neighborhood. Subsequent points are then chosen, one at a time, each conforming to the probabilities in the observed data and newly simulated data. The final map has the same proportion of geologic units and the same pattern elements as the TI (Figure 1).

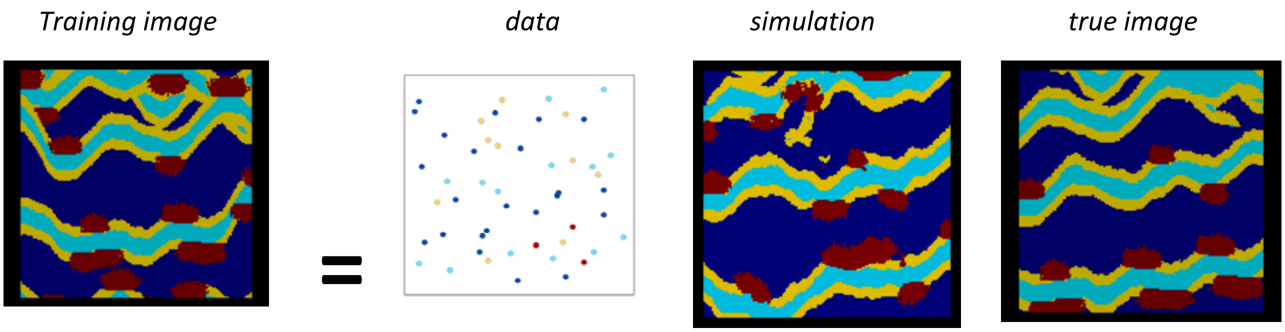

Figure 1. Training image (left) shows synthetic geology: channels (light blue), channel edges (orange), crevasse splays (red) and overbank deposits (dark blue). These pattern elements will be re-created. Data points (center left), combined with the training image (left), yield simulated geology (center right). Actual image from which data points were taken is on the far right.

BEYOND STATIONARITY

Natural geologic analogs help guide our thinking in almost all geologic investigations. They provide a working example that we modify for each new mapping problem we address. Analogs are a rich information source. However, they often represent processes that do not generate simple, repeated patterns. Rather, patterns change as the process continues across time and space. For example, an analog of a basin might show discrete zones of oriented streams flowing perpendicular to the local slope that varies around the basin. Using this as a TI would average the stream orientations across the region of simulation and destroy the local stream direction, failing to capture the essential characteristic of the analog - the local regions of preferentially oriented streams.

In order to use analogs successfully, they can be divided into stationary regions of consistently repeating patterns. Each region can be used separately as a TI, defining a unique set of elemental patterns. During simulation, the regions of elemental patterns are recombined by defining stationary zones, then filling those zones with the elemental patterns defined by a given TI (Figure 2).

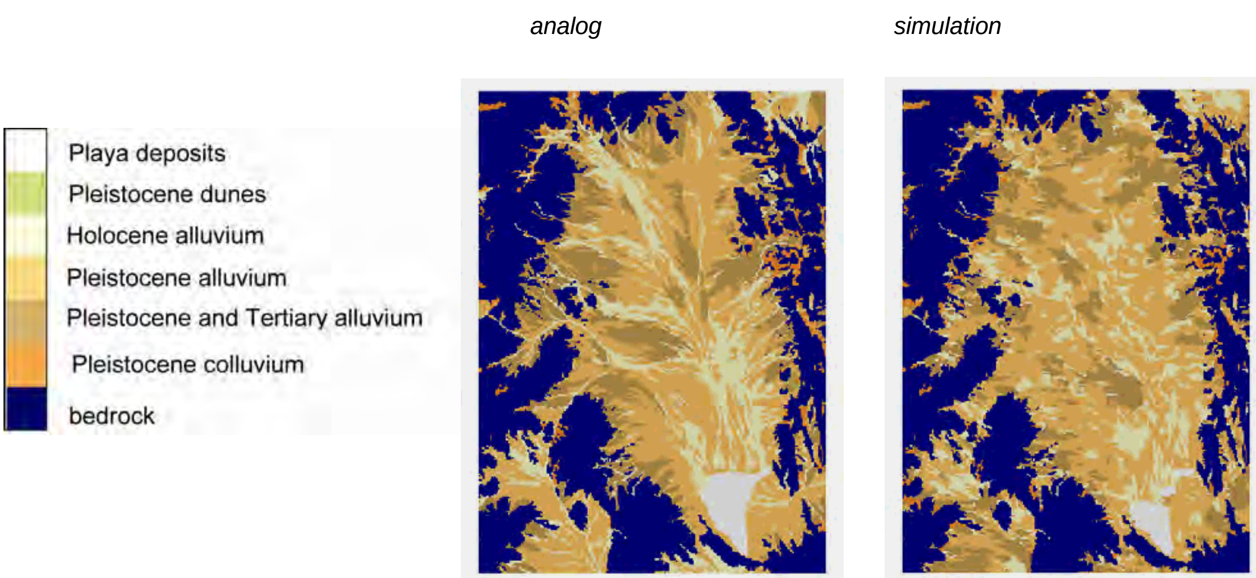

Figure 2. The surficial geologic map of a closed basin in Nevada serves as an analog for the deposits in the subsurface (left). A simulation, created using only the patterns from 5 training images derived from the analog geologic map, is constructed, without matching to any surface data. Vertical dimension is approximately 30 km.

THE VERTICAL DIMENSION

The surface tends to be rich in available geologic data, whereas the subsurface tends to be very poor. Extrapolation of surface trends, and using drill hole data and geophysical measurements that measure physical properties generally do not generate a sufficiently dense data set to map locally complex geologic patterns. A 3D TI is ideal for generating patterns in 3D, but 3D geologic analogs are scarce. Two-point statistics can help bridge the gap between the 2D geologic analogs and 3D volumes. If drill hole data are available, indicator variograms can be constructed, specifying bivariate correlations between geologic units in the vertical direction. The third dimension can be simulated by extending the observed patterns into the subsurface in two dimensions, and correlating the two-dimensional simulations vertically. The 3D geologic map is generated by stacking layers of 2D simulations and ensuring the stack honors the vertical variograms.

APPLICATIONS TO HYDROLOGY

Using the analog geologic map shown in Figure 2, and variograms derived from drill hole data, we generated simulations of a 5x7x0.76 km volume of alluvium, with a cell size of 100x100x20 m. The data consisted of the surface geologic map and seven logged drill holes. The analog for the subsurface was the surface geologic map, which was deconstructed into 5 separate TIs, generating a rich set of patterns for simulations. The drill hole logs were analyzed to generate vertical indicator variograms for each geologic unit.

Each 3D simulation consists of 37 separate 2D simulations (the top layer need not be simulated; it is the surface geologic map). Each subsequent 2D simulation incorporates the pattern elements found in the training image, matches the drill hole data, and is correlated to the layer above using the relationships defined by the indicator variograms.

Using field data for hydraulic conductivity collected for each geologic unit (Nimmo and others, 2009), the bulk hydraulic conductivity was calculated for the modeled volume (Figure 3). The bulk hydraulic conductivity of these models varied by about a factor of two. The difference in bulk hydraulic conductivity between the multi-point method and a simple nearest neighbor interpolation of the geology (any point in the volume is assigned the same geologic unit as the closest drill hole data point) is about a factor of five. A nearest neighbor interpolation predicts primarily vertical flow, whereas the multi-point models predict primarily horizontal flow. The latter behavior is typical of alluvial units (e.g. Moench, 1994; Sumner and Bradner, 1995).

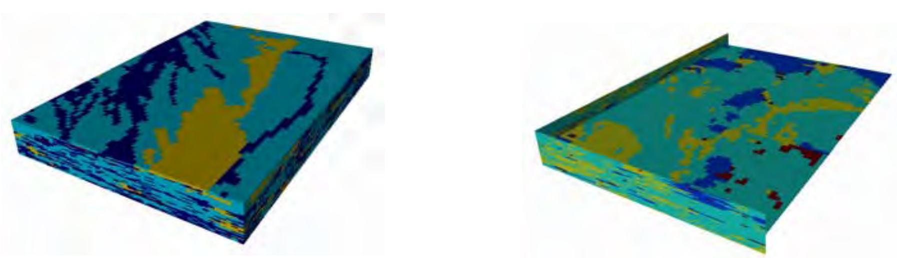

Figure 3. Example of one map generated using multi-point geostatistics, showing the surface (left) and a slice through the map (right).

CONCLUSION

Mapping complex geologic units in 3D involves a new way of thinking about geologic mapping, moving from a single interpretation to multiple interpretations that capture the conceptual model favored by the geologist and also the different possibilities inherent in any interpretation. Multi-point geostatistics can be used to map local geologically complex 3D units that otherwise could not be mapped in detail. Using geologic data, the appropriate geologic analog, and multi-point geostatistical methods, multiple maps can be generated, each one a plausible interpretation of the known geology. Such a suite of maps creates the possibility of quantifying the geologic uncertainty. Each map is used in turn in a process model, such as a flow and transport model. The variation in the results defines a probability distribution of the occurrence of the 3D geologic units. The probability distribution can then be used for analyses such as risk assessment and resource management.

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ONLINE ACCESS, VISUALIZATION AND ANALYSIS OF CANADIAN GROUNDWATER DATA

David Sharpe, Boyan Brodaric, Eric Boisvert, Charles Logan, and Hazen A.J. Russell

Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, Canada, K1A 0E8 dsharpe@nrcan.gc.ca

ABSTRACT

Online access to Canadian groundwater information is being realized through the groundwater information network (GIN). GIN is an evolving collaboration of six provincial agencies, several conservation authorities, along with a federal facilitating agency. Groundwater information is provided via Open Geospatial Consortium (OGC)-compliant Web services (WMS, WFS) and Groundwater Markup Language (GWML). The exposed data reside in custodial provincial databases and they are combined dynamically into a seamless virtual database using the Web services and GWML.

GIN can serve a range of client applications that are able to utilize WMS/WFS data sources. Two Web-based portals have been developed and will shortly be made available to a wide range of users. The first is a data access portal that allows comprehensive discovery, viewing, and download of water well data from GIN. The second is an analysis portal that allows for 2-D and 3-D map interrogation, visualization, and statistical reporting of user selected data. It also provides a number of features previously available only in sophisticated Geographic Information Systems (GIS). These features include: location searching, summary statistics, thematic mapping, time-series analysis, and the graphic display of well logs (e.g., water levels, materials, and well construction) that can be manipulated and analyzed in a 3-D perspective view.

Standardized data fields (e.g., well log lithologic codes) allow for ease and more consistent analysis of aquifer-aquitard structure, water level, and other trends (e.g., gradients) that traverse provincial boundaries. Wider use of the data via GIN is revealing issues related to data content, structure, and systems as well as groundwater data completeness, consistency, and location accuracy.

INTRODUCTION

Progress is continuing on Web-based mapping, access, and data visualization of groundwater information in Canada (Russell et al., 2007). An evolving partnership of Canadian government agencies, entitled the Groundwater Information Network (GIN), is enabling access to Canadian groundwater information as part of a Canadian Framework for Collaboration on Groundwater (Rivera et al., 2003). GIN is designed to coordinate groundwater information holdings in Canada, and to deliver the information in a usable form to governments, educators, practitioners, and the general public

GIN takes advantage of advances in Web based mapping standards and technologies (e.g., Peterson, 2003; Zaslavsky,, 2003; Jackson, 2009), to deliver local to national-scale information as well as Web-mapping and analysis portals to the Canadian public. The design of GIN is focussed on four key areas:

- **Data access standards**– partners provide access to selected data via OGC services;
- **Data structure standards** – all data are served in a common data format, called Groundwater Markup Language (GWML) ;
- **Data content standards** – some data are served using common content standards (e.g. lithology);
- **Web portals** – data are available via two portals: i) a data access portal provides basic data discovery, viewing, and download capability; ii) an analysis portal provides tools to cache, display, and analyze water well and watershed information.

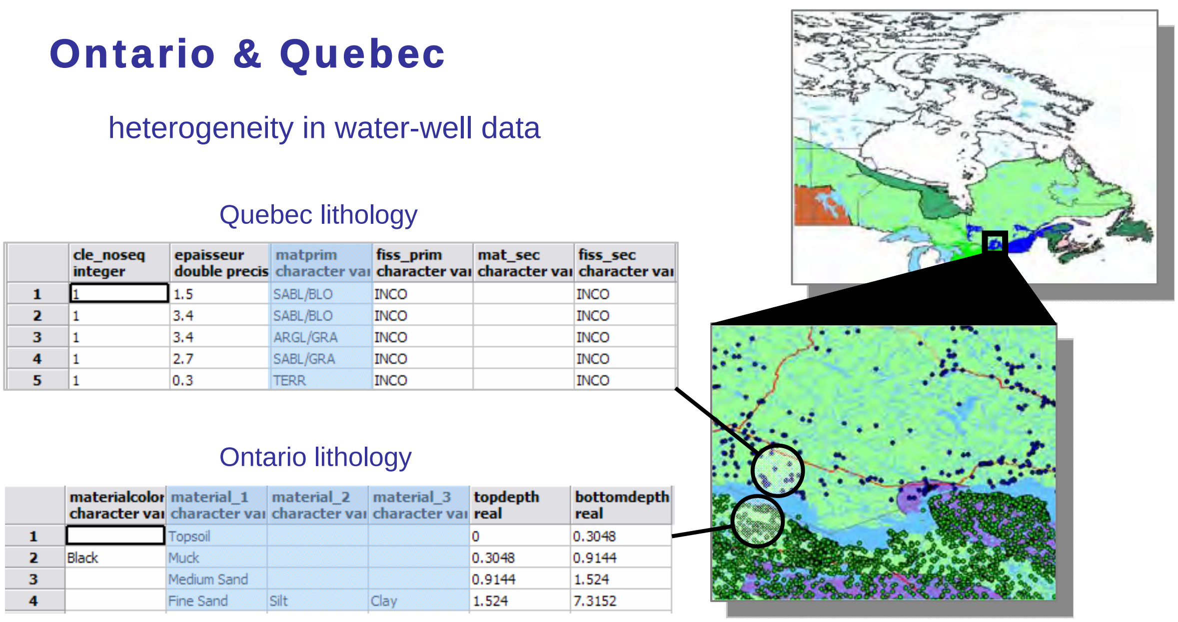
In this paper we describe GIN using these four focal areas. The next section sets the context by describing the state of groundwater data in Canada; the following three sections discuss GIN's use of standards for data access, structure, and content, respectively; this is followed by a section that discusses Web portals, a section that discusses users and usages, and a section concluding with some summary remarks.

GROUNDWATER DATA IN CANADA

While there is increasing awareness that regional, provincial and national accounting of water resource information is required, for example to assess groundwater sustainability (CCA, 2009), this is impeded by the state of groundwater data; groundwater data are distributed, uncoordinated, heterogeneous and of variable quality.

<u>Distributed, uncoordinated, and heterogeneous data</u>

Federal departments, provincial agencies, municipalities, and watershed authorities all have groundwater databases (e.g., Gilliland, 1990). However, data are geographically distributed and managed in individual offices with little coordination among agencies. Each respective agency employs different database structures, vocabularies, and reporting protocols. Hence, access to data and data integration are problematic. As data providers use Web-enabled systems such as GIN to provide access to their data, the distributed databases become one virtual data repository. Development of GIN has highlighted the heterogeneous and uncoordinated nature of data management. Data standards have been developed to enable applications to use variable data in a uniform way. Figure 1 illustrates this heterogeneity, as it displays fragments of water well databases from Ontario and Quebec—note the variation in database content, structure, and host systems. The main aim of the GIN partnership is to provide a system that can overcome these differences through the implementation of open geospatial standards. Overcoming the heterogeneity barrier is crucial to enabling meaningful data analysis for groundwater resource assessment and management.



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1	1	1.5	SABL/BLO	INCO		INCO
2	1	3.4	SABL/BLO	INCO		INCO
3	1	3.4	ARGL/GRA	INCO		INCO
4	1	2.7	SABL/GRA	INCO		INCO
5	1	0.3	TERR	INCO		INCO

	materialcolor character va	material_1 character va	material_2 character va	material_3 character va	topdepth real	bottomdepth real
1		Topsoil			0	0.3048
2	Black	Muck			0.3048	0.9144
3		Medium Sand			0.9144	1.524
4		Fine Sand	Silt	Clay	1.524	7.3152

Figure 1. An example of water well data heterogeneity between two provincial water well databases.

<u>Variable quality of water well data</u>

Groundwater data across the country have issues with respect to completeness, consistency, and location accuracy (e.g. Kenny et al., 1997; Russell et al., 1999). New Web technologies allow easy, widespread access and viewing of water well data that can expose some data quality problems very quickly. For example, mis-located wells do not match reported elevations, and when plotted, show as located above or below ground surface. As a result, water level information and groundwater flow directions can not be evaluated reasonably given the poor data location/elevation feeds of some GIN partners.

DATA ACCESS STANDARDS

To overcome the above issues related to groundwater data, GIN is being developed within the broader Canadian Geospatial Data Infrastructure (CGDI) framework. CGDI provides two principal services to users of online geospatial data. First, a registry mechanism enables agencies and their individual users with an internet connection to discover location-registered databases throughout Canada, thus serving as a one-stop catalogue for geographic data. Second, CGDI advocates the use of standards for online query, delivery, and visualization, enabling the construction of networks of linked data such as GIN. Both these services are deployed using international Open Geospatial Consortium (OGC) specifications, which ensure compatibility with non-Canadian information sources. The primary specifications utilized include the Web Map Service (WMS) and the Web Feature Service (WFS), which deliver map images or actual feature information (e.g., for water wells or aquifers), respectively, and the Geography Markup Language (GML) which is the data format used by WFS to deliver the features online. GIN uses these specifications in the following way:

- a WMS and WFS Web service is placed over each database, standardizing online access to each database;
- each WMS and WFS is registered with GIN and the CGDI, standardizing online discovery of the data source and its related Web services;
- each WMS and WFS is connected to the central mediator, which standardizes access to the complete distributed data repository by providing a single WMS and WFS interface to the repository. The mediator receives queries from portals and other applications, distributes them to the source WFS and WMS, and returns the results to applications. In essence, the mediator acts as a central data pipeline which carries out two important functions: it translates the queries and results between the common data standard (GWML) and the source data structures, and it acts as a central point of access to the repository, making it appear to be a single homogeneous entity.

These interactions are implemented in GIN using a three-tier architecture, as shown in Figure 2: data sources, data pipeline, and applications. This architecture enables multiple applications to simultaneously access the data, allowing for specialized tools to be built and possibly shared by developers; it also enables multiple data sources to be added as required, while keeping authority for the data with the source data providers.

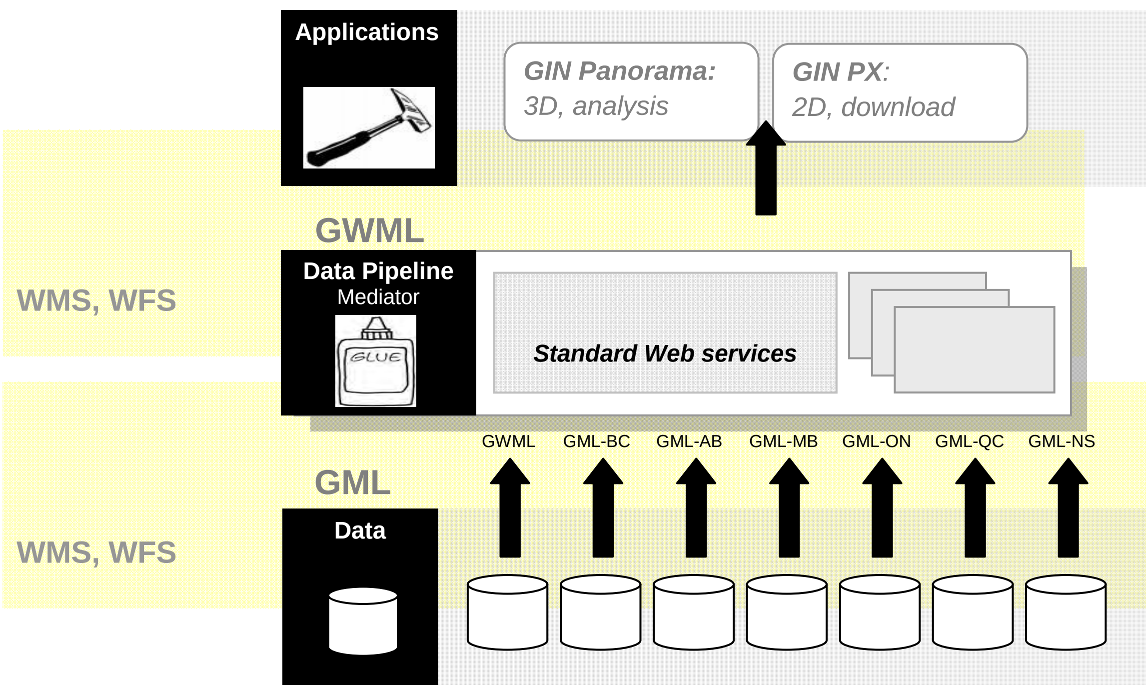

Figure 2. Architecture of GIN.

DATA STRUCTURE STANDARDS

GIN utilizes GWML as its canonical data structure to transfer data between the mediator and applications, both for enabling applications to query the data repository, and for transferring data back to applications. GWML is a groundwater-specific extension of GeoSciML, which is a data transfer format for geological information, and which itself is based on the Geography Markup Language. GWML encompasses the following types of groundwater information:

- groundwater
- groundwater properties
- water budgets
- hydrogeological units such as aquifers
- water wells
- observations, such those taken by monitoring instruments

DATA CONTENT STANDARDS

GIN also provides some standards for the content transferred using GWML. The most significant of these is the GIN Lithology specification. GIN Lithology represents a set of about 40 standard rock type terms to be used with GWML. These terms are both a subset and extension of the GeoSciML Simple Lithology standard, one that is focussed on rock types commonly associated with groundwater as determined by the GIN partnership (Figure 3).

0	Unknown material
1	Bedrock
1a	Metamorphic rock
1a-2	Quartzite
1a-3	Marble
1a-4	Gneiss
1a-5	Schist
1a-6	Slate
1b	Igneous rock
1b-1	Volcanic rock
1b-1a	Basalt
1b-1b	Andesite
1b-1c	Rhyolite
1b-2	Plutonic rock
1b-2a	Diorite
1b-2c	Granite
1b-2d	Gabbro
1c	Sedimentary rock
1c-2	Conglomerate
1c-3	Sandstone
1c-4	Siltstone
1c-5	Shale
1c-6	Carbonate sedimentary rock
1c-6a	Dolostone
1c-6b	Limestone
1c-7	Evaporite
1c-8	Coal
2	Unconsolidated material
2a	Diamicton
2a-1	Till
2b	Gravel
2c	Sand
2d	Mud
2d-1	Silt
2d-2	Clay
2e	Organic material
2e-1	Humus
2e-2	Soil
2e-3	Peat
2f	Anthropogenic material
2g	Undifferentiated sediment

Figure 3. GIN lithology from the GeoSciML vocabulary to facilitate common data reporting.

WEB PORTALS

At present, two portals exist for exploring GIN, the data access portal, and the analysis portal. Other portals and applications also access the GIN data pipeline, but here we describe the GIN specific portals.

<u>Data access portal</u>

The data access portal is an OGC compliant application that provides basic data access, borehole viewing (including the primary well record), metadata details, and a download utility. The portal is quick and responsive to data requests on moderate numbers of water-well records (e.g., from 500-5000 wells), typically processed from seconds to a couple of minutes using a broadband internet connection. This response speed is quite impressive, because data transactions are carried out dynamically as operations generally pass through each layer of the architecture (data, mediator, application).

<u>Analysis portal</u>

The analysis portal is an implementation of the commercial **troo**track™system. It provides a fast, full screen, GIS style visual interface that allows data to be displayed over standard base map layers, including searchable address information. Tools permit dynamic map-based queries and viewing of geographic and document data. Data analysis options include thematic mapping, calculation of summary statistics, three-dimensional visualization, water level assessment, and time series data charting. Users can manipulate map layers, select data subsets, view individual borehole logs, construct subsurface cross-sections, construct graphs, and view historic time-series data. Users may also better understand and utilize map-based groundwater information with the help of science vignettes and tutorials designed by geoscientists. The analysis portal allows for map interrogation in '3D'. Groups of wells can be selected in radius, cross-section, or 3-D mode. Radius select allows summary statistics to be readily viewed for selected wells. Selected wells in any mode can be viewed, rotated, and analyzed in a 3D perspective view referenced to a digital elevation model. Coded lithologies on well logs allow for easy analysis of aquifer-aquitard trends in cross-section or 3-D views. Where a 3D grid geological model is available, as is the case with some GIN providers, well data can allow users to view /assess the integrity of the 3D model and/or inspect lithologic variability within presented hydro-stratigraphic strata, as shown in Figure 4.

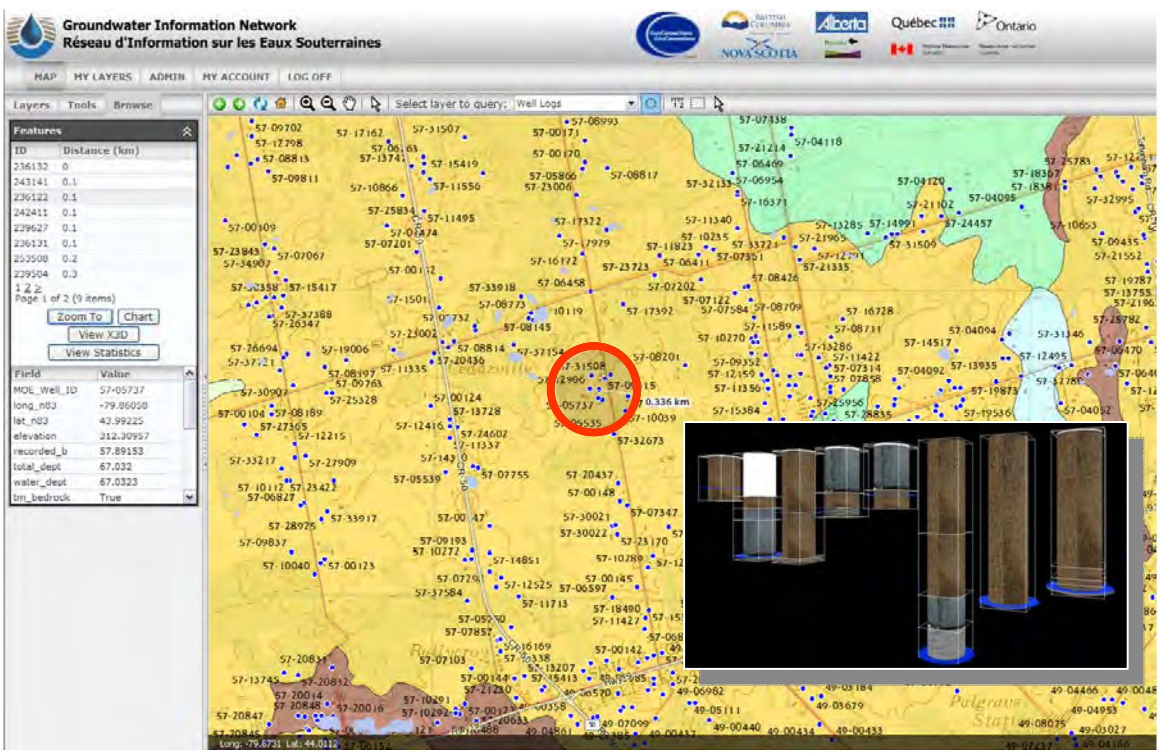

Figure 4. Perspective 3D view of well logs and water level data queried within the red circle and overlain on a 3D stratigraphic model.

USERS

In general, three types of GIS-like services can be identified to address the needs of different end users (Jiang, 2003): i) general public or novice users; ii) the domain specialists, i.e., professionals who collect, maintain, and use geoscience data in their professional work; and iii) government, for instance, in planning and land-use activities. It is anticipated that GIN users will be drawn from each of the three groups. GIN addresses the needs of these three groups variably. The domain specialist, e.g., the GIS professional or groundwater researcher, is directly supported through increased access to fairly detailed water-well information. The general public is supported through the user-friendliness of the Web interface, which allows them to easily find locations of interest and related water wells. Finally, the immediate value for groundwater managers, and researchers, is the ability to view and interrogate data beyond the confines of expensive GIS software and without the aid of specialized GIS staff.

Source water protection

A recent water policy example illustrates collective user needs and that of a key partner, Conservation Ontario. Ontario's Clean Water Act directs local agencies (e.g., Conservation Authorities) to characterize land and water resources of all source-water watersheds in Ontario. They require tools to access information for analysis and regulation under their Source Water Protection responsibilities. The ability to store, access, display, analyze, and update a ~600,000 well-water-record database together with other layers (e.g., land use) is a good outcome for GIN. Further, it may help to delineate the extent and vulnerability of all municipal wellhead areas, as well as sensitive and/or highly vulnerable recharge zones. The generic business case of all users is to prevent another contaminated-well scenario like that of Walkerton, Ontario. The GIN partnership has been very successful to date in enhancing the functions required by users in support of decision-making in the water resources and land use domains.

CONCLUSIONS AND NEXT STEPS

We have described the Groundwater Information Network (GIN), a collaboration of Canadian groundwater data providers who are partnering to integrate their data using common standards for data access, structure, content, and to develop Web applications that allow various users to readily access and analyse these data. The GIN partnership hopes to expand to include all Canadian provinces and territories. Tests are being planned to Web-enable data access across the Canada and US border. Plans also include expanding to other groundwater data types, for example, aquifer maps and additional time series data, perhaps to include real-time data trends.

ACKNOWLEDGEMENTS

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THREE-DIMENSIONAL PROPERTY MODELING OF A COMPLEX FLUVIO-DELTAIC ENVIRONMENT: RHINE-MEUSE DELTA, THE NETHERLANDS

Jan Stafleu, Freek S. Busschers, Denise Maljers, and Jan L. Gunnink

Deltares/TNO – Geological Survey of the Netherlands, P.O. Box 85467, 3508 AL Utrecht, the Netherlands, jan.stafleu@tno.nl

INTRODUCTION

The Geological Survey of the Netherlands aims at building a 3D geological property model of the upper 50 meters of the Dutch subsurface. This 3D model provides a basis for answering subsurface related questions on, amongst others, groundwater extraction and infrastructural issues. modeling is carried out per province using a digital core-database containing several hundreds of thousands of core-descriptions and a context of geological maps created during the last few decades. Following the completion of a model of the province of Zeeland (Stafleu et al., 2008), modeling focussed on the province of Zuid-Holland where major cities like Rotterdam and The Hague are situated, and the Rivers Rhine and Meuse enter the North Sea. The area is characterised by a thick Holocene coastal wedge that is underlain by a stack of Pleistocene (sandy) units. The Holocene sequence is the main focus of our paper.

A stepwise procedure consisting of automated database queries, 2D modeling of stratigraphic surfaces and 3D property modeling, resulted in a schematisation of the Zuid-Holland subsurface in using 50 million grid cells (blocks), each measuring 100 by 100 meters in horizontal directions and 0.5 meters in the vertical direction. Each grid cell of the final model includes estimates of stratigraphy, lithology (clay, sand, peat) and if applicable, sand-grain size class data, all up to a depth of 60m below the Dutch Ordnance Datum. The use of stochastic techniques allowed us to compute probabilities for these parameters, providing a quantification of model uncertainty. In a final model step (not further discussed in this paper), the 3D lithological model is used as a basis for the parameterisation of physical and chemical properties, such as hydraulic conductivity and chloride content.

In contrast to its predecessors (DGM, REGIS), the Zuid-Holland model is no longer a layer-based model consisting of stratigraphical layers with uniform properties, but a cell-based model where individual cells have uniform properties. The cell-based nature of the model allows modeling of the internal heterogeneity of lithostratigraphical units in terms of lithology, sand-grain size classes, and other parameters.

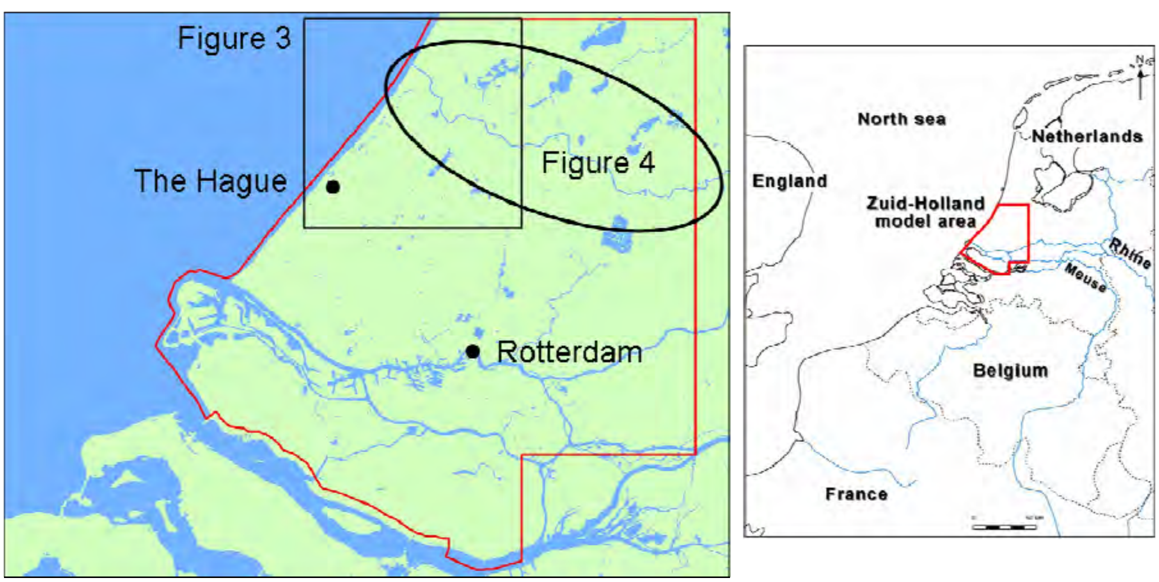

Figure 1. (a) Location maps showing (a) the position of the Province of Zuid-Holland in the west of the Netherlands and (b) in the southern North Sea area.

GEOLOGICAL SETTING

The province of Zuid-Holland is positioned at the southern rim of the North Sea sedimentary basin. Its subsurface (upper tens of meters) mainly consists of fluvial and estuarine sediments that were deposited by the Rhine and Meuse throughout the Pleistocene and Holocene. The Pleistocene deposits mainly consist of fluvial sands that will not be further discussed here.

The Holocene coastal wedge reaches thicknesses of 5 to 20m. Sea-level controlled Holocene sedimentation in the area started with the formation of a distinctive peat layer (Basal peat Layer, Figure 2). The peat covers Late Pleistocene eolian sands (Wierden Member) and a clay layer that formed prior to sea-level rise (Wijchen Member). Widespread aggradation of fluvial sediments on top of the peat initiated about 8500 years BP (base Echteld Formation). In the western portion of the area, an open coastal barrier system developed (Zandvoort Member). Deposition of tidal channel and tidal flat sediments occurred in the back barrier area (Wormer Member). East of this zone, fluvial aggradation continued as reflected in the presence of fluvial channel belt (dotted lines in Figure 2), overbank, and floodbasin sediments. Closure of the barrier inlets after ~4000 years BP lead to widespread peat formation (Hollandveen Member). Re-opening of the barrier inlets system after ~2500 years BP led to a continuation of marine sediment deposition (Walcheren Member) in the western part of the area. Natural sedimentation of rivers and estuaries largely ended after 1000-1200 AD when dikes were established throughout the area.

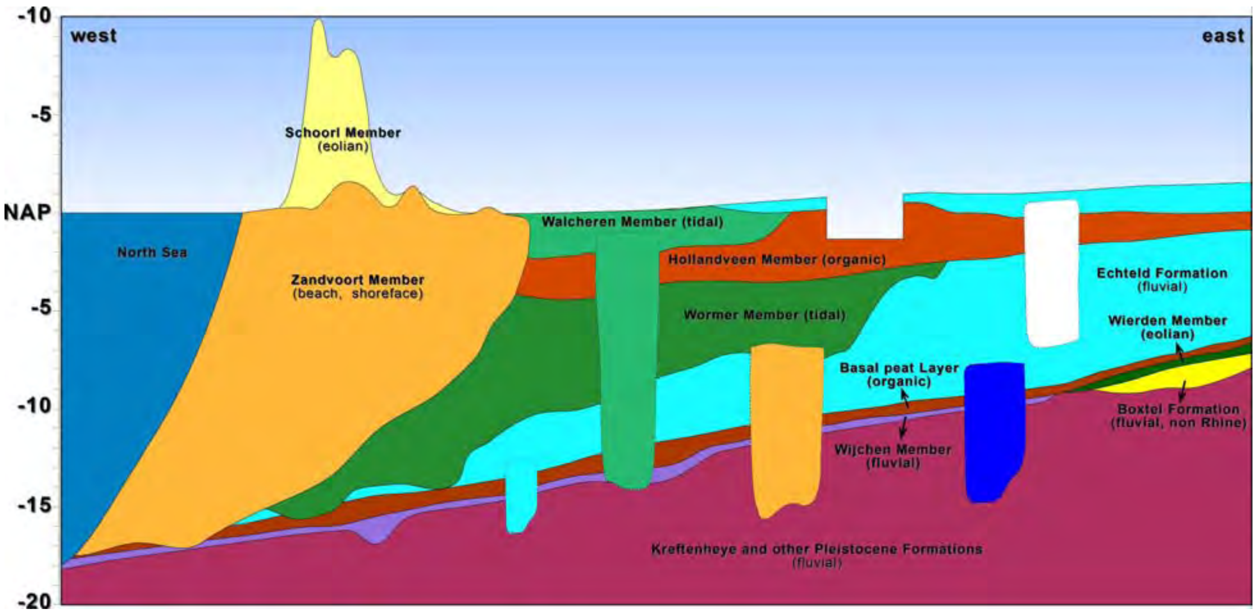

Figure 2. Schematic east-west oriented cross-section through the Holocene deposits in the Province of Zuid-Holland. The horizontal distance is about 70 km, while the vertical distance runs down to 20 meters below Dutch Ordnance Datum. See text for discussion of the units.

METHODS

The starting point for the Zuid-Holland model are the borehole descriptions stored in the DINO database, the Dutch national database for Data and Information of the Subsurface (www.dinoloket.nl). This database provides us with over 50,000 borehole descriptions for the model area (65 by 65 km). Each borehole description reveals detailed information of the subsurface at one particular location. The modeling procedure involves a number of steps.

The first step is a geological schematisation of the boreholes into units that have uniform sediment characteristics, using both lithostratigraphical and lithological criteria. During the second modeling step, 2D bounding surfaces are constructed. These surfaces represent the top and base of the lithostratigraphical units and are used to place each 3D grid cell in the model within the correct lithostratigraphical unit. The lithological units in the boreholes were used to perform a final 3D stochastic interpolation of lithology within each lithostratigraphical unit. After this step, a cell-based (100 by 100 by 0.5 meter) three-dimensional geological model is obtained. The 3D interpolation is carried out for each lithostratigraphical unit separately. Fluvial and estuarine channel belts in the area were modelled as separate lithostratigraphical units. The location of the belts was derived from detailed maps published by the Geological Survey and the University of Utrecht (Berendsen and Stouthamer, 2001). Newly developed, Python-based scripts were used to determine the top and base of the belts within the boreholes. Finally, the use of stochastic techniques, such as Sequential Gaussian Simulation and Sequential Indicator Simulation (Goovaerts, 1997), allowed us to compute probabilities for both lithostratigraphy and lithology for each grid cell, providing a measure of model uncertainty.

RESULTS

Part of the lithostratigraphical model of Zuid-Holland is shown in Figure 3. The model shows the Pleistocene substratum covered by the complex of Holocene fluvial, marine, and organic sediments.

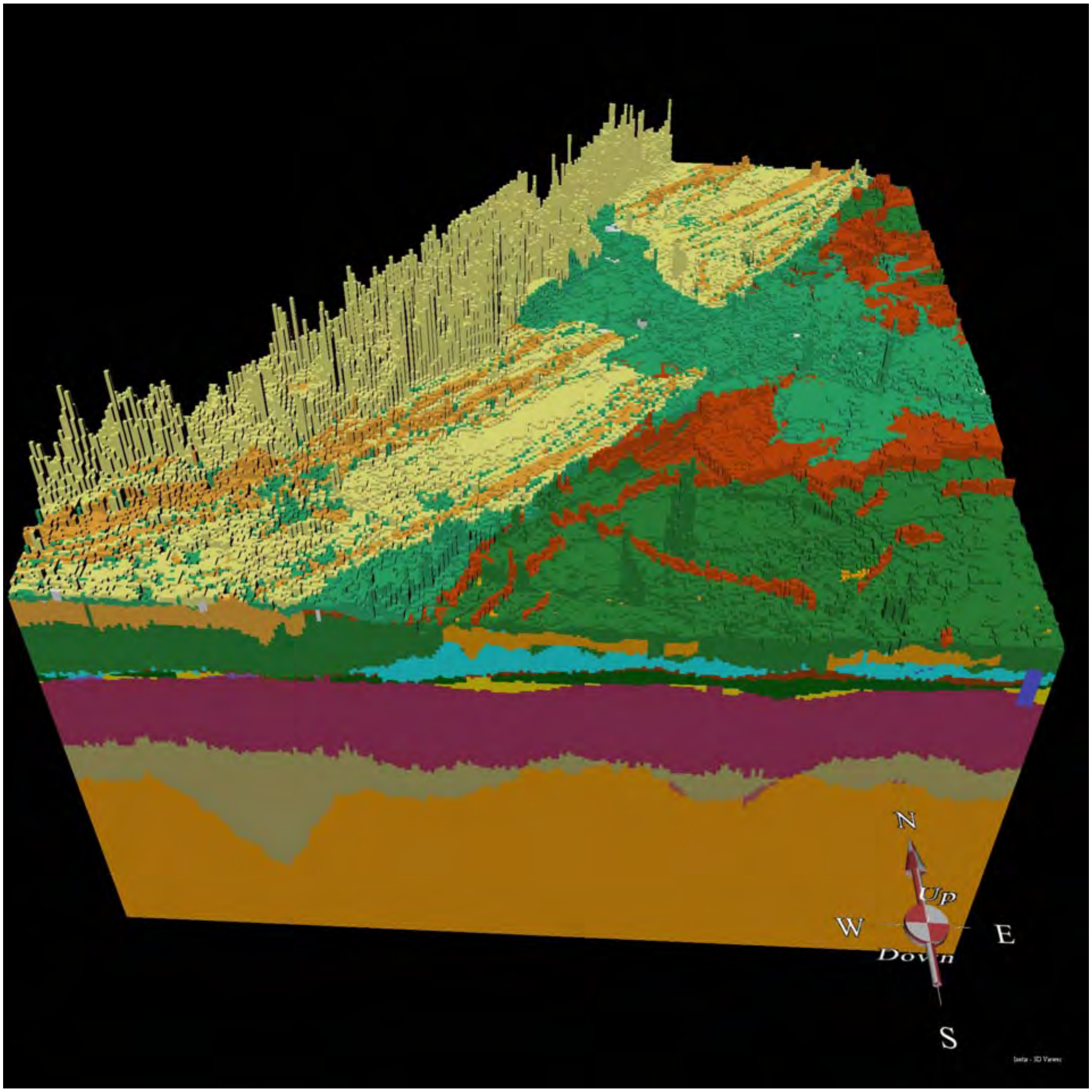

Figure 3. Part of the 3D lithostratigraphical model of Zuid-Holland (see Figure 1 for location). See Figure 2 for information on unit colour codes.

The Holocene deposits of Zuid-Holland are characterised by complex fluvial channel systems of the Rhine and Meuse Rivers. By modeling the channel belts as separate lithostratigraphical units, a 3D model of the geometry of the channel belts was obtained. The colours in Figure 4 represent channel belt generations (relative ages). For example, Generation B (white in Figure 4a) corresponds to the course of the Rhine in Roman times. Figure 4b shows the same channel system with grid cells filled with lithology and sand-grain size classes, providing more insights into the internal build-up of the channel belts and occurrence of grain-size trends in vertical and horizontal (downstream) directions.

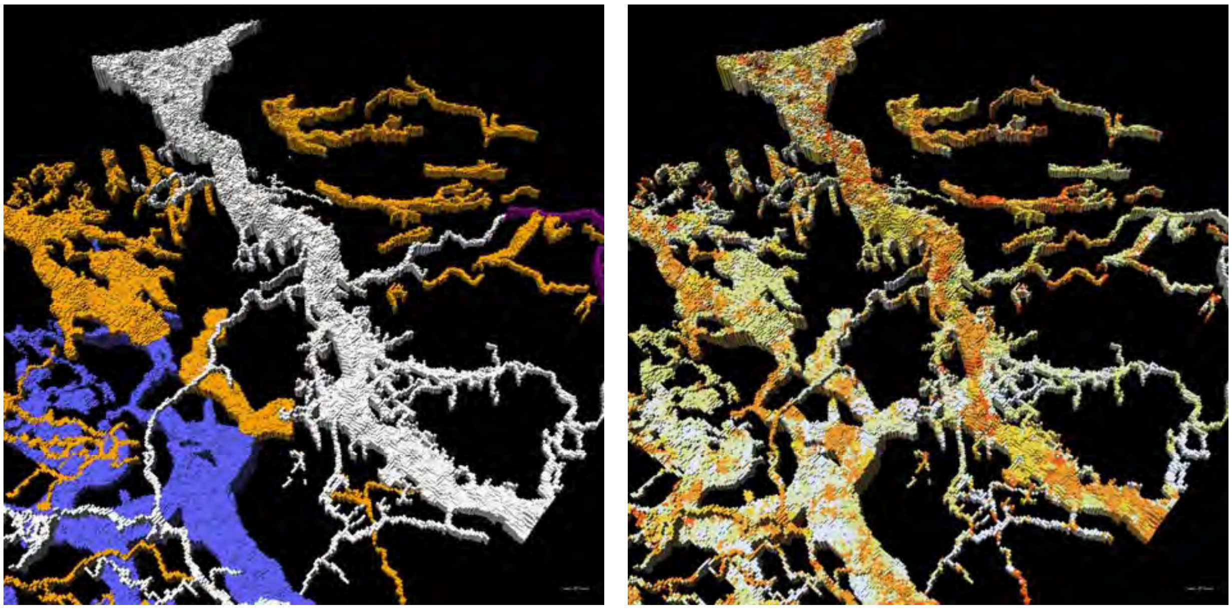

Figure 4. (a) Holocene channel belt systems in Zuid-Holland (see Figure 1 for location). The colours represent generations (relative ages) of the channel belts. (b) Same channel system as in (b) with colours representing lithology and sand-grain size classes. Darker colours are coarser sediments.

APPLICATIONS AND FUTURE DEVELOPMENTS

The Zuid-Holland model serves as a source of subsurface information and provides the regional, geological composition as well as the spatial variability in lithology and sedimentation patterns. An example of the use of the model is the planning of a new subway in the city of Rotterdam. Here the model is used as a background (frame) model in order to plan detailed studies of sediment variation at the sub-grid scale (1-10m).

In addition to the modeling described above, we collected and measured physical and chemical parameters. The sampling strategy is such that measured values can be assigned to lithostratigraphical and lithological units, making it possible to obtain insights into the spatial variability of physical and chemical properties in three dimensions. Examples of physical and chemical parameters include horizontal and vertical hydraulic conductivity, which are crucial in groundwater models and the reactivity of sediments, which is used in the modeling of contaminant plumes.

In the future, we will extend the models towards the north, east, and south of the Netherlands, ultimately leading to a full model cover of the Netherlands (41,000 km^2).

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AN AGENDA FOR DEVELOPMENT OF VERTICALLY GEOREFERENCED, WEB-OPTIMIZED SUBSURFACE INFORMATION

Harvey Thorleifson

Minnesota Geological Survey, 2642 University Ave W, St Paul, MN 55114 USA thorleif@umn.edu

Geological mapping is an essential service provided by geological survey agencies at the federal and state/provincial level. The mapping represents an authoritative prediction regarding the composition, structure, and origin of sediments and rocks, based on observations and inferences backed by research on material, process, and history. This spatial accounting is needed to support the progress of research and societal applications related to energy, minerals, water, climate change, waste disposal, construction, and hazards.

Through most of the nearly 200 years of geological mapping history, the printing press was our means for preparing information for dissemination, customarily as a map and a report. Three-dimensional aspects of the geology were accommodated by publishing surficial geological maps to depict the uppermost sediments, bedrock maps to depict the uppermost rocks, structural symbols to indicate geometric trends that could be projected into the subsurface, an accounting of superposition conveyed by the legend, along with selected cross sections.

To be regarded as legitimate, these maps and reports have undergone peer review in a manner dictated by the workings of government agencies that are obliged to ensure that something is produced for any funded project. The publications have clear authorship to provide credit, and to indicate responsibility for the work. Geological survey agency culture differs from the anonymous authorship of, for example, less interpretive meteorological and topographic mapping.

Having been packaged as maps and reports that are authored and peer-reviewed, our products were then made ready for the printing press, an appropriate number of copies were produced, and they were then distributed to libraries and sales outlets. Upon depletion of sales outlet inventory, the publication was declared out of print, and users were referred to libraries. To facilitate storage, discovery, and unique identification, a series number was assigned, thus becoming the entry point to the information, through a library card catalog or publications catalog.

From the 1980s through the millennium, digital methods were adopted, and we learned how to make a paper map or a paper report with the aid of a computer. This took a great effort, and those responsible for the success of this transition are commended. Concurrently, databases produced in association with geological mapping, or as products of geophysical and geochemical surveys, greatly increased in prominence alongside our paper maps and reports.

Throughout this transition to digital methods, however, geological mapping has remained committed to the paper map and paper report format. This is good, and we should continue to do so, as these formats are familiar to our existing user community, these are formats that unquestionably will be usable decades in the future, we have meticulously developed procedures for detailed legends to be affixed to each map, and these formats facilitate authorship and peer review. Whether actual paper, a vector layout, or a raster copy, we will continue to use map formats that were designed for the printing press indefinitely.

This being said, we are all aware that we now live in the Web paradigm. We produced paper maps using photomechanical methods in the 1980s, we learned how to make paper publications with a computer in the 1990s, and with the turn of the millennium, we increasingly made digital versions of our publications available via the Web. As we enter the second decade of the millennium, however, we increasingly recognize that we can serve our users more efficiently and effectively if we optimize our content for the Web, rather than for the printing press.

Web users now seek conceptual information such as news, temporal information such as weather forecasts and stock prices, and when they seek spatial information, their entry point is location, rather than a keyword search for a series-numbered publication. Users are accustomed to Web mapping sites, in which they first choose an area, and then select the topic of interest. Users now assume that they can zoom out for context, and zoom in for detail. Some sites provide a text message advising the user to zoom back if a more detailed layer is not available.

It also is customary to browse Web maps laterally, whether across a county or across a continent, while double-clicking a symbol generally is seen as a natural way to obtain information about a feature. This method of query is now a way of life for a growing segment of the population, many of whom have never experienced a library card catalog, nor are they interested in ordering a copy of a map or a report. They simply want the fact or the figure that will allow them to move on toward their actual objective, while using a Web service that they happily take for granted.

While geological survey agencies have made much progress in making our standard information products Web accessible, we have barely begun the process of Web optimization. To do so, we must vertically georeference all of our content, and optimize it for zoom, browse, and query.

As we structure our maps as zoom layers, we likely will rely on 1:25M global mapping, 1:5M continental mapping, regional mapping at scales of about 1:1M, and detailed mapping at scales of about 1:100,000, although varying from 1:24,000 to 1:125,000.

Geological survey agencies are rightly proud of the hundreds of maps we have produced. But Web-savvy users do not want hundreds of maps; they want one browsable and queryable map at each zoom level. This means that we must stitch our detailed mapping together as a single, queryable layer for a given jurisdiction, bringing together both onshore and offshore mapping, at each zoom level relevant to that level of government. This can begin as an unreconciled mosaic, followed by gradual progress toward full harmonization. These map layers will also facilitate needed jurisdiction-wide analyses, such as the material along proposed pipeline corridors.

Each layer must be queryable, and to do this efficiently, every legend needs to be coded to a one-word lithology, as well as other attributes parsed from the full legend. In addition to the standard legend, we will be able to make multiple languages and multiple derived maps available on the fly by allowing a choice of legends, each adapted to the needs of a different user community.

As we produce these Web-optimized layers, we will remain committed to the scientifically more rigorous and comprehensive content that will continue to reside in our authored, peer-reviewed maps and reports. In the Web paradigm, the logical way to access these publications would be, for example, by right-clicking a feature.

The paper map format in this context becomes the documentation for a Web-optimized color polygon coded with a one-word lithology, and a raster of the paper map would be an ideal format for the few knowledgeable users who need detailed information, and who comprehend formal geological maps. Ideally, the text in the raster would be searchable, through some sort of optical character recognition (OCR) procedure.

Concurrently, a Web-optimized geological mapping layer ideally would also link to reports. Whereas geological mapping agencies previously were able to declare a publication to be out of print, and thus the responsibility of libraries, we now must again take responsibility for our page content, as page scans now will become the universal format at least for our legacy content. While some of us will wait to have this done for us, others will take control of their future, and have the page scans done. To do this, every geological survey agency needs a complete listing of every publication they have ever produced, and they need to scan every map and every page. The least expensive, most consistent, and most efficient way to do this is in large batches sent to a capable contractor. While OCR-searchable pdf files available as whole-file downloads are an established format, formats for digital books that are Web–accessible a page at a time are not.

In the printing press era, we were able to justify two color maps, surficial and bedrock. In the digital era, there is no reason to be constrained in this manner, as the number of color maps that can be produced is unlimited. We thus can now transition from a focus on surficial and bedrock, to strata and basement. In this approach, polygons for undeformed strata can be superimposed, and thus made removable, to reveal what is below, to the extent that it can be mapped. Eventually, deformed rocks are encountered, and these can be declared basement. In this approach, decisions on what are strata, and what is basement, will be required early in a project.

This style of mapping is, in a way, an established activity for geological mapping agencies, who have been producing surficial geology maps, depth to bedrock maps, and bedrock maps for decades. Bedrock maps commonly had large blanks in them, until we began to use airborne geophysical surveys. As 3D mapping of strata matures, we will similarly develop guidelines for the amount of information that is required to justify full 3D mapping.

Earth surface mapping is a well-known activity, in the form of topographic maps depicting roads and rivers, and these features can readily be vertically georeferenced by draping them on a terrain model. Similarly, 3D mapping of the atmosphere is well-developed, and virtual globes now offer near-real-time clouds and precipitation depicted in some manner above ground. These Web services also have begun to show water depth, thus beginning to enter the 3D subsurface world.

As geological survey agencies enter this paradigm, we similarly will recognize that the first layer of subsurface information is bathymetry. Jurisdiction-wide water layers at multiple zoom levels therefore need to become a well-known institutional resource. By making this layer available on the Web, emergency response teams dealing with an offshore plane crash, for example, or someone pondering offshore coring or drilling, will be supported.

The second layer of subsurface information is agricultural soil mapping. This is a highly mature activity, but it operates in a world and a culture quite separate from geological mapping, with respect to academic traditions, terminology, and user communities. Nevertheless, soil mapping and geological mapping are the same thing, with the former measuring depth in centimeters, and the latter making measurements in meters and kilometers. Despite this similarity in method and topic, there is little coordination between these two worlds.

Despite these cultural barriers, however, soil mapping and geological mapping will have to be reconciled. As users such as land-use planners more and more expect the integration of Web-accessible information, they will demand that the two be made to work together. While soil mappers may claim that their mapping is relevant to multiple meters of depth, and geological surveys will present competing claims that imply that their surficial maps are relevant to the surface, our users will likely be better served if we simply declare soil maps to be the official government prediction for the top meter, while the surficial geology map is the authoritative word for the second meter. Both soil maps and surficial geology maps readily can be made queryable to the same one-word lithologies, although soil mappers will protest that they map soil development rather than parent material composition.

We thus can now begin to build maps with superimposed polygons, depicting a stack of extents. The next step in this process then is to specify the thickness of each layer, thus producing a 3D map, which can be conveyed in the form of an extent and a grid of tops for each layer. This can then be followed by progress toward production of a 3D grid of discretized properties for each layer, thus producing a 3D map ready for modeling.

We then will need Web interfaces that can optimally make 3D maps available. Development of capable Web interfaces will be frustrating for us all. We know that a suitable interface could readily be programmed, but we all have learned about the in-house software syndrome, in which custom software works well for a small community for a few years, but staff turnover and technological progress eventually cause the demise of the procedures. Thus we do not want to be producers of Web interfaces any more than we have to. We would prefer to be pure content providers, not maintainers of interfaces.

But commercial interface providers will not build an interface until the content and user community are there. In a classic chicken and egg situation, we will not prepare the content until the interfaces are adequately available. For Web accessible 3D geological mapping, we thus may have to emulate the great success of the OneGeology portal, which was built as a community project of the geological surveys of the world, largely to a stimulate coordinated effort on a standard format for Web-accessible 2D geological maps. Soil mapping agencies have built similar portals.

A solution will be found, however, and capable interfaces will offer our increasingly comprehensive 3D maps. As we make available our 3D layers, we will want the user to be able to concurrently query databases such as drillhole data and geophysical databases, as well as databases of geological observations.

This information depicting the world beneath our feet could be called geology, or perhaps words such as subsurface or underground will be more accessible. Varying ways to Web query 3D geological mapping will be found. A location could be specified, and a drillhole forecast down to basement could be produced in a window. Layer one would be water if present, or commonly the top meter would be the one-word lithology derived from the soil map, followed by a prediction of material in the second meter derived from the surficial geology map. Areas lacking full 3D mapping would then have a layer of unspecified sediments derived from the depth to bedrock map. Forecasts for rock layers would follow, either multiple layers, total thickness of strata, and/or finally perhaps a meter-thick interval presenting uppermost basement lithology would complete the drillhole forecast.

This drillhole forecast would be accompanied by an indication of reliability, perhaps an accompanying column that would be green to indicate a high confidence prediction based on much previous drilling of simple geology, yellow for a medium confidence prediction in an area of little previous drilling, and red for low confidence in an area lacking drilling. These confidence levels could be built quantitatively by dividing a region into cubes, perhaps 10 km square by 10 meters think, and by inferring a score based on a combination of number of drillhole intersections penetrating that cube, balanced by a consideration of geological complexity. Few drillholes are required to allow good predictions of unvarying horizontal strata, while more drillholes are required to adequately characterize areas of greater complexity.

Beyond drillhole forecasts for a mouse-clicked point, a postal code, or an address, we can readily obtain additional ideas for optimal future Web accessibility of 3D geological maps by considering the procedures now readily available in a 3D GIS. Ideally, these 3D GIS procedures will some day be Web enabled, thus allowing lift-off of strata, or removal of cut-out blocks or wedges.

Our thinking on scales of geological maps is stable, and four zoom layers are here proposed – ~1:25M, ~1:5M, ~1:1M, and detail at ~1:100K. Our thinking on varying scales of 3D mapping is less mature. Much new 3D mapping in the geological survey agency world is being done at the county scale to support groundwater management. In an earlier phase of 3D geological mapping in the 1980s and 1990s, atlases were produced for hydrocarbon-producing sedimentary basins, as well as for regional groundwater systems. These were done at a lesser level of detail than present-day county-scale 3D mapping, but we have a limited ability to characterize this varying level of detail.

To consider this topic of 3D scale further, we can consider a user browsing a 1:25M geological map of the world, who might wish to query various points around the world, to clarify varying of a sedimentary basin thickness. Similarly, a user browsing a 1:5M continental map might want to query and view variations in Mesozoic thickness relative to Paleozoic thickness, for example. Someone looking at a state or provincial bedrock map might be interested in depth to bedrock, or in the thickness of Silurian relative to that of Devonian. When viewing a county geologic map, the user would want the highest level of detail, typically at the formation level, or lithological depiction of aquifer and non-aquifer materials.

It would seem logical to marry the 3D strata to the polygons on the map, although it might not be possible to match the two. Commonly, a 2D map will show more detail than the 3D map that it will logically be matched to. We thus need to develop thinking, perhaps on four levels of 3D detail that can be associated with the four levels of 2D zoom proposed here. Sediments might only appear in the one or two most detailed scales.

The Web revolution thus has made people hungry to have all information at their fingertips, so they can do their jobs, and quickly get on with their lives. The questions before us are: (1) how far Web optimization can go in the world of geology, (2) how quickly geological survey agencies can reformat their information for this style of Web query, (3) whether we can assemble consistent information world-wide, (4) whether we can 'go underground' in Web interfaces, (4) the business models that will cause needed Web interfaces to be supported, and (5) whether we will be able to successfully coordinate with bathymetric and soil mapping.

While clearly authored and peer-reviewed geologic maps and reports will remain the foundation of our knowledge on regional geology, users increasingly will demand the ability to quickly and efficiently obtain geologic map information via the Web in order to efficiently do their jobs on a day-to-day basis.

New layers of Web-optimized mapping therefore will be required to facilitate efficient Web accessibility, and also to act as a gateway to more detailed maps and reports. We thus require consistent and readily queried geologic map data layers, at 1:25M, 1:5M, 1:1M, and 1:100K, each matched appropriately to accompanying 3D content.

3D GEOLOGICAL MAPPING: AN INESCAPABLE EVOLUTION FOR NATIONAL GEOLOGICAL SURVEYS

Catherine Truffert

BRGM, France. C.truffert@brgm.fr

According to EuroGeoSurveys, the European Geological Surveys association, "Geological spatial data and models describe the solid Earth's surface and subsurface on-shore and off-shore, its nature, structure, properties, dynamics and evolution over time; including its related (geo)resources and (geo) hazards". This illustrates a modern vision of the core mission that National Geological Surveys have to accomplish.

CURRENT STATUS: THE NATIONAL GEOLOGICAL SURVEYS

Within the private sector, exploration decisions are increasingly requiring that geoscientists assess more complex data quickly and efficiently. Building 3D models of the data has been recognised in private industry to assist in making the best decisions in the required time frames. The use of 3D geological models to aid in the interpretation of Geosciences has grown in a progressive way since the early 1990s. Initially this technology was focused primarily on oil and gas exploration and required performing computers to drive the applications. Mineral exploration, such as for oil and gas, has progressively evolved from the migration of 2D GIS applications into 3D applications. Now it is very common for such industries to use 3D modelling for decision making support.

Concurrent with oil and gas and mineral exploration challenges, European National Geological Surveys are in charge of (1) collecting, processing, and disseminating the information related to geological infrastructure, and (2) transforming the geosciences information into helpful models. Most of them have already achieved a first edition of National Geological Maps and performed geophysical survey programs that provide a first level of information, concerning mainly outcropping geological formations and physical parameters. Moreover, in most sedimentary basins in Europe, seismic profiles and drill holes have been carried out mainly for oil and gas exploration and constitute highly valuable datasets that become progressively available in the public domain. Crystalline basement domains and mountains are less documented except for some places which have been studied for mining exploration. Offshore, the continental plateau has been recently studied by Exclusive Economic Zone programs.

National Geological Surveys must both address the challenge of the near-end of 2D conventional geological mapping, catch the opportunities offered by the fast development of new technologies in geology, geophysics, and remote sensing, and then produce 3D modelling informed by geological unit's physical properties and uncertainties. These models need to be based on geostatistics, information technologies, and interoperability rules.

All of these new challenges, linked to environmental, social, and economic constraints within the realm of sustainable development, define a global perspective for European geological surveys and lead them to adapt their practices and anticipate future needs.

First, appropriate answers must be provided to new challenges that will drive their activities for the next 20 years: climate change and its impact on erodability of cultivated lands and water resources, mitigation and risk assessment, land and underground uses, and conflicts of interest (water and geothermal resources, CO_2 storage, etc). National Geological Surveys must provide new vectors to disseminate the knowledge of the surface and underground geology that satisfies 3 main conditions:

- Although in situ observations are rare and discontinuous underground, quantification of any physical parameters in a 3D space, with an estimated accuracy and uncertainty, will more and more become a requirement for all underground works and monitoring projects. All efforts in processing, reprocessing, and acquiring data should then converge towards the building of a continuous 3D geometrical reference model and the calibration of the physical properties of the main lithotypes.
- The vectors of dissemination must facilitate the interfacing between scientific knowledge and decision makers by providing this knowledge through 3D models and 3D information systems.

- Available data systems and models must be updated to best integrate new datasets as soon as they are available and to make them compatible with all data sources that concur with the Global Earth Observation.

This is the right time for National Geological Surveys to think about the geological infrastructure, products, and services of the future, beyond the current 2D geological layers. Three-dimensional information systems and models are part of the solution of the issues that the political realm will have to address to secure the well-being of tomorrow's world.

ONGOING RESEARCH

BRGM has more than 10 years experience in 3D modelling. This National Geological Survey used to deal with geostatistics as decision-making support for mineral exploration, its former scope of work. As soon as computers were able to take into account reasonably large datasets, BRGM started developing 3D modelling software based on geostatistics rules. 3D information systems have also been designed to address public requests. All of them meet inspirational objectives for total interoperability.
Two different software packages were born from BRGM's Research and Development efforts:

- GDM MultiLayer, dedicated for data control and layer cake modelling;
- 3D Geomodeller for more full 3D geological modelling (Calcagno et al. 2008). Geological knowledge of the chrono-stratigraphic sequence of geological events, and the tectonic-relationships between the geological bodies, allows automatic computation of intersections between geological bodies.

These are respectively used to model (i) sedimentary basins not much affected by tectonic events and (ii) crystalline basement or mountains areas. The choice from one to the other is guided by the degree of tectonic complexity of the model. Particular attention has been paid to allow 3D modelling in complex geometries, as well as in the medium to deep underground, which become eagerly expected by new sustainable development challenges (e.g., ground-water, geothermal energy, and CO2 storage).

APPLICATIONS AND EXAMPLE

Through an iterative process of visualisation and interpretive review by the geologist, an improved and realistic 3D geology model can be developed. The 3D modelling task is not only the last segment in the study process, it can be introduced very soon in the study process to verify hypotheses and/or may be an input for simulations used to quantify physical processes.

Demand is increasing for 3D modelling of underground reservoirs because of applications for ground-water management, oil and gas exploration, and CO2 storage. Therefore, it is now obvious that facies and petrophysical properties control flow and have to be implemented in the model. This, in turn, requires that National Geological surveys must collect and attribute physical parameters, as well as facies, to each geological component.

Three-dimensional modelling in complex geological areas is illustrated by the "Vallée des Ponts-de-Martel" example (Figures 1, 2 and 3). The Jura Mountains in Switzerland have springs as Noiraigue for which water comes from a karstic aquifer. The geometric model has been built using Geomodeller. The objective of this modelling was for flow simulation. Simulation is possible when the "geometric model" have been transformed to a "parameters model".

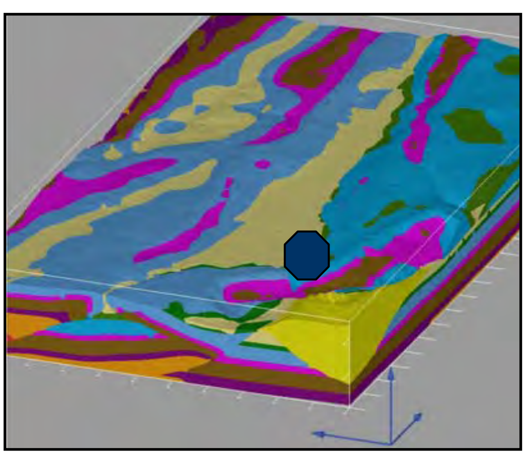

Figure 1. Three-dimensional model of the "Valee des Ponts de-Martel" (Jura Mountains, Switzerland). Noiraique Spring drains the karstic aquifer (blue dot). Courtesy of University of Neuchatel.

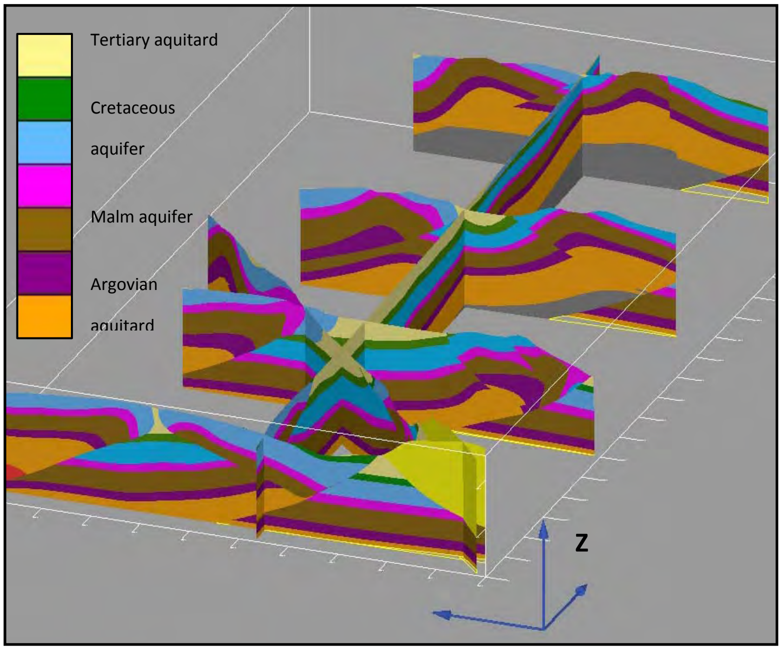

Figure 2. Cross sections within the 3D model.

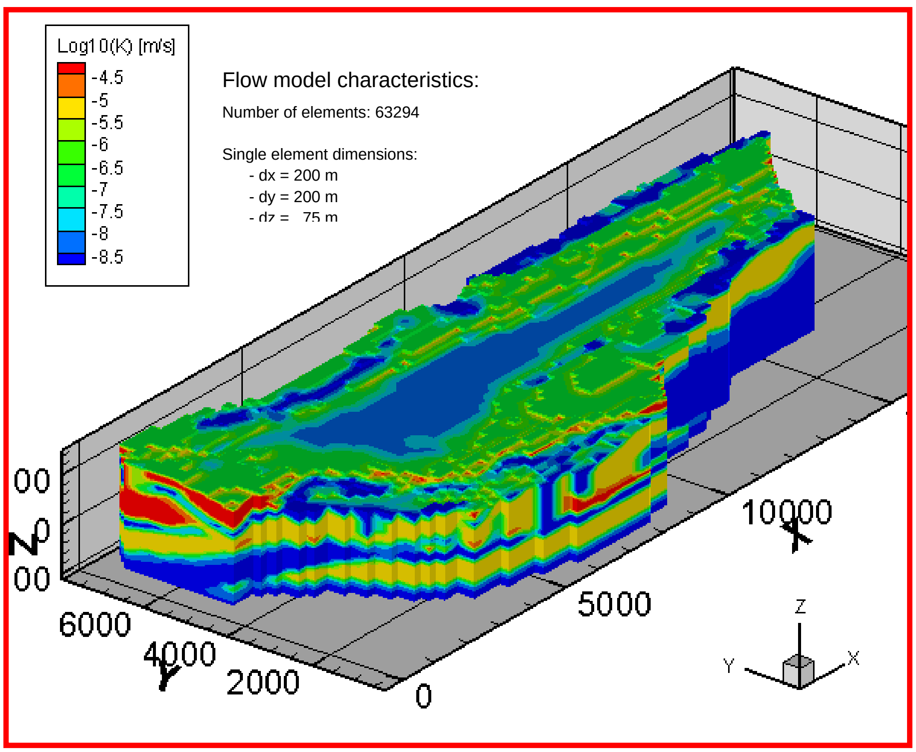

Figure 3. Conversion to 3D hydraulic parameters for flow simulation.

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THE ROLE OF GEOLOGICAL MODELING IN A WEB-BASED COLLABORATIVE ENVIRONMENT

Keith Turner[1] and Frank A. D'Agnese[2]

[1]Colorado School of Mines, Golden, Colorado, 80401, USA, kturner@mines.edu, [2]Earth Knowledge, Inc., Tucson, Arizona 85716, USA, frank@earthknowledge.net

INTRODUCTION

Over the past two decades, a series of sophisticated three-dimensional modeling technologies have been developed to address the need for a precise definition of subsurface conditions (Turner, 1991). Because geological modeling requires the extension of traditional GIS methods (Turner, 2000; 2006), the modeling process remains technically challenging. In 2001, during a conference sponsored by the European Science Foundation, four major impediments to the greater use of subsurface geological modeling by a broad spectrum of users were identified (Rosenbaum & Turner, 2003). These constraints were: (1) a lack of 3D/4D mathematical, cognitive, and statistical spatial tools, (2) a lack of cheap modeling tools designed for the shallow subsurface that can be operated without specialist personnel, (3) the inability of models to depict natural variability of geological systems, and (4) a shortage of case histories. By 2008, these constraints had been largely overcome with the use of new modeling software and techniques and, importantly, with an understanding of the needs of the client (Kessler, *et al*., 2008).

Unlike the older resource-industry-based user-community, many of today's potential users of geological models and visualizations cannot interpret basic geoscience data or evaluate the merits of alternative interpretations. They may be unable to distinguish between theories and facts. In short, these new users clearly desire "*solutions, not data*" and "*information in understandable form*" (Turner, 2006). Society increasingly demands that earth- and environmental-resource issues be evaluated and addressed by interdisciplinary investigators from the scientific, engineering, planning, and regulatory communities. Often these investigators are required to interact with a larger community of public stakeholders. These investigators, also, by necessity, develop databases and models derived from disparate data sets that are often large, complex, and vary dramatically in scale and quality.

Two critical technological innovations can assist participants engaged in these societal decision-making exercises: (1) second-generation internet, or Web 2.0, technologies and hosted services facilitate communication among online groups belonging to Web-based communities, and (2) client- and Web-based 2-D and 3-D visualization systems (including Google Earth and Google Maps).

THE GEOLOGICAL MODEL-BUILDING PROCESS

Figure 1 illustrates the steps in a typical geological modeling process. Raw data collected from various sources can be considered as two types – spatial data and properties data. The spatial data are used to create a 3-D geometry model, shown on the left-hand side of Figure 1. Geometry modeling involves two steps – first the development of a suitable geometric representation of the fundamental "geological framework," and subsequently the subdivision, or "discretization," of this framework to allow for the attribution of spatially varying properties. Discretization also supports analytical computations within the numerical models used in predictive modeling. The horizontal arrow linking the discretization and analytical modeling operations in Figure 1 defines this linkage.

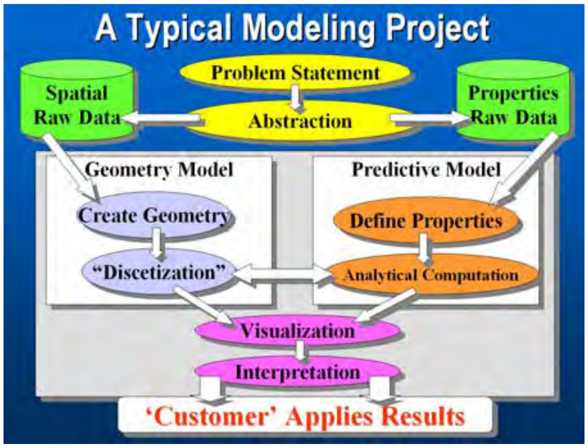

Figure 1. Overview of the geological modeling process.

An accurate representation of the geological framework allows for 3-D visualization, but even more importantly defines and controls the spatial distribution and propagation of rock-properties required by modeling. Sedimentary environments are usually modeled by creating surfaces defining the strata interfaces, stacking the surfaces in stratigraphic order, and subsequently defining the zones between surfaces as geologic units. Construction of individual surfaces generally proceeds by one of three methods: (1) using the borehole observations to create triangles defining a surface, (2) applying surface generation and contouring procedures to borehole observations, or (3) developing a series of interpretive cross-sections between boreholes. Regardless of the method used, several problems remain. Surfaces created independently may intersect each other in geologically impossible situations, thus careful review and editing of all surfaces is usually required to allow for areas of erosion or non-deposition (Turner, 2006; Turner & Gable, 2007). Figure 2 is an example of a 3-D geologic framework model of a layered sedimentary environment – a part of the Edwards Aquifer in Texas.

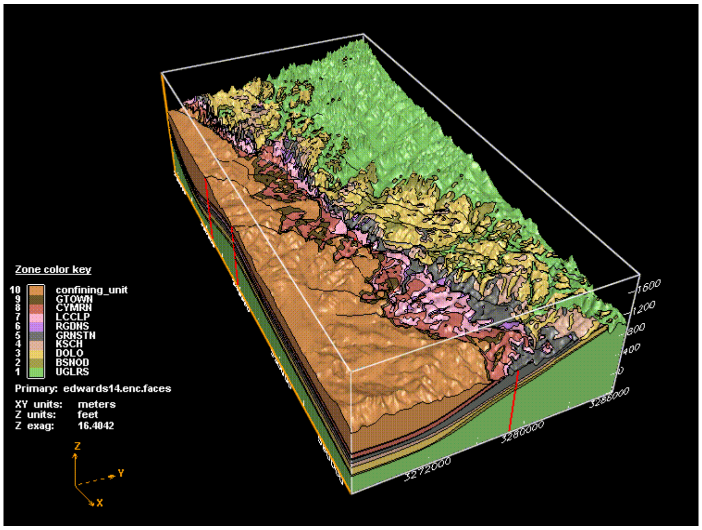

Figure 2. Overview of the Edwards Aquifer stratigraphic model (Pantea & Cole, 2004),

Other techniques are used to model regions with complex geological structures, or without layered sequences. One approach is to develop a series of complex shapes enclosing volumes derived from a series of interpreted cross-sections. The individual volumes must share common bounding surfaces so that there are no voids or overlapped volumes. Several 3-D modeling products used by the mining industry provide such model building capabilities (Houlding, 1994). An alternative approach begins with an entire regional volume and then progressively subdivides it into regions with a series of intersecting surfaces that represent major discontinuities such as shear zones or faults. The various regions may have distinct material properties with oriented anisotropies or gradients, while the discontinuity surfaces may also be assigned widths and unique properties (Turner, 2006; Turner & Gable 2007).

A number of modeling tools have been proposed to assist the accurate representation of faults. Rock strata on opposite sides of a fault may have similar or different thicknesses and characteristics depending on the type of fault and the temporal relationships between the depositional processes and the faulting. Faults may provide preferential conduits for fluid flow, or they may act as barriers to flow. They typically add anisotropy to property distributions required by the numerical models. Vertical, or nearly vertical, faults and nearly horizontal thrust zones can be defined by adding additional surfaces to the existing stratigraphic models (Figure 3). This increases the complexity of model creation, but otherwise is relatively straightforward. Moderately inclined faults present greater modeling difficulties.

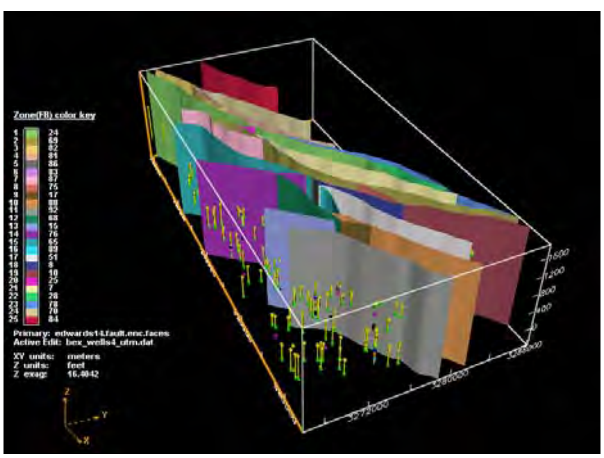

Figure 3. Overview of faults and wells contained within the Edwards Aquifer model (Pantea & Cole, 2004).

Property distributions are generally modeled by applying discretization methods to subdivide the framework objects into a series of small elements. There are two broad classes of meshes – structured and unstructured (Turner, 2006;

Turner & Gable, 2007). Available commercial geological modeling products mostly use basic structured meshes – a 3-D volume is divided into discrete cubical “volume elements”, or “voxels.” Unless the cell dimensions are very small, important geometric details may be lost, but small cells produce extremely large model files. Hierarchical cells provide greater flexibility in adapting grid resolution to where it is needed – in 3-D, the “octree” representation provides this functionality. Unstructured meshes are not constrained by having to have a constant node and face structure, and can link with finite element models. Three-dimensional unstructured meshes, based on tetrahedrons, hexahedrons, are particularly useful in modeling faults and fracture discontinuities (Figure 4). This provides added flexibility during model development, but this flexibility comes at a price: added computational demands and more effort in model construction that requires use of sophisticated mesh generation software (Gable, et al., 1996).

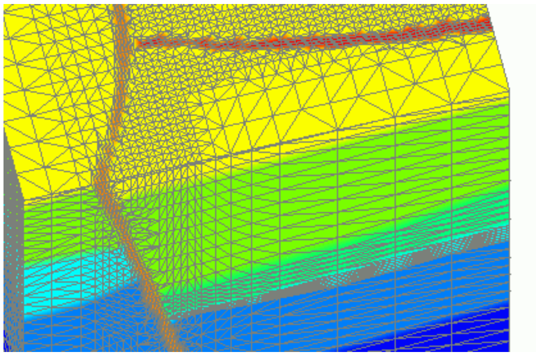

Figure 4. A 3-D unstructured mesh model of a faulted layered sequence (Source: Carl Gable, Los Alamos National Laboratory)

As shown on the right-hand side of Figure 1, the primary objective of subsurface geometry modeling is to provide geometric controls and property distributions for some type of analytical modeling, and the purpose of this analytical modeling is prediction. Prediction has an extrapolative rather than interpolative character; thus it involves risk and uncertainty. Prediction leads to decision-making. Predicted results often require supporting visualizations and interpretations that can be presented to and used by the “customer” of the modeling results (Figure 5).

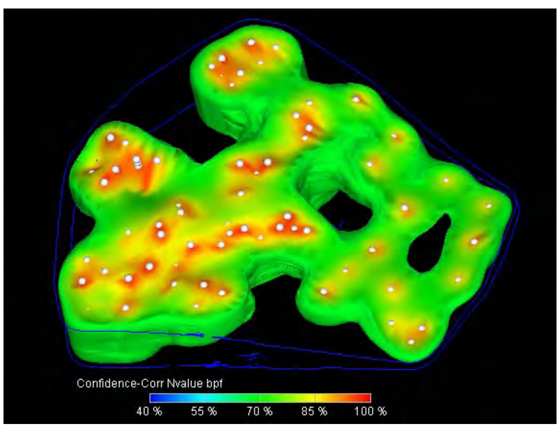

Figure 5. A 3-D predictive model showing confidence levels of the density of till underlying the Boston financial district (Source: Laurie Baise, Tufts University).

THE ROLE OF 3-D MODELS IN A WEB-BASED COLLABORATION ENVIRONMENT

The entire 3-D geological modeling process is but a single component of a much larger, modular “Internet-based Earth-Systems Monitoring, Analysis, and Management Tool” (Figure 6) that provides the essential earth-science business and data-management processes required for Web-based collaboration in an “Earth-Systems Investigation Enterprise”. The “Knowledge Portal” and the “Collaboration Environment” are key additional components required to function successfully within a Web-based collaborative enterprise. These components provide users with the capability of searching, discovering, posting, mapping, visualizing, and archiving data, information, news, and commentary. They also provide essential enterprise security and control functions, including user interaction and access, group management, and content management (Figure 6).

Visualizing 2-D maps and 3-D models is a critical function of the tool’s “Knowledge Portal” that also should allow users the ability to query, explore, comment on, and potentially contribute additional data and information to, these models. Utilization of tools such as Google Maps and Google Earth permits a richer fusion of these models with information that previously has not been viewed in the context of 3-D models, including scientist or other user-contributed photos, video, audio, wikis, Web-logs, and online news.

In contrast to Web-based data management and analysis systems designed to serve the scientific community, a platform that employs “off-the-shelf” and consumer-oriented, hosted Web-services better reflects the information needs and Web-interface usage behavior of the general public. An early form of these tools and services is being used to facilitate the investigations and conversations of scientists, resource managers, and citizen stakeholders addressing water-resource sustainability issues in the Great Basin region of the desert southwestern United States (Figure 7).

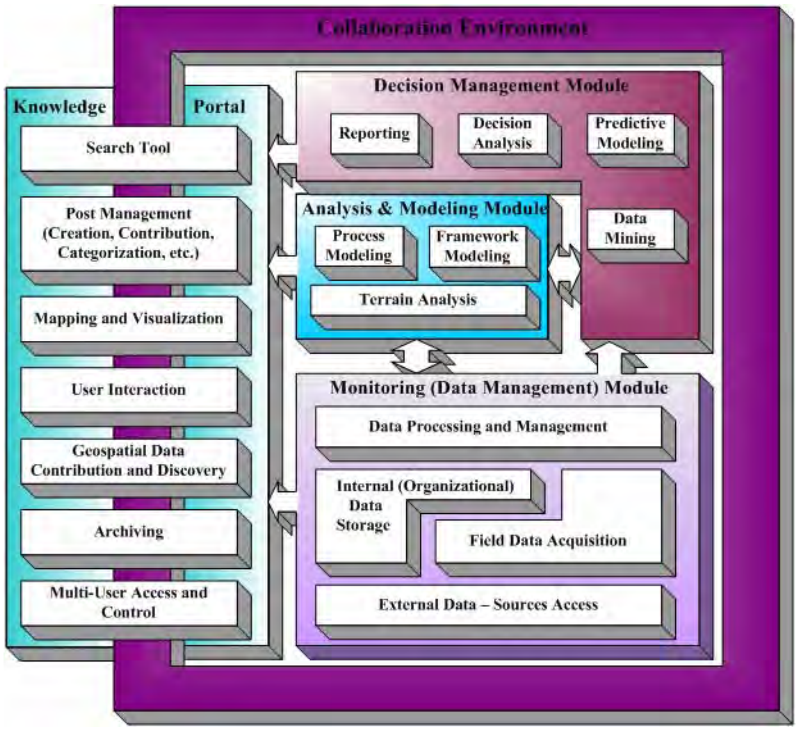

Figure 6. The modular components of the Internet-based Earth-Systems Monitoring, Analysis, and Management Tool.

The Knowledge Portal and Collaboration Environment are the essential information-technology building blocks of the larger platform.

Figure 7. A volumetric model of a portion of the aquifer systems in the Great Basin, southwestern United States visualized in Google Earth.

During the past decade, several European, Canadian, and American geological surveys have gained considerable experience with applying existing commercial technologies to create 3-D geological framework models. These models have been developed for a variety of geological situations at various scales and levels of geologic complexity. Large advantages have been demonstrated when such models have been linked to numerical models of physical processes, specifically ground-water flow models, to provide specific and quantifiable answers to decision makers. Yet, these experiences clearly demonstrate that computer technology alone cannot enable geoscience knowledge integration. Rather, they emphasize that human-computer interaction must be supported by a 'geoinfrastructure' that contains integrated, formalized, and fully documented protocols. O'Brien, et al. (2002) define such a 'protocol' as equivalent to a 'business process' and specify that appropriate protocols contain the rules that define the data flow, sequencing of events, techniques, and standards that integrate various inputs to create a measurable output. Thus, widespread future use of geological models will require adoption of Web-based tools that are familiar to, and accessible by, the general public, making geological modeling and visualization accessible to a broader user base. This will support increased collaboration, which will, in turn, result in better models and greater applicability to societal needs.

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FROM 2D CROSS-SECTIONS TO A 3D MODEL: A TOOLSET FOR INTEGRATED DATA MANAGEMENT, MODELING, AND VISUALIZATION

Nat Voorhies[1], Scott Bowen[2], Tom Battenhouse[3], Rob Porges[3], and Tad Fox[3]

[1]SAIC, Oakland, CA, USA, [2]Tinker AFB, Oklahoma, USA, [3]SAIC, Twinsburg, OH, USA, voorhiesn@saic.com

ABSTRACT

Two-dimensional (2D) cross-sections are a common aid in understanding three-dimensional (3D) subsurface conditions for purposes including environmental restoration, water resource evaluation, and resource extraction. This case study describes translation of the institutional knowledge and interpretations captured on existing 2D hydrogeologic cross-sections into an integrated, dynamic 3D hydrogeologic framework model that flexibly supports site goals. A premium is placed on automation and structured data management, allowing geoscientists to focus on visualization and analysis rather than on data manipulation and model assembly.

INTRODUCTION

Tinker Air Force Base (AFB) is a major logistics center and aircraft, weapons, and engine repair depot located in Oklahoma City, OK. As a result of past waste handling practices, contaminants (primarily chlorinated solvents) are present in groundwater at the Base. Groundwater contamination occurs primarily in the Garber sandstone, which is present across the entire Base and outcrops over the northeastern portion of the Base. Contamination decreases with depth in the Garber sandstone, but extends up to about 200 ft below ground surface (BGS) in some areas. The Garber sandstone is overlain by the Hennessey Formation in the southeast portion of the Base. The Garber sandstone and the underlying Wellington Formation are the main geologic units comprising the Central Oklahoma Aquifer, which is the primary source of potable groundwater in the Oklahoma City area and the water supply source for the Base (via water supply wells perforated between approximately 200 to 750 ft BGS). The Garber sandstone was deposited in a fluvial-deltaic environment and consists of lenticular beds of fine-grained, cross-bedded sandstone interbedded with siltstone, mudstone, and shale. The lower conductivity mudstones/shales exert strong control on groundwater flow and thus contaminant transport, especially where their lateral continuity is greater. Beneath the Base, two laterally continuous mudstone aquitards have been identified within about 200 ft of ground surface. Head differences of approximately 20 to 150 ft occur across these aquitards. Within the intervening aquifer units, vertical head differences are near zero in areas where the intra-aquifer mudstones have little lateral continuity and up to 20 ft in areas of greater mudstone continuity.

HISTORICAL CROSS-SECTION DEVELOPMENT

Given the aforementioned geologic controls on groundwater flow and contaminant transport in the Garber sandstone, a thorough understanding of the hydrogeology is critical for predicting potential future impacts due to existing contamination at the Base and for designing effective remedies. To this end, the Base geologist developed over 130 hand-drawn hydrogeologic cross-sections (Figure 1) beginning in the early 1990's. The lack of key marker beds in the Permian strata necessitated the development of a consistent methodology to correlate sandstone and mudstone lithologies between adjacent boreholes. The methodology includes the following:

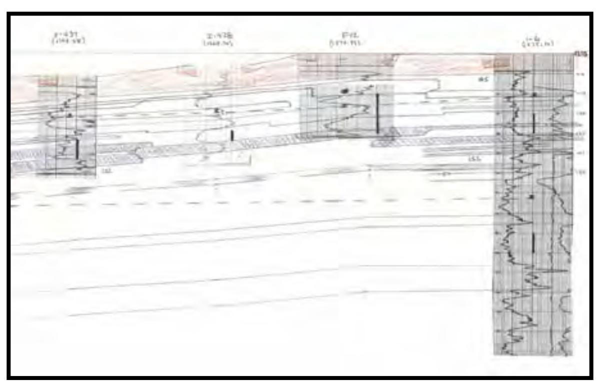


Figure 5. Base geologist's cross-section

- Use of wireline logs (primarily natural gamma) and cores to define downhole lithology
- Use of the published formation structure (strike and dip), the depositional environment (fluvial deltaic), and the Hennessey-Garber contact (in southwest part of Base) to guide correlations
- Use of water level and groundwater quality data in conjunction with wireline logs and cores to define primary HSU boundaries

- Development of standard unit thickness for HSUs from borings in the northeast quadrant of the Base and application of these rules of thumb throughout the Base.

Although the latter two items refer specifically to HSU boundaries, these are critical elements in identifying the several relatively continuous mudstone lithologic bodies that comprise aquitards within the Garber sandstone.

IMPETUS FOR 3D MODEL CONSTRUCTION

The Base geologist's cross-sections have been an invaluable tool in the groundwater restoration process at Tinker AFB. Construction of a 3D hydrogeologic framework model (HGFM) from these cross-sections captures the interpretations and institutional knowledge of the Base geologist in an integrated, dynamic model that can flexibly support ongoing Base restoration. Traditional 2D mapping products (cross-sections and plan-view maps) can be produced from this 3D model in an automated fashion, and the model supports a range of activities from drilling to numerical model construction to stakeholder communication.

DATA DEVELOPMENT AND MANAGEMENT

The foundation of the 3D HGFM is sandstone versus mudstone lithologic determinations made in 1-ft intervals at nearly 1000 boreholes distributed across the Base. Lithology is assigned using gamma log data and supplemented by the interpretation on the Base geologist's cross-sections. Thus, additional information available to the Base geologist, such as lithologic core data, contributes to the lithology assignment. A total of 927 gamma logs are interpreted. Gamma data are from digital files in 477 cases. The remaining 450 gamma logs were available only in hard-copy format and were manually digitized using a structured workflow that ensured accuracy, efficiency, and traceability. Where multiple gamma runs are available for a given well, a composite log is spliced from the open-hole portions of each run to avoid signal degradation introduced by the well casing. Lithology is assigned to two categories: sandstone (including siltstone) and mudstone (including shale).

Hydrostratigraphic unit picks are also essential to construction of the 3D HGFM. Draft picks for five HSU horizons were made from the HSU interpretations on the Base geologist's cross-sections. These were refined via inspection of 2D contour maps developed from these horizon picks and analysis of the 3D HGFM developed from the HSU and lithology picks. For wells not included on the Base geologist's cross-sections, HSU picks were made with the assistance of 2D contour maps and temporary cross-sections cut through the 3D HGFM.

Other important data in the 3D model include topography, potentiometry, well construction details, and the locations of surface features. The topography is developed from a LIDAR DTM and is warped to honor available surveyed ground surface elevation data. Potentiometric data and existing potentiometric surfaces (available as 2D grids) from a representative monitoring event are incorporated into the 3D framework. Well construction data including filter packs and screened intervals are from a Tinker AFB well database or original well construction diagrams. Surface features such as water bodies, roads, buildings, airfield, and property boundaries are incorporated from a GIS maintained by Base Civil Engineering.

Data is managed in a Microsoft SQLServer 2005 database, with a suite of data interfaces and import/export tools permitting efficient data insertion, editing, and exporting for model construction. These tools encompass critical steps in the workflow and allow the database to be used both as a reliable container and a dynamic device for tracking data updates. The underlying data manipulation is built into the database as stored procedures and accessed via push-buttons in simple front-end applications.

MODEL CONSTRUCTION

The 3D model is constructed using Dynamic Graphics® earthVision® software and reflects lithologic interpretations (sandstone versus mudstone/shale) within six HSUs. Mudstone/shale is differentiated from one HSU to the next, yielding a total of six mudstone/shale 'categories'. Sandstone is not differentiated across HSUs. Thus, the model includes a total of seven categories. Input data for these seven categories are generated by assigning each mudstone/shale lithologic pick to one of six HSU-based categories (depending upon where lithologic picks lie vertically relative to the HSU picks for that well) and assigning each sandstone pick to a seventh category. Next, for each input data point, a data field is generated for each of the seven categories. These data fields are indicators; for example, if a given data point is sandstone, then the sandstone field value is 1, otherwise it is 0.

From each of these seven binary fields, a corresponding 3D grid is developed. For example, a sandstone 3D grid is generated by gridding the sandstone field 1's (sandstone) and 0's (not sandstone). A deterministic gridding algorithm is used rather than a geostatistical approach (however, alternate geologic realizations are currently being constructed and explored using transition probabilities geostatistics). A minimum tension gridding algorithm is used, which yields grids that closely honor the input data without unnatural-appearing predictions in areas lacking input data. The lithologic bodies are conformed to the regional strike and dip throughout much of the Base and to the Hennessey-Garber contact in the southwest portion of the Base. Values in each of the seven category 3D grids range between 0 and 1 and can be thought of as pseudo-probabilities that a given category exists at that location (the term 'pseudo-probability' is used here because a geostatistical approach is not used in developing the 3D grids). A 3D grid representing the combined lithologic-hydrostratigraphic interpretation (Figure 2) is produced by assigning to each grid node the category with the highest value (pseudo-probability) among the seven category grids at that node.

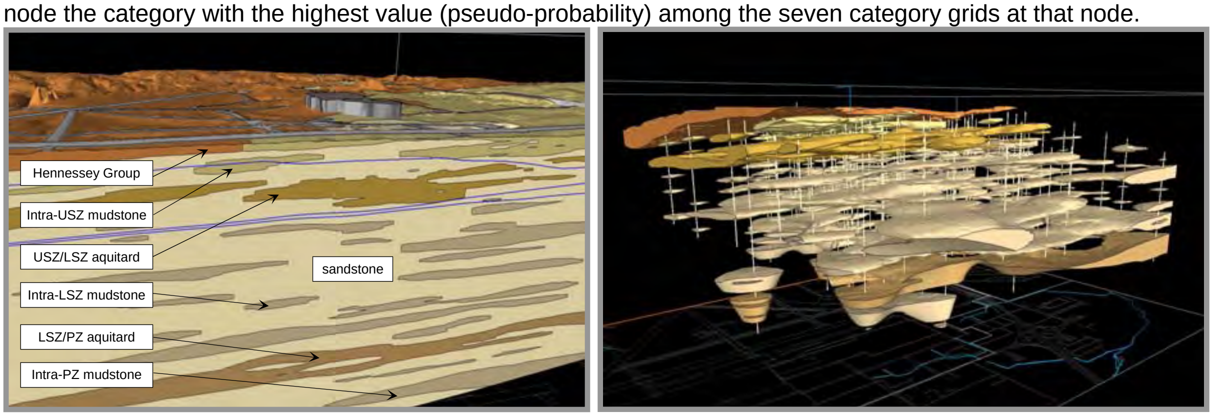


Figure 2. 3D Hydrogeologic framework model in section view (left) and with sandstone removed (right).

The interpreted lithologic and HSU contacts are quality checked via visual inspection of the 3D model, contour maps of the HSU contacts, and cross-sections cut from the 3D HGFM. The model is built iteratively by updating data interpretations and reconstructing the 3D HGFM. Model construction is automated via flexible scripts, freeing project geoscientists to focus on model visualization and analysis rather than model assembly.

Additional data types, including potentiometry and surface features (e.g., roads, buildings, surface water), are integrated into the 3D model to facilitate 3D visualization and analysis with the lithologic and HSU interpretations. The toolset developed for this project allows automated, spatially-accurate placement and labeling of these disparate features on cross-sections cut from the integrated 3D model.

MODEL APPLICATIONS

The 3D HGFM has been and will continue to be used to support Base restoration activities. Applications to-date include:

- The model was used to cost-effectively produce digital versions of the Base geologist's hand-drawn cross-sections, while refining interpretations and ensuring consistency across sections. Cross-sections include lithology, HSUs, potentiometric surfaces, well data (gamma logs, filter packs, screen intervals), surface features (water bodies, roads, buildings), and a polished layout (Figure 3). Custom automation tools allow the production of any desired cross-section in ten minutes.

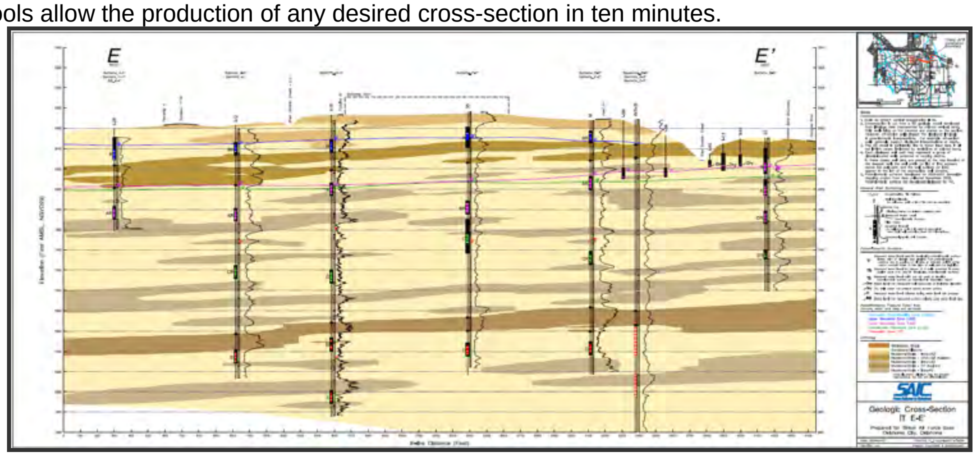


Figure 3. Automated, production-quality cross-section cut from 3D hydrogeologic framework model.

- The model is being used to help underpin a new exit strategy for a contaminated groundwater unit.
  - o The 3D HGFM was used to construct the lithology for a multi-phase model that was utilized to simulate TCE vapor migration and to assess soil vapor extraction as a remedial option.
  - o Cross-sections were cut through the planned locations of three deep, multi-level wells prior to installation to identify monitoring intervals and evaluate consistency of new field data with the current site understanding. Real time cross-sections facilitated decision-making in the field.
  - o Visualization of 3D contaminant models and potentiometric data within the 3D HGFM provided insights into contaminant source area definition, contaminant mass distribution within the subsurface, and potential past and future plume migration pathways.
  - o The project database is currently being evaluated to assess the likelihood of continuous sandstones that could act as preferential pathways through the mudstone aquitards.
- An initial phase of 3D modeling of groundwater quality data within the HGFM has been completed (Figure 4). 3D contaminant models can be used to (1) improve communication among stakeholders, (2) facilitate better understanding of the current contaminant distribution and transport pathways at the Base, (3) define initial transport conditions for predictive solute transport modeling, (4) estimate volume of impacted media, (5) estimate mass distribution in system (sandstone versus mudstone), and (6) inform remediation methods and timeframes (remedies may be prolonged if substantial mass has diffused into mudstones, and *in situ* remedies need to be designed around reagent delivery for optimum effectiveness).
- Alternate geologic realizations are currently being constructed and explored using transition-probability geostatistics (TProGS). The data and the streamlined toolset developed during generation of the 3D HGFM provide a solid foundation from which to do this geostatistical analysis. These alternate geologic realizations will be evaluated in an existing numerical flow and transport model, and as such will contribute to understanding of uncertainty in the model predictions.

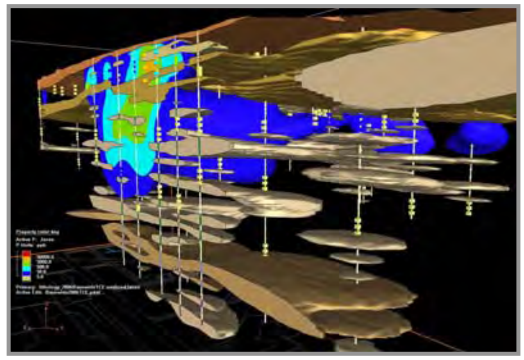


Figure 4. Integrated 3D HGFM & TCE Model.

Next steps include customizing an existing Web portal to allow (1) access to the project database and cross-sections in a GIS framework, (2) visualization of well construction and interpretation details, and (3) dynamic model updates and section generation. Additionally, faults can be included in the 3D model to first understand the relationship between faulting and the underlying geologic structure, and then to test the potential impact of faulting upon groundwater flow and contaminant transport.

CONCLUSIONS

Two-dimensional cross-sections are traditionally used to understand and communicate 3D subsurface conditions for environmental restoration sites. In this case study, the knowledge and interpretations captured on existing 2D cross-sections were readily translated into a 3D HGFM. To-date, the 3D HGFM and the underlying data and toolset have been used to

- cost-effectively produce digital versions of the Base geologist's original hand-drawn cross-sections while refining interpretations and ensuring consistency across cross-sections,
- underpin a new exit strategy for a contaminated groundwater unit via real-time cross-section generation to support field work, identification of contaminant source areas and migration pathways, construction of a multi-phase SVE model, and evaluation of potential preferential pathways through aquitards, and
- initiate development of alternate conceptual lithologic models that contribute to understanding of the uncertainty in predictions from a numerical flow and transport model.

Given current 3D modeling software capabilities, the availability of digital borehole data, and the customized toolset developed here, overall project objectives at new sites can be more efficiently met by developing a dynamic, integrated 3D model than by synthesizing a series of static 2D cross-sections. Data collection for a 3D model involves the same data types as for a single 2D cross-section (e.g., formation strike and dip, key marker beds, formation contacts, lithology, well construction, potentiometry, topography, surface features). Moreover, although this case study uses the lithologic correlations in the existing site cross-sections as the foundation for the 3D model, lithologies are more efficiently correlated using the fundamental 3D lithologic modeling technique described here. During initial model iterations, a “pure” lithologic model (e.g., sandstone versus mudstone) can be built. Correlations can be visualized and analyzed with this initial model, and the input lithologic data can then be categorized by HSU to efficiently build a combined lithologic-hydrostratigraphic model. The customized toolset and structured data management strategy expedites construction of the 3D model. The tools and methods developed here can be applied readily to other sites to support objectives beyond environmental restoration, including water resource evaluation, resource extraction, and carbon sequestration.

CONTRIBUTION OF GEOPHYSICS TO GEOLOGICAL MODELS

Helga Wiederhold[1], Reinhard Kirsch[2], and Wolfgang Scheer[3]

[1]Leibniz Institute for Applied Geophysics, Stilleweg 2, 30655 Hannover, Germany, [2]Technical University Berlin, Angewandte Geophysik, Ackerstr. 71-76, 13355 Berlin, Germany, [3] Landesamt für Landwirtschaft, Umwelt und ländliche Räume Schleswig-Holstein, Hamburger Chaussee 25, 24220 Flintbek, Germany, helga.wiederhold@liag-hannover.de

INTRODUCTION

The near surface underground of the North European Basin (Belgium, The Netherlands, parts of Germany, Denmark, and Poland) is mainly composed of gravel, sand, till, and clay of Quaternary and Tertiary origin. Although originally more or less horizontally layered, disturbances of the layer sequence by glacial tectonics (especially deep erosional valleys) and uplift of salt domes are frequent (Figure 1). This can lead to complicated underground structures which make the correlation between boreholes difficult or impossible. Therefore, geophysical measurements are an essential tool for the construction of geological models.

The application of geophysical techniques, especially seismic and resistivity methods, for geological modeling is demonstrated in this paper. Technical developments of the last decades allow excellent reflection seismic results even in the near surface depth range. With resistivity techniques, the distribution of clay free material (sand, gravel) and clayey material (till, clay) can be achieved. Airborne electromagnetic techniques allow a fast mapping of the clay-sand distribution. Combining the results of seismic and resistivity techniques lead to underground models that show, e.g., for hydrogeological purposes, the sequence of groundwater bearing layers and clayey dividing layers.

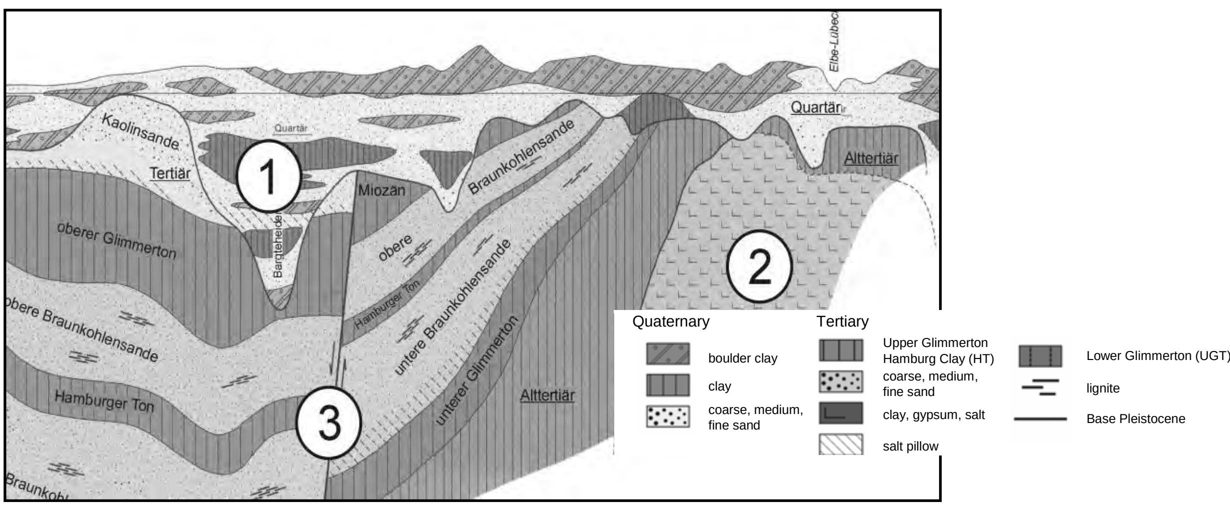


Figure 1. Typical underground structures of the North-European Basin: (1) buried Pleistocene valleys, (2) salt domes, and (3) faults.

EXAMPLE 1: BURIED VALLEYS

A system of buried valleys was created in the North European Basin by subglacial erosion during the ice ages. Filled with sandy material, these are of great importance for water supply. In the scope of the project, BurVal geophysical techniques were applied to survey buried valleys in Denmark, the Netherlands, and Germany. Reflection seismic measurements make the (mainly asymmetric) shape of the buried valley visible giving information of its depth, extent, and the contact to the surrounding layers. For material identification of the buried valley and surrounding deposits, airborne electromagnetic surveys (time and frequency domain) were flown.

As an example, the superposition of the vertical resistivity section to the seismic section (Figure 2) shows that the buried valley is carved into Tertiary clay layers (blue, low resistivities), while the valley fill consists, at least partly, of sandy material (red, high resistivities). These sandy regions are covered by a clay layer (blue). Because of the low permeability of the clay, a good protection of the sandy valley aquifer is provided (see also Figure 3).

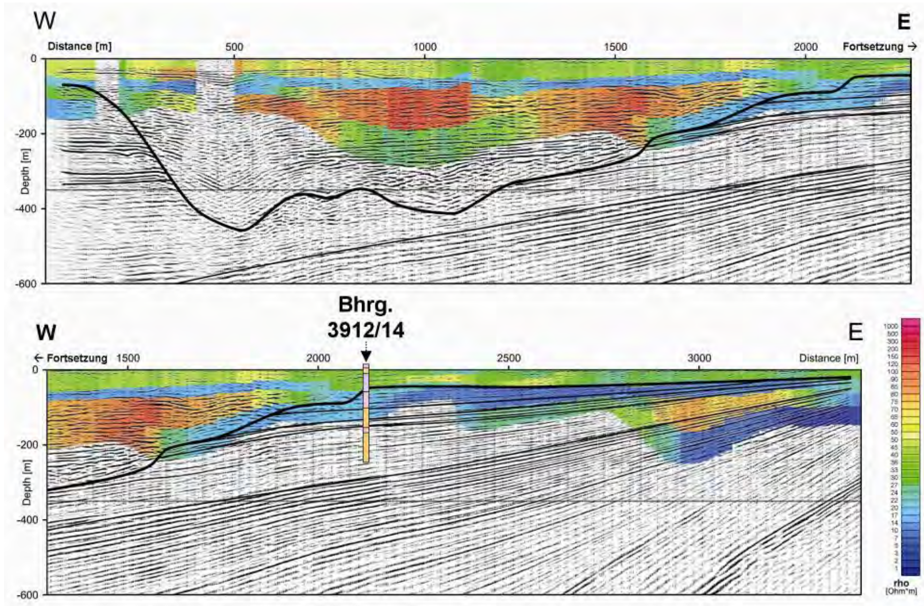
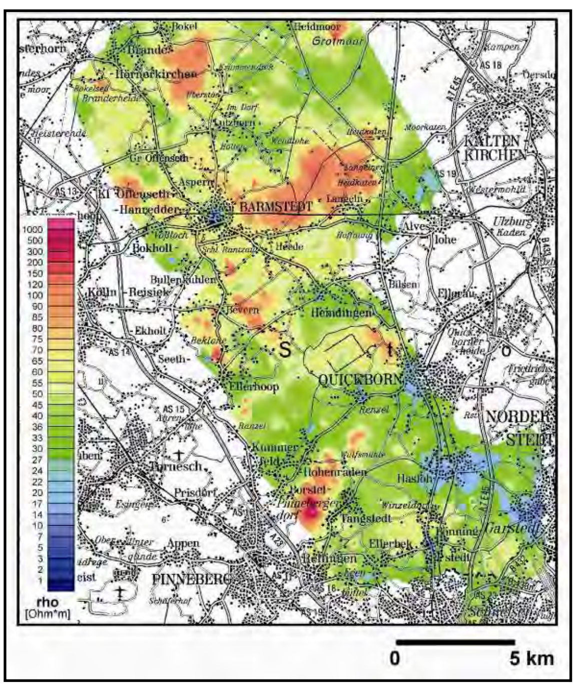


Figure 2. Seismic image of a buried valley with superimposed electrical resistivities from an airborne electromagnetic survey (Department of Earth Sciences, University of Aarhus, Denmark). Low resistivities (blue) refer to clayey material, while sandy material is characterised by high resistivities (red).



Airborne electromagnetic surveys can cover large areas leading to the 3 D distribution of electrical resistivities. Sandy regions with high hydraulic conductivity are characterised by high electrical resistivities, while clayey layers with low hydraulic conductivity are showing low electrical resistivities. This relationship of electrical resistivity and hydraulic conductivity is not unique (resistivities ranging from 50 - 70 Ωm can be related to fine sand or to till with low clay content), so the interpretation of electrical resistivities must be handled with care. An example of an airborne resistivity map from a buried valley area is shown in Figure 3. Some regions with high resistivities (red) interpreted as sand with high hydraulic conductivities are clearly visible. Here surface and precipitation water can infiltrate with relatively high velocity (Röttger et al. 2005) leading to high groundwater recharge, but leading also to possibly fast contaminant transport (high aquifer vulnerability).

Figure 3. Airborne resistivity map for the depth level of 0 m below sea level for Ellerbeker Rinne northwest of Hamburg (BURVAL Working Group 2006, Wiederhold et al. 2008). This survey was flown by Bundesanstalt für Geowissenschaften und Rohstoffe (Hannover, Germany).

EXAMPLE 2: FAULT ZONE

The Sieverstedt fault zone in northern Germany is caused by salt dome uplift resulting in a depth shift of layers of up to 500 m. This leads to an interruption of aquifers which are important for the water supply of the nearby town of Flensburg. Seismic measurements to localise and characterise this fault zone were carried out in the scope of a

Danish-German research project funded by the European community (LANU/SJA 2002, Wiederhold et al. 2002). A compilation of results is shown in Figure 3. Different dips of the layers on opposite sides of the fault zone and the shift of corresponding layers are clearly visible.

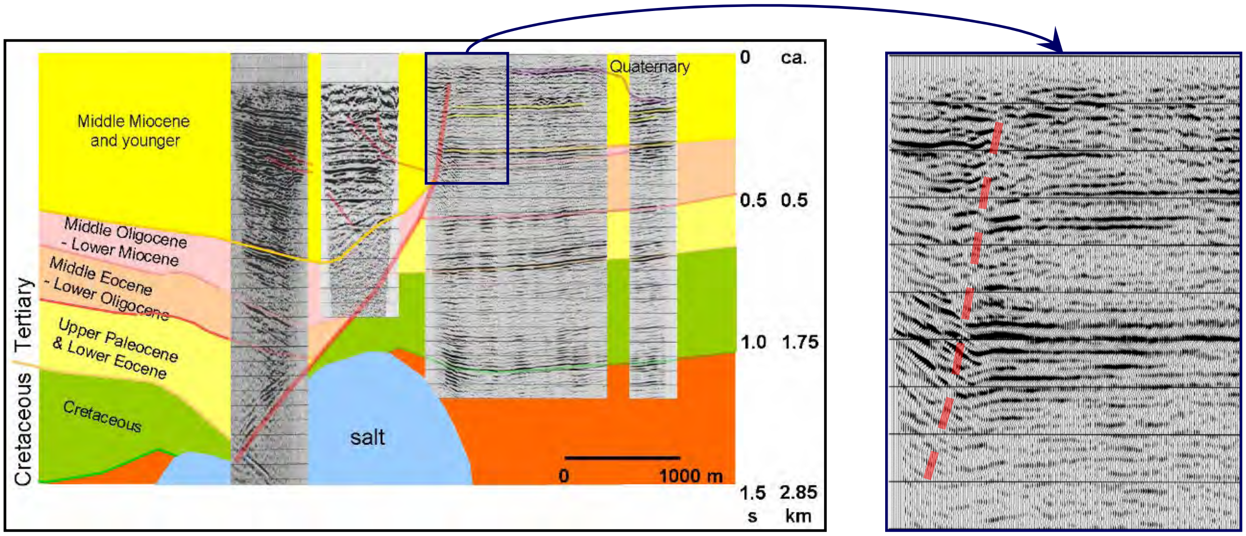


Figure 3. Seismic image of a fault zone (superimposed to Tectonic Atlas of Northwest Germany, Baldschuhn et al. 2001).

ACKNOWLEDGEMENT

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3D STRUCTURE MODELING AT THE FEDERAL INSTITUTE FOR GEOSCIENCES AND NATURAL RESOURCES (BGR), GERMANY

Birgit Willscher, Rolf Rüdiger Ludwig, and Bettina Kühn

Federal Institute for Geosciences and Natural Resources (BGR), Germany, Birgit.Willscher@bgr.de

BGR AND 3D MODELING

The Federal Institute for Geosciences and Natural Resources (BGR) is a geoscientific institute which provides neutral and independent advice and information about geoscientific and natural resource issues to the federal government of Germany and to German industry and research institutions. This includes technical cooperation with developing countries, international geoscientific cooperation, and geoscientific research. BGR is a subordinate agency of the Federal Ministry of Economics and Technology (BMWi).

The 2D presentation and evaluation of geological/hydrogeological data will always show just a small slice of a complex situation. Therefore, we regard 3D structure models as standard. 3D modeling is a necessary tool to guarantee spatial consistency for geological/hydrogeological information. Our team is working predominantly on hydrogeological 3D structure modeling.

METHODS APPLIED AT BGR

There are two kinds of model construction principles very common in modeling software:

1. Discretization of surfaces to grids and discretization of geo-bodies to volumetric polygons. This usually includes smoothing of surfaces by means of interpolation algorithms.

2. Construction of geo-bodies using input data (points or lines).

In geosciences, data are often very heterogeneous, irregularly distributed, and varying in scale. Therefore, smoothing of surfaces during interpolation is used as a method of averaging data. The construction of surfaces using interpolation algorithms can be a helpful and efficient tool. On the other hand, it can cause mistakes like penetration of thin layered surfaces or subcrops not being in direct contact with the surrounding surfaces (Figure 1). Therefore we prefer modeling software producing TIN surfaces (TIN = Triangulated Irregular Network) only based on points or lines placed and controlled by the expert modeler. The construction of geo-bodies using input data without alternation as 3D points or lines is a geometrically accurate method. It is more time consuming but guarantees the geologically/hydrogeologically reasonable construction of:

1. Geo-bodies in model areas where input data are scarce,

2. Complex geological units forming lenses, overfoldings, or diapirs like in the glacial/periglacial and glaciotectonically deformed sediments of the Quaternary in the model described below, and

3. Complex hydrogeological problems like infiltration of brine in fresh water deposits, as well described below.

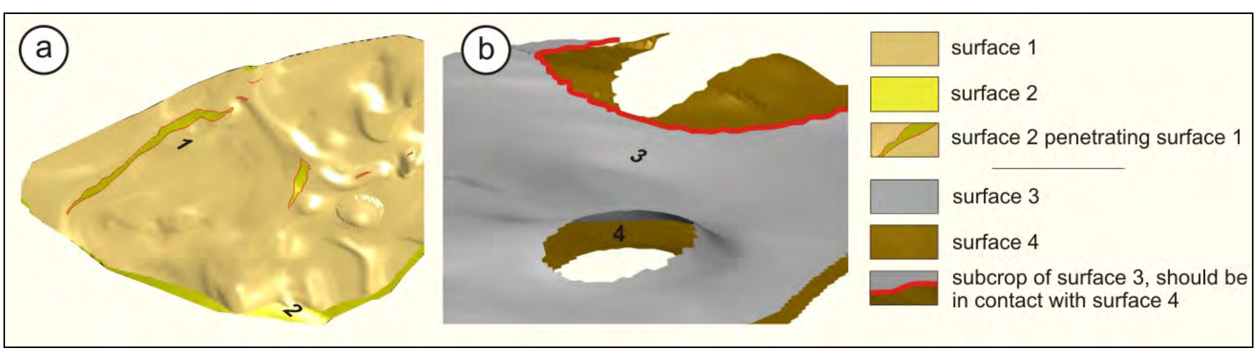

Figure 1. Examples showing inconsistencies caused by interpolation algorithms.

For overview models or less detailed models with simple geological or hydrogeological structures, we use modeling software like GSI3D (Kessler et al. 2009). The TINs are based on points placed by the geo-expert. For more complex geological/hydrogeological situations, we use the software openGEO, which requires AutoCAD as an application environment. Basic construction elements are lines. TIN surfaces are built up using topologically correct polyline networks (Figure 2). In both methodologies, the main element of the modeling process is the construction of vertical cross-sections and horizontal contour-line maps.

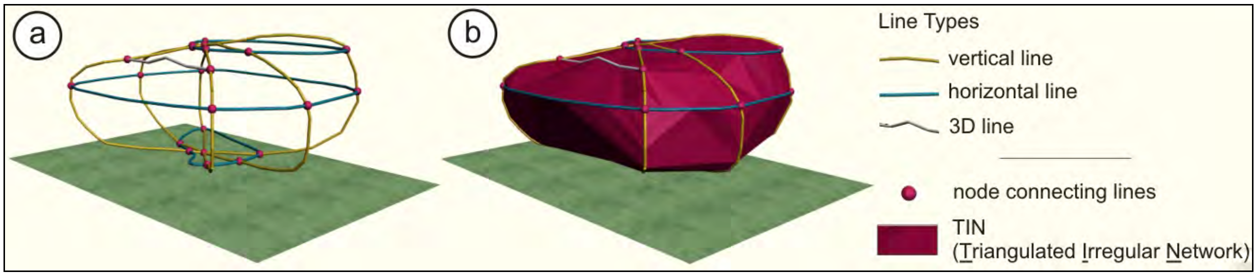

Figure 2. Lines as basic elements of TIN construction in openGEO. The lines are input data. They allow the construction of complex geo-bodies, e.g. lenses.

EXAMPLE OF A DETAILED HYDROGEOLOGICAL 3D STRUCTURE MODEL WITH COMPLEX FEATURES

As an example for a very detailed model created with openGEO, we present the hydrogeological 3D structure model of the Gorleben salt dome overburden in northern Germany. The salt dome was investigated as a potential repository for nuclear waste. Therefore, the overburden as well was evaluated intensively by means of an extensive drilling and exploration programme from 1979 to 1998 to assess assumed contaminant migration from the salt dome surface to ground surface. Summaries of the geological and hydrogeological investigations are published separately in Köthe et al. (2007) and Klinge et al. (2007).

Only a 3D approach was considered adequate for the comprehensive evaluation of the complex geological and hydrogeological situation in the model area:

1. The salt dome and its cap rock are covered by sediments of Tertiary and Quaternary age. The Quaternary deposits include lenses and other complex sediment bodies. Figure 3 shows a detail of the model where glaciofluvial and glaciolacustrine sands can be found isolated (well 1), together with boulder clay (well 2), or together with glaciolacustrine silt and clay (well 3), the last forming a lens within the sands in well 4, where there are also a layer of boulder clay and another layer of sands at the bottom of the sediment complex. These lateral changes can be found within a distance of only a few kilometers.

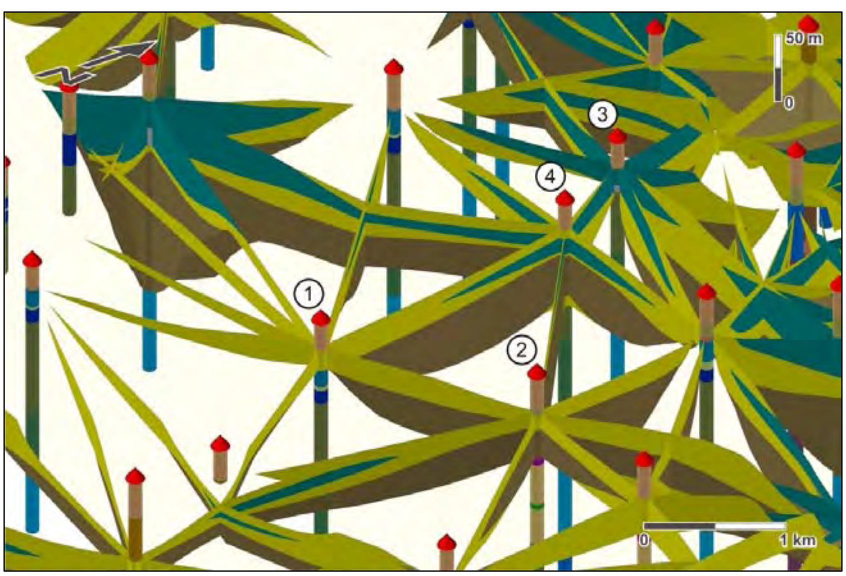

Figure 3. Complex sediment body of Quaternary age (yellow: glaciofluvial and glaciolacustrine sands; brown: boulder clay; blue: glaciolacustrine silt and clay. Geological units are shown as cross-sections. The vertical exaggeration is x12.5). For further information about wells 1-4 see text above.

2. The hydrogeological situation in the model area is very complex as well. A striking feature is the interplay of Tertiary and Quaternary aquifers and aquitards which can be understood comprehensively only through a 3D model. The lower Quaternary sediments are deposited in channels incised into the Tertiary layers. Therefore, Tertiary and Quaternary sediment bodies, consisting mainly of clay, together build up one aquitard which widely separates a narrow fresh water deposit from a deeper one mainly consisting of saltwater (point 1 in Figure 4). Saltwater plumes in the upper aquifer indicate contacts between these two groundwater bodies. They can be found, for example, at the edges of Quaternary channels (point 2 in Figure 4).

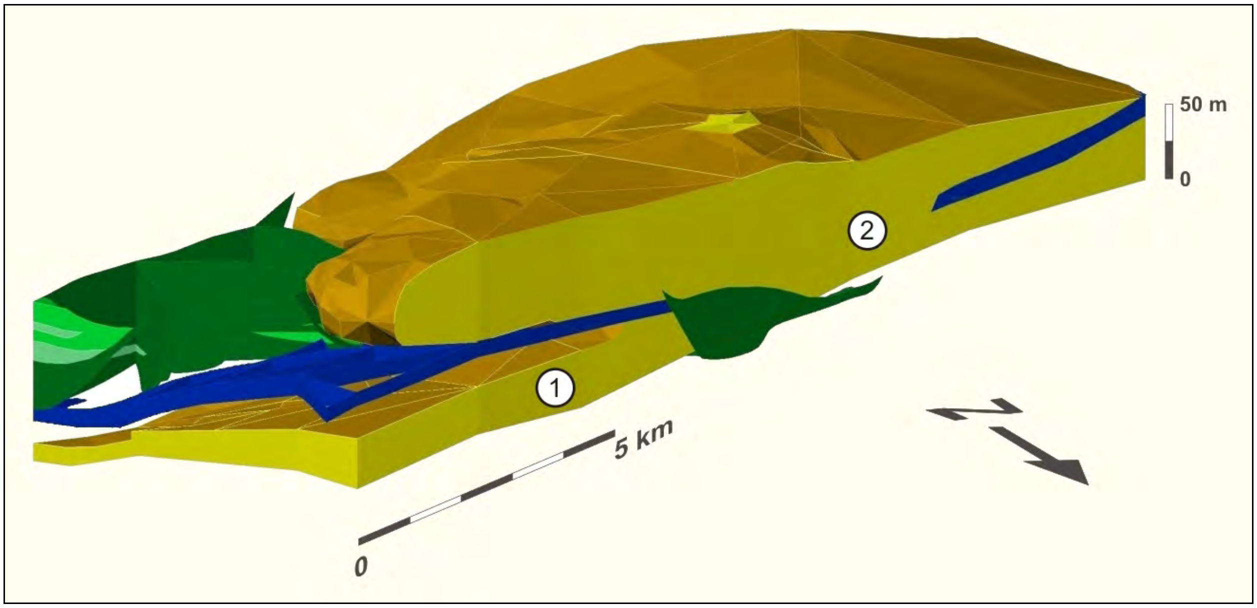

Figure 4. Inter-relationship between Quaternary and Tertiary aquitards (green: Quaternary clay/silt; light green: sandy lenses; blue: Tertiary clay/silt. Hydrogeological units shown as cross-sections) on the one hand and saltwater (here 1-10 mg/l salt concentration body, yellow/amber) on the other hand. The vertical exaggeration is x12.5. For further information about the marked spots see text above.

The model of the Gorleben salt dome overburden is intended to be the basis for three-dimensional numerical modeling of hydrogeological parameters with special emphasis on spatial changes in groundwater density as a function of salt concentration.

EXAMPLE FROM TECHNICAL COOPERATION WITH THE GEOLOGICAL SURVEY OF BANGLADESH (GSB)

The second example we present shows an area near Dhaka City, Bangladesh (Figure 5). We cooperated with the GSB to establish an urban geotechnical information system for the area of Greater Dhaka by providing this pilot study for a planned 3D model. The pilot study has been carried out as a diploma thesis in the BGR team.

The model has been created using GSI3D. There are several good reasons to use this rather intuitive software for this purpose:

1. The model area does not contain very complex geo-bodies or several units interfingering with each other, nor complex fault systems. Therefore, the geological structures can be modeled as a stacked layer model.

2. Users only need little time to become familiar with the software. This is advantageous for projects lasting a rather short period of time.

3. The software is very user friendly. Therefore, it is advantageous for people or institutions who are not very experienced in modeling.

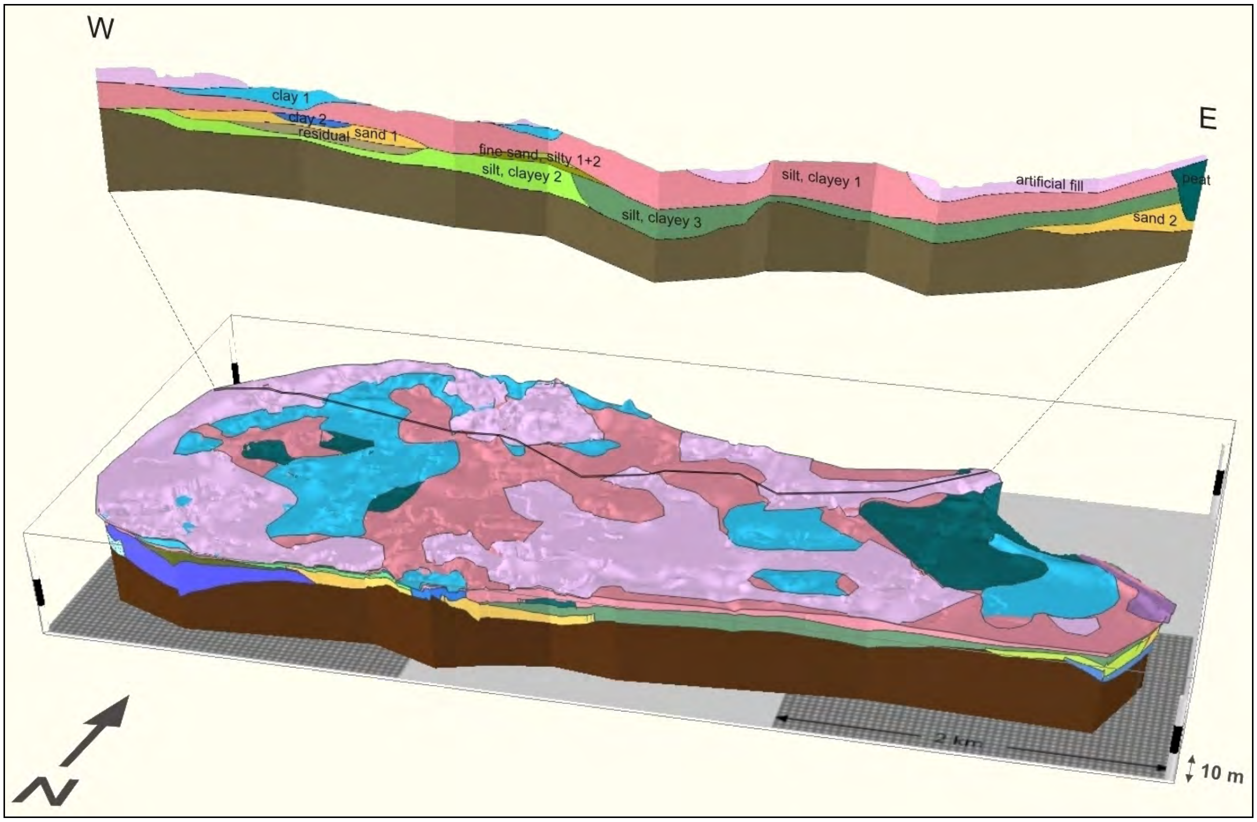

Figure 5. 3D model and cross-section of a pilot project area near Dhaka City, Bangladesh, showing fluvial deposits of Pleistocene and Holocene age above consolidated substratum (brown). The vertical exaggeration is x20.

CONCLUSIONS

Our strategy concerning geological/hydrogeological 3D structure modeling is to apply the appropriate software and methodology to the geological/hydrogeological situation of a study area. It is vital to keep in mind the purposes of the model, as well as the resources available for the project. Also, to achieve a high accuracy during modeling, comes with the realization that model development is time consuming and incurs high costs. Therefore, the corresponding methods should be chosen only where required.

In our team at the BGR, we prefer model construction based on expert defined cross-sections because this is a good method for controlling models during the modeling process with respect to the model's (hydro-) geological plausibility.

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