Synopsis of Current Three-dimensional Geological Mapping and Modeling in Geological Survey Organizations

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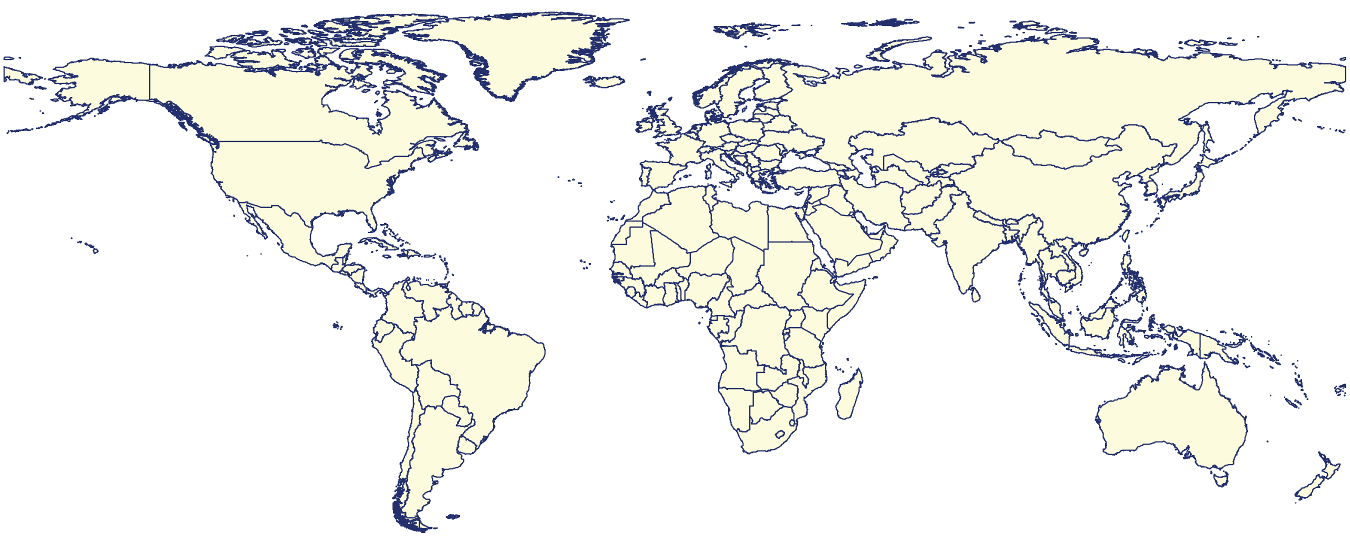

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ILLINOIS STATE GEOLOGICAL SURVEY
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Front Cover: *GCS_WGS_ 1984 projection of the world.*

Acknowledgments

We thank the many contributors to this document, all of whom provided insights regarding three-dimensional geological mapping and modeling from around the globe. We thank Aki Artimo from Turun Seuden Vesi Oy (Regional Water Ltd.), Turku, Finland, and Jason Thomason from the Illinois State Geological Survey for their thoughtful review comments; Cheryl K. Nimz for technical editing; and Michael W. Knapp for graphics support and layout.

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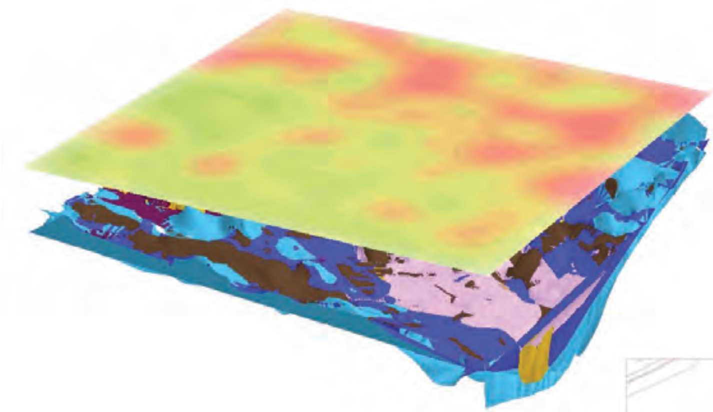
CONTENTS

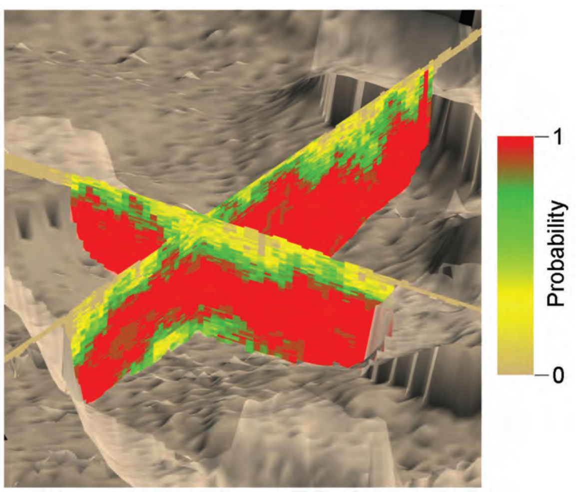
Figures

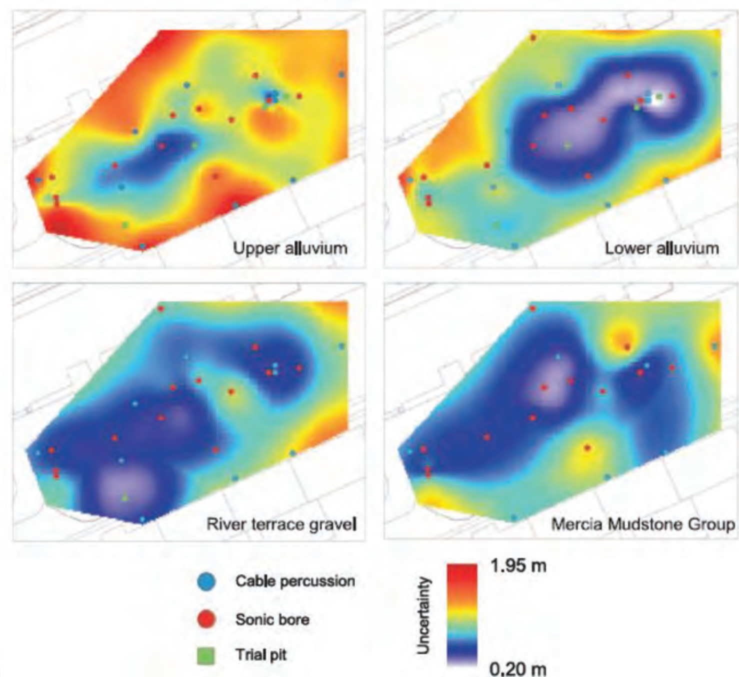
Tables

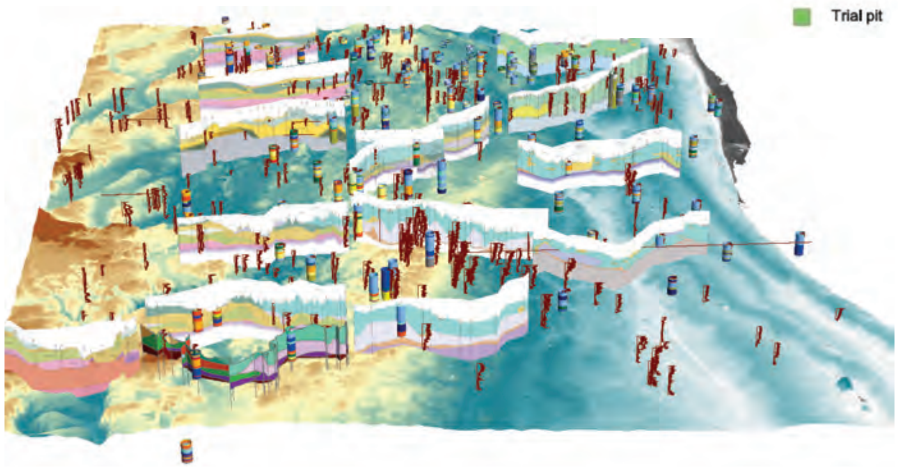
PART 1

BACKGROUND, ISSUES, AND SOFTWARE









Chapter 1: Background and Purpose

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Introduction

Since 2001, six workshops on three-dimensional (3-D) geological mapping have been conducted in association with meetings of the Geological Society of America (GSA) and the Geological Association of Canada. The workshops have documented progress and established working relationships among an international group of geologists who have been developing new methods for geological mapping largely to address the transition from traditional two-dimensional (2-D) to 3-D geological mapping (also referred to as 3-D geological modeling). This transition has been the direct result of increased societal need for a more detailed, improved understanding of the subsurface to address critical land- and water-use issues (Thorleifson et al. 2010), coupled with significant technological advancements in Geographic Information Systems (GIS), digital cartography, data storage and analysis, and visualization techniques (Whitmeyer et al. 2010).

The October 2009 workshop in Portland, Oregon (Berg et al. 2009), was significant because of the unprecedented representation from the world's leading geological survey organizations (GSOs) in 3-D geological mapping. During the workshop it became very apparent that, although these GSOs share the same visions for the use of 3-D geologic maps, the methodologies, software tools, underlying mapping and modeling strategies, and business models are highly varied.

Discussions at the workshop suggested that the time was right to produce a report documenting the current state-of-the-art for 3-D geological mapping in GSOs. Part of the motivation for this report was the need for advice to GSOs that are beginning to migrate from a 2-D to a 3-D mapping and modeling culture.

A similar workshop held in July 2009 in Madrid involved key players from GSOs of seven European countries (France, Germany, Italy, Netherlands, Poland, Spain, and United Kingdom). The goal of that workshop was to take the first steps toward establishing agreement and standardization of 3-D geological modeling approaches in Europe. The conclusions from that workshop were similar to those reached at Portland, and many of the Madrid workshop participants contributed material for this present report.

In this report, we have tried to capture the state-of-the-art of 3-D geological mapping in these participating GSOs. Throughout this document the terms "mapping" and "modeling" will be used interchangeably to recognize the strong institutional preferences of the participating GSOs. Each approach (see Chapters 5 through 13) is unique and reflects geological aspects of the nation or state, the drivers for geoscience information, the stakeholders commissioning maps and models, the external and internal organization of GSOs within the nation or state, the available data resources, and funding. This document is intended to help others learn from our successes and mistakes and to help them make the transition into the world of 3-D geological modeling. Growth of this community may eventually lead to stabilization of methods and the development and international use of geoscience data exchange standards.

This report has benefited from the excellent contributions received from staff serving in GSOs and allied bodies in Australia, Canada, France, Germany, the Netherlands, Great Britain, and the United States (USA).

What Is a GSO?

A GSO is a not-for-profit government organization responsible for a range of tasks that generally include

- geological surveying (mapping) of the nation, state, or province;
- conducting geological research to support economic development, public health, and environmental protection;
- distributing geoscience information; and
- advising government at various levels regarding water, mineral and energy resources, environmental issues, and earth hazards.

Each country has its own governmental structure of ministries, departments, and bureaus. Although not all of the organizations involved in public sector 3-D geological modeling worldwide are geological surveys, these non-survey organizations are still responsible for overseeing national or state geological modeling.

Some nations have a single national geological survey (for example BRGM in France and the BGS in Great Britain); in other countries, responsibilities are shared by both state/provincial and federal organizations (USA, Canada, Australia, and Germany).

Geological Mapping: A Brief History

Geological mapping has been a fundamental activity of GSOs since the early 1800s, when governments began a systematic search for mineral resources to fuel economic growth and industrialization. Beginning with William Smith's 1815 map, *A Geological Map of England and Wales and Part of Scotland*, and its included cross section showing subsurface rock layers, geologists have sought ways to best portray geological information on 2-D maps.

The most conventional technique for portraying successions of geological strata in the subsurface has been through the use of cross sections and maps of the top or bottom surfaces of strata. Although cross sections provide a sense of geological structure and the continuity of geological units in the third dimension, they only provide information for a single plane cut through the Earth, and they do not provide a clear sense of the 3-D nature of the geology. Even with multiple cross sections, there are significant voids in information that the user must infer. In addition, top and bottom surface maps provide insight only on the distribution of individual deposits and do not give a clear sense of the full succession.

Stack-unit maps improved the understanding of the three-dimensionality of geological information by using alphanumeric codes or colors and patterns to represent the vertical succession of geological units to a specified depth. This mapping was termed "three-dimensional mapping" because of the extensive and detailed subsurface information that could be displayed.

The Dutch (e.g., Rijks Geologische Dienst 1925) pioneered the stack-unit technique beginning in the 1920s by mapping the geology in the upper 1 or 2 m. This technique was enhanced considerably between the early 1970s and the mid 1990s (e.g., Berg et al. 1984), as vertical successions commonly were extended to depths of 6, 15, or 30 m at large scale (1:24,000 to 1:100,000). This mapping activity, mainly done by GSOs, was in response to requirements for detailed mapping in support of land- and water-use decision making. Most of the stack-unit mapping was accomplished before computers were widely applied to geological mapping. The primary limitation of stack-unit mapping was that map depth was generally restricted because map unit labeling could be overly complex. However, with improvements in digital mapping technology, sophisticated stack-unit maps to any depth now can be constructed that serve the client community well, as shown by maps from the Ohio Geological Survey in the USA (Shrake et al. 2009).

The availability of personal computers (PCs) in the 1980s and the rapid evolution of hardware and software led to a revolution in geological mapping. Currently, several software applications are available for PCs that allow for the development and visualization of maps for geological surfaces from land surface to any depth (Whitmeyer et al. 2010). Geological modeling and mapping, as discussed in this publication, refers to the use of PCs and software to build, visualize, and analyze the subsurface geology in 3-D. This use has resulted in a wide range of mapping and modeling approaches, many of which are documented in this report.

Applications Benefiting from 3-D Geologic Maps

Three-dimensional geologic maps are an extension of traditional 2-D geological maps into the third dimension. These maps can portray subsurface stacked layers showing depths, thicknesses, and material properties within a 3-D volumetric space. The output is a fully attributed and digital 3-D model created by geological interpretation and rigorous use of raw data geological knowledge and statistical methods.

Both 2-D and 3-D outputs are produced using a similar classification of geological units and are presented at a range of scales or resolutions aimed at specific uses and stakeholder groups. The North American 3-D mapping workshops have targeted hydrogeological applications, but 3-D geological models are finding receptive clients who need information about a range of earth science issues because (1) resulting 3-D geologic maps can explain and portray complex geology with numerous map views in understandable formats, (2) various derivative or interpretive maps can be produced and updated as new information becomes available, and (3) all can be released on demand and customized for clients with specific needs for earth resource information.

Many of the 3-D geological models constructed at GSOs have been commissioned by industrial and government clients. In those situations, the mapping units and resolution are dictated by their needs. Such models generally require considerable modification to be used for other purposes and for other users. For example, when shifting from regional to local site-specific 3-D mapping and modeling efforts, powerful data management tools are a prerequisite for integrating databases with 3-D modeling (Artimo et al. 2008).

Regional 3-D geological models provide the context and framework for detailed investigations by various clients interested in different aspects of earth resource assessments. These more detailed investigations generally provide the best examples of economic benefits of 3-D mapping and modeling (Curry et al. 1994, Artimo et al. 2003), and, perhaps more significantly, they increase the awareness of the importance of 3-D mapping investigations to local decision makers and politicians.

Two detailed economic assessments, as examples, highlight various site-specific applications derived from geological mapping. Bhagwat and Ipe (2000) conducted a cost:benefit study of a statewide 2-D mapping program in Kentucky (USA). The study was based on a detailed questionnaire to hundreds of map users following more than 20 years of geologic map use in that state. Those researchers estimated that project costs increased by up to 40% if geologic maps are not available. Using very conservative assumptions, they also reported a return of $25 to $39 for each government dollar invested in geological mapping. Furthermore, the Kentucky maps, completed originally to boost the mineral and energy industries at a cost of more than $112 million (year 2010 dollars), have been used primarily to address water supply and protection issues, growth and development, environmental problems, and mitigation of a variety of natural hazards. A similarly designed benefit:cost assessment was performed by the Instituto Geológico y Minero de España (Geological and Mining Institute of Spain) by Garcia-

Cortes et al. (2005). That study reported that an initial investment of €122 million for geological maps produced a savings to the Spanish economy of €2.2 billion (18:1 benefit:cost ratio). The greatest uses of geologic maps were for evaluating groundwater resources and industrial minerals, building and foundation construction projects, landslide assessments, and waste site locations.

The main sectors currently requesting 3-D geological models from GSOs include those dealing with the following issues:

Water

- Delineating the distribution and thickness of aquifers and non-aquifers for input to groundwater flow models or for developing interpretive maps to support decisions relating to groundwater management, withdrawal, protection, and recharge.
- Conducting more localized studies for groundwater flooding, river flood protection, contaminant transport, and wetland construction, protection, and maintenance.

Waste Disposal, Management, and Contamination

- Characterizing shallow and deep groundwater systems to assess risks associated with long-term disposal of nuclear wastes and the disposal and storage of municipal and hazardous wastes.
- Evaluating the contamination potential of shallow groundwater from construction refuse sites, underground storage tanks containing gasoline and other chemicals, septic systems, large animal confinement facilities and associated waste lagoons, chemical spills, use of road salts and other deicers on paved surfaces, and over-application of fertilizers, sewage sludge, and chemicals onto agricultural fields.

Hydrocarbon, Energy, and Carbon Capture and Storage

- Characterizing and mapping of oil and gas reservoirs.
- Modeling for evaluation of thickness and quality of coal resources.
- Evaluating geothermal potential.
- Modeling of reservoir capacity and suitability for sequestration of carbon dioxide.

Land-Use Planning and Local Decision Making

- Characterizing the surface and near-surface to aid land-use planning in urban, suburban, and rural areas by helping to balance economic development with wise use of water and mineral resources and ensuring their protection.
- Protecting shallow groundwater through green planning restrictions, protecting vulnerable shallow aquifers, and providing unbiased information for industrial permitting, property tax assessments, and land acquisitions.
- Evaluating sites for city zoning and establishment of building codes.

Civil Engineering and Infrastructure

- Conducting site-specific investigations for construction projects such as highways, tunnels, sewers, railroads, pipelines, dams, dikes, locks, building foundations, linear route alignments for communications and utility infrastructure, and large transportation infrastructure projects (mega sites).
- Providing geological information to help determine risks from natural hazards and impacts on the natural environment as a result of construction projects (e.g., environmental impact assessments).

Archaeology

- Characterizing shallow deposits to evaluate preservation potential and ground conditions.
- Establishing and mapping archaeological stratigraphy.

Mineral Resources

- Conducting regional and site-scale appraisals of mineral resources and reserves, including long-term impacts on the environment.
- Finding a well-balanced approach to mining and land use ensuring that nearby economically available mineral resources are not made unavailable because of competing land uses.

Research

- Conducting research and scientific discovery in earth sciences (e.g., stratigraphy, tectonics, Quaternary evolution, and soil science).
- Conceptualizing and portraying all surfaces, depths, thicknesses, and geological processes over broad geographic areas in ways that were previously not possible and, in so doing, predicting the distribution of materials into regions of sparse data and visually analyzing and interpreting the geology and its history.

Education and Outreach

- Visualizing the “full cube of geology.”
- Communicating the existence and relevance of specific geological features.
- Increasing public understanding of geoscience-related issues, and using geological information for teaching endeavors at all levels.

Chapter 2: Major Mapping and Modeling Issues

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An Overview of Major 3-D Geological Mapping and Modeling Methods

A wide range of software applications can be used for 3-D geological modeling. Some methods use common interpolation routines to make geological surfaces; others use sophisticated statistical methods; and still others use methods more akin to traditional geological mapping. These applications do not fully constrain the user in how they are used; therefore, the range of workflows for conducting a 3-D geological modeling project is almost as large as the number of practitioners who are conducting the mapping and modeling exercises.

Using software to map geology requires geologists to explicitly define considerations that were traditionally part of the intuitive science of geological mapping. It is generally very difficult for most geologists to understand how to translate their geological knowledge into the parameters contained in most mapping software. If a mapper loads data into a common interpolation package and relies on the software to "know" how the data should be mapped, little real geological knowledge is being used in the mapping because only the information contained in the data is used, and the information is limited to the locations where the data reside. Statistical methods of interpolation capture additional information on spatial variation, but alone do not naturally portray the complete spatial structure of specific depositional environments or the effects of certain faulting, and so the value of this information is limited. These more automated approaches to mapping seem to be most common in academia, where students and faculty are exploring insights gained by new methods and not necessarily trying to produce the most geologically accurate map.

In GSOs, it is generally important for geologists to constrain geological mapping software by insight gained through years of training and from work that assimilates intangible aspects regarding the distribution and character of deposits. The editors and authors of this report feel strongly that any individual or organization involved with 3-D geological modeling needs to choose software and methods that allow them to provide significant geological control on the distribution and character of the deposits they are portraying. Although not always easy, it is increasingly possible to find software that simplifies the use of geological constraints on 3-D geological mapping. The discussions from the individual GSOs provide a diverse guide to different ways to model in this context.

The specific approaches to geological modeling at GSOs largely have been driven by the need to develop 3-D maps of geological successions for various areas. The terms used for these 3-D products vary by organization and sometimes by individuals within an organization. The use of the terms modeling and mapping are used interchangeably in this document because of a recognition that conventions are already established in various groups, and it is not the objective of this document to propose standards in terminology or method.

It is important to recognize that there are two basic types of 3-D geologic maps or models. The most common type involves only the delineation of the distribution of specific map units. These models do not explicitly define any distribution of material properties within their boundaries. Sometimes, within this type of 3-D model, the mapped deposits can be divided into broad zones where each zone has distinct patterns in the variability of texture, porosity, or some other important characteristic.

The other common type of 3-D model delineates deposit boundaries and explicitly defines the potential distribution of material properties within these deposits. Typically, these models include plausible distributions of petrophysical properties (e.g., porosity, permeability) and are used as input to flow simulation models. Alternatively, any property can be simulated in this manner. The methods for developing these property models typically involve geostatistical tools and require significant expertise to apply them reliably. It is important to note that these property models should be developed using the same significant involvement by geologists familiar with the basic unit distributions and also with the likely characteristics of the modeled properties. It is also important to understand that property models involve much more inference in the interpolation stage and should be expected to be much more uncertain than the maps showing the distribution of basic units. The TNO–Netherlands Geological Survey GeoTOP model, discussed in Chapter 12, is a good example of 3-D property modeling based on extensive databases of measured physical properties in numerous well-distributed boreholes.

Finally, the importance of geologists being able to visualize their data at various stages of the mapping and modeling process is key for better understanding of the conceptual geological framework, resolving multiple working hypotheses regarding geological process responsible for depositing various sediments, and for advancing applications of software packages. Particularly, the 3-D visualization of raw data early in the modeling process allows the geologist to immediately "see" data trends and to begin the process of evaluating data quality and distribution.

Scale and Resolution

As with geologic maps of the land surface, maps and models of subsurface geological units can be constructed to show features of a certain minimum size. In traditional geological mapping, map scale is the parameter that dictates the minimum feature size, or level of detail, expected on a map. The scale of a geologic map is originally derived from the scale of its base map.

The concept of scale has always had limitations in geological mapping because the distribution of data is always irregular, which is particularly a problem for mapping subsurface geological units where data density generally decreases with depth. Maps in areas with a high data density typically contain more detail than expected for the scale, whereas areas of low data density have much less detail than expected. Map scale also is a concept that is difficult for non-geologists to understand. The term "resolution" has been used increasingly in the digital world, often in the context of digital images or photographs. The reference to the resolution of a geologic map or model is increasingly common, as it can accommodate the fuzziness, or variation, in detail across a map better than just referring to differences in map scale. Reference to resolution of geological models, although more flexible in connotation than the concept of map scale, does not change the fact that geological models are limited in the resolution they capture and cannot reliably predict the distribution of higher (more detailed) resolution map features.

The physical, static nature of printed maps makes them difficult to use at scales beyond their publication. Unlike printed maps, digital maps and models are not physically bound or static in how they are used. Therefore, it is important when models and model data are distributed that a clear indication be made of the reliable level of detail and the limits of reliability within the models and also that recommended map uses be clearly defined to discourage misuse.

Three-dimensional maps and models, because of their digital nature, can be interactive, and if appropriate software is available, users can zoom in and out, effectively redefining the scale of the viewing window. In these situations, it is possible for digital 3-D geological models to be enlarged and used at resolutions beyond their limits of reliability.

Uncertainty in Modeling

With the increasing use of 3-D geological models, it is generally helpful to assess the uncertainty of the modeled deposits and their properties to ensure that end users can better understand the major limitations of the models and map products that are developed from them. The uncertainty of 3-D geological models is not only restricted to the algorithms and data of the model, but also involves the geological inferences and interpretations that are used for the final models. Traditionally, modeling uncertainty in geologic maps relied rigorously on geostatistical models and assumptions that were often violated when the real sediment successions became complex. These uncertainty assessments were commonly applied in the mineral extraction and petroleum industries. Specialized statistical expertise is required to apply these methods reliably. Although some GSOs are exploring the use of geostatistical methods of uncertainty assessment, increasingly new methods are being used that are based less on statistical methods and more on geologist insight about the reliability of data and interpretations. These uncertainty assessments are being used to help GSOs convey the mapper's sense of confidence with the data or interpretations in any mapping project.

This section provides examples of uncertainty assessments that have been developed and applied by GSOs. They illustrate various issues being addressed in these assessments and the ways uncertainty are being characterized for various mapping applications. These examples do not represent an exhaustive list of applicable methods, but they can be used as a starting point for future studies.

A simple depiction of uncertainty can be produced as a color ramped layer for a model. Figure 2-1 is an example of a 5-km × 5-km part of the Glasgow urban area in the United Kingdom (UK) where the reddish areas indicate high uncertainty (low data density), and the green areas indicate low uncertainty (high data density). This scheme tends to reflect the distribution of boreholes, but the locations here are buffered or blurred to take into account the use of confidential borehole logs in the modeling exercise

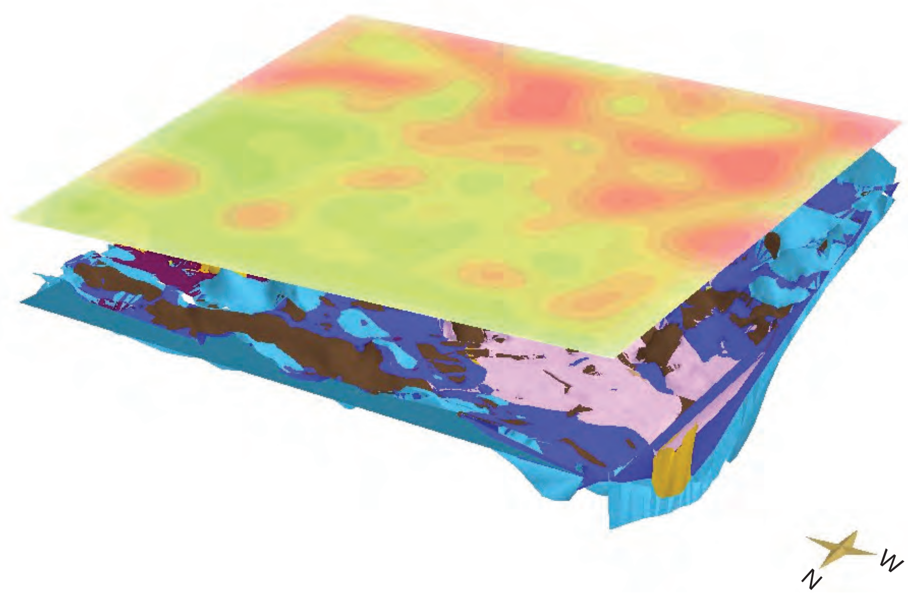


Figure 2-1 Uncertainty drape on a model of central Glasgow, United Kingdom.

because precise locations could not be divulged.

A more sophisticated approach has been applied to the modeling of the Glasgow urban area using the procedure described by Lelliot et al. (2009). Full details of the method are given in that publication, but, in summary, the method combines the 2-D spatial density of the boreholes used to construct the surface with the geological complexity of the surface, where geological complexity refers to the relative change in curvature of the surface or the “tortuosity” of the surface. That is, if the data density is high, then the uncertainty is lower (or vice versa), and if the geological complexity is low, then the uncertainty is lower (or vice versa). The empirical uncertainty obtained from this approach is then calibrated into either an estimated absolute uncertainty or a relative scale using expert judgment. To calibrate the uncertainty the expert provides three pieces of information: the estimated absolute uncertainty of the surface at the borehole (i.e., the uncertainty in depth in the borehole log); the estimated worse case uncertainty on the surface where least information is available; and the distance from the borehole that the expert has confidence to predict the surface (the radius of influence of the borehole). In the examples shown here, the uncertainty has been expressed on a relative scale of 0 to 100 with 0 being very low uncertainty and 100 being very high (Figure 2-2).

The majority of the available boreholes were evaluated in the data selection process, and the deepest, best-logged bores were used to construct the model. A total of 1,852 boreholes (of 13,000) were specifically selected to construct the cross sections on which the surficial model was based. In addition, many more boreholes not directly lying on specific cross section alignments were also considered during the construction of the cross sections so that the overall construction of the model is based on an assessment of approximately 8,000 boreholes.

The uncertainty for the WITI geological unit for the Glasgow urban area was calculated using the procedure outlined by Lelliot et al. (2009) using customized BGS software developed in Matlab programming language to measure data density and geological complexity. The output is a grid file ranked from relatively low (0) to relatively high uncertainty (100). A 200-m radius of influence and a lowest to highest relative uncertainty of 0.5 to 100 were used to calibrate the output (Figure 2-2).

The combined uncertainty scale (Figure 2-2) must be translated by the user into uncertainty categories; the lowest number represents the lowest uncertainty and the highest number the highest uncertainty. For the Clyde Gateway model, five categories could be considered. In ArcGIS this would be easy to achieve on the uncertainty raster grid by symbolizing using five classes.

Lowest uncertainty (highest confidence) areas = 1 are those areas that are well constrained by geological data and where the geology is relatively simple. In these areas, the error on the model might be considered to be on the order of ±10 m in XYZ (e.g., those blue areas of the WITI uncertainty surface on Figure 2-2).

Average uncertainty (average confidence) areas = 3 are those areas that are constrained by some geological data and where the geology is moderately complex (e.g., faulted or folded). In these areas, the error on the model might be considered to be on the order of ±30 m in XYZ (e.g., the green to turquoise areas on Figure 2-2).

Highest uncertainty (lowest confidence) areas = 5 are those areas that are not constrained by any geological data and where the geology is complex (e.g., faulted or folded). In these areas, the error on the model might be considered to be on the order of ±70 m in XYZ (e.g., those red to orange areas of the uncertainty surface on Figure 2-2).

The surficial deposits uncertainty layers are supplied as ArcGIS 9.2 raster grid format and in the subsurface viewer.

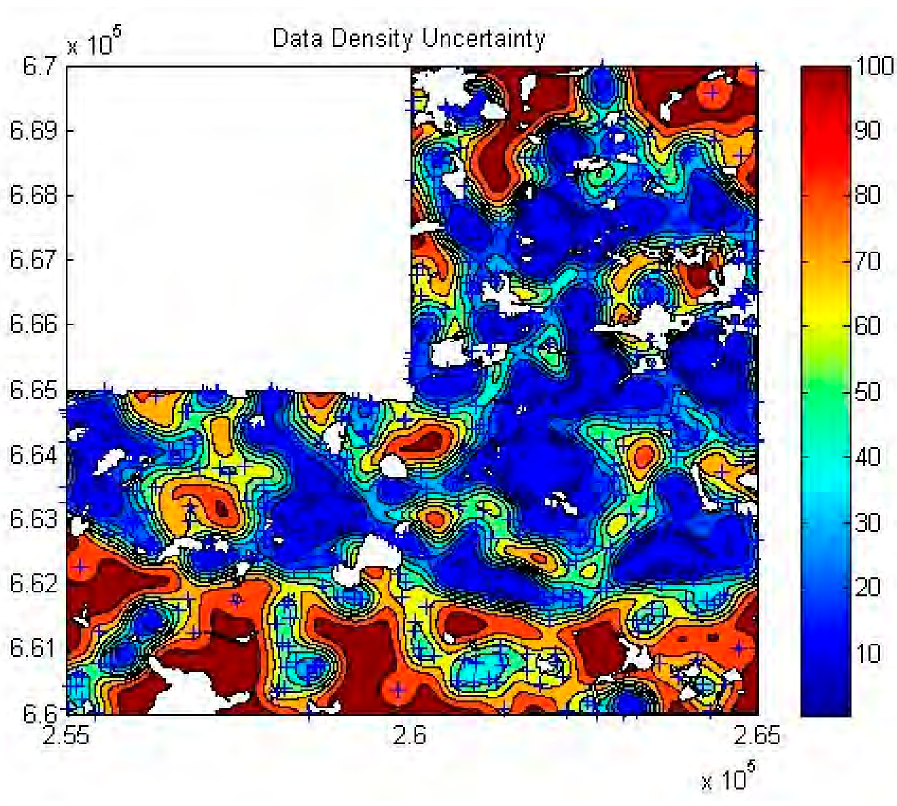


Figure 2-2 Example of data density uncertainty plot for geological unit WITI using an influence distance of 200 m. Blue crosses indicate data points.

Lelliott et al. (2009) provides example outputs (Figure 2-3) for the use of this method for assessing a 3-D geological model of shallow surficial deposits, where a sequence of river terrace gravels and alluvial deposits overlie mudstone bedrock. Values in red show a wide range of calculated elevations (high uncertainty); values in blue show the most consistent values (low uncertainty). The study concluded that the results agreed with intuitive expectations for the uncertainty, but that drilling should be undertaken to validate the uncertainty assessment of the model.

The TNO–Netherlands Geological Survey GeoTOP model, discussed in Chapter 12, uses stochastic techniques during model construction to compute the probability for each grid cell to belong to a specific lithostratigraphic unit and lithofacies. These probabilities provide a geostatistically based measure of model uncertainty. Figure 2-4 shows the results for a tidal channel in the province of Zeeland. The colors indicate the probability that a grid cell contains the sandy tidal channel lithofacies. At the center of the channel, this probability is high (100%). In the upper part of the channel, the green and yellow colors reveal much smaller probabilities. In this upper part, more clayey tidal flat deposits are expected. Similarly, probabilities are lower at the bottom of the channel where shells and shell-rich sand deposits are expected.

A study at the Illinois State Geological Survey (ISGS) recognized the difficulty of traditional geostatistical approaches to adequately capture geological knowledge of the data, deposits, and interpretations that are particularly relevant to making accurate uncertainty assessments. The ISGS recognized the impact of four factors that contribute to uncertainty in geologic maps: (1) variations in data quality, (2) variations in data density, (3) generalizations in texture, and (4) generalizations in thickness (Dey et al. 2007d). The contributions of these factors to map uncertainty were evaluated with respect to terms of their likely impact on the predictive accuracy of a regional groundwater flow model that would use the 3-D geologic map.

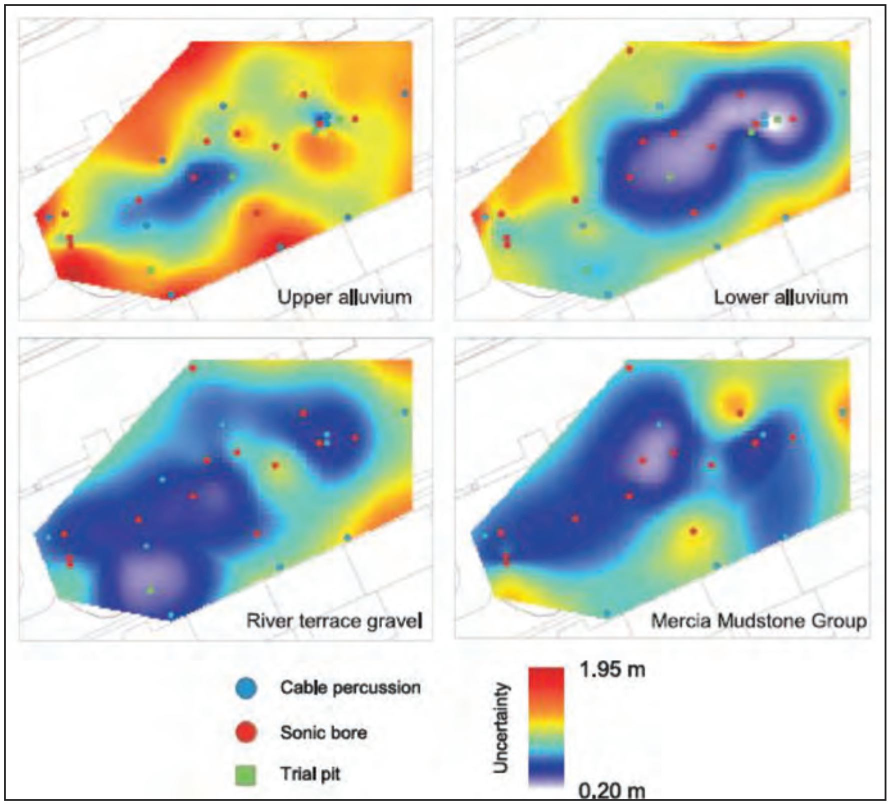


Figure 2-3 Uncertainty assessment showing drill locations and drill type, and a grid of the average assumed error for geological surfaces (Lelliott et al. 2009).

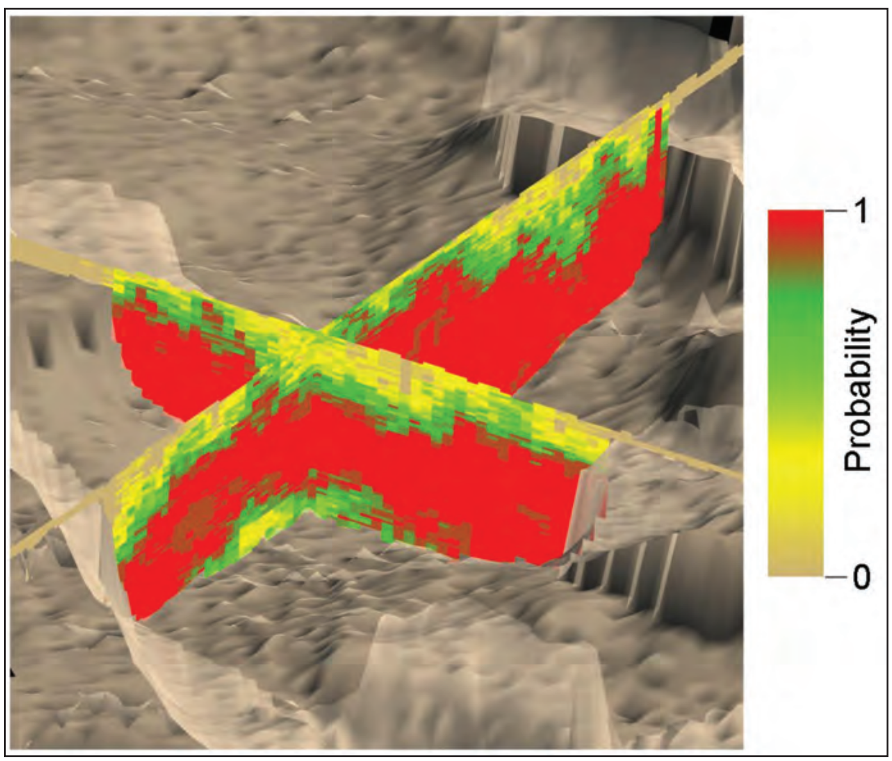


Figure 2-4 Cross section through a tidal channel in Zeeland, the Netherlands, showing the probability that a grid cell belongs to the tidal channel lithofacies.

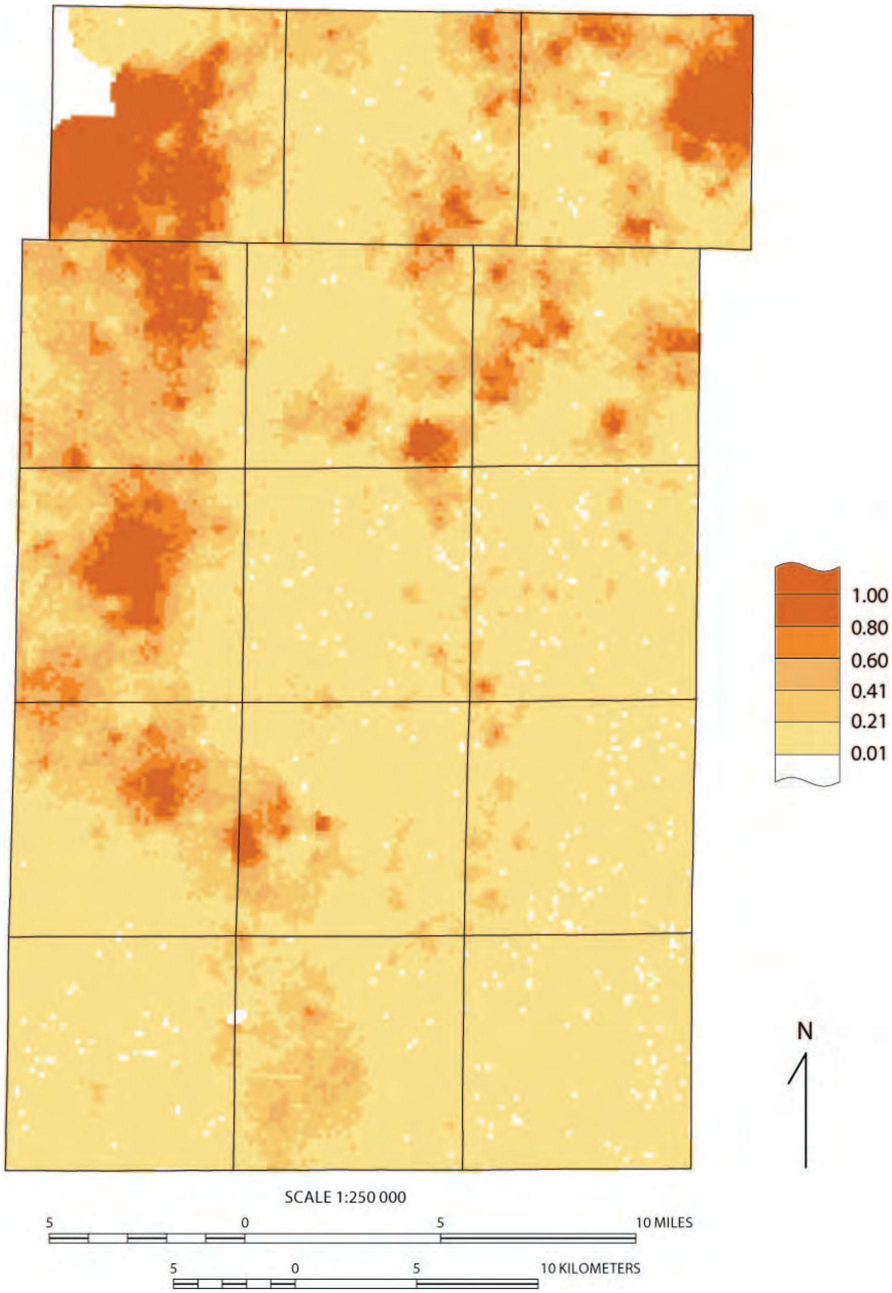


Figure 2-5 Probability that the Ashmore Member sand and gravel is greater than 10 feet thick in Kane County, Illinois, USA.

The evaluation of variations in data quality mirrored results from other studies (Russell et al. 2001): water well drillers tended to make systematic errors in reporting the textures they encountered, and locational coordinates of boreholes were commonly incorrect. Errors in locations result in errors in elevation, which translates to errors in deposit depth and in correlation. To address location errors, the ISGS study committed significant resources to verifying and correcting the locational coordinates of every borehole used in mapping, significantly improving the reliability of resultant maps. Analysis of data errors showed that, after sediment texture reporting errors were accounted for, the reporting errors remaining within the well logs had little impact on the reliability of identifying and correlating unconsolidated deposits more than 5 feet thick and generally more than 0.5 miles wide and several miles long, and in correlating bedrock units.

Dey et al (2009d) recognized that errors in thickness interpretations were dependent on data density, data accuracy, and the underlying complexity of the geologic deposit being mapped. To evaluate the potential error in thickness estimates, they used a novel application of geostatistical methods. In the first stage of analysis, the isopach maps for each map unit were taken from the completed 3-D model and used as best estimates of the geologist's conceptual models. Semivariograms modeled directly from the isopach grid values showed a relatively small variation in thickness for each map unit. These semivariograms were used in a stochastic simulation to estimate the amount and location of errors in the isopach maps. In the second stage of analysis, semivariograms modeled using the thickness values from the borehole data showed relatively large thickness variations for each unit. These semivariograms were used in a stochastic simulation to produce alternative estimates of the amount and location of error in the isopach maps. These sets of simulations allowed for calculations of the probability that map units were less than or greater than various thickness thresholds. For example, maps were created to estimate the probability of a unit being thicker than 10 feet or thinner than 1 foot. These paired simulations provided more insight on the likely uncertainty in the occurrence of mapped units than would be found under traditional geostatistical evaluations.

Figure 2-5 from that study illustrates the probability that one sand and gravel deposit, the Ashmore Member of the Henry Formation, is greater than 10 feet (3.0 m) thick.

Chapter 3: Logistical Considerations Prior to Migrating to 3-D Geological Modeling and Mapping

Holger Kessler[1], Stephen J. Mathers[2], and Donald A. Keefer[2]

[1]British Geological Survey, [2]Illinois State Geological Survey

The migration from 2-D to 3-D geological modeling or mapping for any GSO will benefit from consideration of several important issues. This section briefly discusses these issues and provides some insight on the consequences of different decisions.

Commingling Initial Mapping Strategies with Eventual Outcomes

Regardless of scale, 3-D geological mapping and modeling investigations should be integrated with other activities of a project at an early stage so project outcomes and deliverables reflect a client's needs and are accomplished within the capacity of those producing the information. Artimo et al. (2008) stated the importance of new and updated geological information that can be instantaneously integrated into the daily planning and guiding of a project, which underscores that "geological studies should not be considered as single linear project events that are separated from the technical and legislative planning resulting from the geological investigations." Having a robust database and allowing for integration of other contributing scientific information (e.g., hydrogeological modeling, geophysical investigations, and geochemical data) help shape and refine 3-D geological interpretations at various stages of geological understanding and 3-D model development.

Resource Allocation Strategies

Three-dimensional geological modeling and mapping require different allocations of human, hardware, and software resources than does 2-D geological mapping. The exact differences depend both on how 2-D mapping is currently accomplished at a GSO and how the 3-D mapping will be conducted. As this report highlights, the software for the various approaches to 3-D geological mapping and modeling needs to be specialized. Centralization of various components of mapping (e.g., data management, data analysis, mapping, and visualization) can simplify efforts for the mappers, but often requires a larger investment in software and specialists in these areas. Less standardization in these components creates a more flexible environment for the mappers, but can result in fragmentation of staff expertise, data requirements, and output file formats. These various consequences can be positive or negative, depending on how they are accommodated by the GSO. It takes time to research the costs and benefits of various options. However, without careful research, GSOs can meander through combinations of the various options until they find something that satisfies their needs. Pilot studies (e.g., Lasemi and Berg 2001, Barnhardt et al. 2005) can be helpful for developing new 3-D methods, testing new software, and helping to identify the issues involved with specific changes to a mapping workflow. It also can be helpful for those wanting to initiate 3-D modeling programs to contact colleagues in other GSOs to inquire how they addressed specific issues. This document is designed to help describe the pros and cons of various approaches.

Data Management Standardization

An issue that needs particular attention is the development of various data management standards throughout the mapping workflow. Data management issues need to be identified relatively early in the organizational shift to 3-D mapping to prevent unexpected incompatibilities or development of products that cannot be easily incorporated into existing product lines or centralized database systems. Whether a GSO uses a fully standardized and centrally managed suite of software and data or a more flexible or modular approach to mapping, the organization needs to develop a consistent approach to (1) ensure interoperability between software packages and different mapping projects; (2) ensure long-term accessibility to raw data, interpretations, and final products; and (3) promote effective communication and workflow between staff working on various aspects of mapping and modeling projects. One standard that needs to be established for each 3-D mapping project is map projection. In general, all data, maps, grids, sections, etc., should have the same coordinate system to ensure positional accuracy throughout a project. Although some software applications can reproject data on the fly, care should be taken when using data with different projections, as errors have been known to occur, and subtle differences may not always be readily identifiable.

The solution to interoperability is unique to each GSO and, like the approach to determine resource allocation strategies, can benefit from a cost:benefit analysis of the various options. The individual GSO discussions in Chapters 5 through 13 highlight various options that are being used to manage the data, maps, models, and products at these organizations.

Necessary Data Sets

There is a suite of data sets that ranges between obligatory and helpful for the development of a sound 3-D geologic map or model. The determination of whether a specific data set is obligatory or optional can be somewhat subjective and is dictated by the specific software and workflow or the perspectives of the geologists involved with the mapping.

Digital Terrain Models

A digital terrain model (DTM) of the proper resolution and extent for the map area, also known as a digital elevation model (DEM), is probably the most necessary data set for any 3-D mapping project. Because some 2-D mapping workflows still rely on hand drawing contacts on topographic maps, a given GSO may not be familiar with the requirements of acquisition and management of DTMs that meet the needs of specific 3-D mapping projects. Depending on the country, province, or state, acquisition of the necessary DTMs can range from easy to impossible and from free to prohibitively expensive.

Borehole Drilling Logs

After acquisition of a suitable DTM, the availability of digital borehole driller's descriptions is probably the next most important data set. Data quality issues associated with borehole logs must be evaluated, because these data, depending on their location or quality, might not meet the needs of the project or mappers. The quality of these data must be evaluated early, as unidentified errors can result in boreholes being mislocated by significant distances. The referenced land-surface elevation of the borehole data must also be given consideration. Common practices suggest that the borehole elevations should be taken from the most detailed elevation source, regardless of the resolution of DTM used. Additionally, the quality of the geological descriptions can vary dramatically between individual records, which can significantly affect the value of these data for any mapping project. Finally, when potentially thousands of raw borehole data points are being visualized in 3-D, many points at various sites can be in the same general location. This creates a problem when creating associated databases, and, to ensure data quality, the "best" data point should be selected to represent the site.

Lithologic Dictionaries and Stratigraphic Lexicons

Lithologic dictionaries and stratigraphic lexicons are two additional geological data sets that should be considered when beginning the move to 3-D geological modeling. Although a dictionary that assigns standard lithologies to borehole driller's descriptions may not be required for a given software package or workflow, every project needs to define the formal mapping units that are included in the map area. The format of these data sets is wholly dependent on the software used for modeling.

Color Ramps

One of the last required data sets for any mapping project is the definition of a consistent color scale for all modeled units and properties. Development of internal standards can be worthwhile, but must be recognized as another option that each GSO must consider based on its resource base, timeline, and mapping project priorities.

Optional Data Sets

Several optional data sets are commonly used in 2-D and 3-D mapping that are worth considering:

- Collection and compilation of digital versions of additional borehole data, outcrop descriptions, additional field observations, geophysical borehole logs, and geophysical profile data can all be helpful in providing additional insights on the distribution and character of the mapped deposits.
- Surficial geologic maps often are available for an area before 3-D modeling efforts begin. These maps can be very helpful in expediting a subsurface mapping effort, regardless of the software used. It is common, however, for the surficial maps to be generated during the 3-D mapping effort, so these maps may not be available at the onset of a project.
- Access to digital topographic maps can be of significant value, depending on the products to be generated from the 3-D mapping effort. These topographic map layers should be appropriate in scale to the resolution of mapping and to the desired scale of final map products.
- Finally, available cross sections and other profile data can be scanned and georeferenced for position and used in many mapping software applications. The value of including these types of images needs to be weighed against the mapping objectives, timeline, and expense (time and staffing) of digitizing and georeferencing these data.

Chapter 4: Common 3-D Mapping and Modeling Software Packages

Holger Kessler[1], Stephen J. Mathers[1], Donald A. Keefer[2], and Richard C. Berg[2]

[1]British Geological Survey, [2]Illinois State Geological Survey

The most common software packages used for building 3-D geologic maps and models in many GSOs include ArcGIS, Gocad, EarthVision, 3-D GeoModeller, GSI3D, Multilayer-GDM, and Isatis. Of these, GSI3D, 3-D GeoModeller, and Multilayer-GDM have been developed by GSOs to meet customized geological mapping and modeling needs of their organizations. Many other software packages are also used in GSOs worldwide as part of modeling workflows, and these include software for GIS, geostatistical analysis, seismic depth conversion, visualization, and property modeling.

3-D Geomodeller

3-D Geomodeller was developed as a result of a requirement by the French Geological Survey (BRGM) to create a "geological editor" instead of using CAD or GIS techniques. The BRGM thought it was unnatural to force geologists to think in a way that was contrary to their training in order to create a 3-D model. A research and development project, known as GeoFrance 3-D, was established and ran for six years developing the prototype 3-DWEG (3-D Web Editeur Geologique) tool, which was the precursor to 3-D GeoModeller. At the same time, Intrepid Geophysics was optimizing the use of modern airborne geological data sets to aid geological interpretations. A joint venture was formed between BRGM and Intrepid to commercialize and further develop 3-DWEG under the 3-D Geomodeller brand name.

3-D Geomodeller is based on an implicit modeling of surfaces where each horizon is built by a 3-D interpolation function (potential field co-kriging) that simultaneously takes into account

- data points on horizon locations (isopotential values),
- general orientations and polarities of structures (gradients), and
- existence of discontinuities (faults).

This method is actually very close to "geological thinking." A geological model comprises a set of different horizons that are assembled with respect to their chronology and relationships. In addition, full tensor inversion gravity and magnetic modeling is an integral part of the software, which makes it an original environment in which to combine geological modeling and validation through geophysical inversion.

3-D Geomodeller has been used extensively at BRGM and in public and private sector organizations, particularly in Australia and Canada. (More information about 3-D GeoModeller can be found at http://www.geomodeller.com/geo/index.php?lang=EN&menu=homepage/.)

ArcGIS

The ArcGIS suite of products by ESRI is currently the global leader in GIS software and is widely used within workflows at GSOs for assembling and visualizing 2-D maps and, increasingly, for developing and visualizing 3-D geological models. Even though much of the ArcGIS data structure and functionality are focused on 2-D spatial data, ArcGIS is gradually increasing its capability for analyzing and rendering 3-D spatial data. The ArcScene module allows for the 3-D visualization of a wide range of geological data sets that are used in 3-D geological modeling (Figure 4-1). ESRI also allows customization and extension through VBA (Visual Basic for Applications) and the .net environment, and custom tools and toolbars are being used to extend 3-D geological modeling capability. At the ISGS, for example, workflows have developed around custom tools to create cross sections, make stratigraphic picks on 3-D boreholes, and generate surface maps of the tops or bottoms of map units, all as part of a robust 3-D geological modeling program.

Figure 4-1 ArcScene modeling in Lake County, Illinois, USA, showing data, cross sections, and surficial and 3-D geology (Illinois State Geological Survey screen capture).

EarthVision

EarthVision by Dynamic Graphics is a high-end 3-D geological modeling and visualization application that was developed to support a range of geological modeling applications. EarthVision is well suited to modeling for oil and gas resources, mining applications, and surficial and near-surface geological mapping and modeling projects (Soller et al. 1999, Artimo et al. 2003).

Gocad

Gocad (Geological Object Computer Aided Design) software was developed out of a project started in 1989 by Professor Jean-Laurent Mallet at Nancy Université in France that evolved into a Gocad Research Group. Most new technology created in the Gocad Research Group was made available through plug-ins to the core Gocad software. The software is now owned and marketed by Paradigm Geophysical. Gocad has been in use for model construction by specialized 3-D modelers within many GSOs and the hydrocarbon industry for at least a decade. As its name suggests, Gocad is a CAD system, requiring the input of data and then the application of complex, proprietary interpolation and surface fitting algorithms. (More information is available at http://www.pdgm.com/products/gocad.aspx/.) Gocad is probably the most extensively used modeling package in GSOs worldwide. It has been deployed successfully in most of the organizations contributing to this report.

GSI3D

GSI3D (Geological Surveying and Investigation in three dimensions) is a methodology and associated software tool for 3-D geological modeling developed by Hans-Georg Sobisch over the last 17 years, initially in collaboration with the Geological Survey of Lower Saxony (Germany). For the past 8 years, the British Geological Survey has been acting as a test bed for the accelerated development of the system.

GSI3D is programmed in Java and simply replaces common working practices of geologists with software. Therefore, it is easy to train people to use the software, which has led to its widespread acceptance and implementation as demonstrated at the BGS. Furthermore, GSI3D is programmed to be part of a systematic, iterative, and interpretative geological mapping process.

Based on the acceptance of the software and the increasing demand for 3-D models across a wide range of geological settings in the UK, the BGS embarked on a 3-year research and development project (2007 through 2010) to extend the capability of GSI3D, including the functionality to model more complex bedrock environments. The intention is to maintain the simple intuitive approach of the software and methodology to enable deployment to all BGS scientists. Version 2.6 of the software for use in Quaternary and simply stratified bedrock geology is available through the GSI3D Research Consortium (http://www.gsi3D.org/).

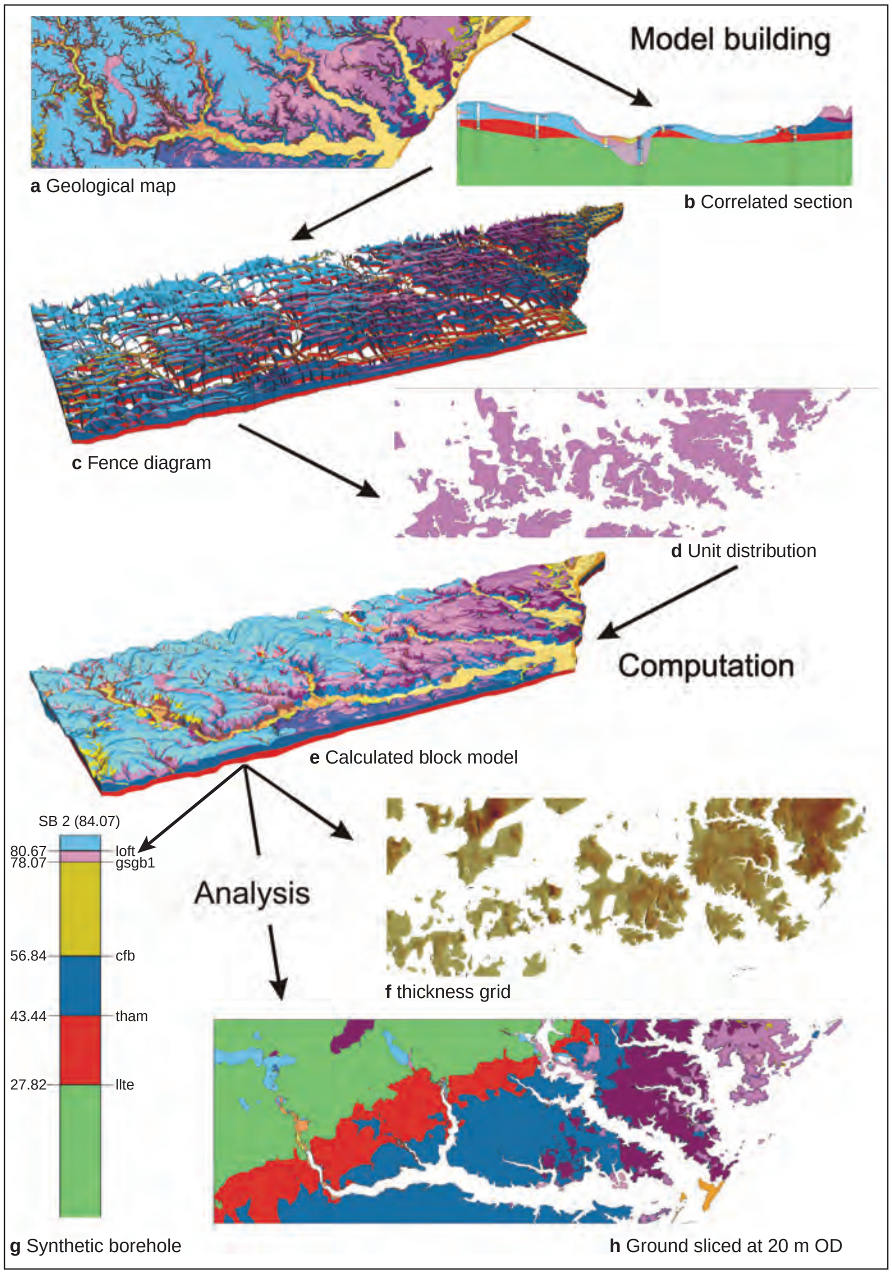


Figure 4-2 The GSI3D workflow. Abbreviation: OD, outside diameter.

The GSI3D methodology and workflow (Figure 4-2) requires the geologist to conduct five tasks:

- define the stratigraphic succession (topology rules),
- survey the area to produce a geological map (if none exists already),
- code and classify available logs of boreholes,
- draw cross sections, and
- draw maps of the distribution (outcrop and/or subcrop) of each geological unit.

The model cap is formed by a DTM. The 3-D spatial model is calculated by triangulation that interpolates between the correlation line nodes in sections and along geological boundaries (Kessler and Mathers 2004).

Multilayer-GDM

Multilayer-GDM, developed by BRGM, is especially suited for data control and for layered models with vertical faults where traditional geostatistics are particularly applicable. The Multilayer-GDM software utilizes BRGM's borehole and geological map data sets including fault traces, outcrop information, existing cross sections and outcrop-subcrop distributions, and a DEM. The software performs consistency checks between these varied sources. The model is controlled by a stratigraphic sequence file with rules concerning the nature of bounding surfaces (e.g., erosional, onlap). Once the data are internally consistent, geostatistical techniques, including the Isatis package, are used to calculate the model. The produced model then can be used to generate automated maps and sections and then deliver the information using a viewer. There are many similarities in approach between GSI3D and Multilayer-GDM. (More details can be found at http://gdm.BRGM.fr/?lang=fr/.)

Other Software

Other 3-D geological modeling and geostatistical packages in use in GSOs include many that have their roots in the hydrocarbon and mining industries. An alphabetical listing of the most prominent of these follows.

GeoVisionary

GeoVisionary by Virtalis, in partnership with the BGS, is a high-resolution 3-D and stereo-visualization package enabling the visualization and analysis of landforms, surficial and subsurface geologic maps, boreholes, cross sections, and geophysical data. GeoVisionary specializes in the management and rendering of very large data structures and can accommodate elevation and imagery files covering entire countries. Although GeoVisionary has limited data editing capabilities, it interfaces directly with ArcGIS to facilitate interactive map creation and editing. (More details can be found at http://www.virtalis.com/systems-a-services/geovisionary.)

Isatis

Isatis by Geovariance is an advanced spatial analysis and geostatistical package that can be used for sophisticated spatial data analysis, geostatistical modeling and simulation, statistically based assessments of uncertainty, and 3-D visualization. It is widely used in GSOs where it is a common tool for modeling porosity and permeability distributions and for modeling the uncertainty in the distribution of stratigraphic map units. (More details can be found at http://www.geovariances.com/en/isatis-ru324.)

Move

Move by Midland Valley Software focuses on structural geology and associated analytical geological modeling tools built upon tested geological algorithms. Geological models are designed to evolve both forward and backward through time, allowing geologists to check assumptions and verify data. The software can help geologists capture data, build models, and field test interpretations. Move has been used to build and test 3-D subsurface models for major geotechnical and civil engineering projects. (More details can be found at http://www.mve.com/.)

Petrel

Petrel by Schlumberger is a high-end 3-D geological framework and property modeling package designed for the petroleum industry. It has very sophisticated tools for integration of a wide range of data types, including 3-D seismic, but does not work easily with surficial and near-surface geological modeling. (More details can be found at http://www.slb.com/content/services/software/geo/petrel/geomodeling.asp.)

Rockworks

Rockworks by Rockware is a PC-based system supporting a wide range of 2-D and 3-D geological mapping and modeling techniques for visualizing, interpreting, and portraying surficial and subsurface information. It interpolates surface and solid models, computes reserve and overburden volumes, and can display maps, logs, cross sections, fence diagrams, solid models, reports, and animations. (More details can be found at http://www.rockware.com/product/overview.php?id=164.)

SKUA

SKUA by Paradigm Geophysics is a 3-D modeling package that is designed primarily for the petroleum industry. However, because its methodology embeds a full 3-D description of faulted volumes, it has application for GSOs mapping in structurally complex geological settings where modelers can create grids consistent with true stratigraphy and structure while honoring data and geological rules. (More details can be found at http://www.pdgm.com/products/skua.aspx.)

Surfer

Surfer by Golden Software is limited to the interpolation and visualization of 2-D surface models. Surfer has the capability to simultaneously view stacked sets of independent surfaces in 3-D space. (More details can be found at http://www.goldensoftware.com/products/surfer/surfer.shtml.)

Surpac

Surpac by GemCom is used to support open pit and underground mining operations and exploration projects. The software employs 3-D graphics and workflow automation that can accommodate a client's specific processes and data flows. (More details can be found at http://www.gemcom-software.com/products/surpac/.)

Vulcan

Vulcan by Maptec is designed specifically for the mining industry to validate and transform raw mining data into 3-D models by providing 3-D software tools that allow geologists to access and view drill hole data, define the geology, and accurately model ore bodies and deposits. Vulcan includes database management and geophysical modules, and resource, geotechnical, and ore control tools. (More details can be found at http://www.maptek.com/products/vulcan/.)

PART 2

MAPPING AND MODELING AT THE GEOLOGICAL SURVEY ORGANIZATIONS

Australian Government
Geoscience Australia

Victoria
The Place To Be

BGS 1835
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

CANADA 1842
GEOLOGICAL SURVEY - COMMISSION GÉOLOGIQUE

Géosciences pour une Terre durable
brgm

Staatliche Geologische Dienste Deutschlands

USGS
science for a changing world

ILLINOIS STATE GEOLOGICAL SURVEY
PRAIRIE RESEARCH INSTITUTE

MANITOBA GEOLOGICAL SURVEY
MGS
1928

TNO innovation for life

Chapter 5: Geoscience Australia and GeoScience Victoria: 3-D Geological Modeling Developments in Australia

Don Cherry[1], Bruce Gill[1], Tony Pack[2], and Tim Rawling[3]

[1]Departmant of Primary Industries, Melbourne, Victoria, Australia, [2]Geoscience Australia, Canberra, Australia, and [3]GeoScience Victoria, Melbourne, Victoria, Australia

Introduction to 3-D Geology in Australia

Australia is similar to the USA, Canada, and Germany in that the country is a federation of states held together under a national government. For the geosciences, this results in each state having a jurisdictional geological survey or geoscience department and the federal government also having a nationally focused department, known as Geoscience Australia.

In the development and use of 3-D geology, Geoscience Australia and GeoScience Victoria have been the most active GSOs in Australia. The use of 3-D geological methods for hydrogeological purposes has been a more recent development, with the study carried out by Cherry and Gill in Victoria, which is summarized in this article. An Australian national 3-D hydrogeology workshop held in September 2009 brought together a range of government and university researchers to present their work and discuss the development of national objectives for 3-D geology-based groundwater mapping. The workshop extended abstracts can be found at http://www.ga.gov.au/image_cache/GA15507.pdf

Geoscience Australia

Geoscience Australia (GA) was established in 1946 as the Bureau of Mineral Resources, Geology and Geophysics (BMR) to provide geological and geophysical maps of Australia to underpin mineral exploration.

Today, GA's role has expanded to providing geoscientific information and knowledge to enable government and the community to make informed decisions about

- the exploitation of resources,
- the management of the environment,
- the safety of critical infrastructure, and
- the resultant well-being of all Australians.

Excluding the Australian Antarctic Territory, GA's activities cover a land area of 7.7 million km^2 (the world's sixth largest country and smallest continent) and a marine jurisdiction of 11.38 million km^2 (the world's third largest) including 2.56 million km^2 of extended continental shelf confirmed by the United Nations Convention on the Law of the Sea (UNCLOS) in April 2008 (http://www.ga.gov.au/ausgeonews/ausgeonews200903/limits.jsp).

The onshore activities of GA focus on enhancing mineral exploration and environmental land-use planning by producing geological maps, databases, and information systems and conducting regional geological and mineral systems research. Activities also contribute to safer communities and critical infrastructure and the maintenance of fundamental gravity, geomagnetic, and seismic networks.

Offshore activities focus on providing pre-competitive data and information to assist in identifying new areas for petroleum exploration and the geological storage of carbon dioxide. Additional activities also include mapping and documentation of Australia's maritime boundaries, studies of the marine environment, and sea floor mapping.

Spatial information activities focus on providing key spatial information of Australia with an emphasis on response to rapid and slow onset hazards, the detection of change, emergency management requirements, natural risk assessment, and marine zone management. Australia's Land and Marine Jurisdictions are shown in Figure 5-1.

Geoscience Australia uses a range of different 2-D and 3-D modeling applications including Gocad, ArcGIS, ER Mapper, and PetroMod, depending on the professional subject area, the type of data being processed, and the desired output.

Most 3-D geological models are created using specialized and expensive software and have fairly large storage requirements. As a result, online publishing of 3-D models has been restricted. Model data are being distributed via CD, DVD, portable hard drives, and restricted and constrained downloads.

In an effort to improve access to its 3-D models, GA has been converting 3-D geological models into Web-viewable formats for distribution and publication online.

Initially, models were converted to VRML (Virtual Reality Modeling Language) and, since 2007, to X3D (Extensible 3-D), the XML-based successor to VRML. Both these formats are open source ISO standards for 3-D graphics on the Web developed and supported by the Web3D Consortium (http://www.web3d.org).

Both X3D and VRML allow interaction with the 3-D data using a Web browser plug-in; hence, 3-D Web mapping. Both VRML and X3D have proven to be very effective methods for communicating large amounts of complex 3-D geoscientific and geospatial information to a wide audience. Since 2000, over 40 unique 3-D Web models have

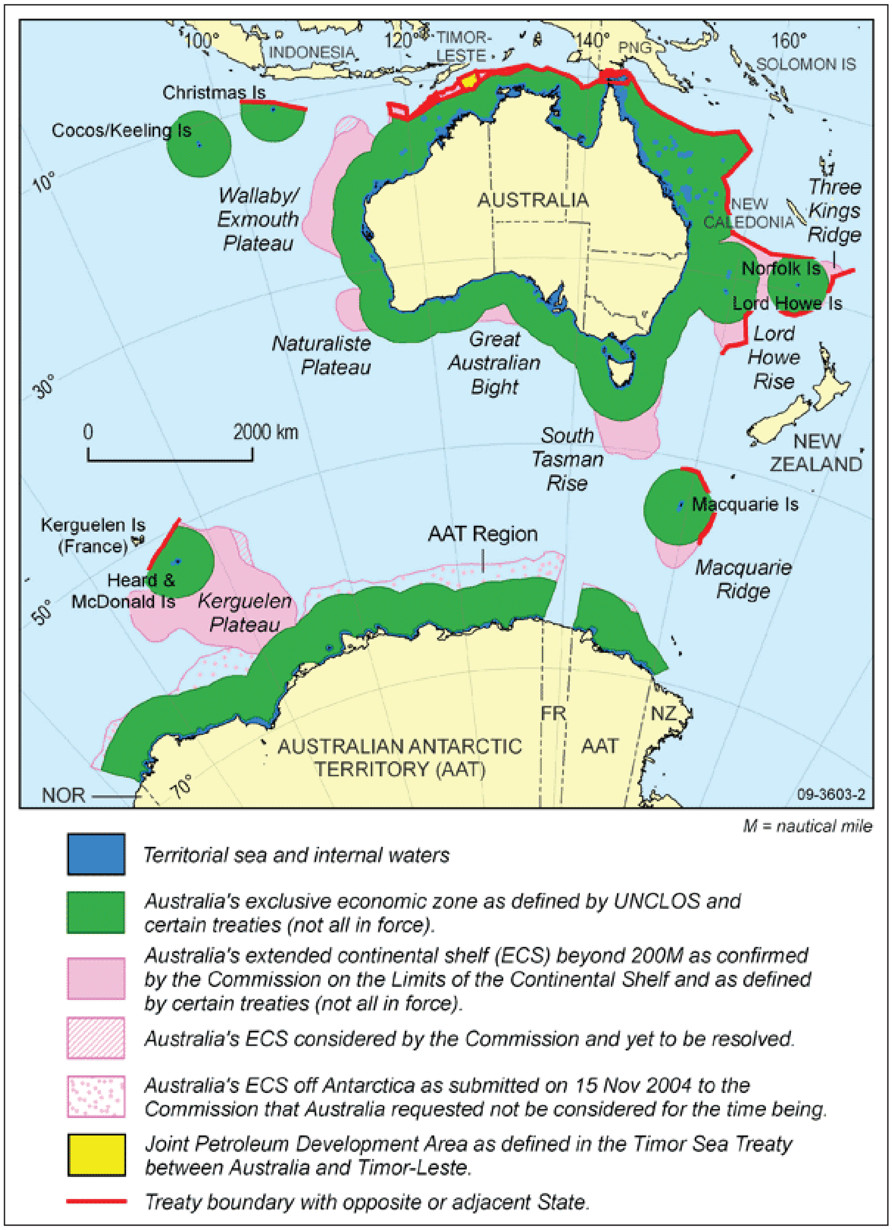


Figure 5-1 Australia's Land and Marine Jurisdictions.

been produced, some of which are available online (Figure 5-2).

Since 2008, GA has been exploring the use of NASA's World Wind software development kit to allow the public to explore and compare Australia's continental data sets, such as radioelements, surface-related uranium, gravity and magnetic anomalies, and other mapping layers and to show the data draped over the Australian terrain in three dimensions. For example, Figure 5-3 shows Mt. Warning, New South Wales, with surface geology from the 3D Data Viewer at 1:1,000,000 scale. Subsurface data such as seismic lines, earthquakes at depth, and 3-D geology are being explored for future releases. (http://www.ga.gov.au/resources/multimedia/world-wind.jsp and http://worldwind.arc.nasa.gov/java/)

GeoScience Victoria

GeoScience Victoria (GSV) is the mining and geology branch within the Victorian Department of Primary Industries, the Australian state government agency responsible for mapping the geology of Victoria. It originally was founded in 1852 during the Victorian gold rush era. In 2004, its name was changed from the Geological Survey of Victoria after it merged with the Petroleum Development Branch.

The Earth Resources Division (ERD) of the Department of Primary Industries has about 130 staff in four branches across Victoria. The key responsibilities of GSV are

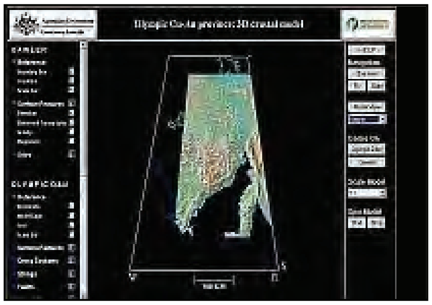
- managing geoscience information on behalf of the State,
- assessing and promoting the minerals and petroleum exploration potential to investors and government,
- providing regional geological frameworks for mineral exploration entities and other stakeholders, and
- providing geoscience advice to government and industry.

Key stakeholders of the GSV are Victoria's government ministers; local, state, territory, and commonwealth government organizations; extractive, geothermal, mineral, and petroleum industries and industry bodies; explorers and producers and their agents; and the broad community including recreational prospectors, community, environment, special interest groups, and students. The minerals, petroleum, geothermal, and extractive industries make a major contribution to Victoria, generating some A$5.4 billion per annum for the economy.

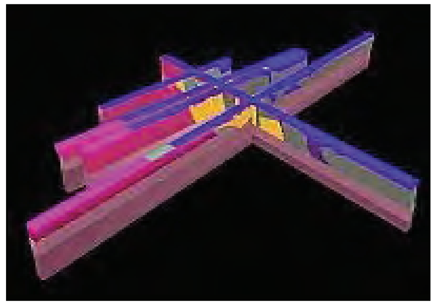
For decades, exploration geologists in the coal, oil, and gas industries and, more recently, in the minerals industry have been using 3-D modeling software to collate, visualize, and analyse their data sets. Generally, this effort has been focused at the reservoir/field or deposit/camp scale, and few regional, full-crustal 3-D geological models have been developed.

In 2002, GSV recognized the need to provide regional-scale 3-D models of Victoria's geology. Soon after, the Victorian government committed to providing to industry the next generation of exploration tools for the mineral resources of Victoria. After

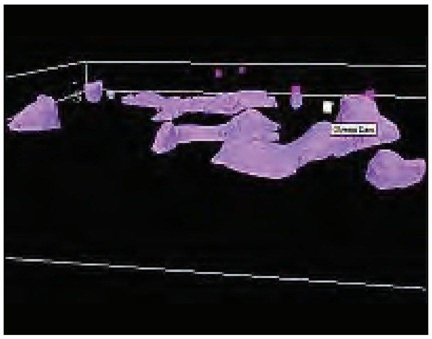
Gawler Craton 3-D crustal model snapshots



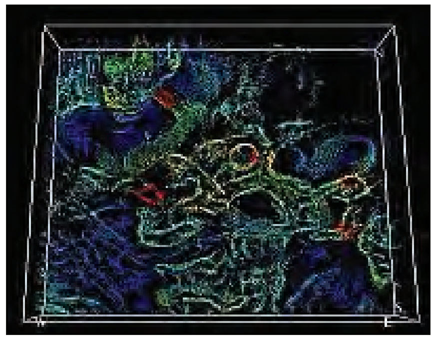
Model interface, with DEM and coastline



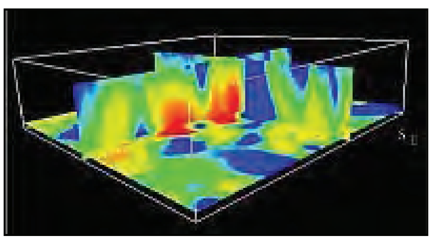
Modelled cross sections



Magnetite isosurface with prospect sites



Gradient points for susceptibility



Interactive volume slices

Figure 5-2 Gawler Craton 3-D crustal VRML model.

consulting with numerous exploration geologists, researchers, and government geologists, it was recognized that 3-D geological models would provide critical tools to explorers interested in understanding not only the distribution and history of mineral deposits as well as energy and water resources, but also the entire Earth system that was responsible for their development. To that end, GSV established a 3-D modeling program in 2004, and a well-funded 3-D geological modeling project began in 2007. This project was designed to develop a sophisticated, fully attributed 1:250,000-scale 3-D model of the whole crust incorporating the onshore and offshore geology of the state.

As a result of taking this “Moho to the sky” approach (e.g., Figure 5-4), that the modeling workflows needed to be flexible and allow incorporation of numerous geophysical data sets and their derivatives to aid in the interpretation of the 3-D structure of the Earth at depths beyond the scope of drilling control (as much as 40 km in places).

Modeling Workflow

GeoScience Victoria’s 3-D modeling team developed a model-building workflow that is applicable to both onshore and offshore settings and includes integration modeling between basement and basin blocks. The workflow is based on the following steps:

- Integrate all available surface mapping, drilling constraints, potential field data sets, 3-D inversion models, seismic data, and other 2-D and 3-D data sets into a 3-D storage and visualization environment.
- Define an agreed upon stratigraphy for the model region.
- Construct serial cross sections based on surface geology and geophysical constraints perpendicular to major

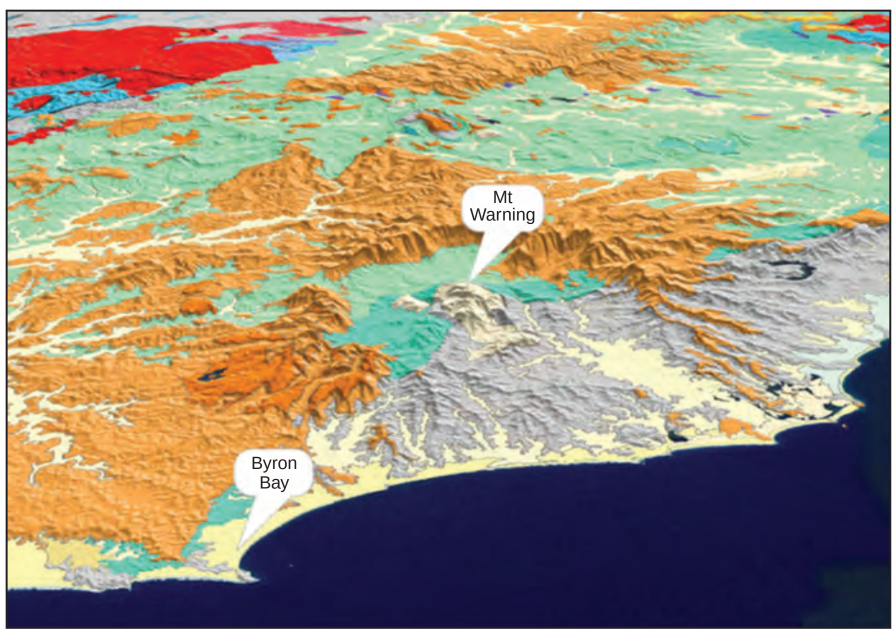


Figure 5-3 Mt. Warning, New South Wales, from Geoscience Australia’s 3-D Data Viewer showing surface geology (lithostratigraphy) with contacts and terrain hill shading. 1:1,000,000.

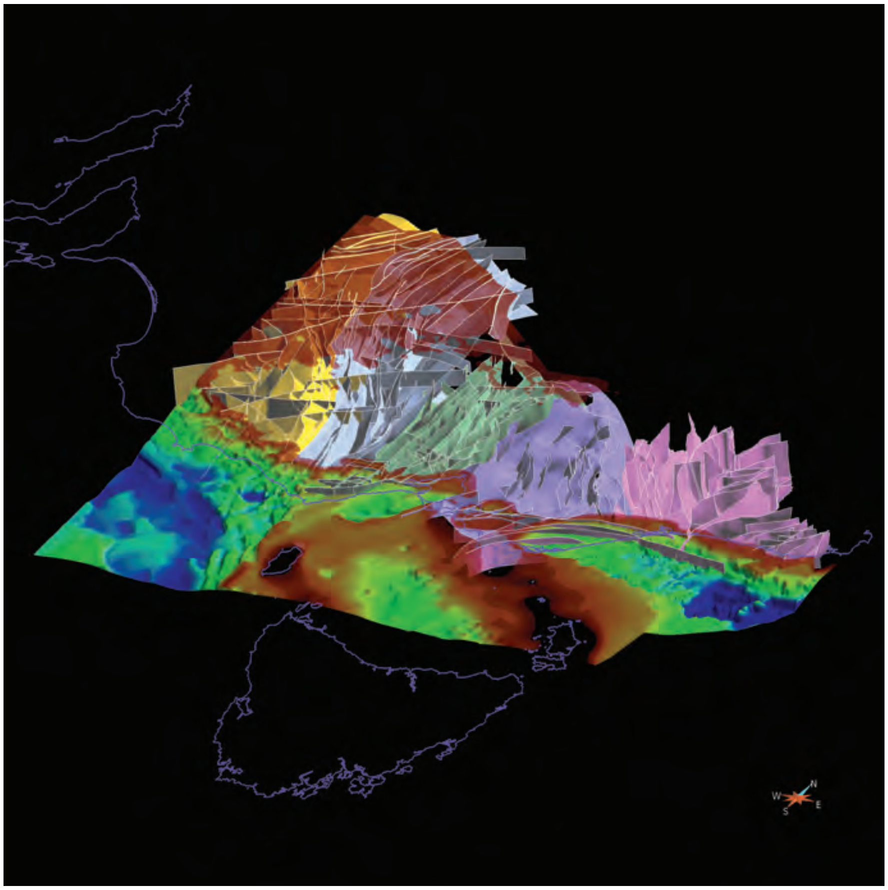


Figure 5-4 Three-dimensional geological model of Victoria incorporating Paleozoic and older basement as well as younger onshore and offshore basin fill and overlying volcanic cover. 1:1,000,000.

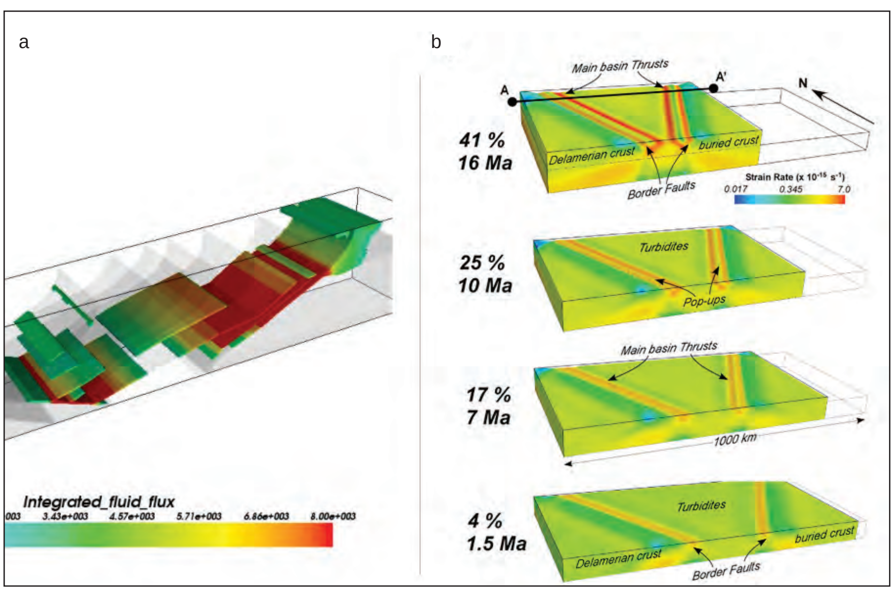


Figure 5-5 Numerical simulation results from 3-D Victoria modeling program. (a) Fluid flow associated with orogenic gold mineralization within an accreted Cambrian ocean basin; (b) strain partitioning around a Proterozoic basement block accreted during the same event. Abbreviation: Ma, million years ago.

structural trends with some tie sections parallel to trend if there is sufficient structure to constrain the geometry in this direction.

- Digitize serial cross sections into a 2-D/3-D/4-D potential field forward modeling package such as Model-Vision or GMsys. These programs allow the measured potential field response of the section to be compared with the calculated response for the interpreted section based on the geometry and rock properties assigned. Although the cross sections are essentially 2-D, the 2-D/3-D/4-D forward modeling algorithms allow the strike of the geology to be at an angle to the section (i.e., not perpendicular) and allow bodies that terminate out of the plane of the model to be included and contribute to the calculated signal. Forward modeling of this type allows a first-order assessment of the validity of the starting geometry.
- Use a combination of implicit and explicit modeling methodologies (primarily SKUA, Gocad, and Geomodeller). Implicit modeling (e.g., SKUA, Geomodeller) requires that contacts and observations are assigned geological types and are placed within a defined stratigraphic column. The model is then constructed from the constraining data by the software and respects the defined relationships. This approach is ideal for organizations such as GSV because (1) models can be regenerated easily if new data become available, (2) higher resolution models for smaller project areas can be derived from the same set of constraint data, and (3) the model surfaces match exactly, which is important if the outputs are to be used for subsequent finite element analysis. The implicit approach is data driven, so where there is a vast amount of available data, the regional models can contain complex overprinting relationships, and the implicit algorithm can be slow or unstable. As a result, GSV typically combines this approach with a traditional CAD-based explicit modeling approach using Gocad. Models are also refined and visualized in Gocad.

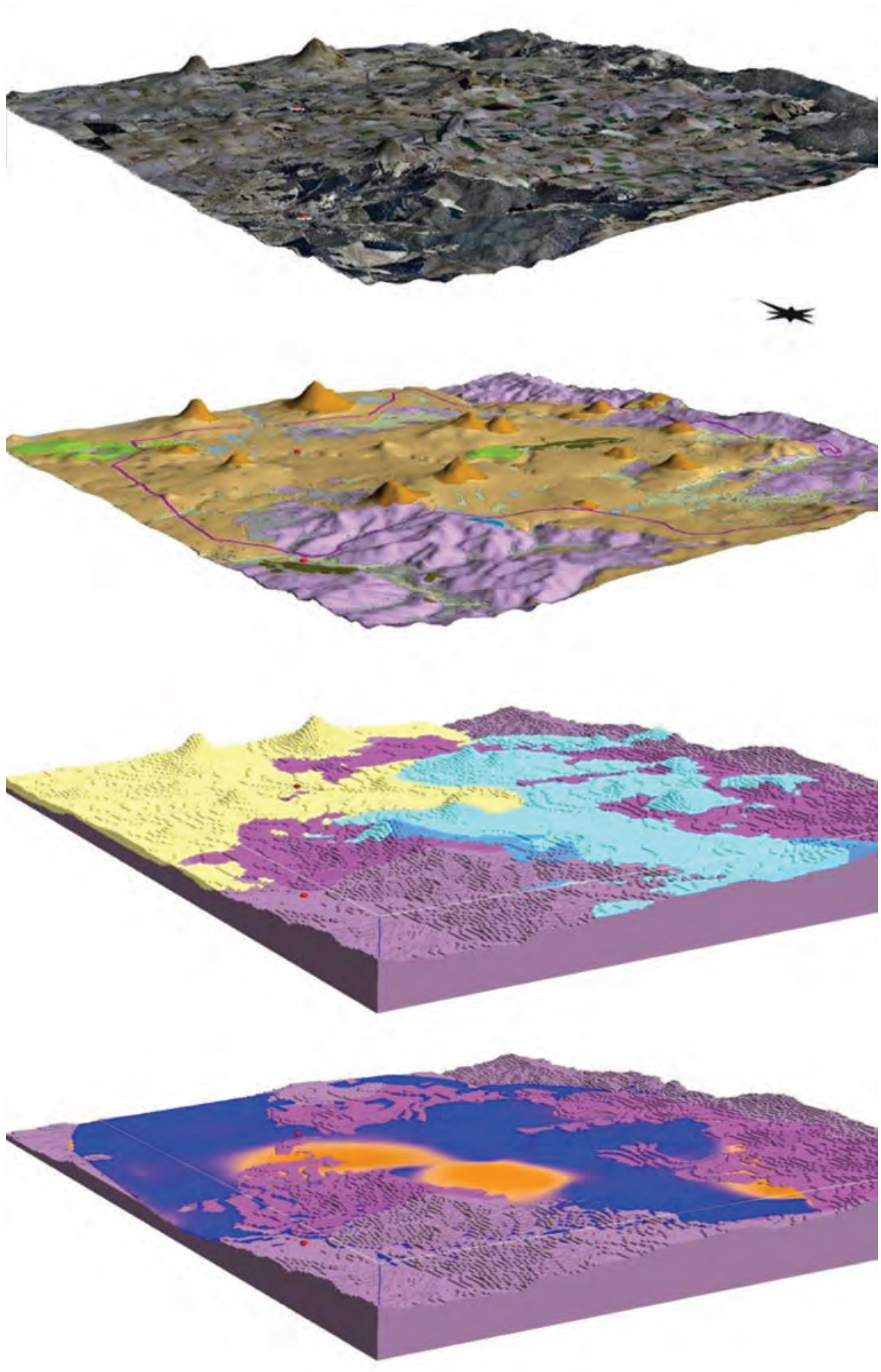


Figure 5-6 Four 3-D block diagrams of a study area in central Victoria (Spring Hill groundwater management area). The top two diagrams show aerial photography and geology draped on the digital terrain model; the lower two are voxel models of the area. The second bottom image is colored according to water salinity range. The lowermost voxel image contains a water table change surface that shows the decline in level over the period 2000 to 2009 (the water table in the orange area has declined as much as 20 m).

- Run 3-D potential field inversions on the model (or its individual parts), ensuring that the 3-D geological model is consistent with the available geophysical data sets. These inversions can highlight regions where the model's predicted potential field response varies from the measured data. Here, the rock properties (such as density or magnetic susceptibility) can be modified within a rock volume to better match the measured response, thus potentially indicating zones of alteration associated with mineralization, or the shape of model surfaces or volumes can be modified again to better match measured responses. The results of these inversions are fed back into the modeling workflow, further enhancing the model.
- Visualize the modeling, primarily done using Gocad, where the model constrains serial and seismic sections, and any other appropriate data sets and surfaces are visualized and analyzed.

Value-Added 3-D Geological Models

3-D models are useful visualization and analysis aids that provide the third dimension to traditional 2-D map-based approaches. However, using them in this way underutilizes their true power, which is unlocked when the 3-D model outputs are used to constrain numerical simulation models using finite element or particle modeling codes to investigate Earth system behavior in 3-D or 4-D.

The outputs of the 3-D Victoria modeling program (Figure 5-5) have been used to develop finite element models that predict the behavior, throughout the crust, of gold-bearing fluids associated with mineralizing events. These models are tested in regions of known geology and then are used predictively in greenfield regions where the major elements of the geology are understood (e.g., from geophysics under shallow cover), but few deposits have yet been discovered. Numerical simulation of geodynamic processes, also based on regional 3-D control, has also allowed investigation into the nature of strain partitioning around Proterozoic crustal blocks entrained in accretionary environments. This simulation has allowed investigation into the controls of basin formation during subsequent rifting and has direct application to hydrocarbon exploration, geological storage of carbon, geothermal energy, and groundwater resource investigations.

Finally, derivative 2-D data sets from the 3-D models have been produced to allow stakeholders who do not have access to sophisticated 3-D applications to take advantage of the model outputs. These include depth surfaces for major stratigraphic contacts, depth to basement surfaces, granite thickness maps, fault maps, and inflection point layers. All of these can be loaded into a traditional 2-D GIS application and used as inputs to area selection mapping or weights of evidence style predictive analysis.

3-D Hydrogeology in Victoria

Within the Victorian Department of Primary Industries, the Groundwater Research Group developed an interest in using 3-D geological mapping methods for hydrogeological investigations when Mintern (2004) wrote a paper on the potential of the techniques for a Murray Darling Basin Groundwater Conference. The paper was inspired by developments at the Alberta Provincial Geological Survey in Canada following a study tour in 2003.

Cherry (2006) undertook a review of software platforms suitable for 3-D hydrogeology applications to establish the foundations for a more substantial study into 3-D hydrogeology applications for Victorian groundwater resource management needs. During this review, the value of workshops sponsored by the Illinois State Geological Survey, Geological Survey of Canada, and Minnesota Geological Survey became apparent (e.g., Berg et al. 2009). The experiences of others around the globe in utilizing these new methods helped establish the validity of the emerging technology and brought sufficient evidence of the potential of the techniques for a more substantial project to be developed in 2006. Although the hydrogeology application research project arose independently of the GSV work, the 3-D hydrogeology project gained support from the larger GSV initiative in terms of in-principle support, expertise, and experience in the use of Gocad, data sharing, and use of a 3-D visualization facility.

The Victorian 3-D hydrogeology project has focused on three areas of interest to develop, test, and demonstrate the new methods: two intensely developed groundwater resource management areas and an area of surface water–groundwater interest. Progress to date has been to assemble the available geological data into suitable 3-D geology databases; explore the use of Gocad to model the main aquifers, faults, groundwater data; and develop visualizations of the data (Figure 5-6). The virtual models of the main aquifers have greatly improved conceptual models of the groundwater system in each area to be developed. An immediate benefit has been the ability to identify more logical boundaries for the groundwater resource management area as well as to identify flow constrictions in the aquifers.

Using query tools in Gocad, the aquifer volumes have been calculated. A crucial step for calculating groundwater movement into and out of each area was to use the software to measure aquifer cross sectional areas at key points in the aquifer flows paths. Mass balance models were then constructed on the basis of the virtual model calculations, allowing groundwater resource estimates to be made. Reducing the uncertainty in the physical dimensions of the aquifers also reduces uncertainty in mass balance modeling of the groundwater resource. The aquifer surfaces are also able to be exported into numerical modeling packages (such as MODFLOW) to simulate the dynamic behavior of the aquifer system. For groundwater resource assessment purposes, the use of 3-D geology shows great promise in improving the technical understanding of groundwater resources and in allowing groundwater users and administrators new ways of developing a shared understanding of the resource.

Chapter 6: British Geological Survey: A Nationwide Commitment to 3-D Geological Modeling

Stephen J. Mathers, Holger Kessler, and Bruce Napier

British Geological Survey

The British Geological Survey (BGS), founded in 1835, is the national geological survey for Great Britain (including England, Scotland, and Wales). In addition to its government core funding, the BGS earns around 50% of its income through commercially funded projects, services and sales. Its total annual turnover is around £55 million.

The BGS undertakes an integrated core program of geological mapping and modeling with an annual budget of about £5 million, and commercial contracts raise an additional £1 million per year for these activities. The BGS program produces digital geological maps (DigMap) and attributed 3-D geological models (LithoFrame) as its primary outputs.

Of the 500 BGS scientific staff, about 30% have been trained to use 3-D geological modeling techniques and to employ these tools in primary surveys; coastal, urban, and engineering site remediation; and groundwater studies. Approximately 20 scientists are engaged in 3-D modeling on a daily basis. The modeling community is supported by a help desk and training courses.

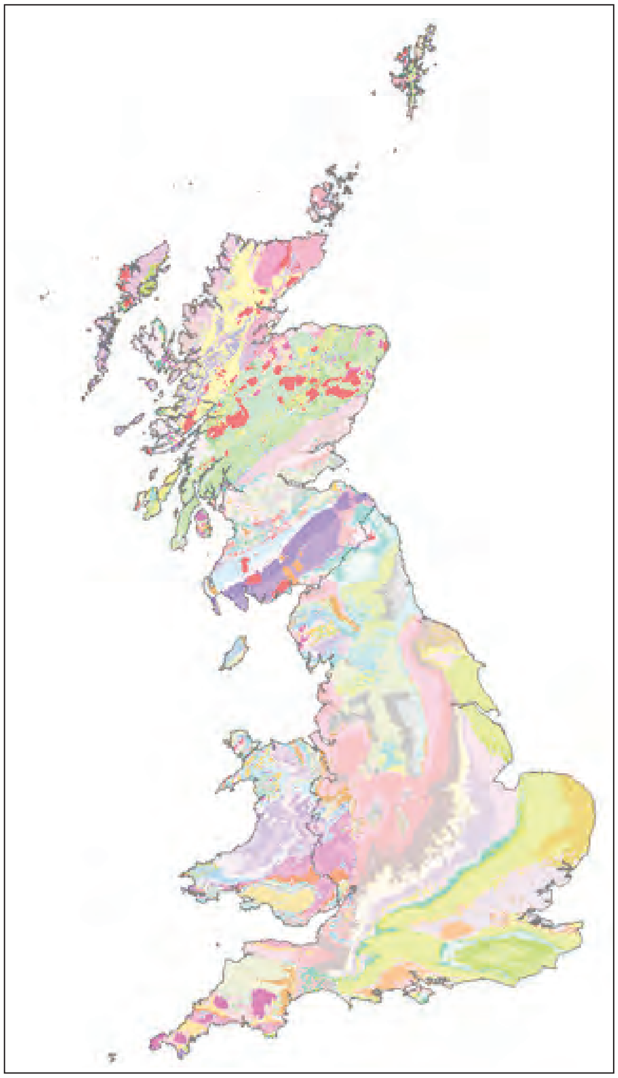


Figure 6-1 Bedrock geology of Great Britain.

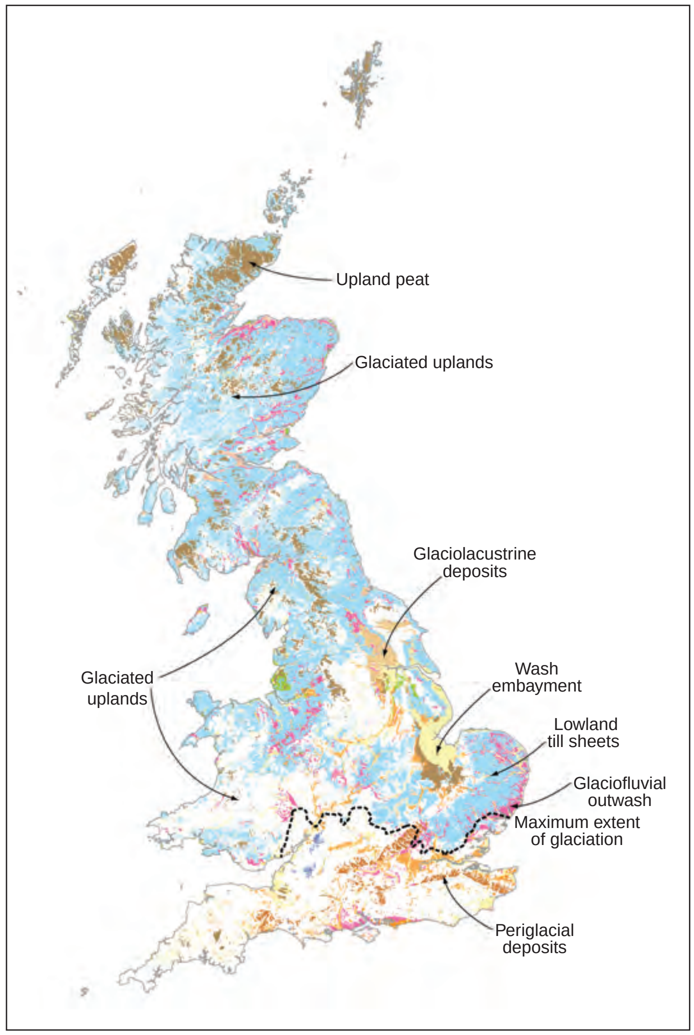


Figure 6-2 Superficial geology of Great Britain.

Geological Setting

Great Britain is the largest of the British Isles lying in northwest Europe and covering an onshore area of about 210,000 km^2. The island is geologically diverse; the oldest rocks occur in the north and west and progressively younger rocks occur to the south and east toward the still subsiding southern North Sea Basin (Figure 6-1).

Archean gneissose rocks of the Lewisian Complex are found in northwestern Scotland and belong to the Laurentian craton of North America. Elsewhere in northern Scotland, deformed Neo-Proterozoic metasediments of the Moine and Dalradian supergroups are widespread together with Lower Palaeozoic sediments and volcanics in southern Scotland, Wales, and the Lake District of England. These rocks were all deformed during the Caledonian Orogeny at the end of the Silurian Period and are divided into a series of distinct structural terranes by major northeast-southwest aligned faults. Numerous granitic plutons were intruded into these sediments during the orogeny.

The largely terrestrial Devonian red bed rocks accumulated in fault-controlled basins within this Caledonian structural framework, and the overlying initially marine Carboniferous shelf carbonates gradually gave way to extensive fluviatile and deltaic sedimentation leading to the accumulation of major coal resources during the Pennsylvanian. These have subsequently acted as source rocks for the oil and gas reserves that are trapped in the overlying sediments. The Variscan (Hercynian) Orogeny at the close of the Carboniferous is well recorded by the deformation of the Devonian-Carboniferous sediments of southwestern England, where a large granitic batholith at depth is evidenced at the surface by a string of granite bosses. Elsewhere in southern England the rocks deformed by the Variscan Orogeny lie buried beneath Mesozoic and Tertiary cover.

The succeeding Permian deposits of northeastern England fringe the large Zechstein continental basin that developed across northwestern Europe in which thick evaporate sequences were deposited. The succeeding Triassic sequences are almost exclusively terrestrial red beds recording a diverse history of independent basin evolution in the post orogenic extensional tectonic regime. They include the important Sherwood Sandstone Group that is widely exposed in the English Midlands and comprises both a major aquifer and a hydrocarbon reservoir. The succeeding Jurassic and Cretaceous sediments record sedimentation in epeiric shelf seas culminating in the globally high sea levels and sedimentation of the Chalk Group across much of western Europe in the Upper Cretaceous. Due to subsequent erosion, the Chalk is now only exposed in southeastern England where it also constitutes a major aquifer.

Initial rifting associated with the opening of the North Atlantic resulted in the volcanic rocks of the Hebrides in northwestern Scotland; in southeastern England, terrestrial and marine Palaeogene sediments accumulated. These sediments were then folded during the Miocene-Oligocene in response to reactivation of underlying Variscan basement structures in southern England during the Alpine Orogeny.

Most of Great Britain has been glaciated several times during the Quaternary, resulting in the deposition of extensive sheets of till in lowland areas (shown in blue in Figure 6-2) and glaciated uplands in Wales and Scotland. These deposits are associated with large spreads of glaciofluvial sand and gravel (pink) and glaciolacustrine sediments (brown) in proglacial and ice-marginal settings. The extreme southern part of England remained ice-free throughout, and there periglacial mass movement and aeolian sediments and permafrost structures are widespread. Holocene deposits are located along major river courses and in coastal plains (yellow) including the large Wash embayment.

Data Sets for Modeling

In the 1990s, BGS converted its key national data sets into digital form and produced supporting dictionaries and lexicons for these databases. The data sets include borehole index and downhole logs, geological map linework captured as a series of themes (or layers), and key national geophysical data sets and seismic lines.

Additionally, digitally georectified nationwide topographic maps including historic versions, aerial photographs, satellite imagery, and DEMs were licensed or purchased, and the availability of such data sets has been maintained and upgraded where new and improved products have become available.

The BGS LithoFrame Concept

The BGS models are branded under the name LithoFrame. They represent the extension of the 2-D geological map into 3-D (Tables 6-1 and 6-2).

Central to the LithoFrame concept is that varied resolutions are consistent with one another so that collectively they form a seamless transition from the general national model to a detailed site-specific one. Figure 6-3 shows that the highest-order stratigraphic units (regionally extensive and well defined) shown in dashed red lines should be defined first and be included in all models of a higher (more detailed) resolution. Here the major stratigraphic boundaries selected at LithoFrame 250 are applied to the higher resolution 50 and 10 models. At LithoFrame 50, more detail is applied, showing seven rather than two units, but this detail is likely to be observed and depicted to a shallower depth. These units then extend through the more detailed LithoFrame 10 model, and more detail (here 17 units) is nested within them in the shallow subsurface. Similar simplification of fault networks is shown on the right side of Figure 6-3.

The depth of modeling reflects the available data and the importance of seismic lines and deep boreholes to provide information when building low definition models, whereas the detailed LithoFrame 50 and 10 resolutions rely more heavily on surface geological mapping and shallow boreholes. Hence, deeply buried surfaces constructed at LithoFrame 250 resolution in some areas can be constructed

Table 6-1 Main features of the LithoFrame resolutions.[1]

Feature	LithoFrame 1M (National)	LithoFrame 250 (Regional)	LithoFrame 50 (Detailed)	LithoFrame 10 (Site-specific)
Proposed coverage (long-term)	Entire onshore and UK continental shelf	Entire onshore and UK continental shelf	Onshore UK	Major urban and development areas; areas of complex and classic near-surface geology
Tile size	Single tile	100 x 100 km	20 x 20 km	5–10 km x 5–10 km
Resolution of grid output	1 km	500 m	100–200 m	50–100 m
Depth	50 km	5–10 km	1–2 m	100–200 m or base of surficial deposits if deeper
Uses	Visualization, national and international collaboration, public understanding of science, education	Visualization, popular science, overviews for the energy and water sectors, deep structural studies	Analysis, the standard output, hydrocarbons, aggregates, bulk minerals, aquifers, planning, major infrastructure	Detailed analysis and problem solving; site-specific and detailed studies of all kinds
Key data sets	Geological linework Digmap 625 deep seismic lines, national and regional magnetic and gravity data, very deep boreholes	Geological linework Digmap 250 seismic lines and regional magnetic and gravity data, deep boreholes	Geological linework Digmap 50 seismic lines, boreholes, deep mining data	Geological linework Digmap10 all boreholes and mining data
Commercial potential	Low; popular publications, atlases	Modest; contextual models for energy, water sectors	Moderate to high; the standard product for geoscientists and allied professions	Very high, custom models to resolve problems and deliver geoscience solutions at a detailed site-specific level

[1]LithoFrame scales: 1M, 1:1,000,000; 250, 1:250,000; 50, 1:50,000; 10, 1:10,000.

considering all the available data, and therefore they can be magnified to form the deeper parts of the higher resolution, LithoFrame 50 and 10 models if required. This concept reinforces the suggestion that key surfaces should be first defined for low-resolution models and then used to form the framework for nested detail at higher definition for more detailed models.

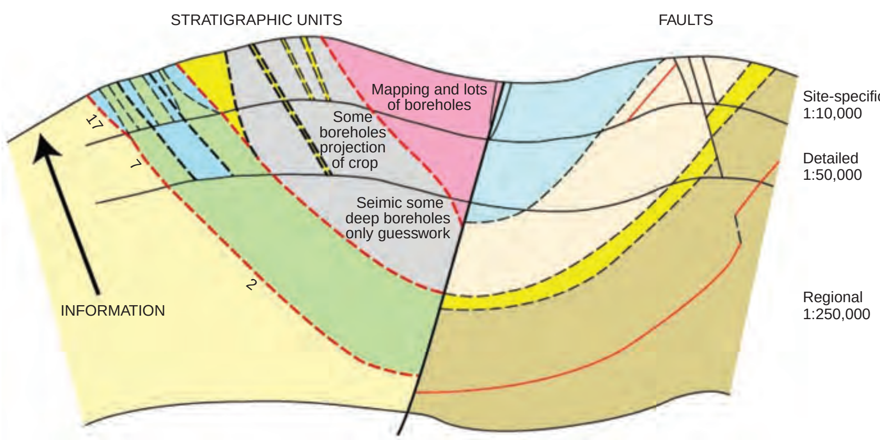


Figure 6-3 Schematic section showing effective depth of modeling and definition across the LithoFrame 250, LithoFrame 50, and LithoFrame 10 resolutions.

Example Models

National Model of Great Britain

An onshore LithoFrame 1 M model (1:1,000,000 scale) (Tables 6-1 and 6-2) has been produced for Great Britain. The model is principally derived from

Table 6-2 Geological detail possible at the various LithoFrame resolutions.[1]

Detail	LithoFrame 1M (National)	LithoFrame 250 (Regional)	LithoFrame 50 (Detailed)	LithoFrame 10 (Site-specific)
Stratigraphic resolution (bedrock)	Major stratigraphic systems and deep crustal layers to the Moho picking out overall structure	Group level likely to be the most commonly applied level, especially for concealed strata	Formation level likely to be the most commonly applied level, especially for concealed strata	Members and scientifically or economically important beds down to 1-m-thick lenses
Stratigraphic resolution (superficial)	Not depicted	Superficial undivided	Major units modeled	Detailed modeling of beds, lenses, etc. as required
Unconformities	Delineated at major system boundaries	Major unconformities delineated by stratigraphic boundaries	Unconformities delineated by stratigraphic boundaries	Minor unconformities revealed by detailed stratigraphic units
Folding	Depicted by overall form of major sedimentary packets	Depicted by overall form of major sedimentary packets	Detailed form depicted using structural observations in Digmap 50	Very detailed form depicted by thin sedimentary packets and structural observations at Digmap 10 scale
Faulting	Major faults bounding domains of British geology, e.g., Great Glen, Highland Boundary faults; vertical displacements of kilometers and/or significant lateral displacements of 100 km	Those with throws of hundreds meters or lateral displacement of several kilometers likely to be included in the model	Faults with throws of more than 50 m; also slightly smaller faults where these are laterally persistent or strongly influence the outcrop pattern; subparallel faults amalgamated where spacing is <200 m	Faults with throws of more than 10 to 15 m; also slightly smaller faults where laterally persistent or strongly influencing the outcrop pattern; subparallel faults amalgamated where their spacing is <50 m
Intrusions and lavas	Major plutons such as the southwestern England and Lake District batholiths covering several hundred square kilometers in extent	Plutons with outcrops-subcrops of at least 10 km^2 should be included; major lava piles	Plutons with outcrops-subcrops of at least 5 km^2 should be included; thick lava sequences and major sheet intrusions	Plutons with outcrops-subcrops of at least 1 km^2 sheet intrusions at least 5 m thick; individual lava flows and sheet intrusions
Artificial ground	Not shown	Not shown	Large pits and quarries worked and/or infilled, and extensive thick areas of made ground	Quarries worked and/or infilled, and large mappable areas of made ground

[1]LithoFrame scales: 1M, 1:1,000,000; 250, 1:250,000; 50, 1:50,000; 10, 1:10,000.

the compilation of contoured stratigraphic surfaces, deep boreholes, seismic profiles, and regional geophysical interpretations (Whittaker 1985). The model (Figure 6-4) was constructed in Gocad by the BGS and shows the base of major geological units as 2-D surfaces ("flying carpets"). Also shown are the foci of significant earthquakes, major faults, and igneous plutons. The model extends to a depth of about 30 km; the lowest, purple surface represents the base of the crust (Moho). The model is mainly used for educational purposes, visualizations of the nation's geology, and a basic spatial framework for more detailed modeling exercises. (For more information, see http://www.bgs.ac.uk/science/3dModeling/lithoframe1m.html.)

Surfaces modeled include these bases:

- Palaeogene
- Cretaceous
- Jurassic
- Triassic
- Permian
- Carboniferous

Figure 6-4 The LithoFrame 1M resolution onshore model of Great Britain.

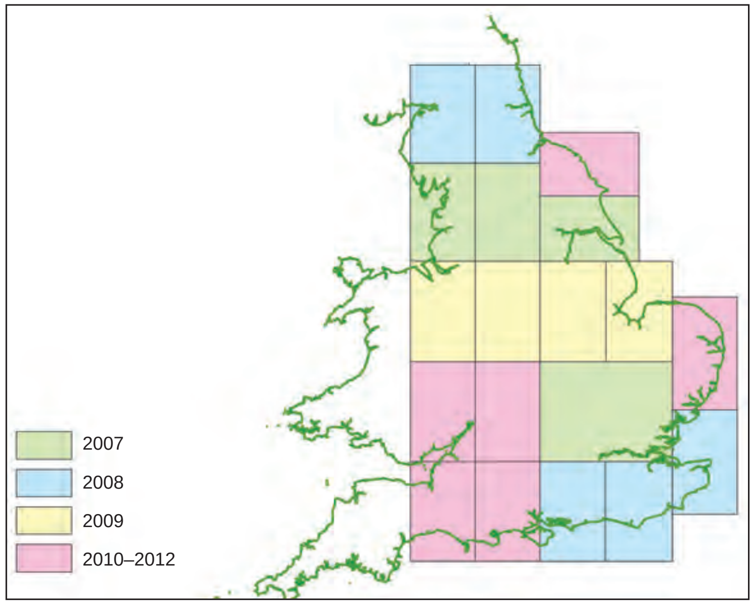


Figure 6-6 Scheduled availability of LithoFrame 250 resolution regional models for England and Wales.

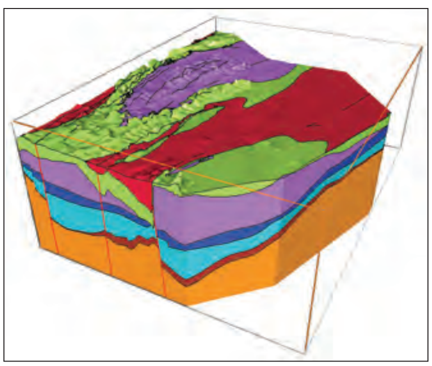


Figure 6-5 Example LithoFrame 250 model covering the Weald and adjacent parts of the English Channel.

- Devonian
- Lower Palaeozoic
- Precambrian
- Crust (Moho)

Regional Model: The Weald

At the next level of detail, regional LithoFrame 250 resolution models (1:250,000 scale) (Tables 6-1 and 6-2) are being constructed for the whole of England and Wales. An example from the Weald-English Channel model is shown in Figure 6-5. This model was developed in Gocad and is based on extensive depth-converted seismic interpretations, deep boreholes with downhole geophysics, and surface geology. The progress toward regional LithoFrame 250K coverage is shown in Figure 6-6.

Detailed Model: Southern East Anglia, Eastern England

A systematic LithoFrame 50 (1:50,000 scale) detailed model (Tables 6-1 and 6-2) has been built for 1,200 km^2 of southern East Anglia in the Ipswich-Sudbury area. Modeling was carried out in conjunction with a primary geological survey of much of the area. The model was constructed as the survey progressed in 10-km × 10-km tiles, and then the various tiles were merged (Figure 6-7).

The model contains the major artificial deposits, about 25 superficial layers, including a complex, interleaved, Anglian glacial succession and bedrock. The glacial succession includes a widespread till sheet (in blue) in the north and west and extensive periglacial and ice-marginal glaciofluvial sand and gravel deposits (pink) underlying the till and exposed in the south and west of the area. The geometry of the latter deposits is especially important as they constitute a major aggregate resource. The bedrock comprises Plio-Pleistocene shallow marine sediments (Crags in deep purple) and Palaeogene marine and marginal sediments dominated by clays (blue and red). The distribution of these clay-rich Palaeogene strata is crucial as they act as a protective seal for the underlying Upper Cretaceous Chalk Group aquifer (green). The model extends to the base of the Chalk Group at an average depth of about 300 m. The Chalk is one of Britain's principal aquifers, and this model has been licensed to the Environment Agency of England and Wales for use by the hydrogeological consultants to investigate issues of aquifer protection, recharge, and groundwater management. The model is also used to generate borehole prognoses for site-specific inquiries and has improved scientific understanding of the complex glacial succession of the area.

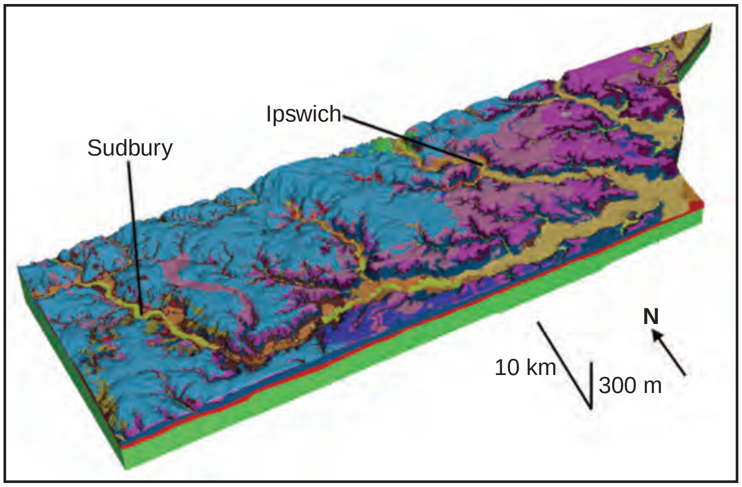


Figure 6-7 The LithoFrame 50 resolution southern East Anglia model of the Ipswich-Sudbury area covering 1,200 km^2.

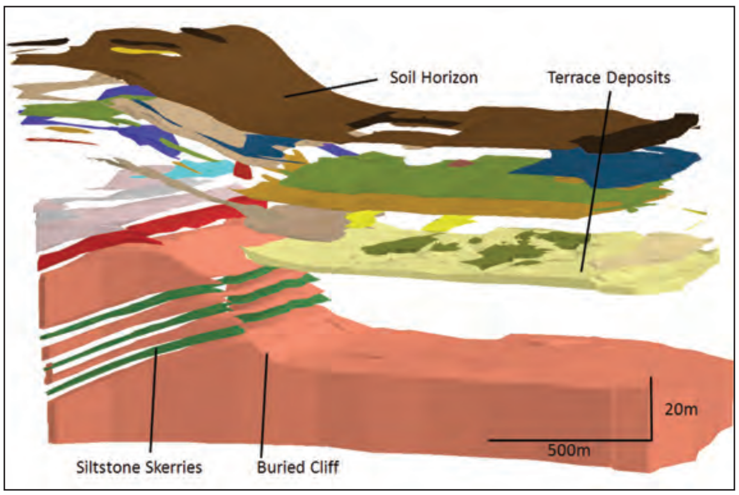


Figure 6-8 The site-specific Shelford model.

Site-Specific Resolution: Shelford, Trent Valley

An integrated geological, geophysical, and remote sensing survey was undertaken to construct a high resolution 3-D LithoFrame 10 (1:10,000 scale) site-specific model (Tables 6-1 and 6-2) of the shallow subsurface geology of part of the Trent Valley in Nottinghamshire, UK. The 3-D model (Figure 6-8) was created using the GSI3D software package to evaluate the 1:10,000-scale geological survey, borehole data, and remote sensing images, plus vertical and horizontal profiles derived from geophysical techniques such as ground-penetrating radar (GPR), electrical resistivity tomography (ERT), and automated resistivity profiling (ARP). The site covers about 2 km^2 and consists of a Triassic mudstone overlain by Quaternary sand and gravel river terrace deposits and the modern floodplain deposits of the River Trent. Additionally, soil horizons were modeled together with areas of artificial deposits (Whitaker 1985, Tye et al. 2010).

The combined investigations enabled several advances in the understanding of the area including

- delineation of a buried river cliff forming the southern limit of the incised Trent valley,
- precise positioning of hard thin silt stone beds (skerries) within the bedrock Gunthorpe Member of the Mercia Mudstone Group, and
- resolution of the lithologic variability of the sediments within the river terrace deposits.

This study demonstrates the potential for combining many and varied data sets within a single spatial reference system (GSI3D) to maximize the interpretation of subsurface conditions. Such investigations are very well-suited to ground investigations for major civil engineering and infrastructure projects, together with site-based evaluation for environmental problems such as evaluating and tracking of pollution plumes. Similar resolution models have also been constructed for archaeological investigations and to model the chronology of artificial deposits.

The distribution of detailed and site-specific models produced by the BGS is shown in Figure 6-9.

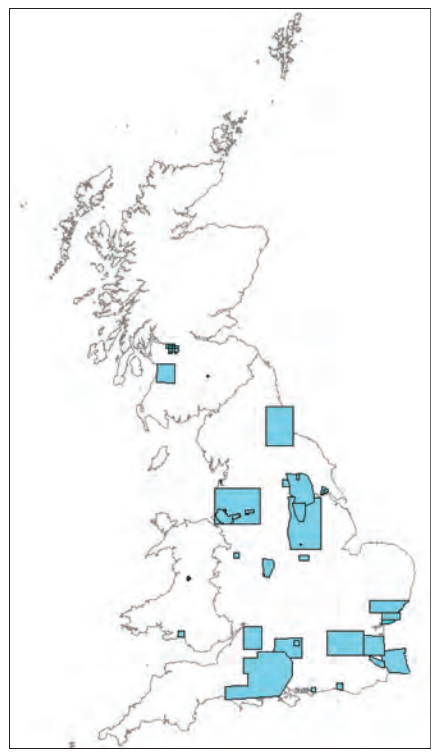


Figure 6-9 Current LithoFrame 10 and LithoFrame 50 coverage for Great Britain.

Chapter 7: Geological Survey of Canada: Three-dimensional Geological Mapping for Groundwater Applications

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The Geological Survey of Canada (GSC) is a federal agency that operates collaboratively with multiple provincial and territorial agencies that have direct responsibility for natural resource and groundwater management. Three-dimensional geological mapping has been embraced at the GSC during the past 20 years as data collection, analysis, interpolation, visualization, and presentation modes have evolved with the advent of increased computer processing capacity, graphic user interfaces, and 2-D and 3-D GIS (Geographic Information Systems). Nevertheless, for groundwater studies the fundamental requirements for 3-D geological mapping have not changed radically from traditional geological investigations. Basin analysis concepts provide the cornerstone of 3-D mapping at the GSC. Within this framework, emphasis is placed on data collection and understanding of the geological history of the basin. This knowledge base provides a framework for interpretation and correlation of disparate data sets necessary for input to interpolation algorithms for the construction of 3-D models. Basin analysis has been adapted across the groundwater program as a common methodology for 3-D studies. Subsequent data processing, interpolation, and visualization within GIS software remain discretionary depending upon geographic and geological complexity, study objectives, and partnership requirements.

This paper highlights work completed in the past 17 years within the GSC's Groundwater Geoscience Program (and its predecessor activities) toward mapping key Canadian aquifers, specifically 3-D subsurface geological model construction. Modeling techniques and underlying philosophical approaches (basin analysis) are reviewed, and three case studies are presented to illustrate variations in study approaches.

Introduction

Prior to the widespread use of desktop computing and advanced GIS, text descriptions, geological maps, cross sections, and attached stratigraphic legends were the only way to communicate a 3-D conceptualization of complex geological structures and their interrelationships. This 3-D conceptualization was illustrated using structural measurements (e.g., strike and dip), cross sections, isosurface maps (e.g., isopach maps), stratigraphic concepts (e.g., lithostratigraphy, allostratigraphy), and depositional facies concepts (Wather's Law). Because paper maps are highly subjective and based on the skill and experience of the author, they convey a unique interpretation of the available information (e.g., aerial photographs, field observations). Moreover, correct interpretation of the map also relies on the ability of the end user to understand the 2-D map components and correctly visualize the implied 3-D structure. Digital 3-D modeling techniques that take advantage of innovations in hardware and software (e.g., Thorleifson et al. 2010) are a logical extension of hand-drafted geological maps that have for decades been the norm at the GSC. Like hand-drafted geological maps, digital models are realizations of 3-D geology based on extrapolating discreet and often sparse observations or measurements. Unlike hand-drafted maps, digital 3-D models provide a readily understandable means of visualizing geology and estimating geological unit volumes and also permitting advanced hydrogeological study by supporting quantitative flow modeling. Conceptually the differences between the 3-D modeling techniques presented here are primarily in the amount of expert input utilized. Techniques range from largely automated and data-driven to 3-D CAD techniques that rely heavily on an expert to interpret and construct 3-D contacts.

Within the new paradigm of 3-D geological mapping, various groups at the GSC have pursued 3-D modeling and visualization for mineral resource development (e.g., Hughes 1993, Mossop and Shetsen 1994, de Kemp 2007) and for groundwater issues (e.g., Logan et al. 2002, 2006; Ross et al. 2005; Sharpe et al. 2007; Smirnoff et al. 2008).

Geological Survey of Canada

Founded in 1842, the GSC is the oldest government research agency in Canada. It is part of the Earth Science Sector of the Department of Natural Resources along with the Canadian Centre of Remote Sensing and Geomatics Canada. The GSC has traditionally focused on the production of geoscience knowledge. More recently its mandate has expanded to include issues pertaining to geological hazards, groundwater, the environment, and climate change. The GSC operates in all 10 provinces and three territories on a cooperative basis with respective pro-

Table 7-1 Key Canadian aquifers grouped according to hydrogeological regions. No currently designated key Canadian aquifers are identified in the Maritime and Permafrost regions.

Cordillera
1. Gulf Islands
2. Nanaimo Lowland
3. Fraser Valley
4. Okanagan Valley
5. Shushwap Highlands

Western Canadian Sedimentary Basin
6. Paskapoo
7. Buried Valleys
8. Upper Cretaceous Sand
9. Milk River
10. Judith River
11. Eastend - Ravenscrag
12. Intertill
13. Manitoba Carbonate Rock
14. Manitoba Basal Clastic unit
15 Odanah Shale
16. Sandilands
17. Assiniboine Delta

Southern Ontario Lowlands
18. Oak Ridges Moraine
19. Grand River Basin
20. Credit River
21. Waterloo Moraine
22. Upper Thames River

Appalachians
23. Annapolis–Cornwallis valleys
24. Carboniferous Bain

St. Lawrence Platform
25. Mirabel
26. Châteauguay
27 Richelieu
28 Chaudière
29. Maurice
30. Portneuf

vincial and territorial agencies to fulfill a requirement of the Resources and Technical Surveys Act of 1949 and 1994 that the Minister of Natural Resources "make a full and scientific examination of the geological structure and mineralogy of Canada." Provinces are vested with the primary mandate for natural resource and groundwater management, whereas the GSC has particular interest in areas of federal jurisdiction such as trans-boundary aquifers (Table 7-1; e.g., Richelieu, Milk River) and federal lands within provinces (military and First Nations reserves). To respond to federal government mandates and objectives, the GSC maintains a suite of programs that are funded on a 5-year cycle. To fulfill this mandate, the GSC has seven offices across Canada: a central office in Ottawa and six regional offices. The GSC maintains an applied research staff of 184 technical staff of which a group of 20 to 25 work on groundwater. The annual operating budget for the Groundwater Program in 2009 was 2.8 million dollars (ESS 2006) of which more than two-thirds was allocated to salaries. Study teams commonly consist of fewer than 10 staff members, most of whom are engaged in multiple projects. To supplement this limited capacity, the GSC actively develops partnerships with provincial, territorial, and other federal government agencies, industry, universities, and other state and national geological surveys.

Groundwater resource investigations and research at the GSC date back to 1875 (Brown 1967). In 1972, however, the mandate for water resource management (including groundwater) was passed to the newly formed Environment Canada, and the GSC ceased to be active in groundwater studies. During the late 1980s and early 1990s, client surveys indicated that there was a demand for increased geological input to regional water supply studies (e.g., Canadian Geoscience Council 1993). Following an absence from regional groundwater studies of more than 20 years, the GSC reinitiated work on regional hydrogeology in a series of projects in the early 1990s (e.g., Sharpe et al. 1996, Parent et al. 1998, Ricketts 2000, Thorleifson et al. 2002). Within a decade, these early studies evolved into a national groundwater program at the GSC. A collaborative document between the provinces, territories, and the federal government established a framework for progress on groundwater studies in Canada (Rivera et al. 2003). Subsequently, the groundwater program of the GSC developed a strategy to map and assess 30 key aquifers across the country (Table 7-1; Figure 7-1).

These 30 key aquifers consist of bedrock and glacial sediment aquifers involving fracture media and porous media flow systems, and they range in size up to 60,000 km^2 and up to several hundred meters in depth (Tables 7-1 and 7-2). In a country considered to have abundant surface water, the groundwater resources were largely ignored prior to the 1990s. The focus of groundwater research during the 1970s and 1980s shifted to groundwater contamination (e.g., Cherry 1996) and remediation. Nevertheless, groundwater use in Canada is significant; 30% of Canadians, and 80% of rural Canada, depend on aquifers for potable water supply (Environment Canada). As might be anticipated in a country of almost 10,000,000 km^2 with a rather modest population (35,000,000) concentrated in urban areas, enormous challenges are presented for the development of a comprehensive understanding of groundwater resources.

Hydrogeological Framework of Canada

The geology, groundwater regimes, and hydrology of Canada are complex. The major hydrogeological domains of Canada have been assigned to nine hydrogeological regions (Sharpe et al. 2008). This classification is built on previous work by Brown (1967) and Heath (1988). The delineation of these regions is based on geological provinces and rock formations, surficial geology, topography, and the extent of permafrost. The 30 key Canadian aquifers form local elements within these regions and can be assigned to one of two principal classes: bedrock aquifers and surficial sediment aquifers. Within each of these two categories, the key aquifers can be classified based on geological environments (Table 7-2).

Methods

Reflecting a long history of encouraging creative problem-solving and methods development at the GSC, study teams working on 3-D geological modeling for groundwater are permitted latitude in how they approach 3-D geological mapping and the tools used for model construction and visualization. This approach also implicitly recognizes differences and preferences within provincial agencies and the need to maximize collaboration

Table 7-2 Grouping of key Canadian aquifers according to host geology.

Style	Index to Figure 7-1	Comment
Bedrock (undefined)	1, 2, 5, 8, 15	Areas of fractured bedrock aquifers and secondary porosity
Fluvial	6, 10, 11, 24	Predominantly braided fluvial systems
Carbonate	13, 14	Paleozoic carbonate systems
Deltaic-coastal	9	Cretaceous bedrock system
Bedrock/surficial mixed	19, 20, 22, 23, 25, 26, 28	Large regional, commonly watershed scale aquifer complexes; contains fracture flow bedrock and porous media in eskers, moraines, and outwash
Surficial (undefined)	3	Likely fluvial
Moraine	16, 18, 21	Sand and gravel bodies up to 200 m thick overlying erosional unconformities with tunnel channels
Esker	27	Linear sand and gravel ridges in clay basins and moraines
Buried valley	4, 7, 12	Bedrock and sediment hosted valleys of tens of kilometers scale
Delta	17, 29, 30	Kilometer-scale glaciofluvial deltas constructed into paleo-glaciolacustrine and glacio-marine environments
Outwash	12	Relatively thin, spatially extensive sand and gravel deposits of braided outwash and valley trains

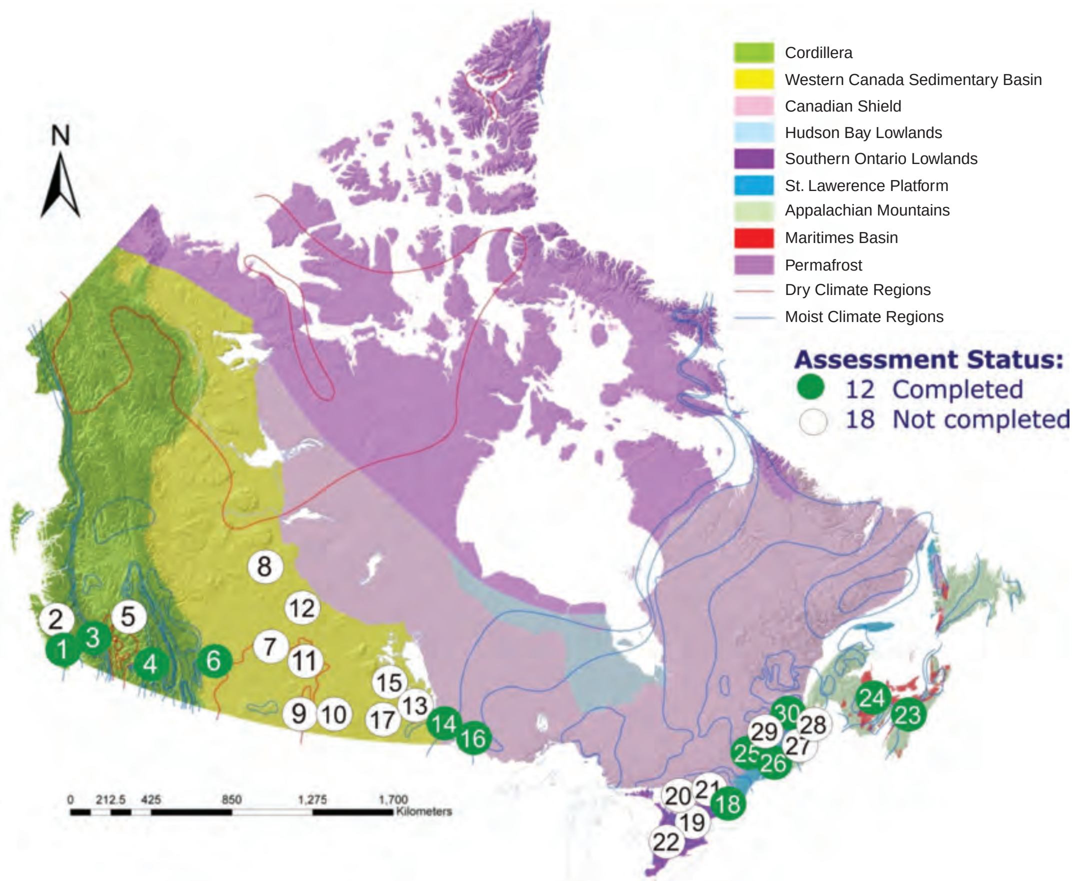

Figure 7-1 Hydrogeological regions of Canada and key Canadian aquifers (base from Sharpe et al. 2009). (http://ess.nrcan.gc.ca/gm-ces/aquifer_map_e.php.) Case studies are 4, 18, and 25.

and post project utilization of models. Regardless of the methodology, however, a concept common to 3-D model construction is the importance of integrating geological knowledge to ensure appropriate geological conceptualization and subsequent model construction. Basin analysis provides a framework that supports this approach.

Basin Analysis

Basin analysis is a methodological framework for regional hydrogeological analyses that integrates data from a variety of sources and scales of investigations (Miall 2000, Sharpe et al. 2002). The strength of this approach is its emphasis on geological analysis leading to the development of an understanding of basin history and, hence, a knowledge base that permits development of a predictive framework for understanding the textural, stratigraphic, and structural controls on groundwater flow at a hierarchy of scales within the basin. It is particularly appropriate for groundwater studies in geological environments where geological heterogeneity and flow systems occur at a hierarchy of scales.

The basin analysis approach used for studies of most key Canadian aquifers follows a progression of data compilation, conceptualization, model development, and quantitative analysis of flow systems (Figure 7-2; Sharpe et al. 2002) with feedback/interactions among components allowing continuous improvement of the database and models as the study progresses. By directly linking geological setting and basin history to aquifer properties, the basin analysis approach strives to develop more plausible hydrogeological models and supports development of numeric GIS rendering of data-driven models (e.g., Anderson 1989; LeGrand and Rosen 1998, 2000). Geological model development for basins falls into two distinct styles: (1) predictive, process-based models, such as depositional models (e.g., Russell et al. 2003) and event stratigraphic models (Figure 7-3; Sharpe et al. 2002); and (2) GIS-based, data-driven models. The development of process-based models assists geological interpretation and development of GIS-based models. In GIS-based modeling, stratigraphic interpretations developed in the basin analysis approach are used to help interpret more abundant, lower-quality archival data such as from water-well records (Bolduc et al. 2005, Ross et al. 2005, Logan et al. 2006, Paradis et al. 2010).

To support basin analysis, the GSC employs a multi-disciplinary approach to data collection that follows a systematic progression. Initial data collection and analysis consist of procuring published data and collating archival data. Surface data such as geological mapping (Sharpe et al. 1997), evapotranspiration mapping (Fernandes et al. 2007) and DEMs are common examples (Kenny et al. 1999). A key data set in Canada is the provincially administered water-well records. All of the provinces maintain digital databases with a variety of attributes (Sharpe et al. 2009), and, in a number of cases (e.g., Ontario and Manitoba), the GSC has worked collaboratively with the provinces to assess the integrity and utility of the water-well databases (e.g., Russell et al. 1998). In the oil-producing regions of the Western Canada Sedimentary Basin, petroleum boreholes and associated geophysical logs are an important data set (Chen et al. 2007). To handle the wealth of data collated from archival and published sources, a variety of database approaches have been adopted at a project level from the use of relational databases (e.g., Boisvert and Michaud 1998, Russell et al. 1998, Knight et al. 2008) to the use of distributed database and Web services technologies (Sharpe et al. 2009). Depending on the location and scale of the study area, the number of water wells can range from the thousands to the tens of thousands (Bolduc et al. 2005, Logan et al. 2006). Subsequent data collection commonly focuses on geological mapping (e.g., Paradis et al. 2010), the collection of geophysical data (Pugin et al. 1999) for subsurface definition of the stratigraphic architecture, and high-quality boreholes (Sharpe et al. 2002).

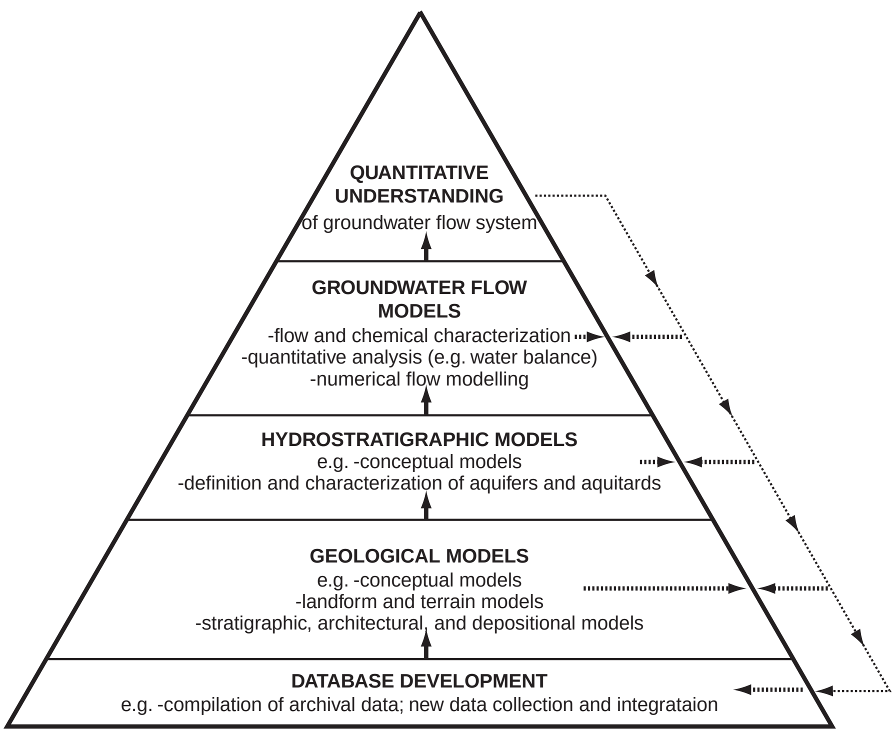

Figure 7-2 Simplified basin analysis approach used in regional hydrogeological analysis of key Canadian aquifers. The approach leads progressively from database development to quantitative understanding of the groundwater flow system as the study matures (Sharpe et al. 2002).

Geophysical methods have focused on 2-D seismic profiling techniques

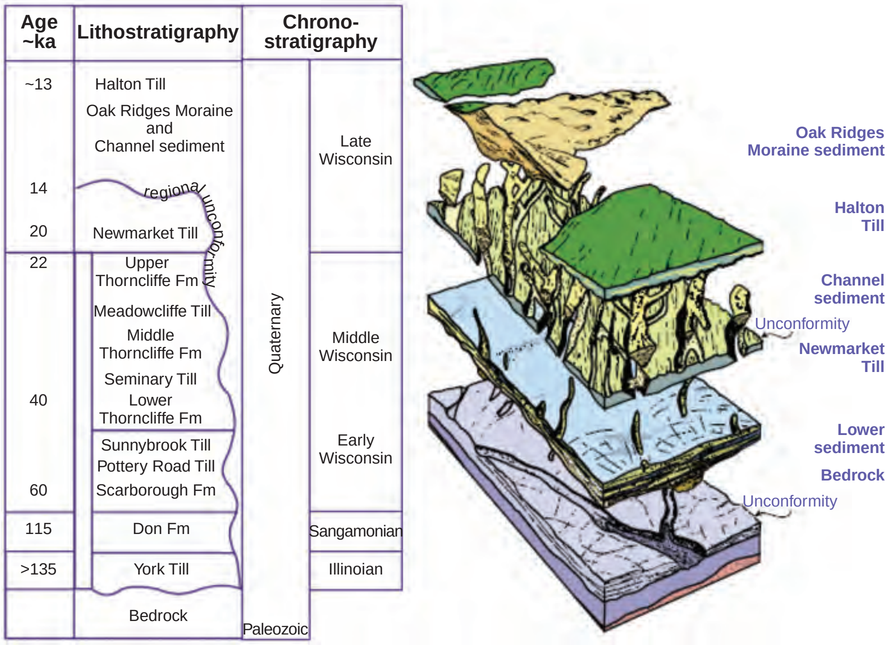

Figure 7-3 Example of an event stratigraphic model and integration of existing lithostratigraphic framework for the Oak Ridges Moraine Area (Sharpe et al. 2002).

that have evolved from labor-intensive planting and drilling of individual geophone and shot holes (e.g., Pugin et al. 1999) to semi-continuous data collection with a landstreamer system of S- and P-waves (Pugin et al. 2009). More recently, airborne electromagnetic surveys are being employed in the prairies of Manitoba to map conductivity contrasts for aquifer delineation (Oldenborger et al. 2011). Geophysical interpretations are commonly verified by drilling of continuously cored boreholes (Knight et al. 2008) and downhole geophysics (Pullan et al. 2002). Supplementary data commonly used to further constrain and refine basin understanding include piezometric, stream flow (Hinton et al. 1998), and hydrochemistry data (e.g., Cloutier et al. 2006).

Data standardization has been accomplished on an ad hoc basis within respective projects, collaboratively with provincial agencies (e.g., Russell et al. 1998), and through participation in distributed database development (Sharpe et al. 2009) and developments of GroundWater Markup Language (GWML) (Boisvert and Broderic, unpublished data) and participation in GeoSciML (http://www.geosciml.org).

An objective common in many modeling approaches has been to establish a standard basin (regional) stratigraphic framework for both regional and site-specific hydrogeological applications. In part because modeling activities have generally been completed in basins with no previous regional subsurface model, each project has developed an approach that is most suited to the specific situation (i.e., geological setting, available data, available technology and expertise, and partnership mandates). As a result, a number of approaches have evolved at the GSC that can be categorized according to stratigraphic approach, interpolation choices, and modeling software selection. In some cases, the geological model is constructed with direct consideration of subsequent numerical flow modeling (Rivera et al. 2003). In other cases, the model has been developed as a stratigraphic repository that could be used for various applications by extracting the needed (simplified) information (e.g., Ross et al. 2005).

Stratigraphic Approaches

The standard stratigraphic approach in surficial (glacial) basins remains lithostratigraphy (Paradis et al. 2010). However, event stratigraphy (allostratigraphy, sequence stratigraphy; Walker 1992) has been adapted in a number of studies. In common with sequence stratigraphy, regional unconformities forming bounding surfaces are a key element of this approach (Figure 7-3; e.g., Sharpe et al. 2002; Cummings et al. 2011).

Interpretive Methods

Two approaches have generally been followed by GSC for rendering 3-D models: cross section methodology and stratigraphic database method. Both approaches rely heavily on borehole log data for subsurface model control.

The cross section approach provides a direct method of simplifying the geological heterogeneity by allowing the geologist to interpret the data as stratigraphic correlations are made (Thorleifson et al. 2002, Bolduc et al. 2005). Interpretations are deterministic in nature, and because the model's integrity depends largely on the geologist's ability to apply a set of correlation rules throughout the model area, there is potential for inconsistent stratigraphic correlations from section to section and across model iterations.

Alternatively, the stratigraphic database method relies on a well-structured database of coded borehole logs that contains contact information on all potential stratigraphic units, including those that have a zero thickness in portions of the study area (Hughes 1993). Although the ability of humans to recognize patterns and eliminate data "noise" helps the cross section model appear more geologically plausible, the level of expert input is variable from place to place throughout the model. The stratigraphic assignments in a stratigraphic database are also deterministic in nature, but once made and vetted, they can be combined with new data and reinterpolated without having to repeat the borehole interpretation and stratigraphic coding process. The data-driven stratigraphic database model can, however, display unlikely geological structures due to interpolation of sparse data coverage or poor data.

Based on these two methods, a variety of approaches have been used to produce subsurface GIS-based geological models (commonly 2.5-D models). Manually interpolated cross sections are either extruded using manually drawn tie lines or converted at defined intervals into "pseudo-sections" and interpolated using inverse distance weighting (IDW), discrete smooth interpolation (DSI), kriging (case study 1) and other common techniques. The data in a stratigraphic database are interpreted; assembled into XYZ point data sets; and rendered into stratigraphic surfaces using similar spatial interpolation techniques (case study 2; Logan et al. 2006, Ross et al. 2005). Alternatively, a hybrid approach using cross section input and point data is implemented using either Gocad (Ross et al. 2005) or the support vector machine methodology (e.g., Smirnoff et al. 2008; case study 3).

Modeling Software

The most commonly chosen modeling software at the GSC has been Gocad (Bolduc et al. 2005, Ross et al. 2005) (Figure 7-4); MapInfo and Vertical Mapper also are used (Logan et al. 2002, 2006, 2009) along with other 2-D GIS software solutions (e.g., ESRI ArcInfo, Surfer). For smaller model areas and smaller data sets, Gocad has proven to be a very effective tool (Bolduc et al. 2005, Ross et al. 2005). For larger study areas and larger data sets, data handling and interpolation has been more efficiently dealt with using traditional GIS software. With the emergence of 64-bit processing and increased memory access, some of these issues have been resolved. For the Oak Ridges Moraine study area in Ontario, where modeling was initially completed during the mid 1990s, a low-cost GIS software solution was considered important in an attempt to encourage model adoption by local watershed conservation authorities. Similarly, Ross et al. (2007) have addressed data exchange issues to encourage broader application of geological models by groundwater modelers.

GSC Case Studies

Work within the Groundwater Program has generally focused on sound geological framework development to support predictive decision making beyond that permitted by the data input. Data collection has focused on geological mapping, most commonly with a focus on surficial geology, sedimentological investigations, and borehole data analysis followed by geophysical surveys and verification with continuous cored boreholes. Consequently, the following case studies highlight some of the differences in computer-based model development adopted at the GSC. Much of the modeling output at the GSC has been in a 2-D format of structural, isopach, and probability maps (e.g., Sharpe et al. 2007; Desbarats et al. 2001, 2002), and a limited number of solid models (e.g., Bolduc et al. 2005, Ross et al. 2005).

Case Study 1: Cross Sections

A number of studies have adapted the traditional cross section method of model construction to the digital environment. Five studies have used this approach in combination with Gocad. The Manitoba study (Thorleifson et al. 1998) is more fully documented in Chapter 11. Two other studies in the late 1990s and early 2000s developed 3-D geological models of distinctly different glaciogenic basin fills. In the Mirabel area north of Montreal, Ross et al. (2005) developed a 1,400-km^2 model of the glaciogenic sediment fill of a glacimarine basin within the St Lawrence Lowlands (Figure 7-1). Further to the north on the Canadian Shield, Bolduc et al. (2005) modeled an esker aquifer in a glaciogenic clay basin (Figure 7-1). Both studies used a discrete modeling approach, whereby discrete triangu-

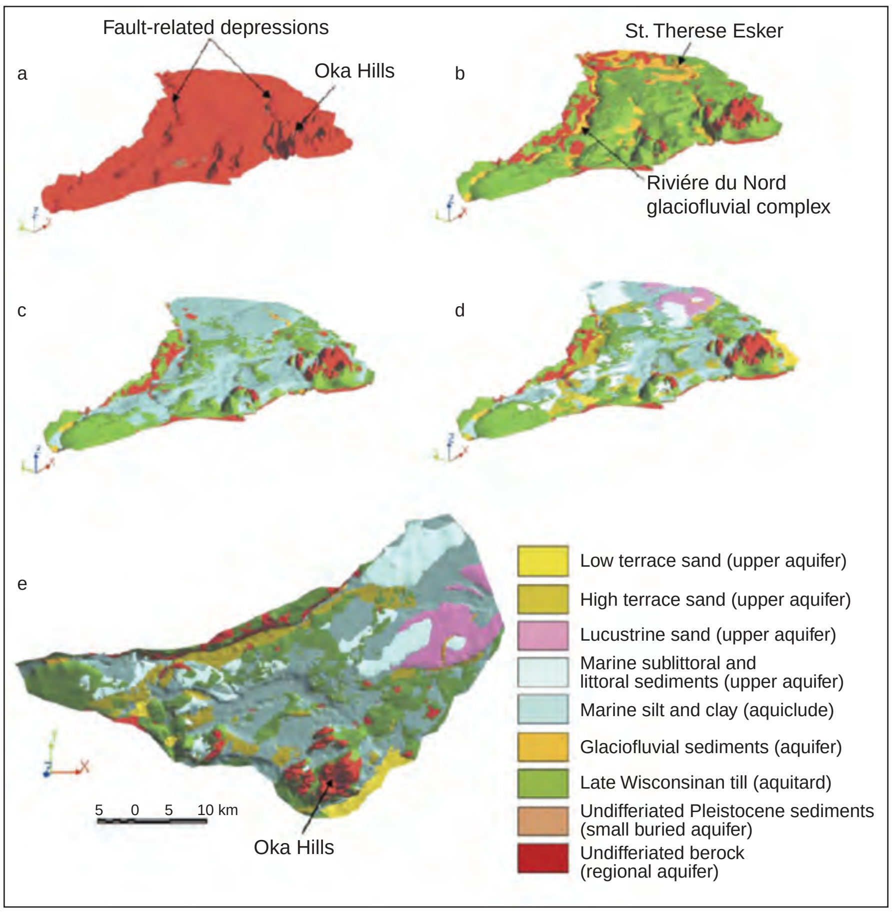

Figure 7-4 Example of the geological framework model for the Mirabel area (Ross et al. 2005).

lated surfaces were constructed from points and open and closed curves and then modified by applying the DSI algorithm, which minimizes the roughness while honoring linear hard and soft constraints. Hard constraint refers to cases where the surface honors the data and does not move at that location during subsequent interpolation. By contrast, soft constraint refers to areas where the surface only tries to approach the data while keeping the roughness low. Data management was completed in Microsoft Access.

The initial data correlation and interpolation were completed in 2-D as it was easier for the geologist to understand data relationships in this environment. Geological cross sections were built directly in the 3-D graphic, geo-referenced environment using vertical 2-D working planes and data buffers to select data for correlation along specific planes and to help reduce data transfers. It also exploited the 3-D visualization capabilities that were used to interactively test the consistency of a newly built cross section with other data in the system. For the Mirabel model, more than 40 cross sections were constructed as the basis of the 3-D framework.

To ensure stratigraphic consistency away from the input cross sections, an increased mesh density and minimum thickness constraint were applied locally to reduce inconsistencies between structural surfaces. Remaining crossovers were removed manually by adjusting triangle nodes, but this can result in discontinuities within the model. To exploit the data set to the maximum degree possible, shallow boreholes that do not penetrate to bedrock were incorporated in order to respect minimum thickness constraints. Crossovers and other thickness problems were thus corrected locally using an interactive approach.

A compilation of data and their associated reliability factor (training data versus low quality data) indicated that only 40% of the database was used for constructing the groundwater flow model. However, this did not mean that 60% of the boreholes were unreliable. In fact, many consistent data (training) were not integrated in the modeling exercise due to data clustering in site-specific areas.

Case Study 2: Expert Systems

An expert systems approach has been applied in two study areas in southern Ontario, the Oak Ridges Moraine (ORM) (Logan et al. 2006) and the South Nation River watershed (Logan et al. 2009). For each of these studies, a 3-D model of the regional stratigraphy was produced to visualize the architecture of the aquifers and support quantitative hydrogeological modeling. A combination of basin analysis and event stratigraphy was used to provide a sound geological basis for modeling. The stratigraphy of the two basins provided modeling challenges due to stacked and nested erosional valley systems (tunnel valleys) in the ORM and to buried esker systems in the South Nation study. In both studies, and particularly the ORM study, strata are laterally discontinuous, and multiple stratigraphic units may be absent locally due to erosion or non-deposition. Early, in 1994, in the ORM study, a decision was made to use a fully data-driven, semi-automated approach in conventional GIS software with a relational database for support. This methodology evolved into the final expert model system approach that was implemented for the 10,000-km^2 area of the ORM (Logan et al. 2002, 2006).

Based on data analysis and new data collection, a new stratigraphic model for the ORM was proposed based on allostratigraphic principals and a recognition of regional unconformities characterized by drumlins and large buried valleys (Figure 7-3). The high quality of the data collection permitted iterative improvements to the geological model. Similar improvement in understanding the South Nation stratigraphy was achieved from analysis of integrated sedimentological and geophysical data sets. The ORM 3-D model is data-driven, without subjective surface editing or corrections, resulting in a variety of interpolative artifacts in areas of buried valleys. The South Nation Conservation Authority (SNCA) regional model is also largely data-driven, except for one intensively studied esker near Vars, Ontario, for which a series of parallel seismic sections were extrapolated to produce a soft data set to enforce a more realistic shape of the esker.

The stratigraphic models are based on extending surficial geological mapping into the subsurface, which comprises the most reliable and spatially extensive data set. Boreholes and seismic profiles provide subsurface control, and DEMs provide a common elevation reference for all data. In Ontario, the most commonly used source of borehole data is the Ontario Ministry of the Environment water-well records. Ontario water-well data, however, is typically fraught with both location errors (Kenny et al. 1997) and non-rigorous material/depth logging (Russell et al. 1998).

Interpreting material/depth logs in water-well records using expert system rules within a geospatial framework of more reliable data is the central concept of the modeling technique (Logan et al. 2006). Initial data assembly involved processing geological map data, topographic data, water-well data, geotechnical borehole data, and geophysical data. These data were checked for location and geological errors and standardized to a common geological coding system. Data were classified as either training data or low-quality data (water wells). For training data, stratigraphic coding was completed interactively by geologists. Subsequently, the DEM, surficial map polygons, and training data were used to help interpret less-reliable water-well data. The water-well record material descriptions were assigned stratigraphic codes using a system of expert rules developed from surface mapping, seismic data, and sedimentological and stratigraphic studies. Because the stratigraphy is subhorizontal and undeformed, propagating stratigraphic coding with depth was straightforward. To ensure stratigraphic integrity, missing strata were recorded with a zero thickness interval in a comprehensive stratigraphic data table. Following the initial stratigraphic coding of the water-well records, the codes were checked against neighboring training data to ensure consistent stratigraphic assignments.

With a complete stratigraphic database, the model was built by interpolating a series of surfaces from extracted stratigraphic contact elevations. Surfaces were further enhanced by identifying and incorporating well intervals that ended within, and not fully penetrating, a stratigraphic unit. Called "push-down" points, these elevations were only utilized if they were below the elevation of a preliminary model surface that had been interpolated without them. The model surfaces were forced to conform to the surficial geology mapping, and stratigraphic integrity was ensured for each of the five stratigraphic surfaces. The model consists of a series of structural and derived isopach DEM surfaces built on a 100-m grid (e.g., Logan et al. 2006, 2009; Sharpe et al. 2007).

Aquifer thickness maps (isopachs) generated from the ORM model (Figure 7-5) and the SNCA model (Figure 7-6) accurately depict the available data support and are regarded as geologically plausible at a regional scale. Locally, unrealistic discontinuities in channel fill and eskers reflect sporadic data coverage. As was done for the Vars esker, more targeted hydrogeological modeling should use expert-derived synthetic data, extrapolations, and corrections based on these regional, data-driven models for guidance.

Case Study 3: 3-D Geological Model of the Okanagan Basin, British Columbia, with the Support Vector Machine

One of the most robust and best-performing classification algorithms known to date is the support vector machine (SVM) (e.g., Cristianini and Shawe-Taylor 2000). This algorithm is based on statistical learning theory (Vapnik 1995) and uses a set of samples with known class information to build a plane that separates samples of different classes. The initial data set is known as the training set, and every sample within it is characterized by features upon which the classification is based. In nonlinear cases, the task

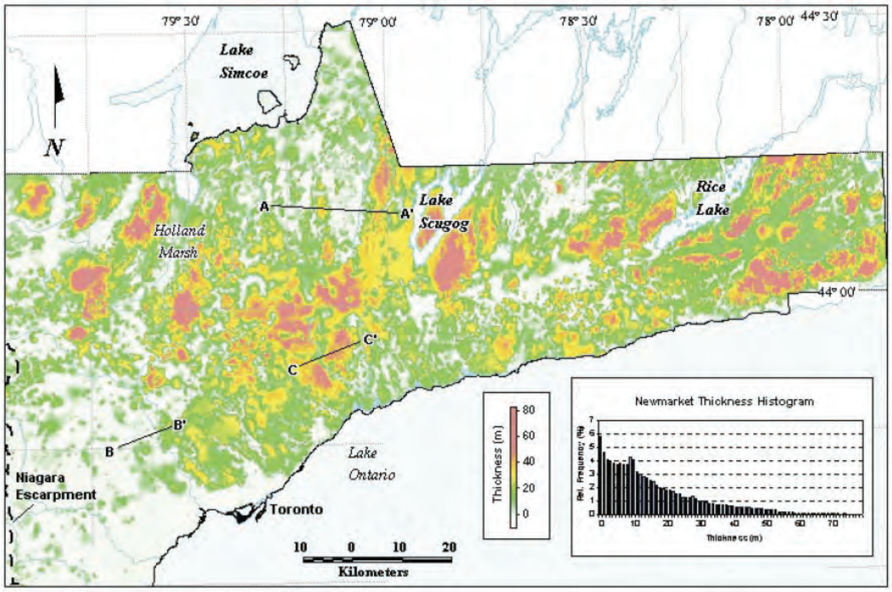

Figure 7-5 An isopach map and thickness histogram for the Newmarket Till unit. Pale areas indicate areas of no Newmaket Till. These areas represent areas of inferred erosion of the till unit, commonly along northeast-southwest–trending tunnel valleys (Sharpe et al. 2007).

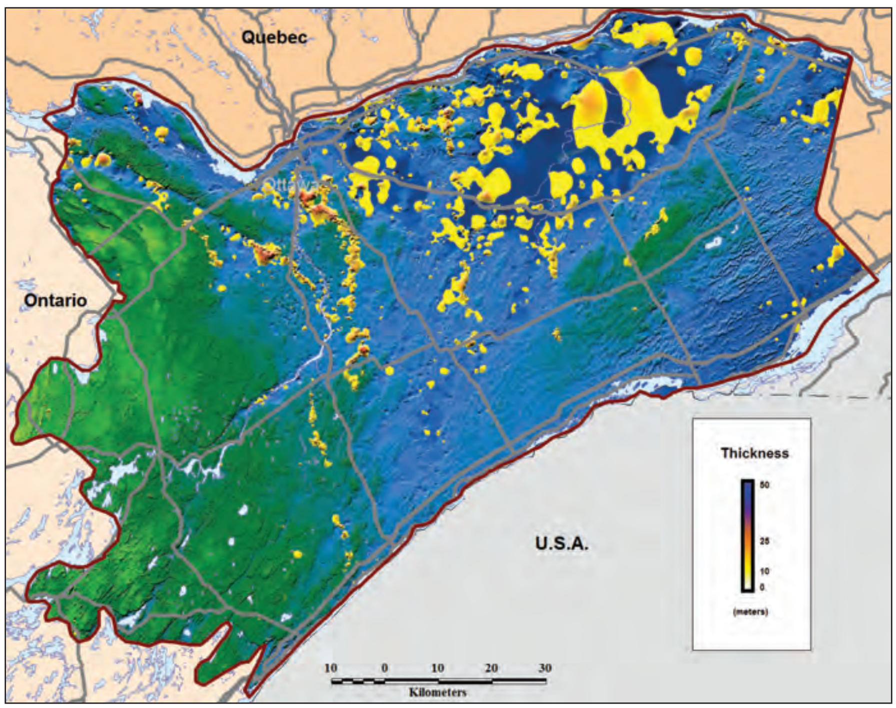

Figure 7-6 South Nation Conservation Authority (SNCA) model area showing a glaciofluvial isopach (eskers) draped over a topographic digital elevation model. Esker volumes are more accurate to the west where data support is high. The large, thin volumes in the east reflect overestimated interpolation due to poor data coverage (Logan et al. 2009).

of discovering the optimal separator is turned into a linear problem by transferring input data into a higher-dimensional space known as the feature space. The solution takes a nonlinear form when projected back in the original data space. Once the equation for the optimal classifier is found, new data with unknown class information can be classified based on their position with regard to the plane.

The use of the SVM for data interpolation at the GSC was first tested using the Esker/Abitibi project (Bolduc et al. 2005) as a test case (Smirnoff et al. 2008). This area provided a Gocad-generated model developed using numerous cross sections as a benchmark model against which to compare a SVM-generated model. The successful demonstration of the SVM-generated model provided the confidence for the application of this modeling approach in the Okanagan Valley of British Columbia for an area of 8,200 km^2. The three-year project (2006 to 2009) included surficial geological mapping, borehole drilling, seismic profiling, and other activities (Paradis et al. 2010). All data were stored in a relational database for further analysis and generalization. One of the major objectives of the data analysis was to produce a 3-D model reflecting the surficial geology of the study area.

As in the other two case studies, data originating from surficial geology mapping (Paradis 2009) provided the most spatially continuous and reliable data for constraining all subsurface units with surface expression. The subsurface stratigraphic information was mainly provided by a small number of borehole logs (about 6,800) and seismic profiles. These data cover an insignificant portion of the target model volume (<10%). Therefore, the data needed to be further analyzed, interpreted, and generalized to increase the number of points controlling stratigraphic interpolation. This generalization was accomplished by creating a series of mutually consistent cross sections that were then subsampled, and the resulting data set was combined with the surficial information to produce the input point data set.

To make the labor-intensive process of building cross sections more efficient and reliable, a software tool was developed (Paradis et al. 2010) to extract the relevant geological information from the log database and DEM along an arbitrary traverse of the study area. The logs are integrated into a traverse when they occur within a specified buffer distance. The closest logs are marked as being of primary importance. The traverse does not have to be straight and can change direction to maximize the proximity of available boreholes. The tool also reports when the traverse crosses other traverses to increase interpretation accuracy and minimize redundancy.

To facilitate initial data viewing and interpretation, linear maps were generated along transects with selected boreholes within a 300-m buffer. Cross sections were generated as a series of scalable vector graphics (SVG) files, imported to CorelDraw, and printed. Stratigraphic correlations were then completed on paper by a geologist and digitized back in CorelDraw, where unit codes were assigned. The data from seismic surveys were handled similarly.

The resulting stratigraphic data set was reprojected from the cross section coordinate system to a real 3-D coordinate system and formatted as a Gocad vertex set containing unit-type code as the single property. For approximately 300,000 points (24%), the stratigraphic unit was identified from cross section and DEM sampling. For the remaining points, the stratigraphic unit was not coded, and the property value was set to zero. This value was determined later, during the modeling phase.

The input data set was loaded in Gocad 3-D GIS software for verification and analysis (Figure 7-7a). The modeling task was then to identify the stratigraphic units for previously unclassified points (shown in white in Figure 7-7). The latter can be treated as a pure classification problem.

Being a boundary classification method, the SVM is not sensitive to data clustering. Therefore, the variable density of sampling points does not influence the final solution. Although the classical SVM task is binary (two-class) classification, a number of methods have been developed to support multi-class problems (see references in Hsu and Lin 2002). More detailed descriptions of the SVM algorithm are available from a number of sources (e.g., Cristianini and Shawe-Taylor 2000, Abe 2005).

Previous experiments demonstrated that the SVM can be an efficient tool in geological modeling (Smirnoff et al. 2008). For this project, the SVM classifier was built using sample coordinates as classification features and samples with known geology as a training set (for details, Paradis et al. 2010).Then, the rest of the data set points were classified into eight geological units based on their coordinates (Table 7-3; Figure 7-7b).

For final visualization and analysis, the classification results were presented in Gocad as a high resolution voxel model (volume element, representing a value on a regular grid in 3-D space; Figure 7-7a). The stratigraphic succession is controlled by the bedrock valley topography and depositional environments. Along its axis, the valley is overlain by undifferentiated old sediments. The Rutland Formation represented by sand and gravel is also aligned with the valley trends and fines stratigraphically upward. A thick layer of Fraser Till blankets elevated areas in the east; in the west, till distribution is discontinuous. Glacial ice-contact sediments are generally observed at lower elevations and somewhat closer to the valley bottom except for the southeastern part of the basin where they are interspaced with till. These are overlain by lacustrine (Penticton) and fluvial sediments centered directly in the valley. Finally, two small areas of unclassified and/or organic deposits are visible in the central and northwestern parts of the basin.

This project confirmed that the SVM can be efficiently applied in modeling surficial geology from data of various origins. With SVM, surface geology, borehole logs, and geophysics data were combined to produce a single input set for the algorithm. To increase the number of control points, the origi-

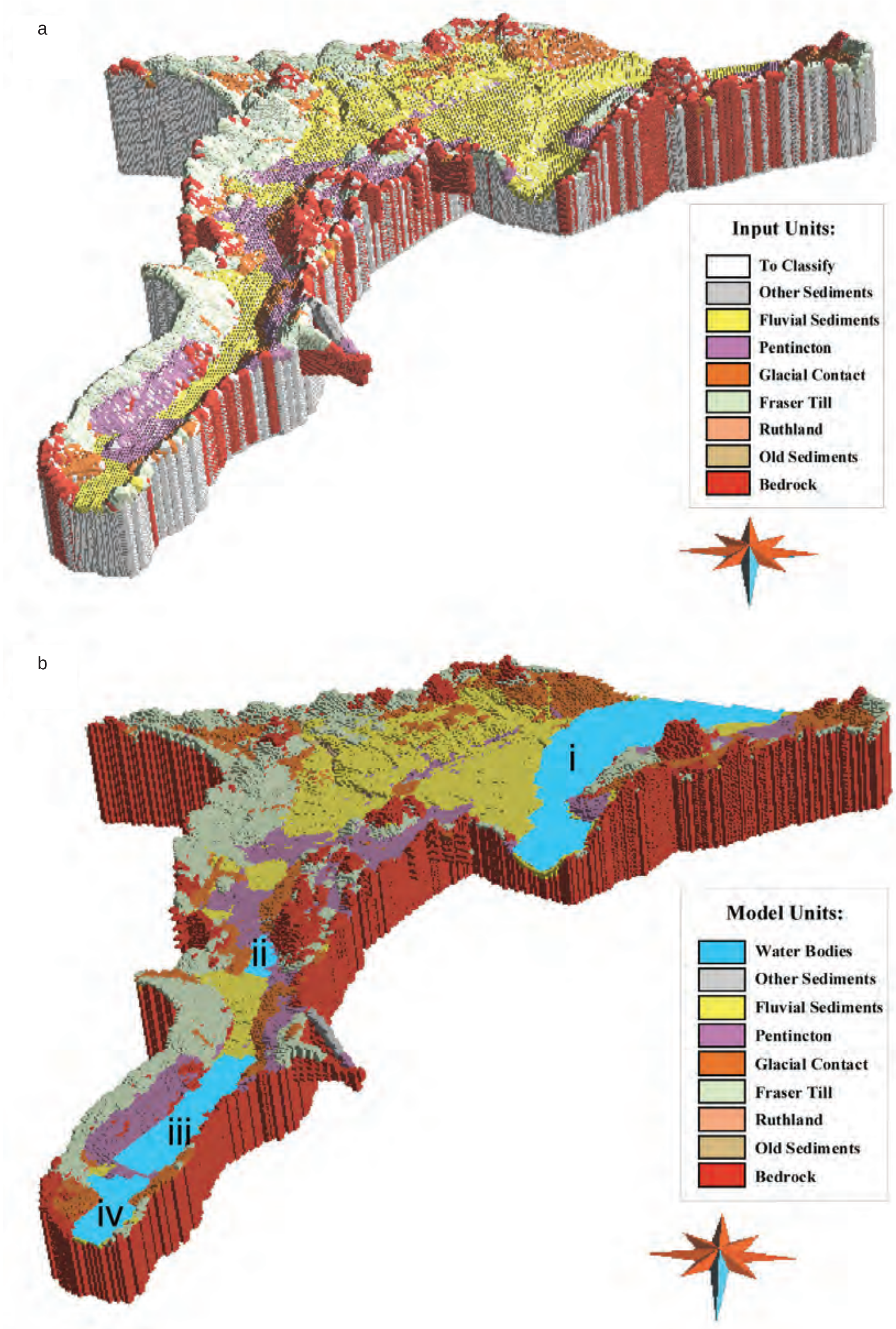

Figure 7-7 Input and output of support vector machine (SVM) modeling: (a) Geological coded input data set imported in Gocad. The white points are unclassified and will be classified by the support vector model (SVM); (b) the SVM classification result as a Gocad voxel object with local water bodies added on top of geological units. From south to north, the water bodies are lakes Okanagan, Ellison, Wood, and Kalamalka. Ellison Lake is about 800 m wide.

Table 7-3 Input data set statistics and support vector machine (SVM) classification results. Units with codes 3 and 4 were merged with code 2 prior to SVM analysis and are missing from the table.

Unit	Geological	Known points (no.)	Known points (%)	SVM classified points (no.)	SVM classified points (%)
Bedrock	1	86,038	6.84	780,233	81.67
Old sediments	2	12,820	1.02	14,609	1.53
Rutland (sand and gravel)	5	20,280	1.61	33,986	3.56
Fraser Till	6	48,111	3.82	34,526	3.61
Glacial (ice) contact	7	33,625	2.67	21,345	2.23
Penticton (lacustrine)	8	44,292	3.52	39,778	4.16
Fluvial sediments	9	56,374	4.48	30,728	3.22
Other sediments	10	1,500	0.12	121	0.01
All units	-	303,040	24.08	955,326	100.00

nal data were pre-processed, the data were validated, and geological expertise was integrated.

Summary

Three-dimensional geological mapping has undergone a transformation in 20 years from traditional approaches of cross sections and planar maps with structural measurements and embedded stratigraphic relationships to fully interpolated structural surfaces and volume models that can be manipulated in 3-D visualization software (Thorleifson et al. 2010).

Within the Groundwater Program of the GSC this new technology has been embraced to bridge the gap between data needed with traditional geological products and the input required for numeric groundwater flow modeling. Nevertheless, the emphasis remains on high-quality data collection within a basin analysis framework that will provide a knowledge framework for understanding the geological history of the basin. This understanding provides the means to interpolate between sparse data and make predictions on the spatial extent and heterogeneity of sedimentary units forming aquifers. This basin analysis approach is common across aquifer studies within the groundwater program, whereas the choice of modeling and visualization software and model construction algorithms remains discretionary, providing individual studies with the flexibility to respond to a host of geographic, geological, data availability, political, and funding variables. Distributed database technologies and Web-based delivery mechanisms are being used to encourage improved data delivery to clients and improved infrastructure for collaborative analysis of key aquifers, both at the GSC and externally.

The mandate of the GSC is to pursue regional studies and develop an improved geological knowledge base for the country. Systematic mapping is not necessarily a component of that mandate, and, consequently, studies focus on methods development, application of emerging methods to Canadian geological settings, and improved geological models.

Acknowledgments

The clarity of this chapter was improved by internal reviews at the GSC by R. Knight and M. Hinton. This paper would never have been submitted without the ongoing encouragement by R. C. Berg. This paper is completed as part of the Groundwater Program of the Geological Survey of Canada, Earth Science Sector, Natural Resources Canada. It is contribution 20100285 of the Earth Science Sector.

Chapter 8: French Geological Survey (Bureau de Recherches Géologiques et Minières): Multiple Software Packages for Addressing Geological Complexities

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The French Geological Survey is the Bureau de Recherches Géologiques et Minières (BRGM). It was founded in 1959 as a public corporation closely aligned with commercial and industrial interests. However, the roots of the organization go back to 1941 when it was called the Bureau de recherches géologiques et géophysiques (BRGG) within the Ministry of Industry.

BRGM research focuses on increasing the knowledge of the geosciences through the development and validation of models, processes, instruments, and software. By developing new techniques and methodologies and distributing high-quality information, the BRGM provides public agencies with the geological information needed to manage surface and subsurface issues for regional economic development and planning, including evaluating and mitigating natural hazards and contamination problem areas.

The BRGM has 22 regional centers in France and 7 centers in French overseas territories. Its 2005 budget was over €84 million, and BRGM had about 850 employees. Internationally, the BRGM works either as part of a cooperative effort or as a commercial institution in over 40 countries with governments, public-sector firms, industry, and international funding institutions. The BRGM offers technology transfer in all earth science subdisciplines via geological investigations, support programs, various types of technical support, and training. (An overview of the BRGM scientific missions can be found at http://www.brgm.fr/inc/bloc/apropos/mission.jsp.)

Six departments in the BRGM utilize geological mapping and modeling: Geology, Mineral Resources, Hydrogeology, Environment, Geothermy, and Natural Risk Assessments. The core staffing expertise for geological mapping and modeling lies within the Geology Department where 3-D geomodeling in the shallow subsurface and regolith is a principal activity that is solely managed by the department. Work is done on a wide variety of different projects in collaboration with other departments:

- 3-D geomodeling of deep sedimentary basins is managed in collaboration with the Hydrogeology Department and Geothermy Department;
- 3-D geomodeling of bedrock terrain for mineral and energy resources is managed in collaboration with the Mineral Resources Department.

Geological Setting

Figure 8-1 shows the diversity of the geology of France; however, there are three main structural settings:

1. The Palaeozoic and Hercynian Terranes, shown in orange on Figure

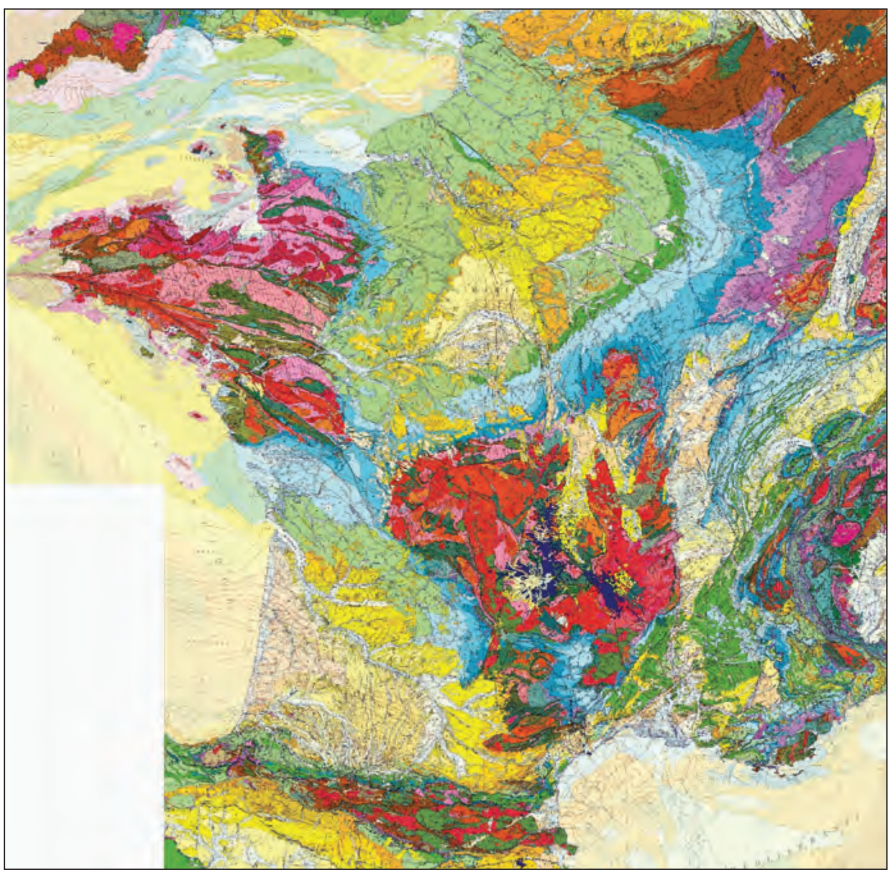

Figure 8-1 Geological map of the geology of France (http://infoterre.BRGM.fr/).

8-2, include the Armorican and Massif Central Mountains together with small parts of the Vosges Massif and Ardennes Massif. The Armorican Massif, which covers a large area in northwestern France, is composed of metamorphic and magmatic rocks affected by the Hercynian or (Variscan) earlier Cadomian Orogeny. The region was uplifted when the Bay of Biscay opened during the Cretaceous Period. The geological evolution of Massif Central started in the late Neoproterozoic and continues to this day. Massif Central has been shaped mainly by the Caledonian and Variscan Orogenies. Structurally it consists mainly of stacked metamorphic basement rocks with recumbent folds.

2. The Ceno-Mesozoic basins, shown in yellow on Figure 8-2, include the Paris Flandres Basin and the Aquitaine Basin. The Paris Basin is the largest Mesozoic and Cenozoic sedimentary basin in France. It overlies geological strata disturbed by the Variscan Orogeny and forms a broad shallow bowl in which successive marine deposits have accumulated from the Triassic to the Pliocene. The borders of the Paris Basin lean on the Armorican Mountains to the west, on the Massif Central Mountains to the south, and on the Ardennes and the Vosges Mountains to the east-northeast. To the north, its strata can be readily correlated with those beneath the English Channel and in southeastern England. The Aquitaine Basin is the second largest Mesozoic and Cenozoic sedimentary basin, occupying a large part of the country's southwestern quadrant. The sedimentary process in the Aquitaine Basin began in the Lower Triassic over the Variscan basement and close to the North Pyrenean Thrust. From here it slowly started spreading farther to the north.

3. The Ceno-Mesozoic orogenic belts are shown in blue on Figure 8-2. These include the Alps, Pyrenees, and Jura Mountains; the Rhine and Rodanien horsts; and the Massif Central volcanics.

The Alps form an extensive Tertiary orogenic belt that extends through southern Europe and Asia all the way to the Himalayas. The Alps were produced as a result of the collision of the African and European tectonic plates, in which the western part of the Tethys Ocean closed. Enormous stress was exerted on the Mesozoic and early Cenozoic sedimentary strata of the Tethys, and these were pushed against the stable Eurasian landmass by the northward-moving African landmass. Most of this deformation occurred during the Oligocene and Miocene Epochs. The collision formed great recumbent folds and gigantic thrust faults with the underlying crystalline basement rocks becoming exposed in the higher central regions. The Alpine Orogeny is also responsible for the important outbreak of Cenozoic volcanism in the Massif Central.

The Pyrenees are older than the Alps. Their sediments were first deposited in coastal basins during the Paleozoic and Mesozoic Eras. During the Lower Cretaceous Period, the Bay of Biscay opened up and pushed present-day Spain against France causing compression. The intense pressure and uplifting first affected the eastern part of the Pyrenees and then stretched progressively to the entire chain, culminating during the Eocene Epoch. The eastern part of the Pyrenees consists largely of granite and gneissose rocks; in the western parts, the granite peaks are flanked by layers of limestone.

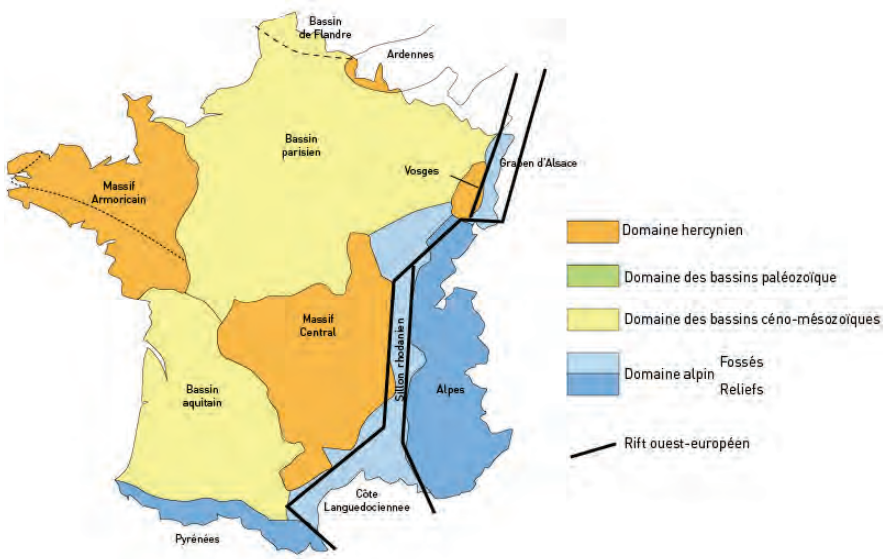

Figure 8-2 Simplified map of the geology of France (http://en.wikipedia.org/wiki/File:Domaines_geologiques_france.png).

Major Clients and the Need for Models

The BRGM works on 3-D modeling projects in three main areas: public services, international projects, and research activities in collaboration with many partners and clients:

- Public services: the European Union, the French State, regional government, and town authorities;
- International projects: private sector companies and foreign governments;
- Research: laboratory and university collaborations.

The major applications of BRGM's 3-D modeling activities are geological surveying, aquifer protection and management, urban geology, seismic risk evaluation, civil engineering, carbon capture and storage research, geothermal potential, mineral resource extraction, and post-mining evaluations.

Modeling at BRGM

About 10 geologists in the Geology Department regularly work on 3-D modeling. Ten additional staff are involved with modeling activities from other departments (e.g., Water, Geothermy, and Mineral Resources).

In serving its customers and meeting international standards, the BRGM uses these commercial software packages:

1. Petrel (Schlumberger) and EarthVision (Dynamic Graphics) for simple geology and basin analysis;
2. Isatis (Geovariance) for studies that need geostatistical analysis and quantification of uncertainty to assess resources;
3. Surpac (GemCom) for mining projects that require construction of 3-D geological models for assessment of resources;
4. 3D GeoModeller (BRGM-Intrepid Geophysics) for helping to define complex 3-D geology based on implicit modeling of surfaces; and
5. MultiLayer/GDM (BRGM), which is specially suited for data control and for layered models where traditional geostatistics is particularly efficient.

In addition to these software packages, the BRGM has developed two in-house tools that are adapted to model the geometry in different geological settings.

Methodologies Used for 3-D Modeling

Initial Data Consistency Analysis

This stage is the key to success for 3-D modeling. To build 3-D models of the subsurface, sedimentary basins, and regions of complex geology, large data sets have been compiled originating from geological maps, shallow and deep boreholes, and geophysical measurements, and all these data have been validated (true coordinates, accurate geological description, good georeferencing, etc.). This part of the process represents about 30% of the 3-D geomodeling process. Data managers then check the data accuracy during the compilation of the databases, and geostatisticians use statistical methods (e.g., histograms, scattergrams, and variance and covariance values) to discriminate the abnormal data before beginning the actual 3-D geomodeling process.

Shallow Subsurface Modeling

The purpose of 3-D modeling is to provide the public and geoscientists with a homogenous digital geological data set of the model. These 3-D models are built with Multilayer-GDM or EarthVision and take into account published geological maps (CHARM database) and boreholes (LOGISO database). In building 3-D models, the BRGM defines a lithostratigraphic table (stratigraphy) and specifies the type of contacts between various units (e.g., conformable, onlap, or eroded), and faults are always considered as vertical objects. Kriging methods are used to calculate 2-D lithologic surfaces (top, base, and thickness) using geological maps, borehole information, and vertical faults system. By considering lithologic relationships, 2-D surfaces are organized so that they build 3-D layered geological models. An example of this process and a typical output is the 3-D layered model of the Tertiary strata of the Aquitain Basin (Figure 8-3).

To populate such models with material properties, stratigraphically interpreted boreholes are used to perform the final 3-D stochastic simulations and to fill the model with lithologic (limestone, sandstone, clay, and marl) and petrophysical properties. The stochastic geostatistical techniques usually used to fill 3-D models are sequential Gaussian simulations (SGS) and sequential indicator simulations (SIS) (Goovaerts 1997). Many simulations are done to compute the probability for each grid cell of the various lithofacies and petrophysical properties. These probabilities quantify the uncertainty of the 3-D volume model.

This methodology is also becoming more popular for hydrogeological and

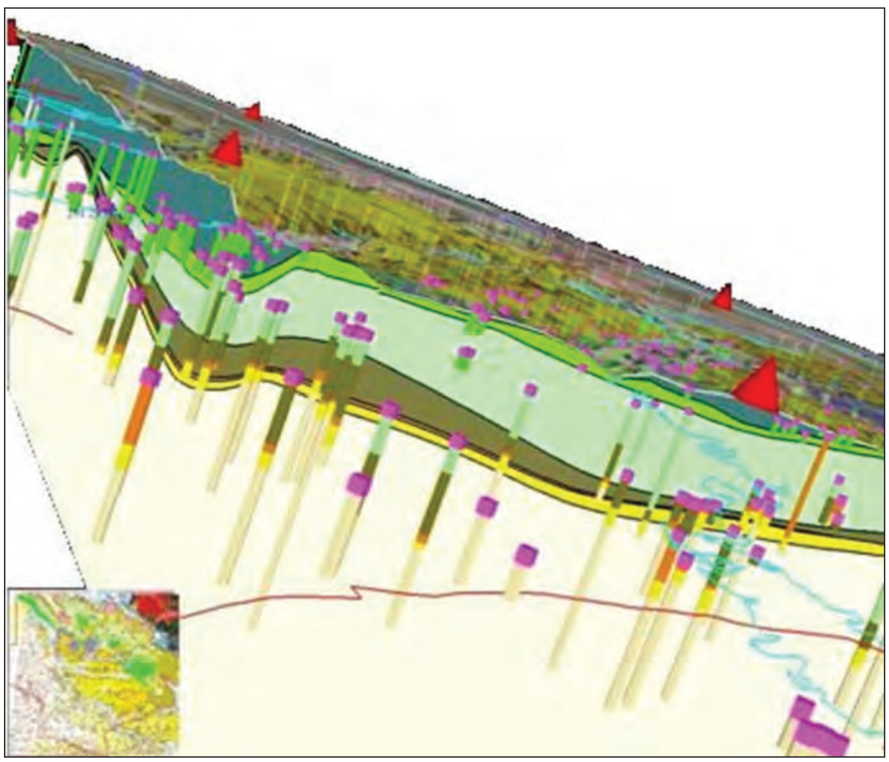

Figure 8-3 Three-dimensional of the Tertiary strata of the Aquitain Basin [EarthVision (Dynamic Graphics) and MultiLayer/GDM (BRGM)].

geotechnical applications to provide a better description of the shallow subsurface (0 to 100 m). Figure 8-4 shows examples of 3-D volume models filled with lithologic and petrophysical properties.

Sedimentary Basin Modeling

The BRGM is dealing with new challenges related to climate change. Current projects are underway for gas and carbon sequestration and geothermal production. To meet these challenges, the BRGM has developed new methodologies, based on approaches from the oil and gas industry, to provide 3-D volume models populated with petrophysical properties. The 3-D geological model is constructed from geophysical surveys, well logs, and stratigraphic interpretations of sedimentary basins. The model is then filled with facies and petrophysical properties by taking into account models of the sedimentology-facies, and the geostatistical methods described. The goal is to model heterogeneities at multiple scales for gas and fluid flow simulations.

Simulation examples include

- geothermal assessment of the thermal resource in the deep Triassic aquifer of the Paris Basin (Figures 8-5 and 8-6);
- carbon sequestration study to assess the deep aquifer reservoir and to model the heterogeneities of the Dogger Formation in the Paris Basin (Figures 8-7 and 8-8);
- further detailed gas sequestration studies in the Dogger Formation of the Paris Basin to model more precisely the heterogeneities in the reservoir using permeability and porosity simulations (Figure 8-9); and
- estimation of the geothermal potential of syn-sedimentary faulted deposits of the Limagne graben in central France. After the structural 3-D model was complete, it was meshed with a 3-D grid. Each cell of the 3-D grid was filled with geological information, and hydrodynamic and thermic properties. Then, simulations in this 3-D grid were performed to assess the thermal potential (Figure 8-10).

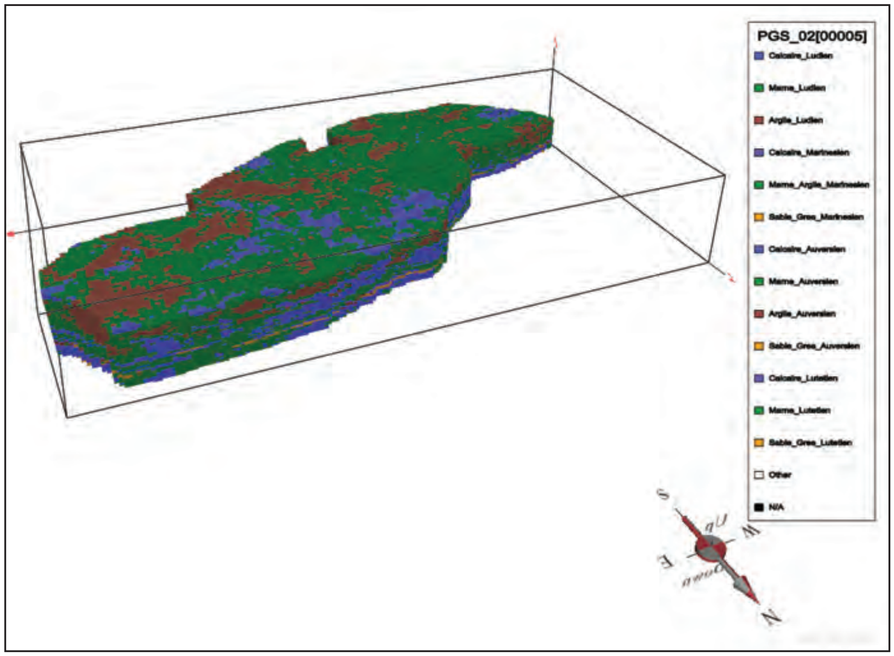

Figure 8-4 Three-dimensional lithofacies model of Middle Eocene formations in Essonne Department (south of Paris Basin) [Isatis (Geovariance) and MultiLayer/Gdm (BRGM)]. The model area is 10 km x 15 km x 100 m, and the grid cell size is 50 m x 50 m x 1m. Lithologies are limestone (blue), sandstone (yellow), clay (brown), and marl (green).

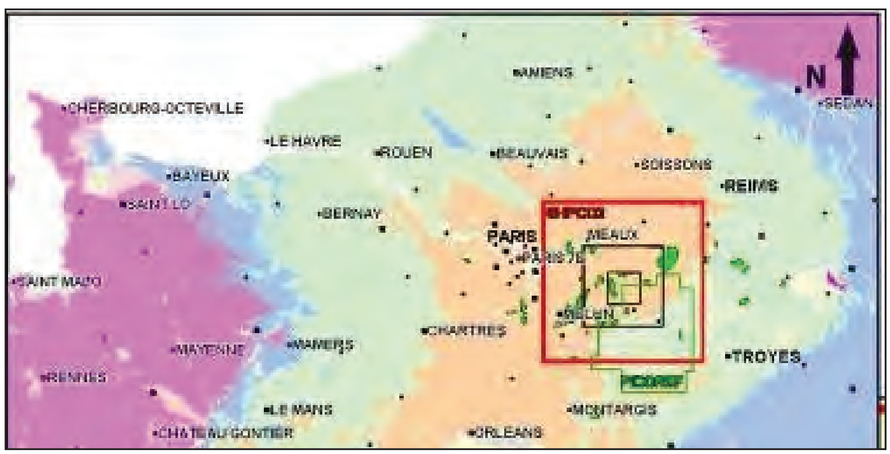

Figure 8-5 Location of two projects modeling the Trias and Dogger Formations of the Paris Basin.

Modeling Structurally Complex Geology

Many projects that have cartographic and geotechnical issues deal with the complex structural geology of France and require 3-D geological models to better understand and visualize complexities as well as to improve knowledge and assess risk. Two examples follow:

- In southeastern France, a 3-D model of a coal basin (Alès, France) was constructed. The complexity of this coal basin is the consequence

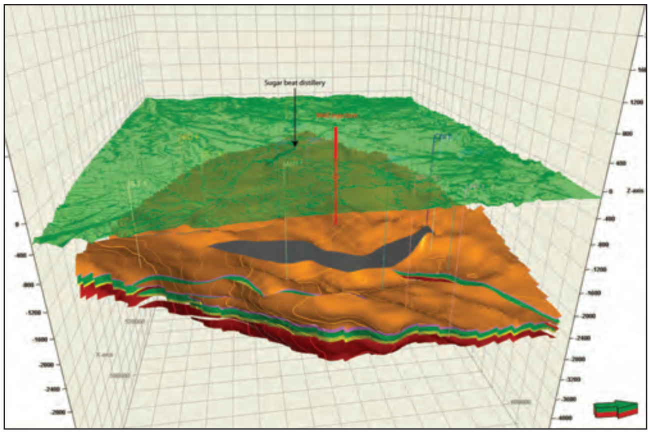

Figure 8-6 Three-dimensional static model of the Trias Formation in the southern Paris Basin for geothermal studies [Petrel (Schlumberger)]. The model area is 100 km x 120 km x 1 km.

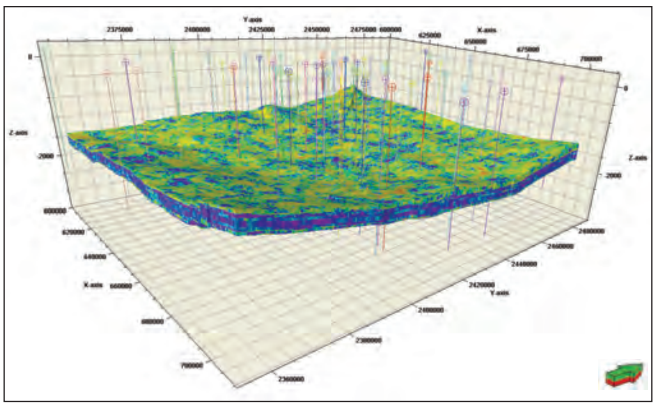

Figure 8-7 Three-dimensional structural and petrophysical properties models of the Dogger Formation in the southern Paris Basin for CO_2 sequestration [Petrel (Schlumberger)]. The model area is 100 km x 120 km x 1 km.

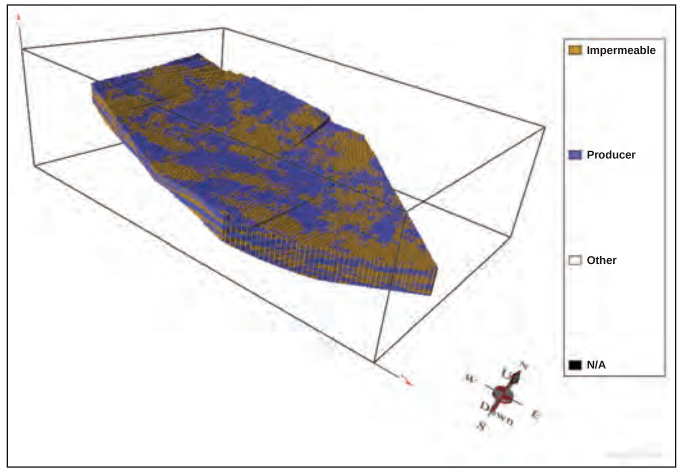

Figure 8-8 Three-dimensional producer facies (top) and porosity (below) model of the Oolitic unit of the Dogger Formation (southeastern Paris Basin) [Isatis (Geovariance)]. Model area size is 15 km x 10 km x 3 km; grid cells are 100 m x 100 m x 10 m. In the facies model, the blue zones are permeable, and the yellow zones are impermeable.

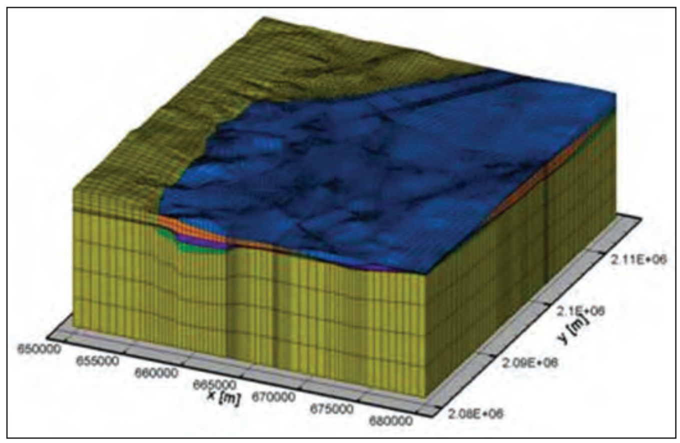

Figure 8-9 Estimation of the thermal resources in syn-sedimentary faulted deposits of the Limagne graben in central France [3D GeoModeller (BRGM–Intrepid Geophysics)]. The model area size is 30 km x 30 km x 3 km.

of different phases of structural deformation over time. This exercise provided an opportunity to apply unique cartographic techniques in the field and to build a complex 3-D model based on field observations. The final 3-D geological model (Figure 8-10) was built by master's degree students during a field trip with the BRGM.

- A tunnel route through the Alps to connect Turin (Italy) with Lyon (France) relied on geotechnical investigations based on a 3-D geological model. The goal was to produce cross sections through the 3-D model and then predict and assess the probability of thickness, top, and base for each geological formation likely to be encountered during tunneling (Figure 8-11).

Choice of 3-D Modeling Software and Methodology

The choice of 3-D modeling software and methodology used by the BRGM depends on many parameters:

- required depth of the models;
- type of geological setting;
- geological context and degree of complexity of the geological objects (e.g., karst, fault networks, dolerite intrusions, buried channels);
- need to mesh models for simulation;
- method to populate the models and the kind of properties needed for population;
- requirement for quantification of uncertainty.

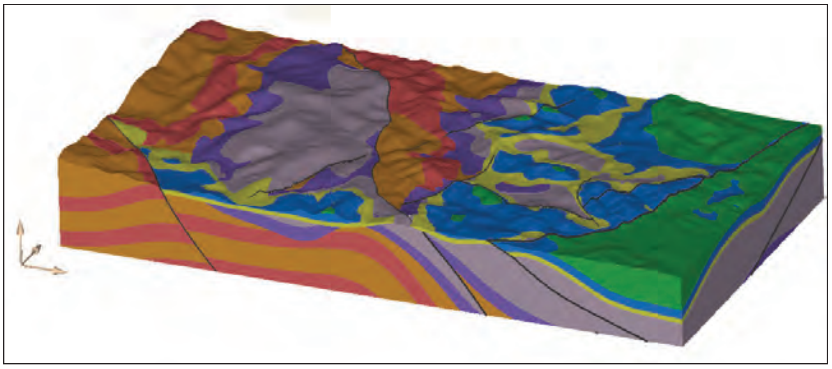

Figure 8-10 A 3-D model of a coal basin based on a cartography field trip (Alès, southeast of France) and building of the model from field observations [3D GeoModeller (BRGM–Intrepid Geophysics)].

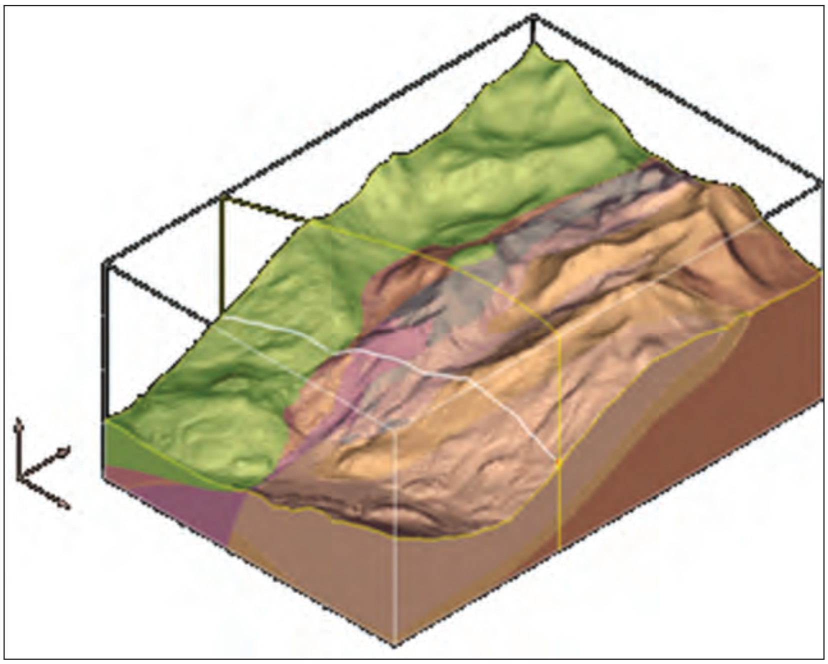

Figure 8-11 Geotechnical studies for a tunnel through the Alps between Turin (Italy) and Lyon (Alps) [3D GeoModeller (BRGM-Intrepid Geophysics)].

Lessons Learned

The BRGM has been involved in 3-D geological mapping and modeling for 10 years. The program began with 3-D geological mapping and now includes 3-D reservoir modeling. Lessons learned during BRGM's 3-D mapping and modeling program are

- 3-D modeling is important for improved understanding of geology and for new applications, such as groundwater evaluations, risk assessment, land use, mineral and energy resources, CO_2 storage, and geothermal resources.
- Data consistency is the key to success for 3-D modeling.
- Different 3-D modeling software packages are used to address different geological conditions and to satisfy other requirements such as quality and complexity of the initial data set and the final purpose of the model.
- There must be the capacity for determining uncertainty to best assess portions of the map or model that are most reliable.
- The 3-D modeling process should be highly integrated as the BRGM has had to enhance links between modeling software packages, databases, GIS simulation software, and 3-D viewers.
- Research projects are currently ongoing to improve methodologies and tools for the 3-D modeling process.

Chapter 9: German Geological Surveys: Federal-State Collaboration for 3-D Geological Modeling

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of the German GSOs

Organizational Structure and Business Model

Germany manifests itself in an aggregation of 16 independent regional GSOs (cf. InfoGEO 2009), plus the federal institutes for Geosciences and Natural Resources (BGR) and the Leibniz Institute for Applied Geophysics (LIAG), all of which vary considerably in regional competence, responsibilities, and organizational structures. Of the 16 German regional GSOs, 8 currently are actively engaged in 3-D modeling, and 2 have assigned 3-D modeling to local universities. Territories covered range from 325 km^2 (Bremen) to 70,550 km^2 (Bavaria). The BGR is involved with project-based geoscientific issues of international and national interest, whereas LIAG is a research institution engaged in the application of geophysical methods to geoscientific problems.

Accordingly, organizational structures within the surveys are very diverse. Staffs range from one-person enterprises to well-staffed sophisticated sections comprising several geoscientists and information technology specialists implementing elaborate workflows for all steps of modeling and the pre- and post-processing of information.

Diversity and multi-faceted GSOs offer many options for cooperation and augmentation of geological perspectives and technological tools to best assess, model, and display the geology. The core of the multilateral cooperation is the Study Group 3-D Modelling (Kommunikationsforum 3D) of the German GSOs. At present it comprises the two federal agencies (BGR and LIAG) and 10 regional GSOs actively engaged in 3-D geological modeling. The main objective of the group is to exchange knowledge and information about workflows and best practices and to define modern, consistent standards for data and data access that facilitate data exchange and enable cross-border modeling with the aim of producing a unified 3-D model of Germany.

Another focus of the Study Group is to enhance software development, especially for Gocad and plug-ins, as this software is used by all Study Group members.

Dealing with the more technical issues of 3-D modeling is the core function of the German Gocad user workshop, which is jointly organized by the Mining Academy of Freiberg and the Geological Survey of Saxony. The Gocad user workshop offers a discussion forum once a year to the modelers focused on technical aspects. For minor agencies with only a few people involved in modeling, this forum is essential as it gives them the opportunity to benefit technically from other agencies that have more advanced 3-D capability.

Geological Setting

The complex geology of Germany (Figure 9-1) shows an overall tripartite arrangement with expansive central uplands separating the Northern German Basin from the Alpine Orogen and its adjacent Molasse Basin. Within the northern basin, Permian and Mesozoic successions greater than 2 km thick are covered by Tertiary sands and clays reaching thicknesses greater than 3 km and overlain by up to 500 m of Quaternary deposits. Salt tectonics and related structures involving late Permian (Zechstein) evaporites are widespread. Salt beds and diapirs are suitable structures for deep repositories for carbon capture and storage (CCS) as these structures are a particular focus of 3-D modeling at present.

In the Central German Uplands, low-grade metamorphic rocks of the Rhenohercynian Zone, predominantly Devonian and Carboniferous shales, are exposed in the Rhenish Massif, which also includes the productive Upper Carboniferous coal-bearing strata of the Ruhr area at its northern edge (Figure 9-1). The western part features the embayment of the Niederrhein Basin filled with Tertiary sediments and large lignite deposits. In the northeastern continuation of the Rhenish Massif, the Harz Mountains, low-grade metamorphic rocks are studded with plutonic bodies. Permian volcanoclastic fillings of channels and basins and lower Triassic red sandstone (Bundsandstein) successions cover the large central parts of the Rhenohercynian Zone and continue far to the south (Figure 9-1).

In southern Germany, Triassic and Jurassic sedimentary rocks are tilted, forming an arch-shaped scarpland. The youngest cuest-forming unit, Jurassic limestone, is partially covered by Cretaceous sediments and features the 14.5 million-year-old Ries impact crater. Below the Mesozoic successions are the crystalline rocks of the Saxothuringian and Moldanubian Zone. These middle- to high-grade metamorphic sediments and embedded granitoid intrusions are exposed in the mountain ranges of the Black Forest and Odenwald in the southwest and in the Bohemian Massif (Erzgebirge and Bavarian Forest) in the east and southeast. Crystalline rock suites and their Triassic cover are sharply cut off along the Oberrhein-Graben, a part of the West-European rift zone filled with Tertiary sediments and volcanic complexes in its southern part and northern offshoot.

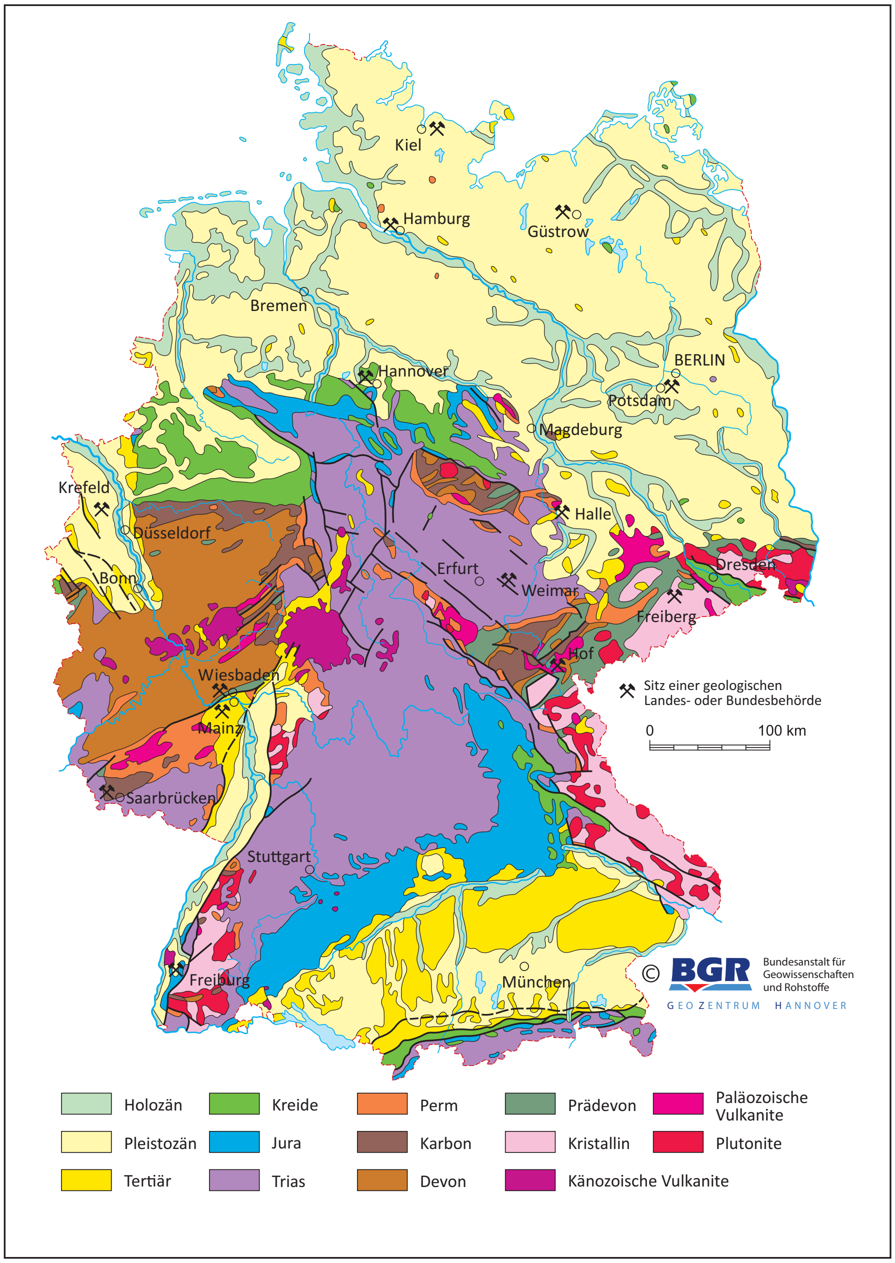

Figure 9-1 Geological map of Germany (BGR 1995). Locations of the state geological surveys (effective 1995) are indicated by hammer and pick symbols.

South of the Danube, the northward thrust of the Alpine Orogen front caused a downdip of the Mesozoic successions including the karstified Upper Jurassic. Beneath the Molasse Basin filled with Alpine debris predominantly of the mid-Tertiary, the Jurassic aquifer reaches depths of more than 5 km, forming one of the highest potential hydrogeothermal systems in Germany. Structural modeling for efficient utilization of this aquifer is another emphasis of present 3-D activities, including modeling of Tertiary sedimentary successions, which are host to minor but presently exploited oil and gas accumulations.

The folded Molasse along the northern margin of the Alps is part of the alpine nappe structures that emerged during the Cretaceous and Tertiary while the Adriatic Plate was thrust over the southern margin of Europe. Thick layers of predominantly Mesozoic carbonate rocks characterize the Northern Calcareous Alps, whereas sediments of the European shelf and the deep-sea trough are wedged in at the orogenic front.

Major Clients and the Need for Models

All German regional GSOs are independent scientific advisors to their territorial governments regarding all geological issues. Similarly, the BGR assists the federal government of Germany and German industry. The core function of all German GSOs is to make the best existing geological information accessible to their clients. As geology is inherently a 3-D science, 3-D geological models are crucial to transform abstract geoscientific information into tangible products and to communicate geological findings and benefits to non-geoscientists and policy makers. Nevertheless, territorial governments and ministries or subordinate agencies are only indirectly the principal customers of 3-D models.

Figure 9-2 shows the current status of 3-D modeling in Germany. Only in a few cases have deliverables consisted of 3-D models. However, GSOs increasingly employ advances in 3-D technology to better visualize and understand natural systems, and many tasks assigned to regional GSOs can be performed only, or more easily and precisely, by utilization of 3-D models. For instance, the Geothermal Information System for Germany (Schulz et al. 2007, Schulz 2009, Pester et al. 2010), developed by the LIAG in collaboration with the regional GSOs, extracts 2-D views of geological structures from 3-D models. The 2-D views comprise geological profiles and maps that are generated and retrieved via the Internet (GeotIS[Geothermisches Informationssystem fur Deutschland 2010; http://www.geotis.de/).

Due to the ongoing discussion of options for the mitigation of climate change, 3-D activities of German GSOs are focused on the deeper subsurface (e.g., for CCS) especially in the

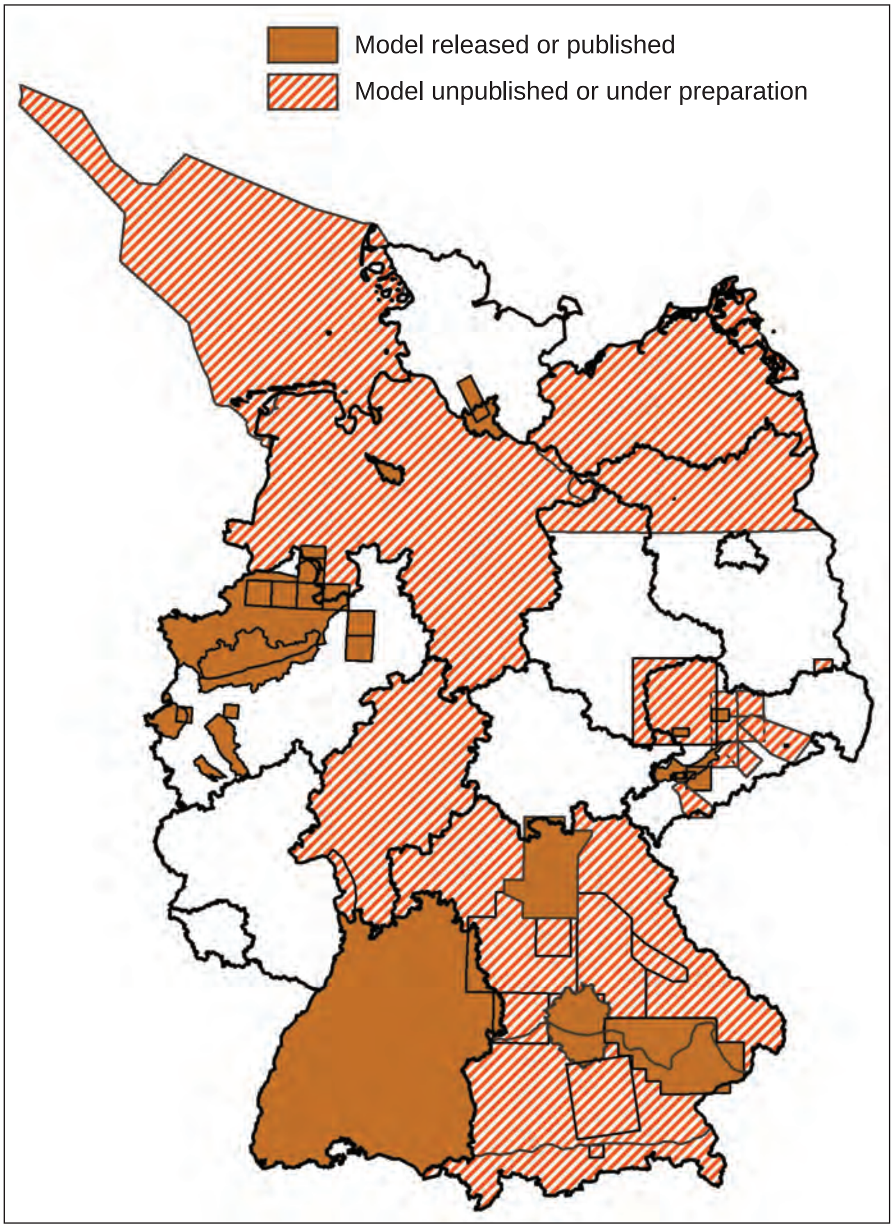

Figure 9-2 State of 3-D geological modeling in Germany including the German sector of the North Sea as of December 2009.

northern German Basin, including the 41,540 km² of the German North Sea sector (accomplished by Lower Saxony's LBEG) as well as northeastern Germany, the Rhine-Ruhr area, the Oberrhein-Graben, and the Molasse Basin. The models are mainly general lithostratigraphic and structural overviews aimed at a multi-purpose utilization of the underground and for geothermal energy and its sustainable exploitation. These 3-D models are a possible preliminary tool for subsurface spatial planning. To promote the economic usability of the underground, subsurface management will become inevitable very soon. Competition for available subsurface space will strongly increase among those wanting to develop the subsurface for geothermal energy, natural gas storage, waste storage including CO_2 (CCS), and pressure reservoirs as buffer storage for wind energy generation.

Another major application of geological 3-D models is Web services that provide local information on the efficiency (and possible restrictions) of shallow geothermal energy facilities as presently realized for greater parts of Baden-Württemberg (LGRB 2009). Other German GSOs are dealing with the same issue. Further applications of subsurface 3-D modeling range from small-scale, high-resolution models (e.g., for infrastructure planning), to topical or general regional models (e.g., Görne 2009, Sattler and Pamer 2009), to statewide models covering areas up to 36,000 km² (LGRB 2008).

Software, Methodology, and Workflows

The most widespread 3-D modeling software used at German regional GSOs is Paradigm's Gocad. Every GSO actively engaged in geological 3-D modeling owns at least one Gocad base module, and larger surveys utilize several-set bundles plus add-on modules for different purposes. Because Gocad initially was designed for the exploitation of digital seismic mass data existing in the hydrocarbon industry, it lacks many geological rules and constraints, and it is not always capable of reproducing a geologist's way of 3-D modeling, which is highly iterative, conceptual, and usually implicit. Consequently, some of the GSOs are considering the purchase of additional software packages for particular needs. For pre-processing spatial data, calculating grids, or triangulating unevenly distributed data, (1) GIS tools (mainly ESRI products), (2) CAD programs such as MicroStation, or (3) interpolation software such as Surfer are applied.

Because the organizational structures, data storage, and data management protocols of German geological surveys are very diverse, there are no common standards or script-based routines for data extraction and data processing prior to data import. Methods applied depend completely on the objective and scope of the projects and are very different, for example, digitizing analog maps, contour maps, and data such as the Geotectonic Atlas of Lower Saxony (Baldschuhn et al. 2001) versus com-

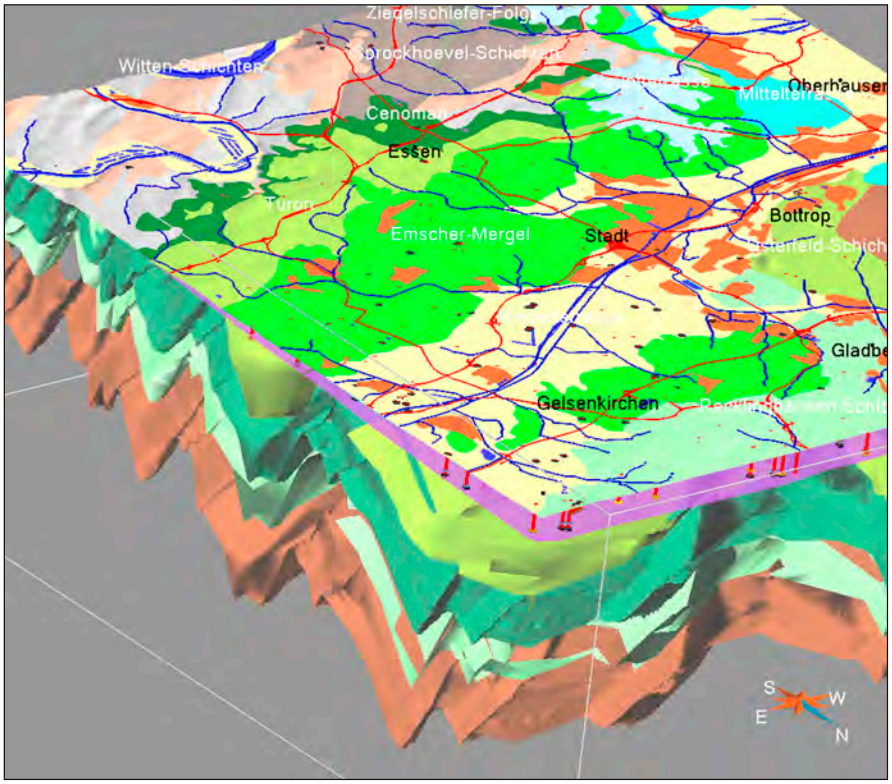

Figure 9-3 Part of a Gocad model depicting folded Carboniferous, coal-bearing strata of the Ruhr area (GD Nordrhine-Westphalia)

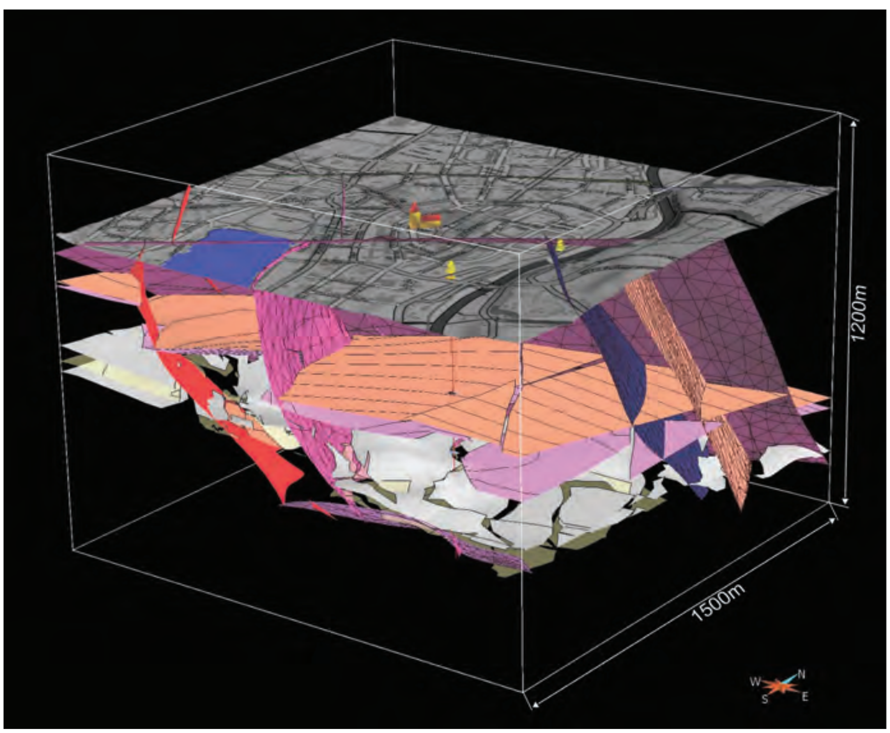

Figure 9-4 Structural model for monitoring an abandoned mining area underneath the city of Zwickau (LfULG Saxony)

pilation of old paper plots and new 3-D seismic profiling for the Molasse Basin in Bavaria. Generally, geological modeling is very specific to each area of interest, and normally several modeling procedures must be combined to achieve plausible results (Jessell 2001).

Nevertheless, using the same standard modeling software at most regional GSOs enables the sharing of model outputs independent of routines or workflows and the ability to customize them to local databases. Also, conceptual parts of workflows and routines covering more general steps of pre- or post-processing are exchanged on demand. Several examples of 3-D subsurface modeling at a German GSO and methodologies implemented are described and illustrated by Pamer and Diepolder (2010).

Lessons Learned

Even though it is generally accepted that geological 3-D modeling improves geological data visualization and interpretation, very few people at German GSOs are engaged in this essential task, because—despite substantial advances in computer technology—model building is still a toilsome task feasible for skilled specialists only. Thus, the acceleration of model building is a major challenge for surveys with limited staffing and limited 3-D modeling expertise. Figures 9-3, 9-4, and 9-5 show examples of 3-D modeling in Germany.

One option for increasing the use of 3-D modeling among more practitioners is to provide easy-to-use modeling software to field geologists. Integrating basic 3-D modeling into the GIS-based digital field data capture toolkits not only facilitates cross-validation of field data and communication of tacit knowledge, but it also ensures that only models that are checked for plausibility by local experts will be imported into a central modeling database. However, stepwise model preparation conducted by more than one person requires mandatory workflows for all geological settings and extensive documentation of each step. Implementation of a fully digital workflow for 3-D geological modeling (Smith 2005) should be a key objective for all German GSOs.

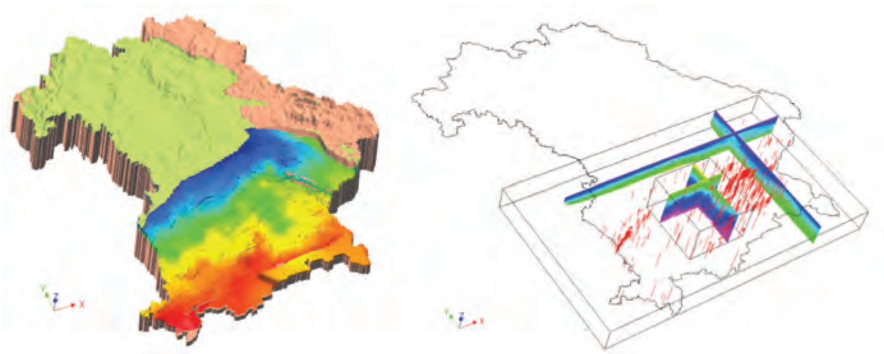

Figure 9-5 Volume grid of Bavaria subdivided into four layers (crystalline basement, Mesozoic sediments, Upper Jurassic aquifer; omitted: Tertiary sediments of the Molasse). Left: Upper Jurassic aquifer gridded with the temperature field derived from deep boreholes throughout the Molasse basin. Right: Volume grids of seismic velocities within the entire Molasse basin based on deep borehole data and a detailed velocity model of the Greater Munich area including stacking velocities of seismic sections (LfU Bavaria).

Current plans by German GSOs also point at the development of a technology that supports storage and management of 3-D data in database management systems. The objective of these joint efforts is to overcome constraints in model size and/or resolution due to hardware or software limitations.

Building a model is just one part of a whole cascade of pre- and post-processing steps; many different processes have to be understood, and various software packages have to be handled in different ways. To stay up-to-date in all aspects is not possible for a GSO employing only a few modelers. Therefore, constant mutual knowledge exchange—as successfully practiced by the German 3-D Study Group on a national level for several years—as well as sharing software developments and best practices, is crucial particularly for small surveys with a limited budget. The Madrid '09 workshop on 3-D modeling organized by the Geo3EU-initiative clearly revealed that even the major 3-D modeling agencies in Europe can strongly benefit from inter-agency and cross-border information exchange and cooperation.

The technical capabilities of agencies, however, are only one aspect of a successful 3-D modeling program. To ensure interoperability, common standards and subject-specific harmonization is necessary. Furthermore, as geology and the resources and risks connected with it do not respect political boundaries, common principles in line with national and international requirements are beneficial for cross-border modeling. Thus, to operate a complex and continuously evolving technology such as 3-D modeling and to ensure its success and orientation toward the future, cooperation and exchange must continue to be strengthened.

Chapter 10: Illinois State Geological Survey: A Modular Approach for 3-D Mapping That Addresses Economic Development Issues

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Organizational Structure and Business Model

The Illinois State Geological Survey (ISGS) was created in its modern form in 1905, but dates back to the 1850s. The ISGS mission is to provide objective scientific information to government, business, and the public (1) to improve the quality of life for Illinois citizens by providing the scientific information and interpretations needed for developing sound environmental policies and practices, and (2) to strengthen the Illinois economy by promoting wise development of the state's abundant mineral resources. The ISGS is a division (since 2008) of the University of Illinois' Praire Research Institute and has an annual appropriated budget (2009) of about US$6 million and total expenditures of more than US$13.2 million. It employs a staff of 185.

Geological mapping at the ISGS is a major programmatic priority and one way in which the Survey meets its larger statutory responsibilities of defining the geological framework of Illinois and supporting economic development and public and environmental health. Much of the research at the ISGS is not focused on production of 3-D maps and models, although geological mapping and some 3-D mapping and modeling is still a large part of the research program. Three-dimensional geological mapping and modeling at the ISGS is being used to address current problems related to groundwater availability or quality, carbon capture and storage, support for energy-sector needs, environmental health, and geological characterization for infrastructure development. The dimension and resolution of the mapping projects are determined by the objectives of the funding agents, available funds, and the complexity of the geological succession being mapped.

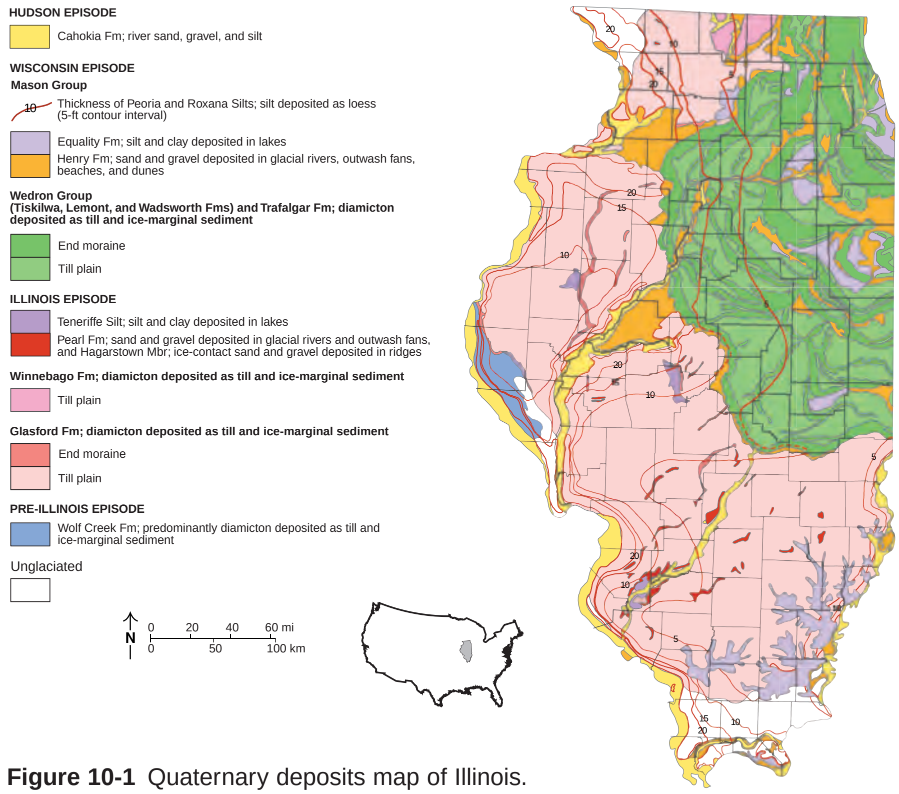

Figure 10-1 Quaternary deposits map of Illinois.

Currently, the staff working on 3-D geological mapping of Quaternary deposits at the ISGS are housed within the Quaternary and hydrology sections. There are approximately 25 full-time staff and 12 students involved with geological mapping, including Quaternary geologists, hydrogeologists, geophysicists, geochemists, GIS specialists, and data managers. The 3-D geological framework modeling and geostatistical simulation of rock properties is being conducted within the carbon capture and storage program, and that work focuses on modeling the geometry and petrophysics of bedrock reservoirs. This modeling is being done by staff of the Advanced Energy Technology Initiative as part of a large project evaluating the viability of storing large quantities of CO_2 in these reservoirs.

Geological Setting

The 3-D geological mapping program is currently focused on describing the distribution and character of Quaternary glacial and postglacial deposits throughout Illinois (Figure 10-1). The Quaternary deposits in Illinois have been characterized by numerous researchers. Key stratigraphic delineations are provided by Willman and Frye (1970) and Hansel and Johnson (1996).

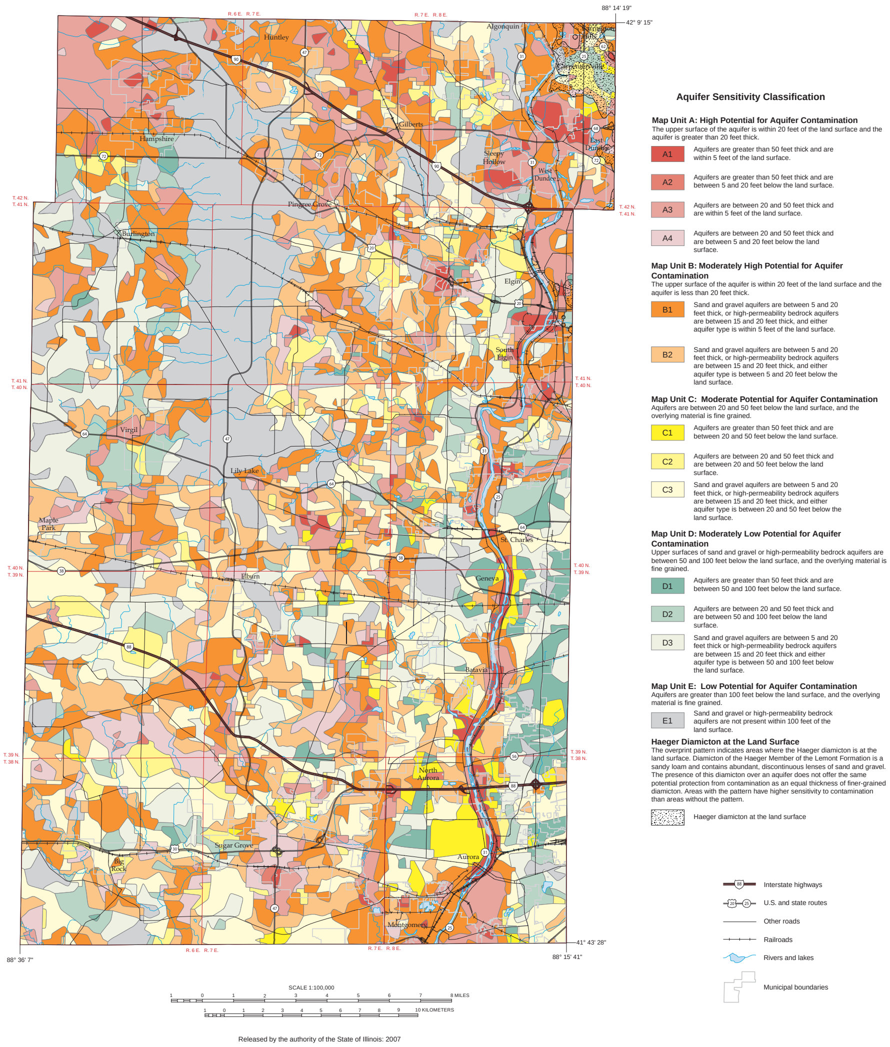

Figure 10-2 Kane County aquifer sensitivity map (Dey 2007a).

Quaternary deposits in Illinois are up to 150 m thick and average about 50 m thick. The areas with the thickest sucessions of Quaternary deposits are located in areas with terminal moraines from the late Wisconsin age and areas overlying preglacial buried bedrock valleys. Most Quaternary deposits in Illinois are glaciogenic diamictons (poorly sorted deposits, often rich in clay and silt) or sorted glaciofluvial or glaciolacustrine deposits (Lineback 1979). Glaciofluvial sands and gravels can be important aquifers and are often the main targets in mapping of these deposits. Correlation and mapping of diamictons are complicated because many of the glacially originated diamictons are similar in color, texture, and mineralogy. In the subsurface, the correlation of diamictons is further complicated by the wide variability in the thickness and occurrence of glaciogenic sand and gravel deposits. Correlation and mapping of the glaciofluvial sands and gravels are complicated by the prevalence of multiple, thin deposits within proglacial sequences proximal to moraines and because of the tendency for episodic scour and local redeposition of thicker sequences of sand and gravel, which creates overlapping textural and mineralogical characteristics.

3-D Geological Mapping Priorities

The 3-D Quaternary mapping priority areas in Illinois include the major population and industrial centers of Illinois:

- an 11-county area that includes metropolitan Chicago,
- a 15-county area of east-central Illinois that overlies the Mahomet Bedrock Valley, and
- large portions of the Illinois River corridor in central Illinois.

The metropolitan Chicago area is the focus of most of the current ISGS 3-D mapping and modeling program because of the area's growing population (currently about 8 million people). The metropolitan Chicago area is experiencing local limitations in sand, gravel, and limestone aggregate resources, and there are significant regional stresses on groundwater supplies from both shallow and deep aquifers. Increasingly, county and city planners are developing plans that encourage recharge to shallow aquifers and protect the quality of these resources. Three-dimensional geological mapping is being used to delineate the extent, character, and potential interconnections between the sand and gravel deposits as well as the depth to the surficial bedrock aquifer. The 3-D mapping has resulted in the development of various 2-D maps (e.g., Figure 10-2) developed to assist decision makers in addressing these problems (Dey et al. 2007a, 2007b, 2007c).

The Mahomet Bedrock Valley in east-central Illinois contains thick sand and gravel deposits, including the Mahomet aquifer that fills the valley and is the main regional aquifer in downstate Illinois (Figure 10-3; Soller et al. 1999). Local groundwater extractions for municipal, industrial, and agricultural supplies have produced significant drawdowns in the piezometric surface, indicating locally significant stress on the aquifer. Three-dimensional geological mapping is being used to delineate the thickness, character, and extent of the sand and gravel within the valley, the distribu-

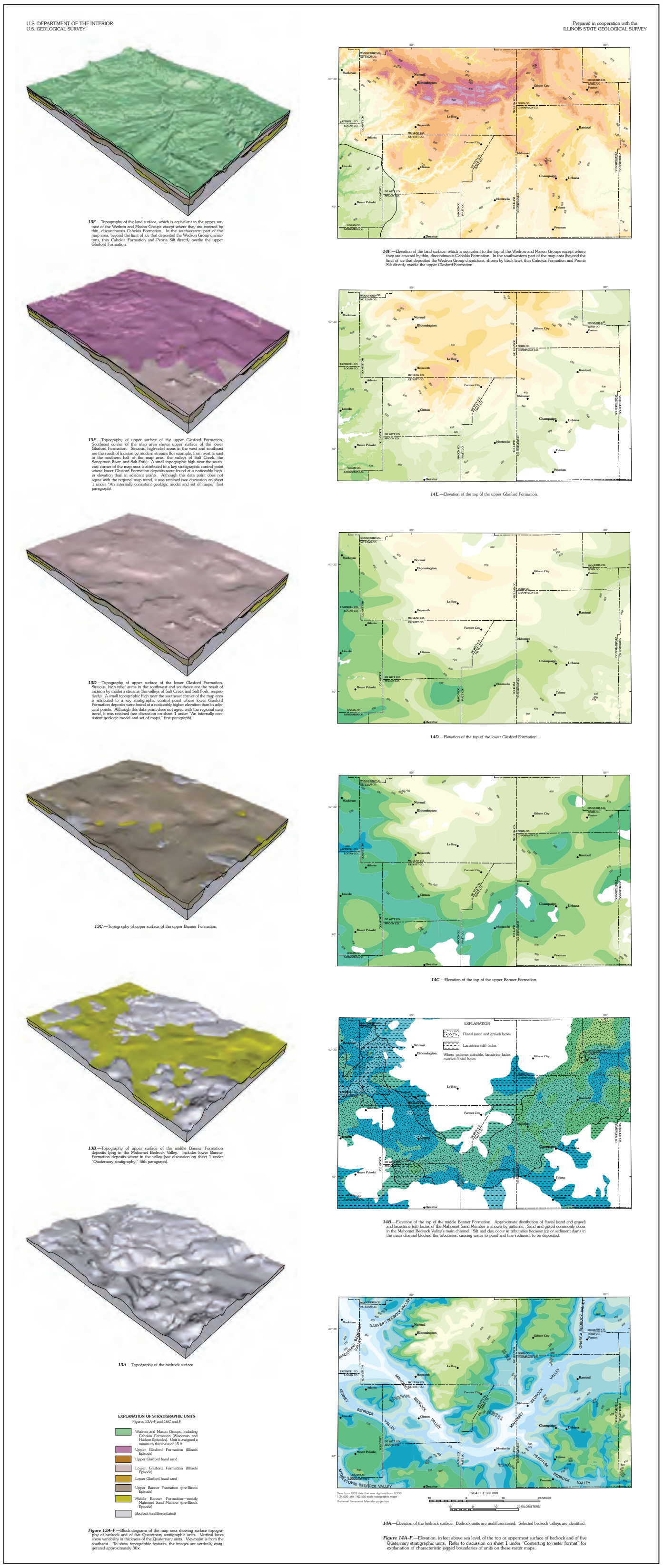

Figure 10-3 Examples of 3-D maps and models of the Mahomet Bedrock Valley (Soller et al. 1999).

tion of fine-grained deposits within the valley succession, and the distribution and interconnection of sand deposits above the main Mahomet Bedrock Valley deposits. Products will include (1) geological framework models of various resolutions for use in regional and local groundwater flow modeling and (2) maps for guiding sustainable management decisions for regional groundwater and surface water systems.

The Illinois River is a critical shipping artery connecting the Great Lakes with the Gulf of Mexico. Landslide and erosion problems have created significant sediment water-quality problems in the river. The ancient Mississippi River, before it was diverted to its present location about 150 km to the west about 20,350 years ago (McKay et al. 2008), occupied what is now the Middle Illinois River valley. Repeated glacial advances and retreats over the area, resulting in numerous interactions of glacial ice with the ancient Mississippi River and later the Illinois River, resulted in a very complex geological history and succession of deposits. The Illinois Department of Transportation is considering state highway expansion through upland and lowland areas adjacent to the Illinois River, and the City of Peoria, which is located on the river, has limited groundwater resources and problems with local groundwater contamination. Three-dimensional mapping is being used (1) to provide insight about the geological conditions expected in various potential highway corridors (Figure 10-4); (2) to identify the distribution, character, and interconnections of sand and gravel deposits; and (3) to characterize the geological deposits along the banks of the Illinois River and its tributaries as a guide for understanding bank erosion problems.

Funding Sources for 3-D Geological Mapping

Funding for 3-D geological mapping at the ISGS can be grouped into four categories:

1. federal and state partnerships;
2. county, local, and state partnerships;

3. federal, county, state partnerships; and
4. private corporation and state partnerships.

Within the federal and state partnership category and the federal, county, state partnership categories, the longest continually funded mapping program at the ISGS is the Great Lakes Geologic Mapping Coalition (GLGMC) (http://www.greatlakesgeology.org). At the ISGS, the GLGMC supports high-resolution 3-D mapping consistent with the detail generally found in 1:24,000-scale maps of surficial deposits. To date, the GLGMC efforts at the ISGS have focused on mapping the Quaternary deposits of extreme northeastern Illinois. Historically, the federal-state partnerships also have paid for medium-resolution mapping of a multi-county portion of the Quaternary deposits above the Mahomet Bedrock Valley in east-central Illinois (Figure 10-3)(Soller et al. 1999).

Partnerships of county and local government agencies matched with state funding from the ISGS have typically supported 3-D geological mapping at a medium resolution that is compatible with geological characterization in support of regional groundwater flow modeling. These efforts have been conducted in central and northeastern Illinois.

Partnerships between private corporations and the state to support 3-D geological mapping have been rare, but important. Currently, a high-resolution 3-D geological mapping program is in progress in and around Champaign County in east-central Illinois. The geological mapping for this project is being funded by the local water utility and is designed to support subsequent groundwater flow modeling and long-term sustainable management of the groundwater resources.

3-D Mapping Methods

While 3-D geological mapping projects are not required to follow a standardized mapping protocol at the ISGS, the basic mapping workflow is fairly consistent:

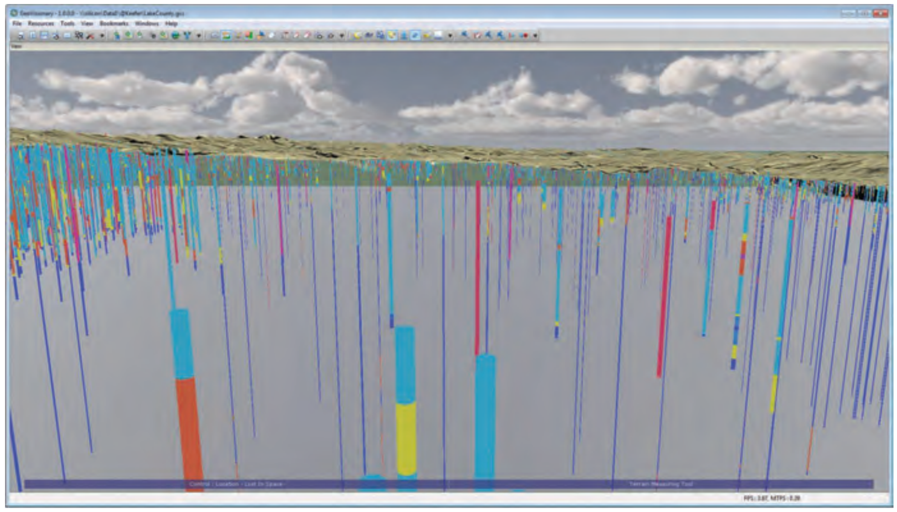

Figure 10-4 GeoVisionary rendering of standardized lithologic borehole logs with a 1-m LiDAR-based digital elevation model.

- data collection and organization;
- interpretation, correlation, and interpolation; and
- production of basic and interpretive maps.

The first phase of any ISGS mapping project is compilation of existing data within the mapping area. Most of these data are driller's logs from water wells. Other, more reliable data used in mapping projects include stratigraphic borings and core descriptions collected by ISGS geologists, geophysical borehole logs from water supply or observation wells, previously published maps or reports, and existing field and outcrop descriptions. Water-well driller's logs (about 450,000 in Illinois) are generally in their original form and include basic lithologic descriptions of the materials that were encountered. To simplify the interpretation and correlation of water-well data, the driller's lithologic descriptions are matched with a set of standard lithotypes. This process is accomplished using a custom Microsoft Access database and user interface that facilitates the assignment of standard lithotypes. Visualizing this lithologically standardized borehole data has become an important element of the ISGS mapping protocol, as it provides a first glimpse of data distribution and quality in 3-D space (Figure 10-4).

A significant amount of time in this phase of a mapping project also is spent verifying the location of the data points. This step is important because many of the map units can be very thin to discontinuous, and errors in location can result in vertical shifts in the reported elevation of individual deposits and can introduce errors into correlations and the final map. Finally, priorities for new data collection are typically identified at this phase of the project. When funds allow, new data are collected during various parts of the project cycle (e.g., from test drilling).

The second phase of each 3-D geological mapping project involves the iterative processes of interpretation, correlation, and interpolation. Early steps are the identification of the mapping objectives, the determination of the detail required in final products, and the identification of the main mapping units. As part of this process, the selected data are reviewed, and the mapping team examines available core samples to identify the likely depositional environments and then delineates the map-unit framework for the area. Cross sections are made, either by hand or via computer, alternate conceptual models are explored, and initial map unit assignments are made. From these initial interpretations, geologists use one of two approaches

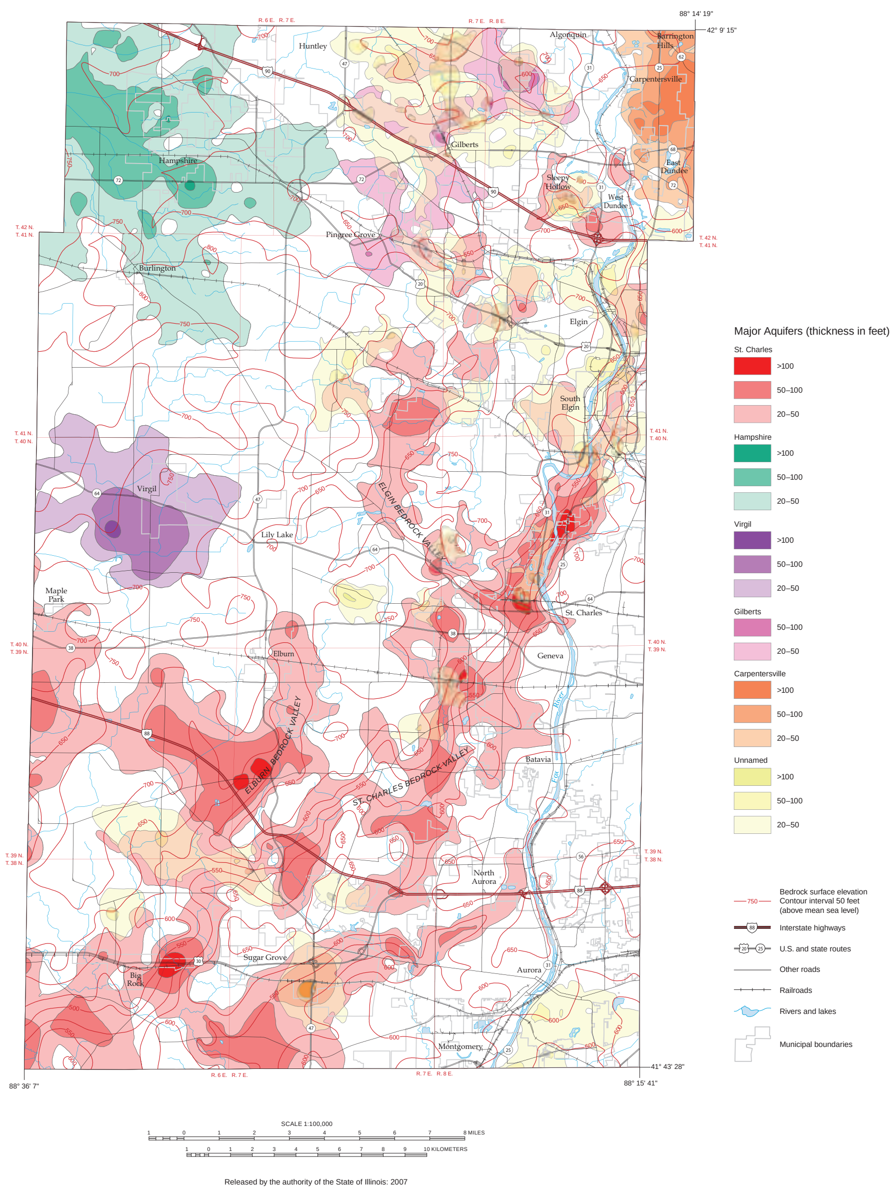

Figure 10-5 Kane County major Quaternary aquifer map (Dey et al. 2007c).

to mapping. In the more traditional approach, structure and isopach maps are generated to evaluate the distribution and thickness of key marker horizons or important map units. Typically these maps are generated using computer interpolation software and then stored as uniformly gridded data sets. Each surface is evaluated against both the data and the set of other surfaces that constitute the 3-D map. When a surface map does not fit the conceptual model, the data, or the other surfaces, that map is corrected to express the desired geometry. The conceptual model is used to determine the order and relationships between the various map units. Erosional and onlap relationships are identified, and grid-to-grid mathematical routines are used to create the correct relationships between pairs of surfaces. This process is repeated until the entire set of surface maps meets the interpretations of the mapping team. Depending on data quality and geological complexity, this can be a very slow process.

Alternatively, ISGS geologists have been intergrating GSI3D into their mapping projects. GSI3D creates 3-D maps through interpolation fron a large set of cross sections.

The third and final phase of the mapping project includes the production of basic and interpretive map layers. During this phase, the mapping objectives and the list of contracted deliverables are revisited to determine the list of 2-D map sheets that will be produced. This list always includes both structure and isopach maps for each map unit. Interpretive maps are developed to address specific issues that are important to the decision makers within the map region. Maps showing the occurrence, depth, and thickness of major aquifers are commonly generated interpretive maps (Figure 10-5). Other interpretive maps can highlight construction-related issues; predict land shaking for specific earthquake scenarios, or address specific shallow groundwater flow issues. Often, the set of surface grids that form the 3-D geologic map are exported for use in groundwater flow models. This process does not involve the creation of new published map products; it typically involves only the reformatting of the surface map files into a form that can be easily input to software used by collaborating groundwater flow modelers. Depending on the software available, 3-D block models and animations can be generated to highlight important geological features that were identified during mapping and that highlight critical mapping objectives.

Mapping Software and Staffing Strategy

Over the past 5 years, the ISGS has explored various software options to support 3-D geological mapping over a range of spatial scales, from site-specific to thousands of square kilometers. The ISGS evaluated high-cost packages developed to support petroleum and mining applications and mid- to low-cost packages developed to support the environmental consulting and regulatory industries. The cost and value of developing custom software for 3-D mapping and visualization were explored as was the feasibility of using modular, ad hoc combinations of desktop software to generate 3-D geologic maps.

After years of evaluation and discussion, the ISGS selected the modular, ad hoc combination of software for creating 3-D geologic maps. This modular approach allows mappers the flexibility of efficiently improving their mapping approach as software evolves to improve its support of various parts of the mapping workflow. This approach allows for continual use of the enterprise database of wells, borings, and outcrops and for utilization of a standardized, open data structure for managing geophysical data types, as well as images, cross sections, surface map grid files, animations, etc. Custom programs and scripts can be easily integrated to provide desired functionality, and there is no need to completely revise the suite of programs, workflow, or data structure if the underlying software changes dramatically. This modular approach also permits the integration of routinely used software products (e.g., ArcGIS, Oracle, Microsoft Access, MAPublisher), and it accommodates new applications for any aspect of the workflow (e.g., visualization or surface interpolation) as they become available. Finally, this approach allows for the inclusion of software and custom scripts that are user-friendly enough for the tech-savvy field geologists to use and that do not require significant training or time for the mapping technicians or support specialists.

The current strategy for ISGS staffing on 3-D mapping projects is fluid and is based on the size of mapping areas, timeframes of projects, budget flexibilities, geological complexities, and technological capabilities of field geologists. Most projects have the assistance of support staff for data management, and all mapping projects receive technical support in the production of map products. Most field geologists are able to manage ArcGIS and surface interpolation software and, for smaller projects, do not require the assistance of support staff in these areas. Larger projects and projects with more geological complexity often have assistance from support staff in GIS and surface interpolation to help construct the structure and isopach maps, and to build and cross-check the various surfaces as 3-D maps and models are built.

Currently, the 3-D mapping program relies on a suite of software for the following phases and tasks in the ISGS mapping workflow.

Data Collection and Organization

Well logs, core and sample descriptions, and outcrop descriptions are managed using both Oracle and Microsoft Access. The ISGS is moving to centralization within the enterprise database under Oracle and reliance on various user interfaces, some via Microsoft Access. New Web-based interfaces to basic data access are expected to be developed over the next year.

The directory and file structure are standardized for the management of the various geophysical borehole logs and geophysical profile data sets. This standardization allows the data sets to be efficiently located and queried by all staff while allowing the geophysicists to manage, update, and interpret these files at any time.

Interpretation, Correlation, and Interpolation

Software used for data analysis includes ArcGIS, Excel, and Isatis. Custom programs also have been developed to work with ArcScene to visualize 3-D borehole data. These in-house programs also allow for borehole data interpretations, assigning mapping unit interpretations to the underlying database, and simplifying the construction of cross sections and surface maps.

Three-dimensional visualization is currently being handled by three software packages, GeoVisionary (Figures 10-4 and 10-6), ArcScene, and GSI3D. The ISGS is in the early stages of combining these two applications into an integrated workflow. These three packages are expected to allow for the integration of all data types into a high-resolution 3-D environment and allow for interpretations in this 3-D space. Visualization of 3-D voxel models of facies and petrophysical properties are

Figure 10-6 Visualization laboratory image on screen on GeoVisionary.

being handled by the Isatis 3-D Viewer. Although these applications will generally be used in a desktop environment, a 3-D/stereo visualization laboratory recently has been constructed to provide a large collaborative space for discussing data and interpretations and for developing 3-D geologic maps with the mapping team (Figure 10-6). This visualization laboratory houses a high-resolution projection with a rear projection 4.2-m × 2.4-m screen, conference tables, a white board, and modular seating for up to 20 people.

As noted in the previous section, the traditional ISGS 3-D mapping approach relies on the creation of individual surface maps for tops or bottoms of each map unit. These surface maps are created and managed as 2-D grids using various software applications. Currently, ArcGIS Spatial Analyst, Surfer, Rockworks, and Isatis are the four main packages used for creating surface maps. Increasingly, GSI3D is being intergrated into 3-D mapping workflows. GSI3D is typically easier to use and allows the geologist to procure more accurate sets of surfaces in a much shorter time. The interface and tools are more intuitive than those we use in ArcGIS or Surfer.

Basic and Interpretive Map Production

ArcGIS, InDesign, and Illustrator are used by specialists in cartography and digital map production to produce all map products. The field geologist's role is to provide the basic map layers to the map production specialists and to provide technical input as needed.

Lessons Learned

1. Pilot studies for 3-D mapping started with high-end, sophisticated software and required one technician per mapping project. This approach was expensive, but successful. Some geologists were frustrated that they could not control the software themselves and felt disconnected from the process and resulting maps. Based on this feedback, a system was selected that included user-friendly software. This system requires support for data management and some part-time help from technicians for creation of traditional surface maps and construction of integrated 3-D maps.
2. When the ISGS started the migration to 3-D geological mapping there was no standard data structure that met the new 3-D mapping needs. A standard data structure and in-house customized tools have recently been developed for interacting with data. Although standardization of mapping software is not part of the planned workflow, the ISGS will only provide centralized purchasing and technical support for some software packages and will require data and maps to be saved in standard formats at the end of every project to ensure an enterprise database that includes all map-related data and products.
3. New software for visualization was purchased based on a model in which costs are shared by all mapping projects. This strategy is fairly new at the ISGS, and it is not clear if it can be supported over time. The cost sharing requires small incremental costs from every project rather than having most costs supported by a small number of projects. Some funding agents will not allow software charges, however, so those costs must be covered by other means.
4. Recently, the ISGS began developing 3-D visualization software tools to analyze data and make interpretations from the data. These tools allow for a much more intuitive process and are preferred by the geologists who have used them. The overhead for this approach is currently higher, as it requires a staff member with expertise in programming. If the efficiency and accuracy of the 3-D mapping projects improve with this approach, this investment will be worthwhile.
5. When the ISGS began its current emphasis on digital mapping, geologists experienced significant problems caused by inefficiencies in map production. At that time, field geologists were allowed to compile and direct the cartographic style of their map products. This flexibility seemed worthwhile, but it created delays in the review and publication process. With time, a standardized approach to map compilation was developed. A professional cartographer was hired to define the cartographic approach to quadrangle map products, define the cartographic style of these products, and define a map production workflow that enables field geologists to provide the geologic map layers to GIS specialists. The GIS specialists then use the geology layers with the cartographic standards to quickly produce the final products. Through this process, production of quadrangle maps has soared.

Chapter 11: Manitoba Geological Survey: Multi-scaled 3-D Geological Modeling with a Single Software Solution and Low Costs

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Organizational Structure, Business Model, and Mission

The Manitoba Geological Survey (MGS) was founded in 1928. Its mission is to conduct investigations of the province's Precambrian Shield, Western Canada Sedimentary Basin, and Hudson Bay Basin to improve the understanding of Manitoba's geology and geological processes and, in so doing, encourage mineral exploration opportunities and contribute to wise land-use management. Investigations conducted by the MGS include those of exposed bedrock, subsurface materials, and surficial sediments including sand, gravel, and peat. The MGS provides data and products such as geological maps and reports, metallic and industrial mineral deposit reports and databases, mineral resource assessments, targeted geoscience research, development of exploration models, and maintenance of data inventories.

The MGS is within Manitoba's Mineral Resources Division along with the Minerals Policy and Business Development Section and the Mines and Petroleum Branches, which are regulatory bodies. Only the geological survey is concerned with 3-D modeling.

Until fairly recently, three-dimensional geological modeling was seen as more of a novelty than a business requirement for the MGS. Beginning as a successful offshoot of the prairie portion of the Canadian National Geoscience Mapping Program (NATMAP), through the 2003 Lake Winnipeg Basin model, the 2008 Western Canada Sedimentary Basin (WCSB) model (Keller and Matile 2009), and the recently completed 2009 Targeted Geoscience Initiative (TGI) Williston Basin model (TGI II Working Group 2009), the MGS's commitment to 3-D modeling has grown to include mapping all of the Phanerozoic terrane of Manitoba in 3-D. Future plans include cooperation of the MGS with the Minnesota and North Dakota Geological Surveys to produce a cross-border Red River valley 3-D geological model. This model will combine the existing North Dakota/Minnesota Fargo-Moorhead regional models (Thorleifson et al. 2005) with Manitoba's 3-D data. Figure 11-1 summarizes 3-D mapping activities.

Geological Setting

Manitoba was completely engulfed in ice during the last glacial period, and most of Manitoba is covered with glacial sediments up to 300 m thick. The bedrock geology is composed of 60% Precambrian terrane, which is covered by the eastern edge of the Phanerozoic Williston Basin in the southwestern portion of the province and the western edge of the Phanerozoic Hudson Bay Basin in the northeastern portion of the province. The Precambrian terrane, otherwise known as the Canadian Shield, has a discontinuous cover of glacial sediment and is made up of deformed crystalline rocks of the Archean Superior Province in the south and east and the Proterozoic Churchill Province in the north and west. The two Phanerozoic basins have a more continuous cover of glacial sediment and are composed of a stratified suite of gently dipping, primarily undeformed, Paleozoic carbonate rocks that in the Williston Basin progress upward to Mesozoic shale. The surface of the Williston Basin comprises a set of eastward-facing bedrock escarpments that step up onto younger rocks in a westward direction.

Major Clients and the Need for Models

To date, 3-D models of the MGS have been used by other government branches, university students, and industry to assist in the planning stages of new pipeline construction, construction of groundwater models and chemical flow through these models, and in groundwater exploration drill holes. The ability to visualize in 3-D is an extremely useful educational tool for the public, the mineral exploration industry, and for students interested in a better understanding of Manitoba's geological landscape.

Model Methodology

Although more than 25 geologists work at the MGS, only two are responsible for 3-D modeling, a geologist and a GIS/3-D modeling specialist, who work as a team. This synergy works very well, allowing each scientist to concentrate on his or her field of expertise. Models are created using data gleaned from a variety of disparate data sets. The bulk of the modeling is based upon well data (water wells, geoscientific and academic wells, and oil and gas wells); however, large lake bathymetry, seismic, digital elevation data, and surficial and bedrock geology are also used to refine the model. The software packages utilized in the modeling workflow include ArcGIS (ESRI), MapInfo (Pitney Bowes), Access (Microsoft), and Gocad (Paradigm). Several different modeling methodologies have been employed at the MGS depending on the type of data available.

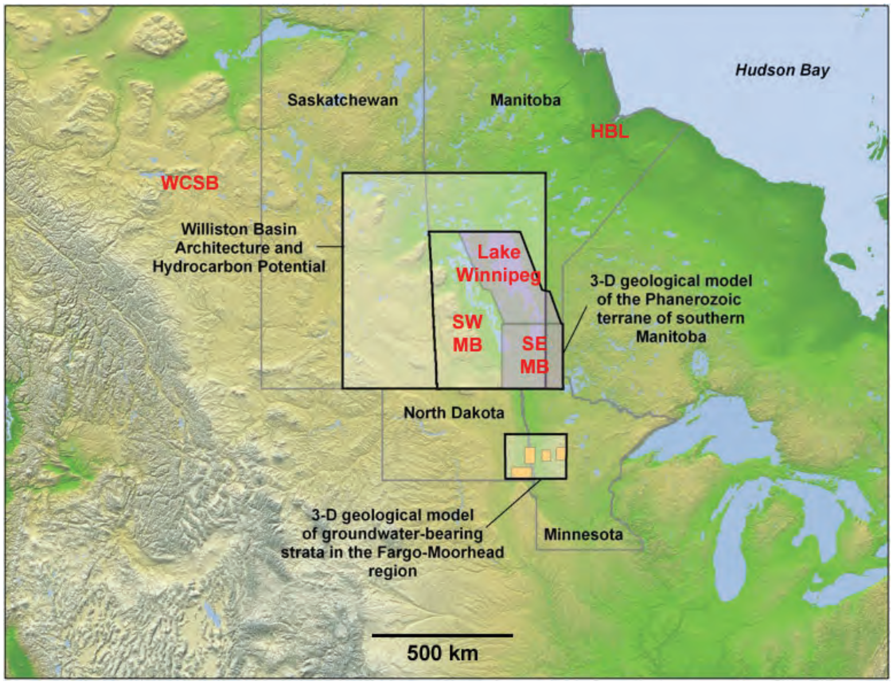

Figure 11-1 Index map outlining the location of the various 3-D geological modeling activities in and around Manitoba. The southwestern Manitoba model is in progress. Yellow blocks indicate areas of higher detail within the Fargo-Moorhead model.

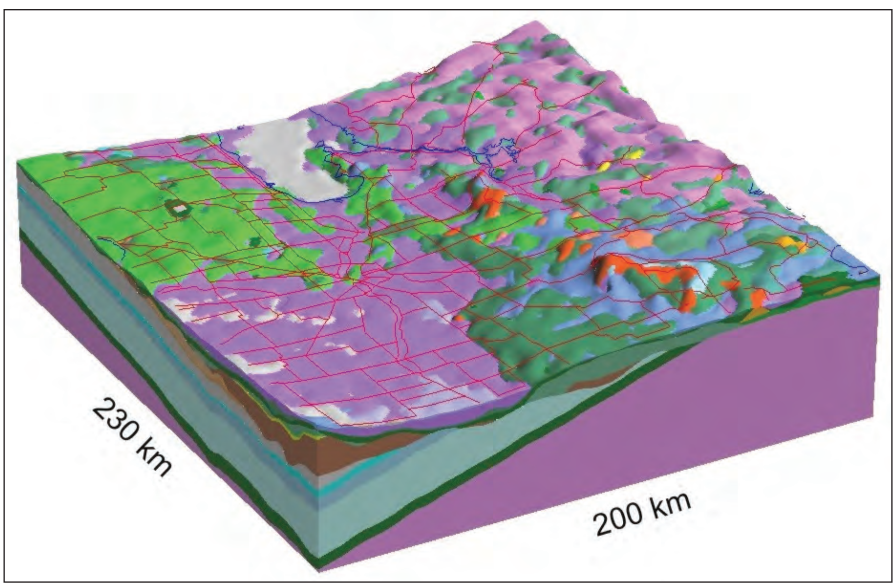

Figure 11-2 Three-dimensional geological Gocad model of southeast Manitoba including the Winnipeg region.

Cross Section Method (Quaternary to Precambrian Surface for Southeastern Manitoba)

- Water-well data (over 80,000 holes), along with surficial geology, bedrock geology, and digital elevation data are collected for the study area.
- These data are then formatted and plotted onto 54-inch cross section traces depicting a 5-km-wide west-east swath through the study area.
- Each cross section trace is then hand-interpreted to define unit tops, which filters data of variable quality based on local trends.
- The interpretation is captured every 5 km along the cross section trace and recorded as "virtual drill holes" or predicted stratigraphic points (PSP), which provides a 5-km grid of PSPs for the project area; these data are then imported into Microsoft Access and formatted.
- The formatted PSPs are then imported into Gocad 3 modeling software and combined with unit edges to create a model surface.
- Model surfaces are then used to "erode" Gocad stratigraphic grids (Sgrid) to create a filled volume or "solid" for each modeled unit (Figure 11-2).

Direct Data Modeling Method (Phanerozoic to Precambrian Surface)

- Five to eight stratigraphically significant deep, detailed drill holes ("golden spikes") per township (10 km × 10 km) are selected, and formation tops are re-picked for consistency at a high level of detail by stratigraphers over the study area.
- The resulting data set of formation tops and a data set of formation edges form the basis of the model.
- These data are imported into Gocad and, because this data has been filtered by stratigraphers, can be directly modeled (Figure 11-3).

Digitization Modeling Method (Chronostratigraphic Rock Units to Precambrian Surface)

- To convert the existing paper 3-D model in the atlas of the WCSB into a digital 3-D model (Figure 11-4), structural contours and formation edges for each of the geological periods were scanned from the WCSB (Mossop and Shetsen 1994) and digitized.
- The digitized contours were tagged for elevation and, along with the edges, were exported into Gocad and directly modeled.

In each of these methodologies, the size of the data cells and/or triangles in the TIN of the resultant model are dependant on data quality and distribution, model size, and available computing power.

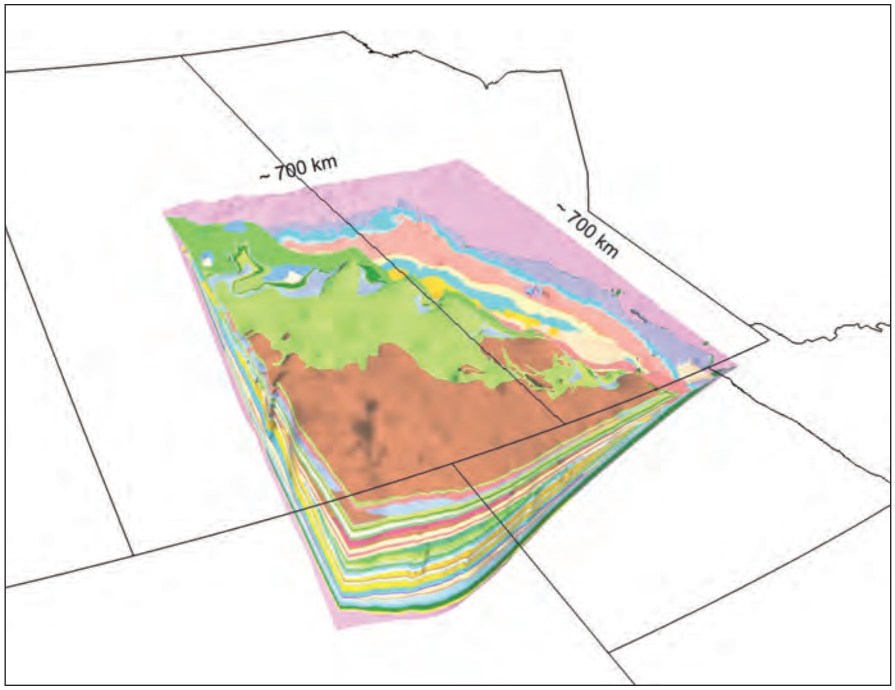

Figure 11-3 Three-dimensional geological Gocad model of the TGI Williston Basin project area.

Advantages of the MGS 3-D Mapping Approach

Using well-established, fairly inexpensive software for the background work (Microsoft Access, MapInfo GIS, text editors), and a single 3-D software solution (Gocad) keeps costs and workflow manageable.

The cross section methodology brings all of the available data together to use in interpreting the stratigraphy. Some data are lost in data-rich areas using this cross section method, but the method allows trends to be projected into data-poor areas.

A free data viewer (Geocando) is available for Gocad that allows clients and the general public free access to the models (3-D visualization, rotation, and simple querying).

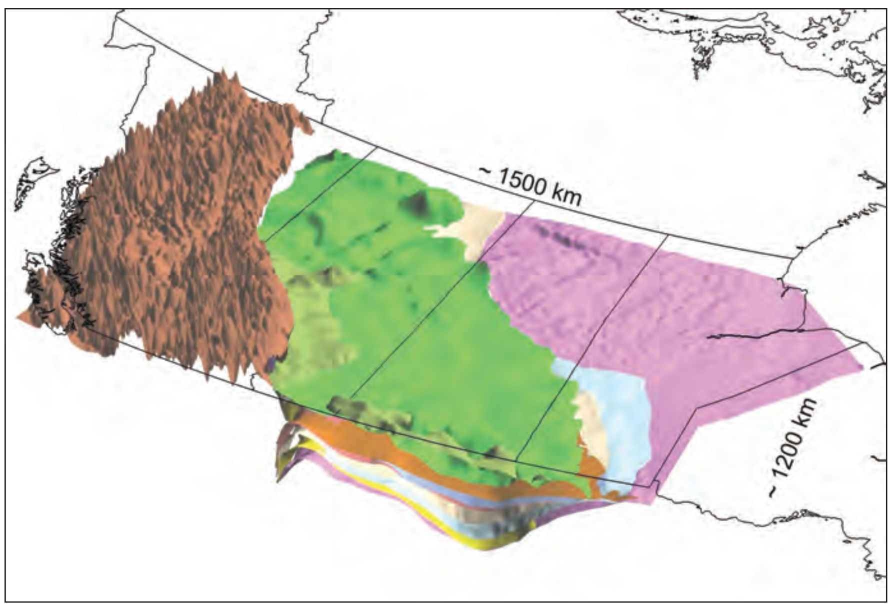

Figure 11-4 Three-dimensional geological Gocad model of the Western Canada Sedimentary Basin spanning Manitoba, Saskatchewan, and Alberta.

Lessons Learned

- Although water-well data are highly variable in quality, they are very useful to fill in data gaps between the “golden spikes,” and data can be filtered by looking for trends using the cross section method just described.
- Model uncertainty can be calculated simply by observing the data density and geological complexity of an area.
- In areas with a large number of drill holes, compressing all of the drill hole data from a 5-km north-south swath to a single cross section trace can make interpretation difficult. This difficulty is due to the scale

of the cross section; holes begin to obscure one another as numbers increase, which is particularly significant in areas with increased local relief.

- Where data are sparse, the cross section methodology can generate parallel ridges on the final surface due to variations in isolated drill data from cross section to cross section, much like steps can be generated when using contoured data. The lack of drill holes makes it difficult to visualize the trend of the data.
- Unit edges that have been drawn in plan view without being cognizant of local relief can lead to flattened bedrock escarpments. Updated edges drawn with shaded relief provided by a digital elevation model will rectify this issue.
- Although buried valleys in southern Manitoba are only recognizable on the cross sections when they intersect a cross section at an angle approaching perpendicular, the cross section method will still be useful for targeting exploration water wells in buried valleys.

Chapter 12: TNO–Geological Survey of the Netherlands: 3-D Geological Modeling of the Upper 500 to 1,000 Meters of the Dutch Subsurface

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Organizational Structure, Business Model, and Mission

The present TNO–Geological Survey of the Netherlands was founded in 1997 by merging the governmental organization Rijks Geologische Dienst (literally State Geological Survey) and the TNO Institute for Groundwater and Geo-Energy. The origin of the State Geological Survey dates back to 1903; the TNO Institute for Groundwater started its work in 1948. Both institutes have always paid considerable attention to applied geoscientific research. The mission of TNO–Geological Survey of the Netherlands is to provide the society with customized geoscientific knowledge, data, and information based on a thorough knowledge of the subsurface. The Institute employs over 300 geoscientists and has a turnover of about €35 million. The Geological Survey of the Netherlands forms part of the Netherlands Organisation for Applied Scientific Research (TNO), which was established in 1932.

The geomodeling department of the TNO–Geological Survey of the Netherlands focuses on the sustainable use and management of the upper 500 to 1,000 m of the Dutch subsurface. The department's most important task is the characterization and modeling of geological deposits. It develops and maintains three models: DGM (digital geological model), REGIS II (Regional Geohydrological Information System), and GeoTOP (3-D model of the upper 30 m). REGIS II emerged from separate mapping tasks commissioned by the 12 Dutch provinces in collaboration with the Directorate-General for Public Works and Water Management and with TNO.

The annual budget for geologists and modelers at TNO–Geological Survey of the Netherlands is about €3 million. There are approximately 10 geologists, 5 geohydrologists, 4 geomodelers, 4 geochemists, and 4 part-time GIS experts working on various modeling projects. From this staff there are 3 modelers and 1 to 2 geologists working more or less full-time only on the 3-D geological modeling of the subsurface of the Netherlands.

Geological Setting

Introductions to the Quaternary geology of the Netherlands can be found in publications by Zagwijn (1989) and De Gans (2007) among others. The following summary is largely adapted from descriptions by Rondeel et al. (1996).

The Netherlands are located on the southeastern rim of the North Sea Basin (Figure 12-1), and the edges of this basin are close to the country's

Figure 12-1 Location and schematic geological map of the Netherlands.

eastern and southern borders. The sediments at the surface are almost exclusively Quaternary. The thickest Quaternary succession (600 m) occurs in the northwest. Tertiary and older sediments are only exposed in the extreme east and south of the country, where the edges of the North Sea Basin were uplifted and eroded. The southeastern portion of the Netherlands is affected by a southeast-northwest string fault system, which formed a number of horst and graben blocks during the Tertiary and Quaternary. These faults are still active.

The Dutch landscape essentially consists of a Holocene coastal barrier and coastal plain and an interior with Pleistocene deposits cut by a Holocene fluvial system. The coastal barrier is interrupted on the south by the estuary of the Rhine, Meuse, and Scheldt Rivers and on the north by the tidal inlets of the Wadden Sea. The barrier is characterized by dunes and is locally up to 10 km wide. In places the barriers were reinforced with dikes.

The coastal plain covers the western half of the country and consists mainly of clay and peat. Much of the plain would be flooded in the absence of dikes. The distribution of land and water has been strongly influenced by humans, and the present-day limited extent of peat, for instance, is artificial. Because peat was historically exploited as fuel both in the coastal plain and further inland, moors partially cover the Pleistocene deposits.

The Rhine and Meuse Rivers enter the country from the east and south, respectively. Throughout the Holocene these rivers formed a thick succession of fluvio-deltaic sediments covering the Pleistocene deposits. In many places, the rivers are straightened artificially, and virtually everywhere they are confined by dikes.

At the surface, the Pleistocene is largely sandy and of glacial, fluvial, and aeolian origin. Ice-pushed ridges locally reach heights of 100 m, but most of the Pleistocene occurs as flat-lying land. Pre-Pleistocene sediments are only exposed near the borders of the country. In the east, these sediments include various Mesozoic and Tertiary formations, whereas those to the southwest are of Pliocene age. In one particular valley in the hills of the southernmost province, Tertiary sands, clays, lignites, and Cretaceous chalk are eroded down to their Carboniferous substratum.

Three Nationwide Models

DGM: The Digital Geological Model

Modern digital mapping of the Dutch subsurface started in 1999 with the development of the so-called Digital Geological Model (DGM; Van Gessel et al. unpublished.). This model, which is available to both professionals and the general public (www.dinoloket.nl), is a 3-D lithostratigraphic framework model of onshore Netherlands. The DGM consists of a series of raster layers. Each lithostratigraphic unit is represented by rasters for the top, bottom, and thickness of the unit. Raster layers are stored in the raster format of ESRI (ArcGIS). The lithostratigraphic units are at the formation level; Holocene deposits are represented as a single layer.

REGIS II: The Regional Geohydrological Information System

A second important step in digital mapping was the development of the Regional Geohydrological Information System (REGIS II; Vernes and Van Doorn 2005), which further subdivides the lithostratigraphic units of the DGM into aquifers and aquitards. Representative values for hydrological parameters (e.g., hydraulic conductivity and effective porosity) are calculated and assigned to the model, making it suitable for groundwater modeling on a regional scale. Like DGM, REGIS II models the Holocene deposits as a single cover layer. REGIS II is downloadable from the TNO Web site (www.dinoloket.nl) and is widely used by regional authorities and water supply companies for groundwater modeling studies.

GeoTOP: A 3-D Volume Model of the Upper 30 Meters

GeoTOP expresses the shallow subsurface schematically in millions of grid cells (blocks), each measuring 100 × 100 m in the horizontal direction and 0.5 m in the vertical direction. Several parameter values are estimated for each grid cell. These parameters include geological characteristics, such as lithostratigraphic and lithofacies units, as well as physical and chemical parameters, such as hydraulic conductivity and chloride content. The cell-based nature of the model allows for modeling of the internal heterogeneity of lithostratigraphic units in terms of lithofacies and other parameters.

Major Clients and the Need for Models

REGIS II is widely used by regional authorities (i.e., provinces and water management agencies) and water supply companies for groundwater modeling studies.

The lithologic detail that is characteristic for the GeoTOP models is used in several areas:

- exploration for aggregate resources (sand, clay, and shells);
- detailed groundwater and contamination studies;
- detailed studies of salt penetration from seawater;
- land subsidence studies; and
- planning of large-scale infrastructural works such as tunnels and railroads

Software

TNO uses a toolbox consisting of several components:

- The geostatistical software package Isatis by Geovariance is the main modeling platform by which statistical data analysis is performed, semi-variograms are constructed, and interpolation procedures are conducted.

- ESRI's ArcGIS is used to create additional input data for the modeling, including fault patterns, maps showing the extent of lithostratigraphic units, and geological features such as channel belts.
- All surfaces that result from the 2-D interpolations in DGM, REGIS II, and GeoTOP are stored and presented in ESRI's raster format.
- Gocad is used for visualization of 3-D models and inspection of 2-D surfaces in 3-D displays.
- There is extensive use of the Python programming/scripting language to create specific programs that perform many tasks, for example: (a) converting data from one data format to another; (b) extracting borehole information from the DINO database and preparing it for input to Isatis; and (c) automating lithostratigraphic interpretation of boreholes.

Workflow for Digital Geological Modeling

Data Selection

The DGM is primarily based on lithologic descriptions of a selection of 16,500 boreholes. This selection aims at an even distribution of good-quality borehole data including key stratigraphic borehole data derived from the Quaternary and Upper Tertiary deposits.

Stratigraphic Interpretation

The selected boreholes are stratigraphically interpreted by assigning the revised lithostratigraphic classification (Weerts et al. 2000) to the individual sample intervals. The base of each of the lithostratigraphic units in the boreholes is subsequently used for interpolation and modeling. The basic strategy for lithostratigraphic interpretation is to work from nationwide cross sections to regional-scale cross sections that constitute the geological framework for the final interpretation of individual boreholes. For the interpolation, these individual interpreted boreholes are used.

Fault Mapping

A tectonic map showing all known major faults in the Tertiary and Quaternary deposits was constructed (Figure 12-2). The map is a thorough revision of fault patterns from earlier publications, including maps based on seismic data acquired for oil and gas exploration. Additional seismic data came from high-resolution surveys in the Roer Valley Graben, which is the most prominent tectonic feature in the Netherlands. For every lithostratigraphic unit, the faults that have influenced the base of the unit are selected and used as "barriers" in the interpolation process.

Interpolation

The depths of the base of each lithostratigraphic unit, as derived from the borehole data, are interpolated to raster surfaces using the "block-kriging" algorithm (Isaaks and Srivastava 1989, Goovaerts 1997). The top surface follows indirectly from the joined basal surfaces of overlying units when all units are stacked (see section on stacking the units). The base surface was chosen because this surface is formed by depositional processes that are linked to the unit itself, whereas the top surface is often the result of multiple geological processes (e.g., erosion and incision).

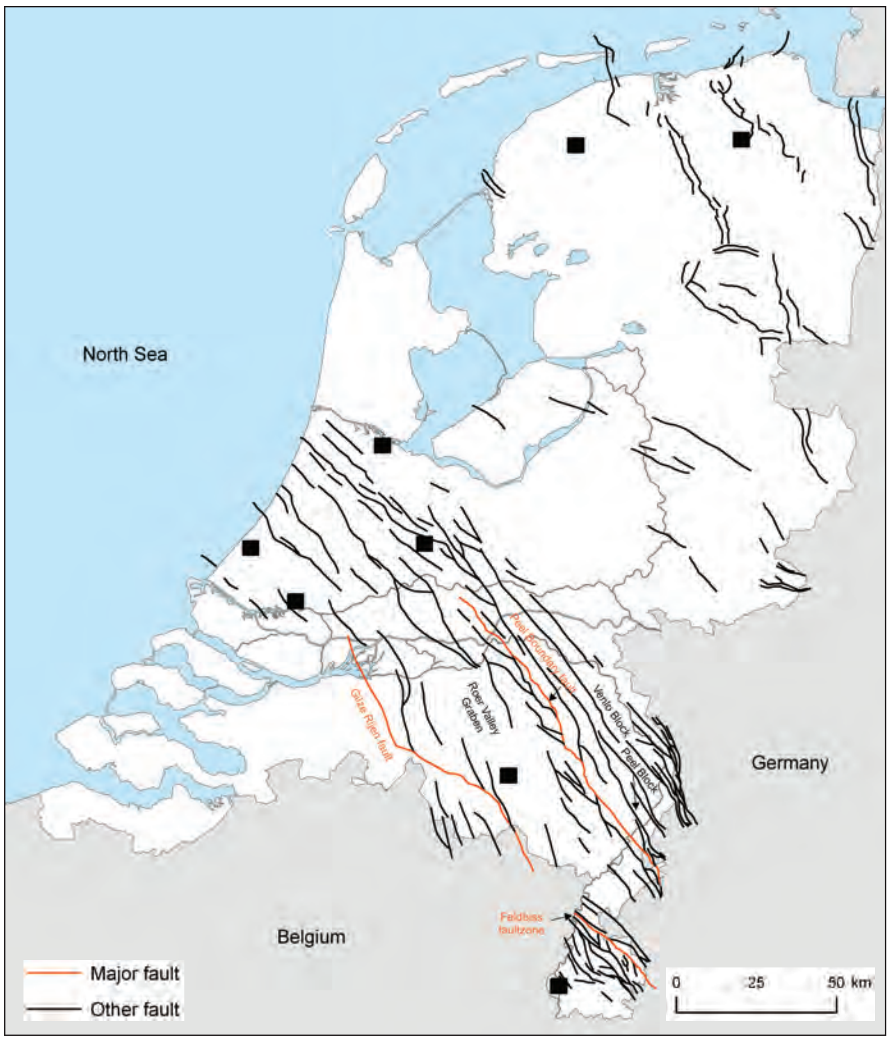

Figure 12-2 Fault data stored in GIS and extracted for modeling.

Block kriging alone often fails to produce a result that corresponds to the geological concept in mind. Therefore, additional information is taken into account, including maps with the maximum spatial extent of each lithostratigraphic unit; trend surfaces showing geological structures (basins) or trends (dip direction and dip angle); and guiding points ("synthetic boreholes") inserted at locations with specific geological features (e.g., units that pinch out or incised channels). Examples are shown in Figure 12-3.

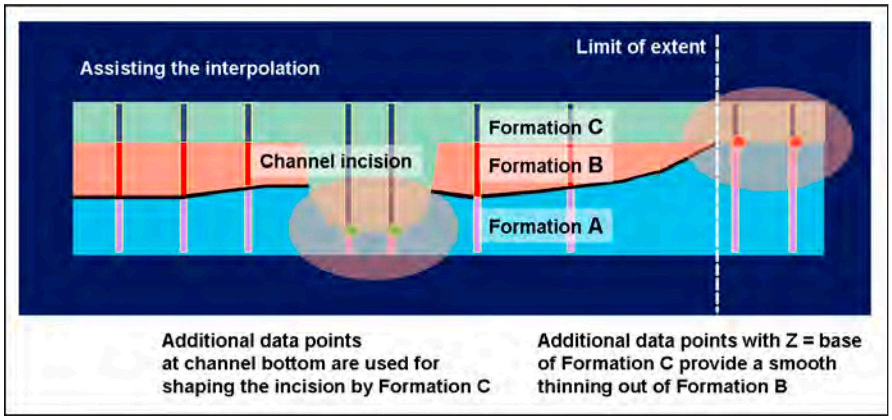

Figure 12-3 Schematic representation of two ways to assist interpolation: channel incision (left) and thinning out near the limit of extent (right).

Stacking the Units

In the final step, the basal surfaces of each unit are stacked in a stratigraphically consistent way. In the stacking process, the basal surfaces may intersect. In general, types of intersections are possible:

- The upper unit has eroded the lower units; in this case, the lower units are clipped by the upper unit.
- The upper unit has been deposited against the relief of the lower unit; in this case, the upper unit is clipped by the lower unit.
- The intersection is an artifact of the interpolation process occurring between two conformable units; in this case, the basal surfaces of the two units are adjusted to remove the intersection.

The preferred choice of the type of intersection to apply depends on the geological concept that must be appropriately represented. The stacking process is performed within Isatis, using grid-to-grid operations that are also available in standard GIS software.

An impression of the resulting DGM is shown in Figure 12-4.

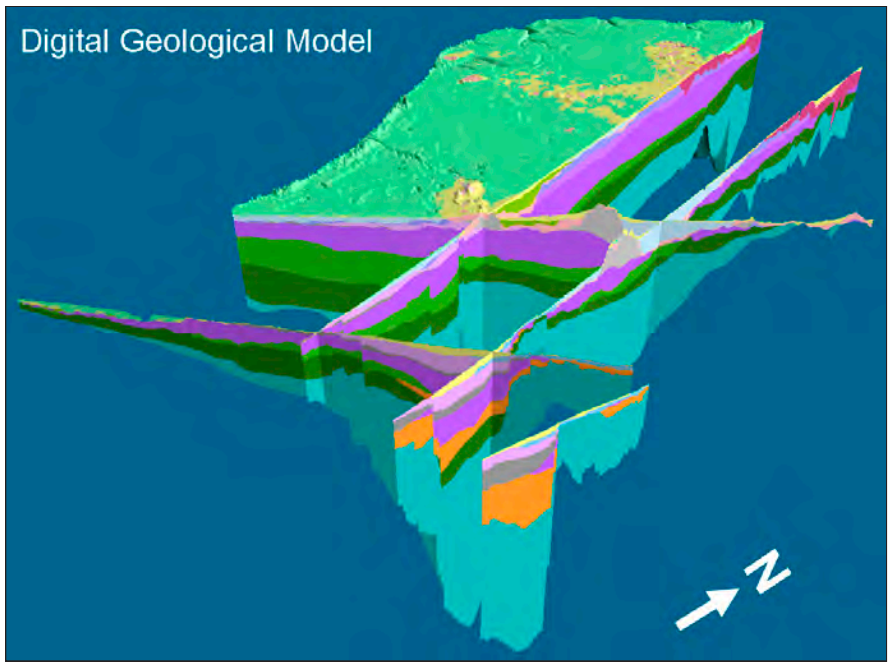

Figure 12-4 Cross sections through the nationwide digital geological model.

Workflow for GeoTOP

GeoTOP modeling is conducted by provinces using the boreholes in DINO and various geological maps created during the last few decades. Following the completion of a model of the Province of Zeeland (70 km × 75 km), modeling focused on the Province of Zuid-Holland (65 km × 65 km) where major cities like Rotterdam and The Hague are situated and the Rhine and Meuse Rivers enter the North Sea. A model of the Province of Noord-Holland, including Amsterdam and the Schiphol Airport, is currently under construction.

Boreholes

The starting point for the GeoTOP models are the borehole descriptions stored in the DINO database. This database provides about 23,000 borehole descriptions for the Province of Zeeland and more than 50,000 borehole descriptions for Zuid-Holland. Cone penetration tests will be incorporated in the near future, resulting in an even more extensive data set.

Stratigraphic Interpolation

It is virtually impossible to interpret 400,000 boreholes stratigraphically using the manual cross section technique used in DGM. Therefore, Python scripts were developed that use lithologic borehole descriptions within a context of digitized geological maps to assign lithostratigraphic labels to the borehole intervals.

2-D Interpolation of Stratigraphic Units

During the second modeling step, 2-D bounding surfaces are constructed. These surfaces represent the top and base of the lithostratigraphic units and are used to place each 3-D grid cell in the model within the correct lithostratigraphic unit. The procedure used to construct 2-D bounding surfaces is basically the same as the one used in DGM. However, in contrast to DGM, a stochastic interpolation technique is used (sequential Gaussian simulation; Goovaerts 1997), which allows for uncertainty to be estimated.

3-D Interpolation of Lithology Classes

The lithologic units in the boreholes are used to perform a final 3-D stochastic interpolation of lithology (e.g., clay, sand, peat) and, if applicable, sand-grain size class data within each lithostratigraphic unit. After this step, a cell-based (100 × 100 × 0.5 m) 3-D geological model is obtained. The 3-D interpolation is conducted for each lithostratigraphic unit separately using a stochastic interpolation technique called sequential indicator simulation (Goovaerts 1997). An example of a 3-D model is shown as Figure 12-5.

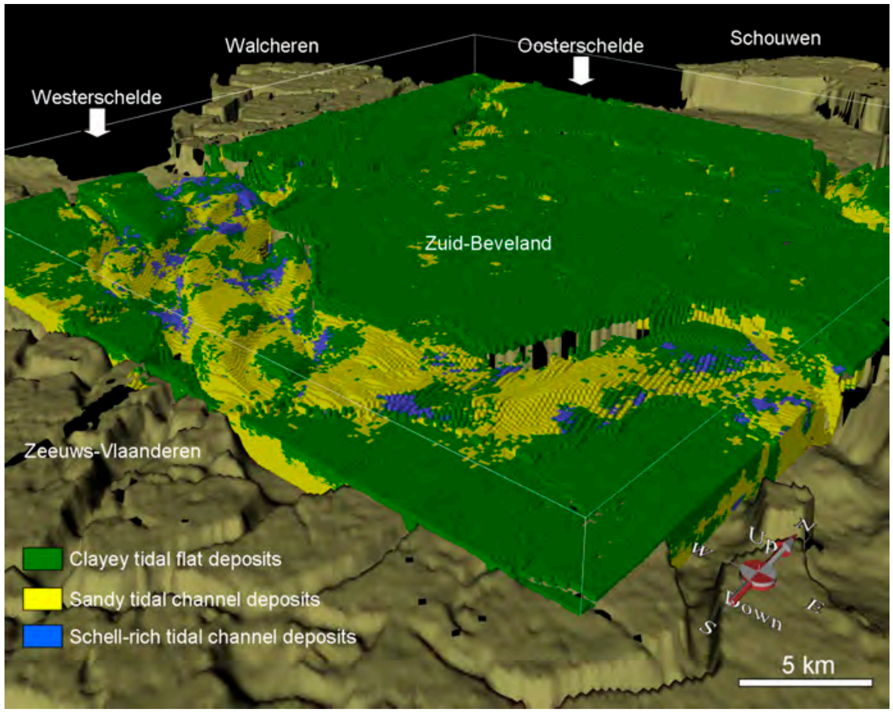

Figure 12-5 Part of the 3-D model of the central part of Zeeland, southwestern Netherlands.

Physical and Chemical Parameters

In addition to the modeling just described, physical and chemical parameters are collected and measured. The sampling strategy is such that measured values can be assigned to lithostratigraphic and lithofacies 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 (1) horizontal and vertical hydraulic conductivity, which is crucial in groundwater models, and (2) the reactivity of sediments, which is used in the modeling of contaminant plumes. The choice of parameters to include in the models is based on the needs of researchers at Deltares, TNO, and other organizations.

Chapter 13: U.S. Geological Survey: A Synopsis of Three-dimensional Modeling

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Mission and Organizational Needs

The U.S. Geological Survey (USGS) is a multidisciplinary agency that provides assessments of natural resources (geological, hydrological, biological), the disturbances that affect those resources, and the disturbances that affect the built environment, natural landscapes, and human society. Until now, USGS map products have been generated and distributed primarily as 2-D maps, occasionally providing cross sections or overlays, but rarely allowing the ability to characterize and understand 3-D systems, how they change over time (4-D), and how they interact. And yet, technological advances in monitoring natural resources and the environment, the ever-increasing diversity of information needed for holistic assessments, and the intrinsic 3-D/4-D nature of the information obtained increases our need to generate, verify, analyze, interpret, confirm, store, and distribute its scientific information and products using 3-D/4-D visualization, analysis, modeling tools, and information frameworks.

Today, USGS scientists use 3-D/4-D tools to (1) visualize and interpret geological information, (2) verify the data, and (3) verify their interpretations and models. 3-D/4-D visualization can be a powerful quality control tool in the analysis of large, multidimensional data sets. USGS scientists use 3-D/4-D technology for 3-D surface (i.e., 2.5-D) visualization as well as for 3-D volumetric analyses. Examples of geological mapping in 3-D include characterization of the subsurface for resource assessments, such as aquifer characterization in the central United States, and for input into process models, such as seismic hazards in the western United States.

The USGS seeks to expand its 3-D/4-D capabilities in monitoring, interpreting, and distributing natural resource information, both by adopting and/or developing new 3-D/4-D tools and frameworks and by promoting and enabling greater use of available technology.

Everything that shapes the Earth or affects its functions does so in 3-D space: water flowing over rocks, through aquifers, or as ice in glaciers; plants growing up into the atmosphere and down into the soil; the movement of animal life and pathogens within ecosystems; the movement of tectonic plates driven by deep convection beneath the crust; volcanic eruptions, floods, debris flows, and fires; the extraction, sequestration or migration of carbon, nutrients, contaminants, biota, minerals, energy, and other resources. Until recently, the computational and visualization power necessary to understand these complex systems was limited to a handful of supercomputing centers or industrious scientists. This situation has now changed: personal computers equipped with fast video cards and vast storage allow wide access to 3-D/4-D tools and visualization.

Business Model

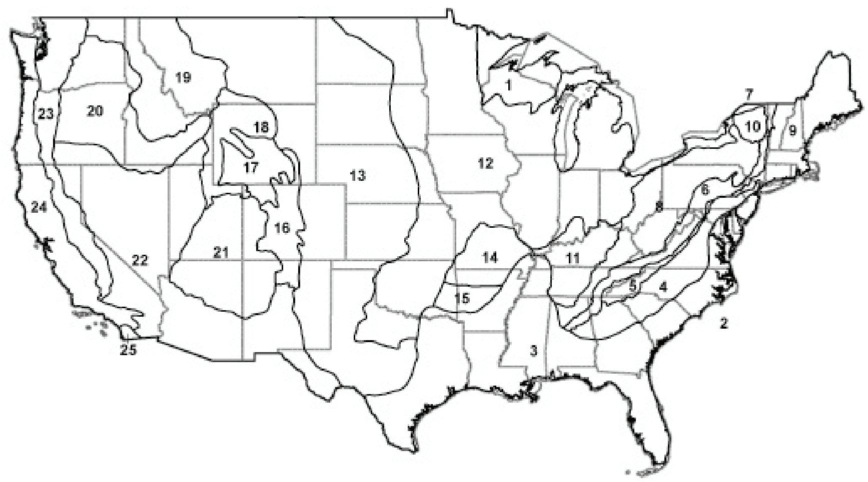
The annual USGS budget is approximately US$1 billion from federal appropriations. The bureau also receives about US$500 million from outside entities such as other federal agencies, foreign governments, international agencies, U.S. states, and local government sources. More than half of the outside funding supports collaborative work in water resources across the country, and the balance of the funding supports work in the geological, biological, and geographic sciences and information delivery.

The USGS has a workforce of approximately 9,000 distributed in three large centers (Reston, Virginia; Denver, Colorado; Menlo Park, California) and in numerous smaller science centers across the 50 states. Scientific work is organized into "projects" run by principal investigators (PIs) who have significant latitude in planning and conducting research, including acquisition of the resources (e.g., equipment, computers, software) needed to carry out their studies. Due to the distributed nature of management and personnel and due to the independence of the PIs, finding common organizational solutions is often a challenge. For example, concerns regarding optimal use of 3-D/4-D technology within the USGS include these:

- Many tools and solutions are expensive.
- The user community is not well coordinated and sometimes does not buy or share software licenses as a group. Buying power is not currently maximized.
- Pockets of specialists are emerging, but there are few forums for sharing ideas and expertise.
- Staying abreast of rapidly evolving technologies is difficult.

Geological Setting

The United States has a large variety of geological terranes that record more than 2 billion years of geological history (Figure 13-1). The complexity of U.S. geology ranges from horizontal stacking of sediments in the Great Plains, Colorado Plateau, and Coastal Plain Physiographic Provinces to overprinting of compressional, extensional, and transform tectonics of the Pacific Border Province of the western United States (Figure 13-1). These varied geological terranes present a challenge to



1. Superior Upland
2. Continental Shelf
3. Coastal Plain
4. Piedmont
5. Blue Ridge
6. Valley and Ridge
7. St. Lawrence Valley
8. Appalachian Plateau
9. New England
10. Adirondack
11. Interior Low Plateaus
12. Central Lowland
13. Great Plains
14. Ozark Plateaus
15. Ouachita
16. Southern Rocky Mtns
17. Wyoming Basin
18. Middle Rocky Mtns
19. Northern Rocky Mtns
20. Columbia Plateau
21. Colorado Plateau
22. Basin And Range
23. Cascade – Sierra Mtns
24. Pacific Border
25. Lower California

Figure 13-1 Simplified version of the King and Beikman (1974) geologic map of the conterminous United States. Colors indicate age of rock formations. Detailed explanation and digital versions are available at http://tapestry.usgs.gov and http://mrdata.usgs.gov/geology/kb.html.

3-D modeling of divergent and convergent plate boundaries, strike-slip fault zones, and the stable craton. Also, surficial geological processes of the last several million years have left variable unconsolidated deposits, including the voluminous deposition of glacial materials in New England and the northern conterminous United States.

The oldest rocks of the United States are igneous and metamorphic rocks that occur in the Adirondacks of New York and the Superior Uplands of Minnesota. These rocks contain complex fracture systems that can be modeled for water and mineral resources, but also have metamorphic fabrics inherent from high heat and pressures that occurred over many millions of years.

The United States contains fold and thrust belts that record several continental plate collisions. Examples of these are the Valley and Ridge, Blue Ridge, and Piedmont Provinces in the eastern United States where rocks were folded and faulted during four plate collision events between 1 billion years ago and 300 million years ago. The Rocky Mountains Province in the western United States records a collision event from about 40 million years ago. Along with overprinting of several tectonic events, these terranes include complex fold relationships and zones of intense faulting that must be taken into account in models. Linear trends of folds and faults are characteristics of these provinces.

Strike-slip fault systems, such as the San Andreas fault system of the Pacific Border Province in California, are regions of particularly complicated geology. As continental plates or structural blocks move past one another in a horizontal direction, complex compression and extensional structures occur. In this setting, rocks are translated great distances horizontally. These offsets are superimposed on a Mesozoic to Paleogene history of subduction, accretion, batholith formation, and extensive extensional attenuation. Understanding structural control and associated seismic hazards along strike-slip fault zones such as the San Andreas fault system requires the fusion of traditional geological mapping, geophysical measurements, seismology, structural geology, and state-of-the-art visualization and modeling techniques to produce detailed 3-D and 4-D geologic maps.

Extensional tectonic events are recorded in Triassic and Jurassic basin sediments within the Piedmont Province of the eastern United States and the Basin and Range Province of the western United States. In both regions, compressional tectonics resulted in folded and faulted rocks that were later torn apart and that developed basins that were filled with sediments shed off highlands. In the Piedmont of the eastern United States, this extension was associated with the opening of the Atlantic Ocean. For the Basin and Range Province, extension is related to back-arc spreading behind the Coast Range and Cascades Provinces.

Volcanic terranes occur in the western U.S. Cascades and Sierra Nevada Provinces. Large masses of intrusive igneous rock represent the deeply eroded roots of a Mesozoic volcanic arc and its Mesozoic and Paleozoic country rock in the Sierra Nevada and an active volcanic arc in the Cascades where the Juan de Fuca plate in the Pacific Ocean is being subducted beneath North America.

The sedimentary rocks of the Interior Plains and Atlantic and Gulf Coastal Plains reflect numerous periods of transgressing and regressing seas. These provinces are generally flat lying to gently dipping marine sediments that show complex facies changes over time. The Atlantic and Gulf Coastal Plain contains marine and terrestrial sediments that span more than 100 million years. In some areas, terrestrial river systems have also deposited sediments within these provinces, such as the Mississippi River in the Gulf Coastal Plain.

Several major glacial advances covered New England and the northern United States from 2.6 million years ago to about 11,000 years ago. The deposits that the melting glaciers left behind are quite variable and include silt, clay, sand, and till. These sediments have complex intertonguing relations that make 3-D modeling a challenge.

Major Clients and the Need for Models

Based on the needs of its clients and of the U.S. public, the USGS has identified seven major science strategy directions: ecosystems, wildlife and human health, climate change, energy and minerals, natural hazards, water availability, and data integration (U.S. Geological Survey 2007). Major users of USGS data and information include federal and state agencies, foreign governments, multinational agencies (e.g., International Atomic Energy Agency, World Meteorological Organization, Food and Agriculture Organization), and national and international nongovernmental organizations.

Because of its long-term monitoring data and resource assessments and the national and international scope of its science, resource and land management agencies use USGS science in developing policies that help them meet their stewardship responsibilities. For example, agencies in the U.S. Department of the Interior and the U.S. Department of Agriculture rely on USGS science to manage federal lands and resources. Other agencies, such as the U.S. Environmental Protection Agency, rely on USGS assessments of anthropogenic contaminants across the landscape to develop and enforce regulations. The USGS provides information that helps other agencies develop policy and provide warnings or mitigation strategies relating to hazards such as volcanoes, fire, floods, and earthquakes. The USGS is developing an ecosystem and global change (climate variability and land-use change) framework that will provide a context for its science and for its clients, such as regulatory and resource management agencies and public safety agencies.

Within the USGS, the greatest needs and applications of 3-D modeling and visualization have been emerging in geological, hydrogeologic, and biologic modeling and visualization. Specific needs include

- displaying, checking raw scientific data collected in multi-dimensional frameworks, and performing mathematical and statistical operation on the data, often all in real time;
- displaying temporal changes in primary scientific information in an "animated" 4-D framework (e.g., energy or material fluxes, disruptions in 3-D structures or boundaries, or changes in the intensities of given distributed characteristic properties);
- integrating diverse types (e.g., point, line, areal, volumetric) of primary spatial-temporal information for any given property (e.g., porosity, permeability, or any physiochemical property) in a 3-D/4-D visual environment that can display not only the information but also the associated uncertainties;
- inverse, statistical, geostatistical, stochastic, or other types of modeling to create 3-D/4-D realizations of natural phenomena;
- interpolating and extrapolating spatial and temporal values from data using a variety of methods and using interpreted and modeled information to build 3-D/4-D information frameworks, such as geological mapping frameworks, that maximize the use of the knowledge available for a given issue or given spatial system;
- maximizing our ability to use the information for given interpretive or predictive studies, simulations, and assessments; and
- using animations, fly-throughs, and data-discovery tools that help researchers individually or collaboratively conduct science and communicate results and their implications to each other, decision makers, and the public.
- providing example models.

Currently, the USGS employs a myriad of 3-D modeling and visualization programs (Table 13-1).

3-D/4-D Visualization for Geological Assessments

The USGS 3-D geological mapping efforts occur on a project-by-project basis. In addition to geological knowledge, at least one member of the staff has expertise in GIS and 3-D software. Others may have expertise in software specific to their discipline. The primary software packages used for, or in support of, 3-D geological mapping in the USGS are EarthVision, 3-D GeoModeller, Move, RockWorks, ArcMap, Oasis montaj, SGeMS, Encom PA, and in-house software for geophysical modeling. Recently published 3-D geologic maps (Faith et al. 2010, Pantea et al. 2008, Phelps et al. 2008) at the USGS incorporate new methods and proper-

Table 13-1 The 3-D modeling and visualization software programs used by the USGS.[1]

Software	Developer	URL
3D GeoModeller	Intrepid-BRGM	http://www.geomodeller.com/geo/index.php
3DMove ™	Midland Valley	http://www.mve.com/Move/advanced-structural-modelling-software-move.html
ArcGIS©	ESRI	http://www.esri.com/software/arcgis/index.html
ArcHydro©	AquaVeo TM	http://www.aquaveo.com/archydro-groundwater
ArcView, ArcMap	Rockware	http://www.rockware.com/product/overviewSection.php?id=189&section=54
Argus ONE	Argus Holdings, Ltd.	http://www.argusint.com/
COMSOL ™	COMSOL	http://www.comsol.com/
EarthVision®	Dynamic Graphics, Inc.	http://www.dgi.com/earthvision/evmain.html
Encom PA	Encom	http://www.encom.com.au/template2.asp?pageid=16
Erdas Imagine	Erdas	http://www.erdas.com/
Fledermaus	IVS 3D	http://www.ivs3d.com/products/fledermaus/
IDL/ENVI	ITT Visual Information Solutions	http://www.ittvis.com/
LiDAR Viewer	University of California Davis	http://www.keckcaves.org/software/lidar/index.html
Model Viewer	USGS	http://water.usgs.gov/nrp/gwsoftware/modelviewer/ModelViewer.html
MODFLOW, GWT, SUTRA, PHAST, MODELMUSE,USGS groundwater codes and visual interfaces	USGS	http://water.usgs.gov/software/lists/groundwater/ http://en.wikipedia.org/wiki/MODFLOW
Oasis montaj	GeoSoft	http://www.geosoft.com/pinfo/oasismontaj/keyfeatures.asp
PolyWorks®	InnovMetric Software, Inc	http://www.innovmetric.com/
Quick Terrain Modeler	Applied Imagery	http://www.appliedimagery.com/
Rockworks ™	RockWare	http://www.rockware.com/product/overview.php?id=165
SGeMS	Stanford University	http://sgems.sourceforge.net/?q=node/20
Voxler®, Surfer®	Golden Software	http://www.goldensoftware.com/products/products.shtml

[1]Use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

ties that go beyond the traditional 2-D geologic map:

- completing descriptions of characteristics of all significant geological features in a map (e.g., units, faults unconformities, structures, physical, and chemical properties), and the methods and techniques used to map them (Descriptions are necessary because 3-D geological mapping relies on a variety of unique mapping methods, whereas 2-D geological mapping uses a standard set of mapping techniques defined from more than a century of prior work.);
- defining some map features solely on the basis of geophysical expression;
- including a discussion of the data model used to construct the map;
- publishing the 3-D map in an open source format in addition to an encrypted proprietary format; and
- publishing geological features such that they can be individually extracted from the map for general use as stand-alone features.

3-D geological framework applications in the USGS include these examples:

- geological models for earthquake assessments and assessments of past tectonic displacements and predictive modeling of the potential impacts of given fault-slip scenarios;

- geological modeling for resource assessments (oil and gas, minerals, geological sequestration of carbon);
- inverse modeling of anomalous geophysical properties;
- visualization of magmatically driven bulging in volcanic areas and predictive modeling of eruption types and timing; and
- visualization and detection of surface structures and landscape changes, such as faults, landslides and debris flows, paleofloods, glaciers, and impact craters.

3-D/4-D Analyses and Use of LiDAR Imagery in Geological Modeling

Geomorphic and surface structure analyses are commonly conducted during mapping and modeling exercises. Indeed, 3-D/4-D analyses of earthquakes can provide valuable insights into the types of events that occurred, their impacts in modifying the land surface, and the likely stability or potential for post-event slip in the near future. For example, 3-D/4-D imagery analysis of precisely relocated earthquakes following the San Simeon earthquake in central California helped characterize the post-seismic slip and fault kinematics of the complex double blind thrust fault system (McLaren et al. 2008). Through 3-D surface contouring of time-varied earthquakes, common earthquake features were identified, mapped, and visualized, revealing the migration and rotation of the transient post-seismic strain migration as a function of time and depth. In another example, repeat ultra-high resolution (sub-centimeter) 3-D ground-based LiDAR imagery was collected in the days and months following the magnitude 6.0 Parkfield earthquake in central California. Immersive virtual reality 4-D analysis (Kreylos et al. 2006, Kellogg et al. 2008) of the land surface and engineered structural features illuminated small active tectonic geomorphic features that would have been overlooked in 2-D analysis. Furthermore, mathematical surface models of a bridge crossing the San Andreas fault near the epicenter showed over 7 cm of post-seismic slip in the 10 weeks after the main shock and bending of the steel support beams holding up the deck of the bridge.

Airborne and ground-based LiDAR have also contributed significantly to 3-D (and sometimes 4-D) geological mapping, particularly of potentially hazardous faults. Airborne LiDAR bare-earth models are especially helpful in heavily vegetated areas with little bedrock exposure. For example, large-scale LiDAR imaging and vegetation removal in the Puget Sound region of Washington state illuminated previously hidden faults and geomorphic expressions of past glacial epochs (Haugerud et al. 2003, Haugerud 2008). Similarly, a 37-km-long active fault was identified north of Lake Tahoe (California) within 500 m of a reservoir dam. The 4-D analysis of high-resolution T-LiDAR imagery determined that the fault was active and slipping at a rate of 0.5 mm/yr, which necessitated a reevaluation and reengineering of the reservoir construction (Hunter et al. 2010, Howle et al. 2009). Similarly, the 3-D/4-D fusion of ground-based and airborne LiDAR was used to measure offset in faulted glacier moraines in the eastern Sierra Nevada. Immersive virtual reality tools were then used to assess the quality of the merged products of the two different data types, allowing for detailed analysis and understanding of the seismic hazards of the newly identified fault system. 3-D/4-D hazard response analysis has also been used to assess structure and surface stability after landslides (e.g., the 2005 Laguna Beach landslide in southern California), rock slides, and debris flows (e.g., following major fires in steep terrain). Detailed 3-D/4-D analyses are used to characterize these events, understand their driving mechanisms, and provide rapid situation awareness to local authorities regarding the post-event stability of the land surface. Immersive 3-D/4-D virtual reality analyses often allow scientists to evaluate hazards in areas that are inaccessible because of ongoing safety concerns.

Case Study: The Hayward Fault—An Example of a 3-D Geological Information Framework

The 3-D geologic map of the Hayward fault in California was constructed to support modeling of earthquake hazards. Models that attempted to predict potential damage from various earthquake scenarios have until recently treated faults as vertical planes in semi-infinite half-spaces, primarily because of technological limitations. The 3-D geologic map of the Hayward fault was one of the first attempts to move away from simplified models and toward incorporating geology into the hazard scenarios. This change allows researchers to study the effect of fault curvature and rheology on fault movement and the resulting energy waves that travel across the landscape. Current research, based on this mapping effort, indicates that both fault curvature and changes in rheology across the fault can significantly affect its behavior (Barall et al. 2008).

The Hayward fault is considered to be the most dangerous fault in the San Francisco Bay region, located in central California (Figure 13-2). There is a 27% chance of a magnitude 6.7 or greater earthquake on this fault over the next 30 years (Working Group on California Earthquake Probabilities 2003). The Hayward fault cuts through several cities that form a densely populated urban area, making it even more dangerous than the nearby, better known San Andreas fault. Earthquakes generated along the fault threaten structures and critical lifelines that include conduits for transportation, power, and water.

A team of geologists and geophysicists explored various approaches of combining geologic map data with subsurface data to develop a 3-D earthquake hazard model of the Hayward fault. The team addressed geological questions regarding tectonics, structure, stratigraphy, and history of the region. The team also addressed broader issues related to mapping in 3-D in general,

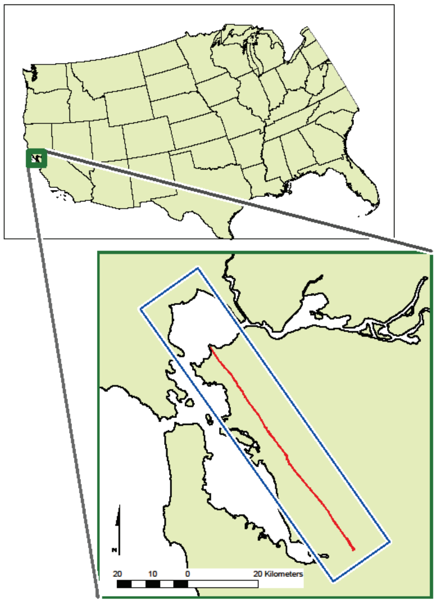


Figure 13-2 Map showing the location of the San Francisco Bay region (inset). The red line demarcates the surface trace of the Hayward fault, and the blue rectangle shows the planimetric boundary of the 3-D map of the Hayward fault zone.

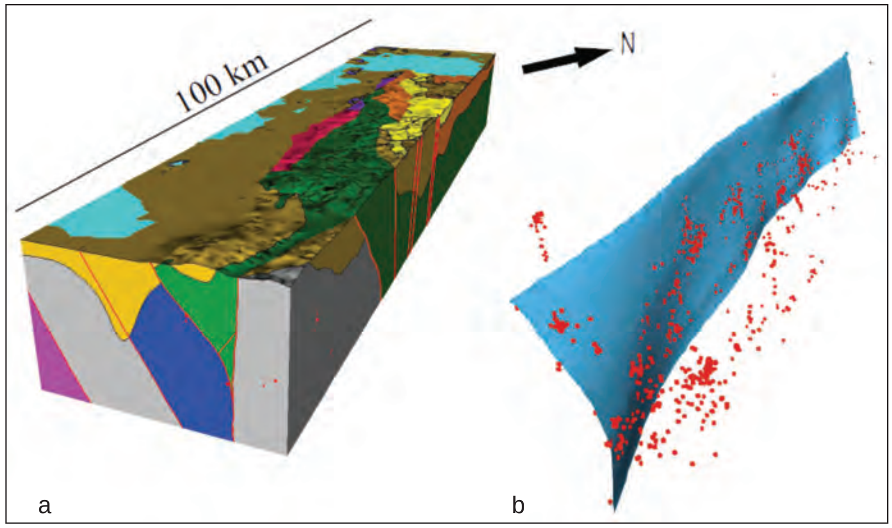


Figure 13-3 (a) Three-dimensional geologic map of the Hayward fault zone and (b) the Hayward fault surface extracted from the map, shown with accompanying earthquake hypocenters.

such as new mapping methods, resolution, uncertainty, database design, and publication options. The resulting 3-D map can be downloaded at http://pubs.usgs.gov/sim/3045. Correlations with fault behavior are discussed by Graymer et al. (2005).

The 3-D geologic map of the Hayward fault includes a volume of 100 × 20 × 14 km^3, with the fault approximately bisecting the long dimension (Figure 13-3). The Hayward fault is an oblique right-lateral strike-slip fault with a compressive component of about 10%. The mapped volume is geologically complex, formed of two contrasting amalgamated suites of Mesozoic terranes and overlying Cenozoic strata that have been juxtaposed by late Miocene and younger right-lateral offset of as much as 175 km. Consistent stratigraphy can usually be determined within the fault-bounded blocks but cannot be traced between them. The terranes themselves are fault-bounded packages of rocks emplaced, folded, faulted, and partially exhumed during subduction and subsequent extensional unroofing and faulted and translated during strike-slip faulting.

The structural style imposed by the complex tectonics of the San Francisco Bay region disallows the regular use of standard geological mapping tools, such as stratigraphic position and down-dip projection. In order to map geological units in 3-D, researchers had to define simplified mappable units, for the most part corresponding to entire terranes. The region lacked relevant well data, so ample use was made of geophysical data to define the subsurface shape of the critical geological features.

Model Construction Methodology

Several somewhat independent modeling efforts mapped individual geological features. The Hayward fault itself was mapped as a single surface using a combination of seismic data and cross sections. Several of the other faults in the model were mapped at the surface and projected downward based on the grain of local and regional geology. Two basins within the model were defined on the basis of their gravitational signature. A subsurface unit, thought to be volcanic, was defined on the basis of its magnetic signature. Geological terranes were mapped at the surface and constrained at depth by faults, their magnetic signature, and other modeled geological features.

These individually modeled features were combined into a unified 3-D geologic map in the proprietary software EarthVision. In the EarthVision data model, faults are surfaces that have precedence over (truncate) all other surfaces. Faults are specified in a hierarchy to determine which faults cut which other surfaces. Unconformities are surfaces that truncate other nonfault surfaces, and depositional surfaces onlap onto other surfaces. Modeled geological features were defined in EarthVision by their bounding surfaces according to the data model. Property information for geological unit volumes, such as formation name, are stored internally but can be queried interactively by modifying the unit volume color based on a property or by interactively clicking on a volume to retrieve the properties.

Once the model was constructed, it was evaluated by project members and received two scientific reviews external to the project. The reviewers interactively explored the map itself and examined the accompanying map pamphlet to look for geological inconsistencies in a manner similar to the review process for printed USGS geologic maps. Review comments were resolved through further collaborative modeling and mapping.

Output

The final publication contains a digital 3-D geologic map, an accompanying informational pamphlet, and a map plate that displays various views of the 3-D map. The map is published in two formats. The first is available in a free version of the 3-D viewer from the proprietary software EarthVision. The map can be viewed in a variety of ways but cannot be modified. The second format makes the fault surfaces and boundaries of the geological units available as a series of files stored in the open-source t-surf format. A user can reconstruct part or all of the features in the Hayward map from the surfaces, and this format has a lifespan longer than the free 3-D EarthVision viewer, which will become increasingly out of sync with newer operating systems. It is also expected that these geological features will be integrated with other data sets including lifeline and infrastructure data.

The pamphlet includes a discussion of the geological setting and history, a description of map features, including map units, map structures, and the data and modeling methods used to generate each feature in the model (feature-level metadata).

Observations, Suggestions, and Best Practices

The diminishing amount of data with depth has several implications:

- Resolution decreases dramatically with depth, geological units in 3-D may be simplified compared with units mapped at the Earth's surface, geophysics is important for modeling and constraining geology at depth, and a range of expertise is needed to process and model various data types.
- Geological mapping can be expanded to include mapping based on geophysical models of geological features in the subsurface. Rather than a description of the rock's appearance in outcrop, a description of the geophysical characteristics and geological and geophysical context is provided.
- Features in the geological map are often themselves the result of an individual modeling effort; the 3-D geological map is an amalgamation of models brought together to form a coherent geological map.
- When constructing the map, critical features (faults and unconformities) that will form the framework of the map need to be identified and built in first to allow the structural and topological relationships to be more easily seen, corrected, and verified early in the mapping process.
- The map should maintain both geological and database integrity; that is, geological rules should not be violated, topological rules should not be violated, and any associated tables should maintain database integrity.
- Putting the "best available data" into a 3-D map is not always practical. Although in theory digital geologic maps can accommodate scales from the microscopic to continental, in practice current software limitations prevent a wide range of resolutions within a map. For example, LiDAR could not have been used as the model of the Earth's surface in the 3-D geologic map of the Hayward fault zone because the data volume could not be supported.
- The 3-D map can exist in its entirety only on a computer; as such, a 3-D viewing tool that can spin, slice, take apart, and query features in the map is a necessity.

Several steps can be taken to alleviate dependence on a particular software package:

- Describe the data model in the text.
- Publish an open-source version of the 3-D map.
- Ensure that eatures within the map can be extracted so that they can be studied independent of the map.
- Ensure that the software can accommodate complex structures that have multiple z-values, including oblique-slip faults, overturned folds, and diapirs.

Case Study: Santa Fe, New Mexico, 3-D Modeling as a Data Integrator

Many geological mapping projects at the USGS involve the development of regional geological frameworks to serve as the basis for understanding groundwater, geological hazards, and natural resources. Project goals focus on extrapolating geological mapping from the surface to depths greater than 1 km over large areas where little borehole information exists. To extrapolate below ground, we acquire airborne geophysics, fill in existing gravity coverage, and collect ground-based geophysics in critical areas. Each of these geophysical data sets provides information on diverse aspects of different physical properties of the Earth, which then must be interpreted in the context of the geology of the area.

In a study near Santa Fe, New Mexico, USA, Grauch et al. (2009) found that 3D GeoModeller was well suited to integrating such diverse types of input in a 3-D world (Figure 13-4). An important objective of the study was to model the position of the surface representing the bottom of the sedimentary section. This surface was needed to assess the aquifer and for groundwater modeling. Using a mixed data-driven and expert-controlled 3-D modeling approach, 3D GeoModeller allowed simultaneous data integration, synthesis, and geological interpretation of geophysical data in conjunction with 3-D geological mapping. Advantages to 3D GeoModeller are that it (1) directly incorporates geological field and borehole data, such as mapped contacts, borehole lithologic contacts, and strike and dip measurements, (2) ensures that the model follows known geological relationships in the area in 3-D, (3) allows indirect input of derivative geophysical products and geological concepts as guides to the geological modeling, (4) provides geophysical forward and inverse modeling to check for geophysical validity, and (5) allows an individual to work in either a 2-D (cross section) or 3-D (points-in-space) environment.

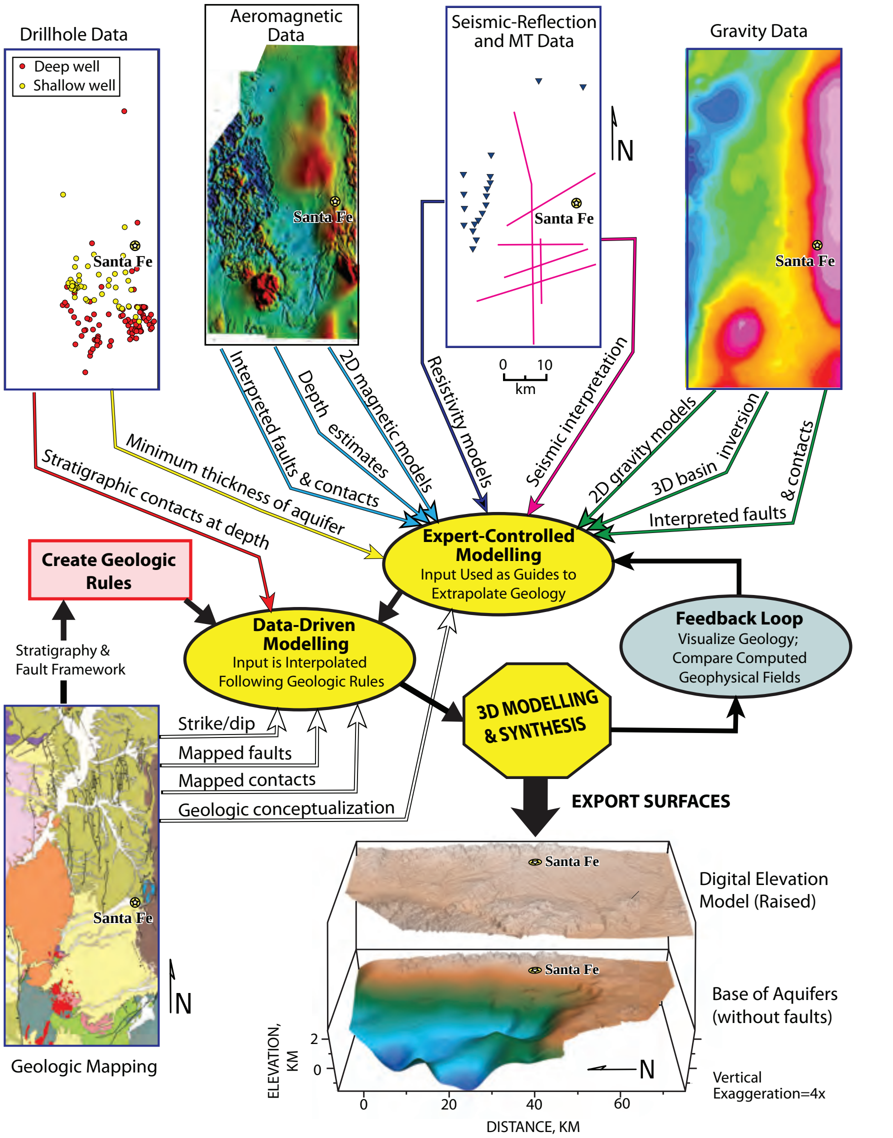


Figure 13-4 Work flow that uses 3-D modeling to integrate and synthesize diverse types of geological and geophysical information for a basin study near Santa Fe, New Mexico, USA (Grauch et al. 2009). Although 3D GeoModeller (BRGM-Intrepid Geophysics) was used for the synthesis (yellow workflow steps), a variety of other software packages were used to analyze geophysical data beforehand, including Oasis montaj and GM-SYS (Geosoft), Geotools MT (AOA Geophysics, Inc.), and methods and software developed by the USGS (Jachens and Moring 1990, Phillips 1997). 3-D visualization is from Oasis montaj.

3-D/4-D Visualization and Geological Modeling for Hydrologic and Biologic Assessments

The need to display and integrate increasingly large data sets and the need to analyze, often collaboratively, a wide variety of multidisciplinary information necessitates using the most advanced visualization tools available, such as 4-D immersive virtual reality systems. Traditional 2-D analyses and rudimentary 3-D analyses (e.g., stereoimages on ordinary 2-D computer screens) are inefficient and do not measure up to the complexity of the interdisciplinary analyses and interpretations that are required. Collaboration among scientists, who often do not have the same scientific disciplinary backgrounds and therefore lack a common scientific language, can be made significantly easier through the use of advanced 4-D immersive visualization systems. These systems utilize the spatial-temporal skills innately developed in people as they interact with their environment and help scientists communicate with each other. This section provides a “walkthrough” of example applications of 3-D/4-D technology in the hydrologic and biologic sciences, from the atmosphere to the subsurface.

Visualizing and representing atmospheric hydrologic processes are essential to the USGS mission. The USGS must be able to understand how orographic processes can affect precipitation, specifically types of precipitation (rain, hail, snow) as well as duration and intensity, over a spectrum of spatial and temporal scales. Visualizing, understanding, and predicting the focusing of precipitation and consequent impacts can help mitigate the damages caused by flooding, landslides, or debris flows. Visualization tools, coupled with “before and after” landscape surveys (e.g., through remote sensing or LiDAR), are being used to benchmark current landscape conditions and to help characterize and model the magnitude and extent of atmospheric events in terms of natural hazards, water availability, ecosystem response, and long-term climatic variability.

The interrelationship of temperature and topography affects our landscapes, their associated ecosystems, and their evolution in time. For example, visualizing and predicting temperature distributions across a mountainous landscape or watershed helps understanding of biologic habitats and how they may change. Understanding and visualizing topographic and climatic drivers can help predict the movement and intensity of fires, the spread of pests or invasive species, and/or the migration or extinction of species. USGS scientists also routinely collect high-resolution 4-D snow depth change data and combine the data with climate models to estimate daily snow melt runoff as a function of solar radiation and incident angle at various elevations. Climate forecast models using 4-D climate data and different global warming scenarios help us understand how ecosystems and water availability might change in the future.

Visualization in 4-D is needed to plan and manage water resources, their availability, and their quality and to plan the investments needed for their sustainable and balanced use and protection. Visualization is needed to understand the effects of (1) climate change on the storage and release of water at higher elevations, (2) land-use change on groundwater recharge, particularly at lower elevations, and (3) climate, land-use, and anthropogenic changes and natural system dynamics on the timing and intensity of the water cycle and its spatial distribution. Groundwater withdrawals not only impact water sustainability in arid or semi-arid environments but can also produce substantial land subsidence, damage infrastructure, and irreversibly decrease an aquifer's ability to store water (Figure 13-5). Repeat satellite InSAR (Synthetic Aperture Radar Interferometery) imagery of active hydrocarbon fields can show how the land surface responds over time to hydrocarbon pumping and CO_2 and water injection. The 3-D/4-D visualization can help show what areas are at the greatest risk and can be used in optimization modeling to more efficiently manage and distribute pumping and recharge in a given area.

The USGS also conducts work visualizing and predicting the impacts of sea level rise and salinity intrusion on coastal habitats (human and natural). Although fixed-level 3-D flooding maps are useful as a first cut interpretation of the consequences of floods or sea level rise, the USGS also uses 4-D dynamic visualization of flood waves, storm surges, tsunamis, tidal surges, and outflows. Deterministic, predictive models, based on mathematical descriptions of both the operative physical processes and mass and energy conservation relations, are often displayed using advanced visualization systems to enhance dynamic patterns that would not otherwise be apparent.

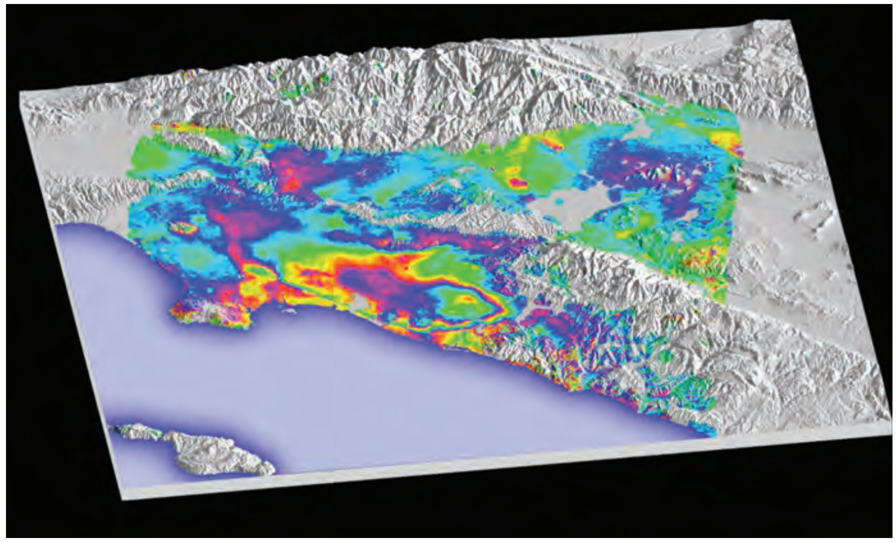


Figure 13-5 Perspective view of the greater Los Angeles region with InSAR imagery showing greater than 6 cm of groundwater pumping-induced subsidence over a region 40 km x 20 km in extent (Bawden et al. 2001).

The USGS extensively uses 3-D/4-D visualization tools (non-stereo) in the representation and modeling of subsurface flow and contaminant transport. In these studies, 3-D/4-D visualization is essential in

- representing and checking the available data and information in a geological context;
- assessing relevant geological structures, as well as the spatial distribution and temporal evolution of the hydrogeological (Figure 13-6) and chemical properties of those structures, i.e., the porosity, permeability, mineralogy, and chemistry associated with various geological units, their matrix, and structural features (open, closed, or partially filled), such as active faults, fractures, joints, channels, and macropores;
- using integrative hydrologic, chemical, or geophysical response information to help determine, through "inverse modeling" numerical simulations, the spatial distribution of hydrogeological or geological properties in various subsurface zones; and
- using predictive or "forward" modeling to numerically simulate the potential movement of water, solutes, contaminants, colloids, viruses, or bacteria in the subsurface and the coupled evolution of the hydrogeological environment.

Hydrogeological studies have focused primarily on the shallow subsurface, which is usually the primary provider of groundwater resources for irrigation or drinking water. Most groundwater contamination studies have also focused on the shallow subsurface because of the importance of its human use and because of its high vulnerability to contamination. Hydrogeological studies and visualization of deeper environments have until recently been mainly confined to studies of sites that might be suitable for the disposal of nuclear wastes (Figure 13-7) or the injection of other industrial wastes. The potential for using geological formations, specifically former oil and gas reservoirs, coal seams, and saline aquifers for the geological sequestration of supercritical CO_2, will likely result in a much greater number of hydrogeological studies investigating the deeper regions of the subsurface. If geological sequestration of CO_2 becomes widely implemented, we expect an exponential increase in

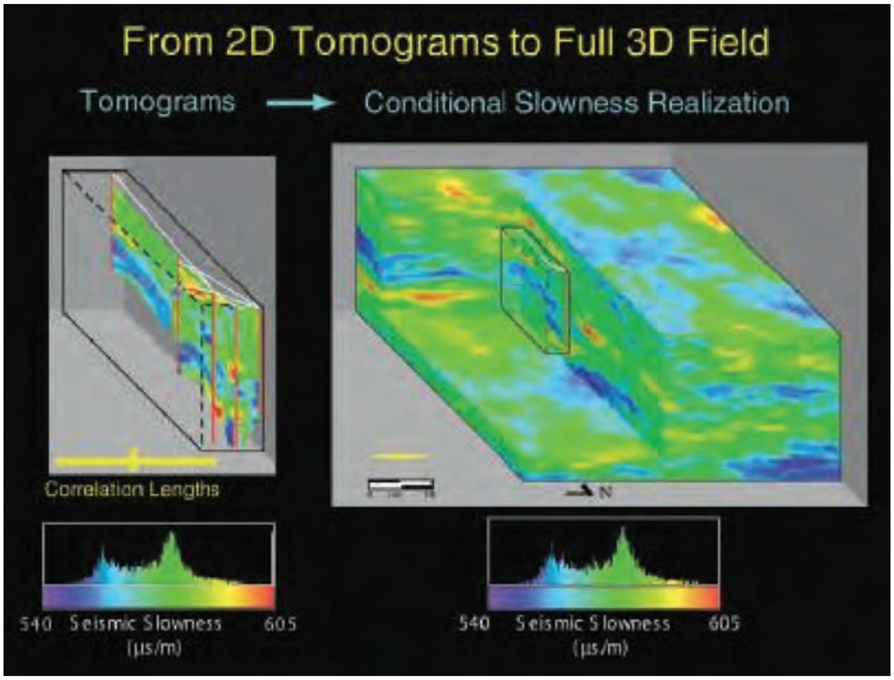


Figure 13-6 Three-dimensional images from seismic surveys of the speed of shock waves through sediment (Hyndman et al. 2000). The speed of waves is controlled partly by the compressibility of the sediment, which is related to the hydraulic conductivity. Therefore, it may be possible to use seismic images to better map heterogeneity in unconsolidated aquifers (from Sanford et al. 2006).

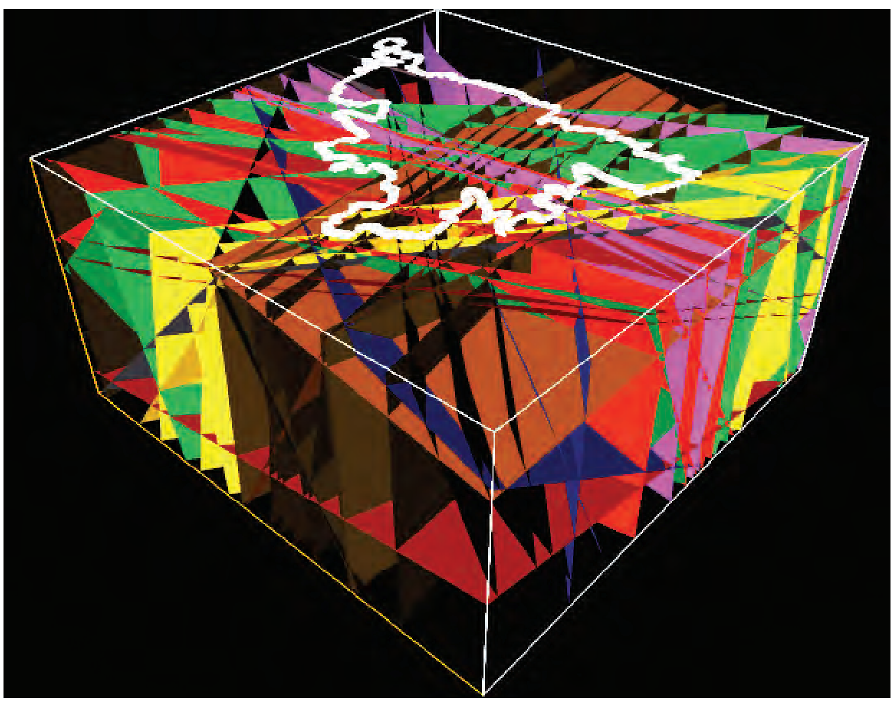


Figure 13-7 Fracture model of the Äspö Hard Rock Laboratory (SKI SITE-94 1997, Glynn and Voss 1999).

studies and geological and hydrologic information obtained for subsurface environments. Once again, having ready access to 3-D/4-D visualization and information frameworks and interpretive tools will be key in making well-informed assessments and decisions based on clearly represented, understood, and quality-controlled data and information.

Lessons Learned

In 2010, a small group of USGS managers and scientists recognized that individual researchers and teams were acquiring 3-D technologies across the USGS with little to no knowledge of other similar efforts. The group also observed that thousands of dollars were being spent on individual licenses across the bureau with no coordination, and, although many scientists were adding 3-D applications as analysis tools, there were few forums for sharing ideas and knowledge of emerging technologies. These findings led to efforts to endeavor to increase communication and coordination across the bureau via workshops; a user-survey; development of a database of 3-D systems, requirements, and users; and use of community-of-practice tools, such as a wiki.

Workshops

A workshop called “3D Visualizations of Geological and Hydrogeological Systems,” held during an annual USGS Modeling Conference, drew almost 50 participants primarily from federal agencies and academia. The purpose of the workshop was to preview state-of-the-art 3-D characterization software and hardware to expand the reach of geological and hydrogeological assessments. Vendors were invited to demonstrate 3-D visualization products, and participants contributed their requirements and knowledge of 3-D visualization tools. Also, a diverse cross section of USGS researchers who are experienced users of 3-D systems was convened to discuss USGS requirements and share knowledge. The result of the meeting was an action plan to better coordinate future purchases, stay in step with technological advances, define and increase opportunities for data integration, and champion communities of practice.

User Survey

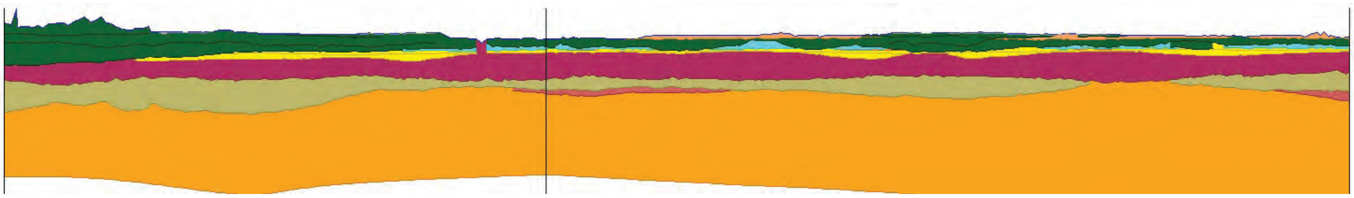
The USGS will conduct a Web-based survey of staff identified as using or having an interest in using 3-D applications. The goal of the survey is (1) to identify the areas of scientific study that employ 3-D/4-D technologies, how the technologies are applied in research, what barriers might exist preventing scientists from applying these technologies, and (2) to raise awareness of a new community designed to broaden the availability of 3-D/4-D technology and the knowledge surrounding it. The survey results will also be used to construct the 3-D systems database.

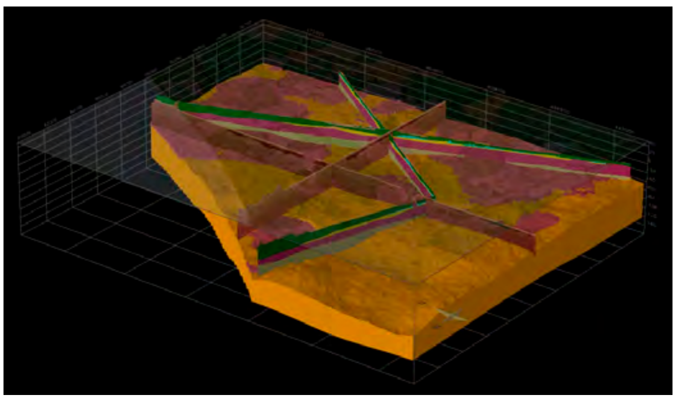
3-D Systems Database

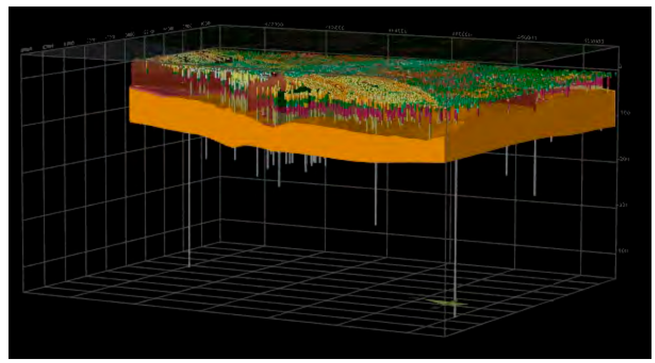
The USGS is developing a Web-based database to serve as a shared resource for exploring the various 3-D visualization systems used throughout the bureau. This storehouse will contain detailed information regarding hardware configurations, visualization systems, software packages, costs, available licenses and/or available hardware, and requirements for use. Points of contact are provided along with any relevant videos that help convey the types of applications that have been developed using 3-D technology. Additional information is provided in the form of documents, Web sites, and slide presentations. Users will be encouraged to add comments, opinions, and observations to help make the 3-D resources useful to both new and experienced users to enhance their knowledge and help them research new software and hardware platforms.

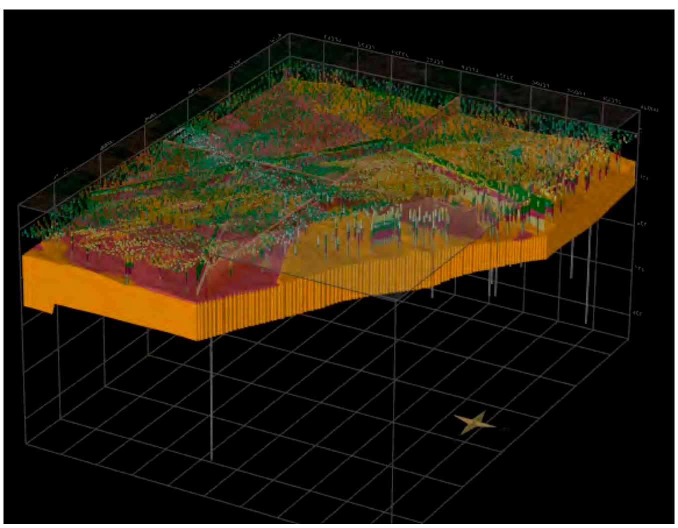
PART 3

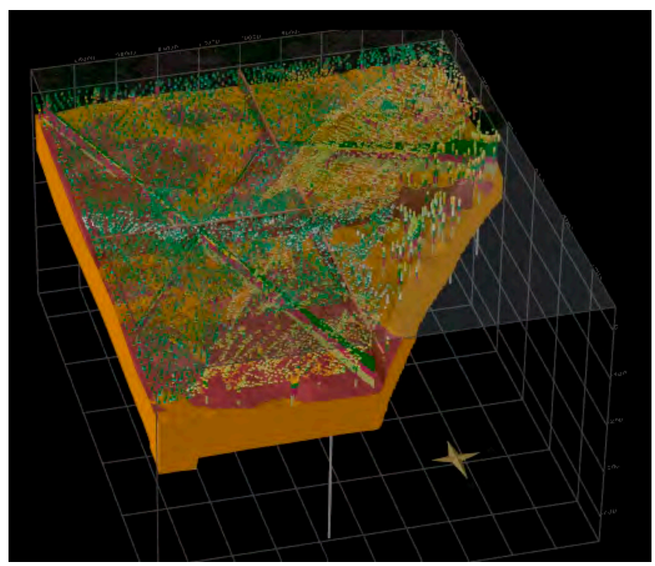
INFORMATION DELIVERY AND RECOMMENDATIONS











Chapter 14: Methods of Delivery and Outputs

Stephen J. Mathers[1], Holger Kessler[1], Donald A. Keefer[2], Don Cherry[3], Bruce Gill[3], Tony Pack[4], and Tim Rawling[5]

[1]British Geological Survey, [2]Illinois State Geological Survey, [3]Department of Primary Industries, [4]Geoscience Australia, [5]Geoscience Victoria

After 3-D models are complete, the information they contain must be made available to various user communities (e.g., planners, regulators, and consultants). Analytical tools (including those for data management) and delivery mechanisms, if designed correctly, can assist both map producers and users deal with scale issues and updating of 3-D models. So far most of these user groups still prefer 3-D model outputs to be presented in traditional 2-D forms such as paper maps and reports and digitally as shapefiles for integration in their GIS systems. It is important to recognize that for the foreseeable future, specific land-use decisions based on geological data, particularly those by planners and regulators, will need to be made using 2-D map products. However, although these products allow users to specifically evaluate the predicted geological succession at any place on the landscape, complex successions of geological deposits are not easily understood using the 2-D map products. Three-dimensional geological block models and various views of a 3-D geological model drawn in 3-D space are extremely effective in communicating how the geological deposits are distributed and can be powerful aids to explain the distribution of lines on any resultant 2-D geologic map. Due to the relatively immature nature of 3-D geological mapping, software for effectively communicating 3-D geology in 3-D space is still evolving.

To overcome the difficulties of communicating 3-D geological map interpretations, model producers such as GSOs have to be innovative and make use of existing technologies such as Google Earth and 3-D PDF. The advantage of these technologies is that they are available globally at no cost to the end user and are relatively simple and intuitive to use. An example of a 3-D PDF can be downloaded from the BGS Web site (http://www.bgs.ac.uk/).

Several examples of outputs and methods of delivery of geological information are provided in the following examples from GSOs.

INSIGHT GmbH Subsurface Viewer

To deliver the full richness of geological models (Figure 14-1) and provide users with fully interactive models, it is necessary to develop entirely new software systems. The BGS Subsurface Viewer is a stand-alone product for the delivery and analysis of geoscience models, partly fulfilling this requirement. It is being developed by INSIGHT GmbH, Cologne, Germany and is used by BGS and at TNO for this purpose (see http://www.dinoloket.nl/nl/download/sobisch.html). The functionality of the Subsurface Viewer includes maps of the buried geology, synthetic boreholes and slices, synthetic sections, views of single geological objects and block models, exploded views, and the ability to switch between different properties of geological models (Figure 14-2). A small demonstration model accompanied by a user manual is served at http://www.bgs.ac.uk/downloads/start.cfm?id=536.

All modeling projects are usually accompanied by a text report that gives details about the geological background, data, and software used and a summary of the results. It is envisaged that in the future these reports will be delivered online as PDFs. Three-dimensional geological

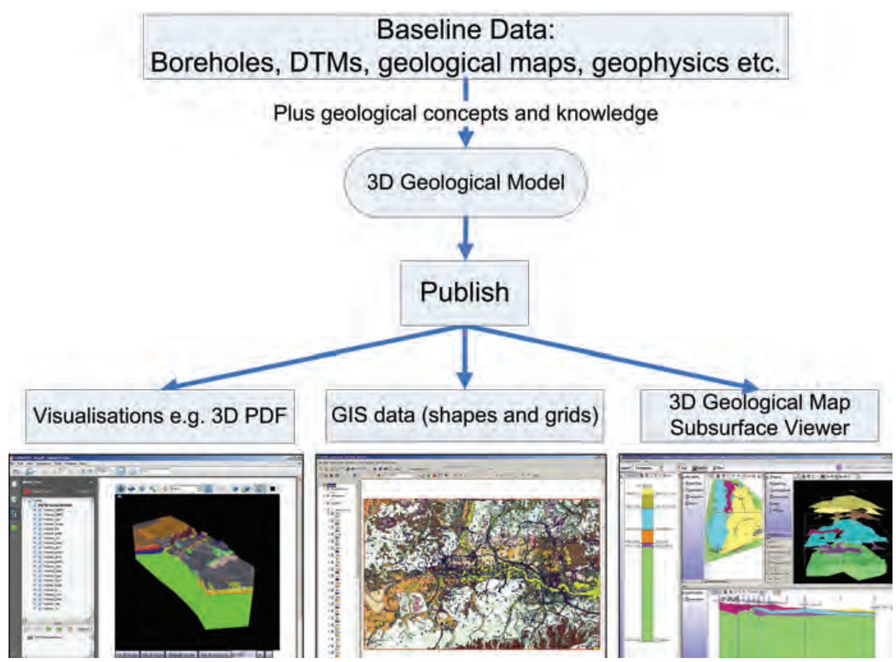


Figure 14-1 Options for delivery of British Geological Survey models.

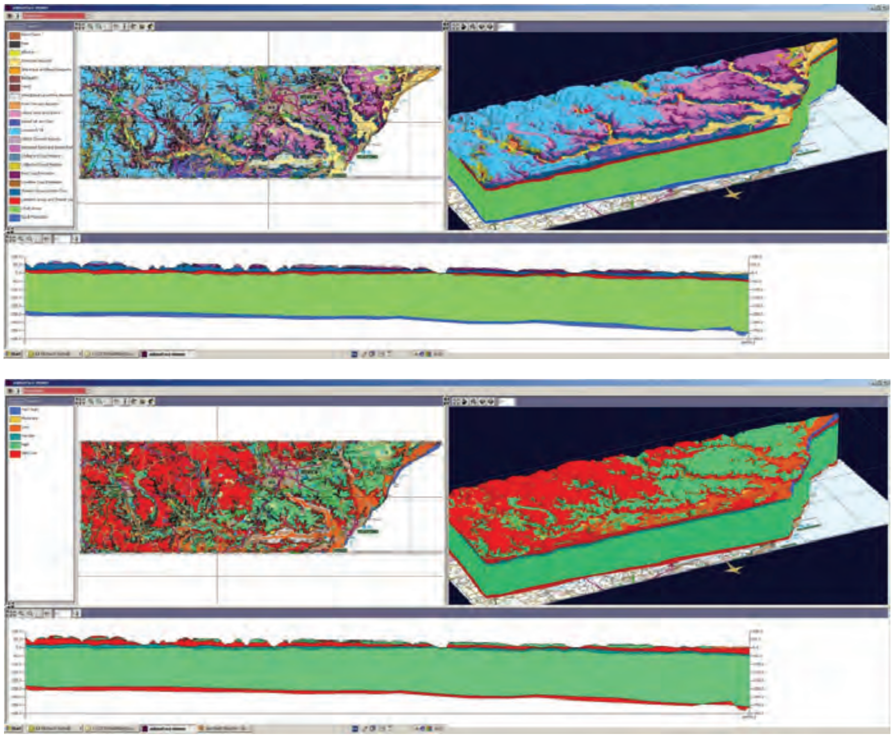


Figure 14-2 The Subsurface Viewer Interface showing the Southern East Anglia Model in the Subsurface Viewer with stratigraphic (top) and permeability attribution (bottom).

models can also be exported to 3-D PDFs, and development of embedded 3-D animations is being planned to better illustrate a report for a given area (Figure 14-2). In addition, a consideration when making 3-D maps or models is creating and using geological databases that are constantly being updated, which provides the means to update accompanying 3-D maps and models, thereby creating "living models."

GeoScience Victoria Storage and Delivery of Information

Model outputs are stored in GSV's 3-D Model Management System (3DMMS), which is a geospatially aware database developed for the GSV by Runge Ltd. (see Chapter 5). This system allows models to be stored with associated metadata and searched or queried accordingly. Importantly, the 3-DMMS also provides a visualization and delivery mechanism by which exploration geologists can visit GSV's office, upload their own 3-D data into a secure and confidential part of the database, and then visualize (in stereo in GSV's 3-D visualization room) the data with the GSV model objects they choose.

The format of company data (e.g., Vulcan, Surpac, Minesight), the map or model projection, and coordinate system are inconsequential (AMG, MGA, local), as all of these conversions are handled ex tempore by the 3-DMMS. Users are able to look at any of the stored (open file) data, select useful objects, and then download them in whatever format and projection they choose.

A Web interface is available for delivery of 3-D models directly from the 3-DMMS, but at present, models are also provided in 3-D PDF, DXF, and Gocad format to allow non-specialists to utilize and better understand model outputs. Stakeholders are also encouraged to utilize the open source and free ParaviewGeo software package, which allows visualization and analysis of Gocad data sets with many common mining data types supported as well.

GeoScience Victoria's long-term vision is to develop a statewide 3-D "living" earth resource model by 2016 (at 1:250,000 scale by 2011). For more information, go to www.3dvictoria.dpi.vic.gov.au/.

Web Delivery at Geoscience Australia

Initially, 3-D geology projects were created using VRML (Virtual Reality Modeling Language), an open source standard for 3-D graphics on the Web, developed by the Web3D Consortium (http://www.web3D.org). Geological models were created using VRML to allow interaction with the 3-D data using a Web browser plug-in; hence, the term "3-D Web mapping." From 2000 to 2005, Geoscience Australia (GA) produced nearly 40 unique 3-D VRML models, some of which are available for online viewing from the GA Web site (http://www.ga.gov.au/map/web3D/)

In 2006, GA switched from VRML to X3D (Extensible 3D), the XML successor to VRML, for creating 3-D models for the Web. X3D is the new open standard for 3-D Web content and is supported by the Web3D Consortium, the same group that supports VRML.

X3D has a number of advantages:

- Its XML format (extensible markup language) allows easier interaction with other XML formats.
- It is a free ISO standard for 3-D on the Web.
- It supports a large range of 3-D geometries.
- It can represent objects in true 3-D space including subsurface, surface, and above-ground features.

Geoscience Australias 3-D Web mapping development is unique and has

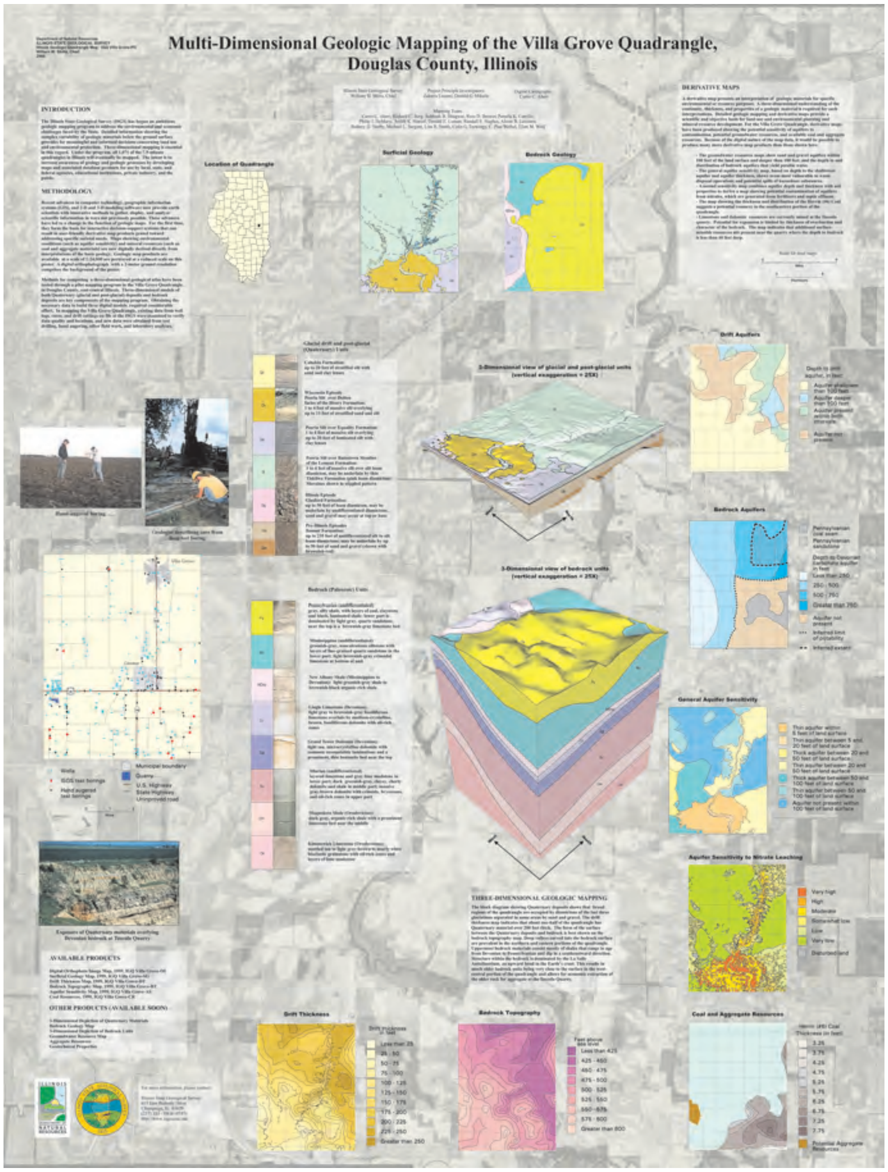


Figure 14-3 Villa Grove 7.5-minute Quadrangle map sheet (Abert 1999).

proved to be a very effective method for communicating large amounts of complex 3-D geoscientific and geospatial information to a wide audience. Originally, a significant driver for 3-D Web mapping was to help communicate the geological and geophysical data held in specialist applications such as Gocad. It did so by converting the 3-D models to a file size and format that were more widely viewable over the Internet. More recently, as Internet speed has increased dramatically, and with the availability of online viewers for specialized geological modeling applications, GA has been reviewing how it publishes 3-D geological models and is looking at other technologies such as 3-D PDF and open source virtual worlds, in addition to X3D.

As an example, GA's 3-D Data Viewer (http://www.ga.gov.au/map/web3d/world-wind/) is an application developed using NASA's World Wind Java (http://worldwind.arc.nasa.gov/) to display Australia's continental data sets. The viewer allows for comparisons between layers such as radio-elements, gravity and magnetic anomalies, and other mapping layers and allows the data to be draped over the Australian terrain in three dimensions. The viewer currently displays the radiometric map, gravity anomaly map, and the magnetic anomaly maps of Australia. Subsurface data, such as earthquakes at depth, have also been incorporated into the viewer and will be available online in future releases.

In the past year, a National Priority to improve water resource management has highlighted the need to develop data management and mapping systems at the continental scale. The Bureau of Meteorology is currently investing in the development of a national water information system, of which groundwater will be a part. To this end, the development of a national scale "geofabric" upon which hydrology and hydrogeology can be incorporated, is being investigated. The groundwater component will undoubtedly utilize 3-D geological data as the framework for this development.

ISGS 3-D Geologic Map Products

The ISGS currently produces three different types of products from 3-D geological mapping efforts. Traditional 2-D map sheets are still the most common product produced. These sheets include the full range of map types, from surficial materials maps, to structure and isopach contour maps, to a range of interpretive maps (i.e., potential for aquifer contamination). In addition to standard 2-D map sheets, the ISGS produces map sheets that provide exploded views of the 3-D map, highlighting the distribution of the succession of mapped units (Lasemi and Berg 2001, Abert et al. 2007). Additionally, GIS-compatible shapefiles of published geologic map layers are distributed free of charge.

Chapter 15: Conclusions and Recommendations

Richard C. Berg[1], Stephen J. Mathers[2], Holger Kessler[2], and Donald A. Keefer[1]

[1]Illinois State Geological Survey and [2]British Geological Survey

Three-dimensional geological mapping and modeling is becoming an established technique for portraying geological information. The organizations that have begun using this technique find that it transforms their approach to geology and to a wider understanding of often complex geological settings.

Three-dimensional geological models and maps at regional scales provide the framework for more detailed investigations by industry and local governments. Robust data management tools are essential when transitioning from regional to more site-specific investigations.

The 3-D geological mapping community is actively exploring a wide range of tools and techniques specifically designed to meet their mapping and information dissemination needs, and needs of their user community. The mappers are willing to share expertise and insights to individuals and organizations and are helping to address societal issues related to environmental protection, public health, water and mineral resources, and economic development.

The software and hardware that supports geological mapping have been in a state of continual evolution, which has required that the workflows and strategies governing 3-D mapping at GSOs periodically evolve as well.

Approaches to geological modeling are different to suit the needs of individual GSOs (partly as a reflection of their customer base), which will likely remain the case in the foreseeable future. Convergence or streamlining of software use might occur over time, but it is impossible at present to envisage a standard piece of software, as this will intrude into individual organizational policies and culture, as well as the possible capabilities of clients.

There is a benefit for individual GSOs to document various aspects of 3-D geological mapping projects, including choices of stratigraphic and rock classification schemes, scales and resolutions of models, and projections. The GSOs also should be encouraged to publish their workflows and methodologies for 3-D geological mapping and modeling.

The GSOs should be encouraged to publish geological models on the Web, and make them as interactive as possible, so that differences and commonalities between geological products from various organizations can be evaluated.

Communications among the 3-D mapping and modeling community must be maintained and formalized through the use of mailing lists, Web technology, and via various national and international workshops, symposia, and other meetings. See, for example, the ISGS-hosted Web site with expanded abstracts and many Power Point presentations from six international workshops conducted since 2001 titled Three-dimensional Geological Mapping for Groundwater Applications Workshops (http://www.isgs.illinois.edu/research/3DWorkshop/). See also the extended abstracts from the 2009 First Australian 3D Hydrogeology Workshop (http://www.ga.gov.au/image_cache/GA15507.pdf).

An ultimate long-term aim of some GSOs is to provide a collective joined up model of the Earth system. Geology does not stop at political boundaries and many of the emerging resource (water and mineral), environmental, and energy issues require global solutions. The authors are aware that this is an ambitious aim given the disparities between the financial resources and priorities for the various GSOs worldwide, and yet, significant advances towards collective seamless 3-D models are being made at a national level in several countries, even though international cross-boundary modeling efforts are rare.

We think that it would be worthwhile to initiate an international dialogue on the value of standards for 3-D geological mapping and modeling. There is a need to (1) evaluate the perceived benefits of various standards, (2) prioritize the standards seen as necessary, and (3) engage 3-D geological mapping and modeling software vendors in this dialogue. Over time, common data formats and relevant standards should emerge, leading to increased interoperability and exchange, perhaps following the lead from OneGeology.

The GSOs should consider participation in initiatives such as GeoSciML and in organizations such as the Open Geospatial Consortium (OGC) and the International Organization for Standardization (ISO). This participation will help involve the 3-D geological mapping community in standards being developed for the larger geoscience community.

In Europe, legal frameworks such as the INSPIRE directive (http://inspire.jrc.ec.europa.eu/) are beginning to set spatial standards. Wider participation from the geoscience community would help lead to more robust standards.

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