Three-Dimensional Geological Mapping

WORKSHOP EXTENDED ABSTRACTS
Geological Society of America Annual Meeting
Denver, Colorado – October 26, 2013
Conveners:
Harvey Thorleifson, Minnesota Geological Survey
Dick Berg, Illinois State Geological Survey
Hazen Russell, Geological Survey of Canada
## Workshop Agenda - Three-Dimensional Geological Mapping
### Denver, Colorado, USA - October 26, 2013

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INTRODUCTION - THREE-DIMENSIONAL GEOLOGICAL MAPPING
Thorleifson¹, L.H., Berg², R.C., and Russell³, H.A.J.

1. ABSTRACT

This workshop is designed for those constructing 3D geological maps and numerical models. Our objective is to bring together people dealing with large datasets, and who must integrate variable quality data with high quality data to construct 3D geological models for application such as hydrogeology, engineering, and energy resource assessment.

Topics include (1) methods of model construction, (2) managing diverse data of variable quality, (3) ensuring data interoperability, (4) visualization tools, and (5) interaction between mappers, hydrogeologists, energy and mineral resource geologists, engineering geologists, and engineers. The emphasis is on deposits that host potable groundwater, as well as sedimentary basins as a whole.

2. INTRODUCTION

There is an increasingly pressing need for high-quality 3D geological information about shallow deposits and sedimentary basins as attention to energy, environmental, and land-use issues grow, particularly in urban and suburban areas (Berg et al., 2011). Attention is also turning to the study of regional groundwater systems and to their long-term sustainable development.

Although technological capability is accelerating even as these demands for information are becoming increasingly more compelling, there is a continuing lack of high-quality data. This situation is particularly true in the densely populated and industrialized parts of the United States, Canada, and Europe, which are covered by thick glacial deposits.

The ongoing challenge of these information requirements produces a sustained and urgent need for developing optimal modeling methods. There thus is a need for communication among mappers who are (1) experimenting with new ways to deal with large data sets, (2) developing ways of integrating data of variable quality with high-quality test holes and geophysics, and (3) developing methods to construct 3D geological models of appropriate detail that can be used for applications such as hydrogeologic modeling.

3. WORKSHOPS

This is the eighth in a series of workshops on three-dimensional geological mapping that have addressed these needs.

The first workshop in this series was held at the 2001 North-Central GSA meeting in Normal, Illinois (Berg and Thorleifson, 2001). The workshop was held prior to the annual 2002 GSA meeting in Denver, Colorado. The Illinois State Geological Survey and the Geological Survey of Canada chaired and sponsored both events.

The third workshop was held at the annual 2004 Geological Association of Canada/Mineralogical Association of Canada meeting in St. Catharines, Ontario. The fourth was held at the 2005 GSA Annual Meeting in Salt Lake City, Utah. The fifth was held at the 2007 GSA Annual Meeting in Denver, Colorado, while the sixth was held at the 2009 GSA Annual Meeting in Portland, Oregon. The seventh workshop was held at the 2011 GSA Annual Meeting in Minneapolis, Minnesota.

These more recent workshops have been sponsored and chaired by the Illinois State Geological Survey, the Geological Survey of Canada, and the Minnesota Geological Survey.

Extended abstracts and presentations from all workshops are available on the Illinois State Geological Survey web site.
All of these workshops have provided opportunities for geologists to share information on methods for constructing, visualizing, and delivering to the public regional 3D geological models intended for groundwater and other applications.

This year, we are immensely pleased to again be working with highly experienced, knowledgeable, and capable speakers from around the world.

4. SUMMARY

The extended abstracts provide an overview of the rapid evolution in three-dimensional geological mapping methods at government agencies and their partners. It is becoming clear that societal needs, particularly for effective groundwater management, are leading to more research in areas of 3D data collection, modelling techniques, and data management, and as a result, progress in multiple-resolutions, jurisdiction-wide 3D mapping.

5. REFERENCES


6. ACKNOWLEDGEMENTS

Appreciation is expressed to:

- Our presenters and their employers, for agreeing to share their experience and progress
- Illinois State Geological Survey staff for maintenance of the workshop series website
- Reviewers and editors of the extended abstract volumes
- Geological Society of America for agreeing to host most of the workshops
OVERVIEW - 3D GEOLOGICAL MAPPING: DEVELOPING MORE WIDESPREAD ADOPTION BY GEOLOGICAL SURVEY ORGANIZATIONS

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1. INTRODUCTION

There is broad international attention to the need for sound subsurface geological models, and thus to the methods required to extend conventional geologic mapping methods to the construction of these models. Geological Survey Organizations (GSO’s) in a number of jurisdictions have made significant progress in the development and implementation of three dimensional (3D) mapping programs (Berg et al., 2011). Nevertheless, such examples are few in number and there is a need to develop a framework that will accelerate more comprehensive 3D geological mapping (Thorleifson et al., 2010). It is apparent that many small geological survey organizations feel they lack the critical human and financial resources to develop 3D geological mapping programs.

A number of western European and North American GSO’s stand out for their early adoption, visionary approach, and progress at the jurisdictional scale, and thus can serve as examples for others on how to proceed. Concurrently, numerous other national, regional and local scale models demonstrate equal integrity and innovation (Berg et al., 2011). Nations such as Britain, Holland, and Denmark are excellent examples of approaches to multiple-resolution 3D mapping of areas of a size comparable to many densely populated areas of the world. The British Geological Survey (BGS) has tackled national scale surface to lower crust depths within their LithoFrame subsurface schema at four scales that range from national 1:1,000,000 scale to local 1:10,000 scale (Mathers et al., 2011). The Dutch have focused on the shallow subsurface, the context of most concern for groundwater and geotechnical issues, and have developed two national scale (42,000 km²) layer models (Stafleu et al., 2011). They have further progressed to development of a solid model with physical property attribution. In Denmark, the need for high quality data was recognized and a program was embarked upon to conduct geophysical data acquisition, initially ground based and subsequently from aerial platforms with integrated data standards, and data management framework coordinated with academia and consultants (Thomensen, 2003). Focus in North America has more commonly been on local to regional scale models, although Manitoba is noteworthy for its jurisdiction-wide approach based on long-term planning, early reconciliation of stratigraphic models, construction of comprehensive databases at jurisdiction rather than project scale, extensive geophysical surveys and drilling, and a comprehensive approach covering sediments and sedimentary rocks down to basement at several km depth (Keller et al., 2011). Illinois, concurrently, has been an early advocate and an influential example of the need to support 3D mapping, based on the tremendous importance of optimal information to support groundwater protection (Berg et al., 2011).

This paper reviews various approaches for 3D geological mapping common to many GSO’s and outlines the range of approaches to 3D model development depending upon data source, opportunities for data collection, and geomatics support. The intent is to demystify the requirements, and provide a concise context for GSO’s considering the need for 3D geological mapping.

2. 3D MAPPING

When undertaking a 3D program, a clear enunciation of the objectives, applications and limitations of the datasets and resultant models is required. Guidance to the user will ensure that a model completed at the achievable regional resolution will not later be used for applications that in fact require additional data and higher-resolution modeling. This consideration is well illustrated by Thomensen et al. (2004), who contrasted regional subsurface models based only on borehole data versus models integrating spatially dense geophysical data that were seen as being needed to establish site-specific groundwater protection zones.
The design of a 3D mapping program encompasses conceptual underpinnings, datasets, information management, model construction, property attribution, and uncertainty. Turner (2006) encapsulated these elements in a workflow that highlights two streams of data processing for geometric modelling and for the property attribution (Fig. 1). Stratigraphic data are used to create a 3D geometry model in the left hand column and in the right hand column property data are used to create a predictive model of properties; the double arrow shows the iterative process of model refinement.

Conceptual Underpinnings

The conceptual underpinning for 3D mapping of sediments and sedimentary basins is basin analysis, which developed as a method for understanding the paleogeographic history of sedimentary basins (e.g. Walker, 1992). This multidisciplinary approach to data collection and analysis provides a predictive knowledge framework for the basin (e.g. Sharpe et al., 2002). Central to basin analysis is stratigraphic correlation, which may follow well-established norms of lithostratigraphy and more recently allostratigraphy. Based on bounding surfaces, allostratigraphy (e.g. Walker, 1992) offers significant advantages over other stratigraphic approaches, particularly when integrating diverse datasets, as it correlates erosional surfaces and laterally equivalent conformable surfaces to delineate genetically related sedimentary units (e.g. Macfarlane et al., 1994; Weissmann and Fogg, 1999), while more directly addressing vertical connectivity and lateral facies changes that are important considerations when constructing a hydrostratigraphic framework (e.g. Fogg, 1986). Facies models based on an understanding of trends within stratigraphic units provide a basis for inferring likely deposit geometry and properties, while thus provide a crucial framework within which to apply geostatistical modeling of properties.

Figure 1. Conceptual workflow for model construction in 3D mapping. From Turner (2006).
Construction of inferred strata and their properties commonly is not straightforward, nor is a single solution necessarily apparent. Depending upon data input, scale of study area, geological complexity, staff expertise, and project objectives, there are two end-member approaches i) manual interpretation of cross-sections, ii) expert systems. Application of the best practices that have been developed over two centuries of plan-view mapping can best be facilitated using cross-section approaches, as exemplified by GSI3D (Mathers et al, 2011), thus allowing the cognitive power of the geologist to construct a framework that constrains subsequent interpolation and ensures conformity with the geological conceptual model. Using machine algorithms to interpolate geology requires adequate geological attribution, and integration of expert rules to replicate decision-making geologists implicitly infer as part of the process of geological mapping. The objective of both methods is to develop geologically plausible depictions of what is regarded to be the most likely deposit geometry and properties, while ensuring that rules of superposition are followed while all stratigraphic units are accounted for (e.g. Hughes, 1993). Alternatively, expert systems approaches have been used to ensure that rules are applied consistently, at the expense of geological realism (Logan et al., 2006).

Datasets

Data collection may span a broad array of scales, spatial continuity, and data types, such as airborne geophysics, downhole geophysics, geochemistry, hydrogeology, hydrology, paleontology, remote sensing, sedimentology, and surface geophysics. Datasets of points, lines, or polygons, and rasters may be archival, legacy and project collected. Archival data encompasses data collected for purposes other than geological investigations, such as water well records. Legacy data includes data from previous investigations compiled by an agency such as a geological survey (e.g. Mathers et al., 2011), such as geological maps and structure contours (e.g. Keller et al., 2009). Project data collected to resolve specific geological hypotheses typically are most valuable while being least plentiful (Sharpe et al., 2002).

Information Management

The most successful data standards seem to be those implemented at the institutional scale (e.g. Ludascher et al., 2006; Møller et al., 2009; Mathers et al., 2011; Boisvert and Brodaric, 2011).

Model Construction: “Rome Was not Built in one Day”

Three-dimensional geological mapping customarily involves modelling contacts as regular grids or irregular triangulated networks representing unit bottoms or tops (e.g. Ross, 2005), and discretization of properties within the strata (Lemon and Jones, 2003; Turner, 2006). Successful programs directed toward jurisdiction-wide, multiple-resolution work typically have required long-term planning and dedicated staffing. Progress can, and likely is, however, being made by all geological survey agencies and their partners, given that a progression commonly is followed from two-layer models such as depth to bedrock, digitized and reconciled legacy stratigraphic models, cross-sections drawn from stratigraphic control points through lithologic data, interpolated stratigraphic data, to solid models built from comprehensive geological and geophysical data. The requirements of this progression ranges dramatically with respect to data, interpretation, support, and software. Most surveys or similar units possess software that will allow at least partial entry into this progression, such as GIS with extensions and custom scripts (e.g. Mei, 2008), or 3D GIS software (Kessler et al., 2011).

Two-layer model:

A two-layer model such as depth to bedrock commonly is a benchmark product that will motivate data compilation and clarify priorities for data collection such as geophysics and drilling (Jordan, 2008). A point file of bedrock surface elevations may undergo machine modelling by some method deemed appropriate after iterative approaches, or may be modeled by hand and digitized to introduce expert opinion on the rock surface geometry deemed most likely. Many regional jurisdictions and nation now have maps for depth to bedrock or depth to basement for large areas exceeding 100,000 km² (e.g. Gao et al., 2006). In Ontario, the regional bedrock surface model has provided a framework for more detailed studies of 500-1000 km² involving extensive drilling and geophysical programs.
Legacy stratigraphic models:
Regions that have produced oil and gas will in most cases have been the subject of stratigraphic compilations, such as sedimentary basin atlases depicting hand-drawn or machine-contoured structure contours (Keller et al., 2009; Mathers et al., 2011). Modeling will have been guided by well-established correlations based on micropaleontology, other stratigraphic markers, seismic surveys, and lithologic trends identified in borehole geophysics and other means. Bringing this stratigraphic mapping into a 3D GIS environment may require infilling of gaps left in hand-drawn contours, and may require reconciliation of intersecting surfaces in data-poor areas if the legacy work involved construction of one surface at a time. Keller et al. (2011) described examples of this approach, notably a 3D model for 450,000 km² area of Western Canada constructed from legacy stratigraphic maps of the Western Canadian Sedimentary Basin Atlas (Mossop and Shetson, 1994). The 1:100,000 scale Lithoframe model of the British Isles is similarly based on legacy mapping and deep boreholes, seismic profiles, and regional geophysical interpretations (Mathers et al., 2011); the model extends to the base of the crust at a depth of 30 km, and includes major faults and igneous plutons. Such models can provide immediate value, for example as a basis for modeling and as a framework to guide planning and to clarify the context for data collection and higher resolution modeling.

Cross-sections drawn through lithologic data:
Beyond basins previously mapped in relation to hydrocarbon potential or production, a common scenario is a region in which 3D mapping is needed to support groundwater management, and the available basis for modeling will at best be scattered drillholes and geophysical surveys, along with an abundance of water well data. In this circumstance, the optimal approach has in many cases been seen as data compilation, acquisition of stratigraphic control sites using coring and geophysics, and construction of cross-sections by the most knowledgeable and experienced geologist who will use an approach similar to mature approaches developed for plan-view mapping, followed by capture and correlation of the sections in 3D GIS. This approach results in depiction of a plausible and visually pleasing geology that conforms to the geological conceptual model, and from which heterogeneity has to some degree been filtered by the geologist (e.g., Aims et al., 1996). This approach forms the basis for the British Geological Survey's development of GSI3D and is also commonly employed in an analogue to digital workflow (Keller et al., 2011). New stratigraphic data can not, however, be readily incorporated into a model constructed in this manner, unless the new data are well correlated and can thus be incorporated as the existing model is remodelled from selected synthetic drillholes derived from the preceding model. Kaufmann and Martin (2008) address this issue by development of a workflow that integrates both punctual and line data for interpolation in a modelling environment.

Interpolated stratigraphic data:
Well-distributed drillholes or other vertical profiles that have confidently been assigned a stratigraphic correlation by micropaleontology, recurring lithological sequences, or some other means may be available for modelling without intervening manual steps, although expert-generated synthetic profiles may be required in data-poor areas for an acceptable result to be obtained. Approaches may range from simple spatial interpolation of stratigraphic assignments in a database (e.g. Mossop and Shetsen, 1994) to expert system approaches to model construction (Hughes, 1993; Logan et al 2006). Stratigraphic assignments in this approach are also deterministic, although once assigned, they can readily be combined with new data and re-interpolated. A well-documented example of this approach with clear expert rules was used to model the 12000 km² Oak Ridges Moraine area of Southern Ontario (Logan et al., 2006). An alternative classification approach is the Support Victor Machine (SVM) that is commonly applied in image analysis (Smirnoff et al., 2008).

Solid Models:
A full progression from modeling of surfaces to full characterization of volumes ultimately will be essential to support applications in hydrogeology, resource and hazard assessment, and engineering (e.g. Turner, 2006; Lemon and Jones, 2003). This process may involve additional data collection, and transfer from one software platform to another depending upon the nature of the discretization and property attribution (Kessler et al., 2008). Ross et al. (Fig. 2; 2005) provides a description of the progression from contacts to the construction of regular 3D voxel model for a 1500 km² area. Alternatively, solid models may be constructed from geophysical data and converted from time domain to depth domain at the appropriate scale (Jørgensen et al, this volume).
Figure 2. Model constructions steps highlighting preliminary surface generation, cross section integration, final surface generation, conversion from boundary geometry model to voxel model. (From Ross et al., 2005)
Property Attribution

A challenge to be faced in solid modeling meant to support inferences such as generation of a 3D grid of hydraulic conductivity values is an accounting of likely heterogeneity. In densely populated regions, a high density of drillhole observations may be available for models of up to 5000km$^2$ or larger (e.g. Stafleu et al., 2011; Royse et al., 2008). In these cases, property attribution may use techniques such as continuous geostatistical models, Boolean, Indicator or Gaussian-Threshold models and Markov chain models (e.g. de Marsily et al., 2005). For regional studies, it may be necessary to work with a small set of physical property measurements, such as hydraulic conductivity, and use another dataset such as hydrofacies to propagate this information. Central to many of these approaches is an understanding of the paleogeographic framework (e.g. Ritzi, et al., 1995; Weissmann and Fogg, 1999). A number of examples now exist of exploiting water-well data, geological knowledge and local measurements to understand the spatial heterogeneity of buried valley fills in the mid-western USA (Ritzi, et al., 1995) and alluvial fans in California (Weissmann and Fogg, 1999).

Uncertainty

An issue in 3D geological mapping is the certainty that can be placed on the spatial position of a given modelled horizon (e.g. Culshaw, 2005; Royse et al., 2008). This uncertainty results from: i) geological complexity, ii) quality, accuracy and reliability of data, and iii) interpolation effects. It is difficult to represent all of these aspects of data quality in a single metric, although Tacher et al. (2006) provide a comprehensive attempt. As demonstrated by Weber and Guens (1990), the density of data support to represent the geology increases with the complexity of the geology, including feature scale and variability of orientation. Data quality, accuracy and reliability can be assessed qualitatively and commonly quantitatively given adequate variability in data inputs. For example, an error in location results in an error in the depth to the unit, and furthermore results in a translocation of the represented geology (Keefer, 2011). Questions of quality and reliability of data descriptions can be assessed by comparison of data when it is collocated or in close proximity, or is not represented by statistical datasets or geological knowledge developed from many studies (e.g. Russell et al., 1998). One attraction of stochastic modelling is the generation of a probability outcome for the sum of the model iterations where each iteration is considered equally plausible (Stafleu et al. 2011).

3. WHAT DOES AN INSTITUTION NEED: PEOPLE FIRST

The crucial factor in permitting an institution to accelerate its progress in 3D geological mapping commonly is the presence of an individual or group with the commitment and influence to advance a vision for the activity. The critical attributes of this person or people are the ability to think in three dimensions, to visualize the geology on a well-informed basis, to foresee the plausible options for data collection, to recognize achievable mechanisms to fund the activity, and to appreciate current and potential applications. Many existing 3D programs at GSO’s evolved from the vision and inspiration of individuals with no little or no background in geomatics or 3D modelling.

4. SUMMARY / CONCLUSION

Three-dimensional geological mapping in some manner is achievable for all GSO’s. The critical juncture to achieve progress is an individual with the commitment to forge the necessary interagency collaboration and to advance a mapping agenda suitable to the level of resources available. As demonstrated by a number of agencies, sound geological understanding with conventional geomatics support is adequate to construct a basic two-layer bedrock surface geological model. Once such a model is in place there is both a framework for future 3D mapping and an opportunity to test and revise the model – progress is assured. No 3D mapping is final and consequently it is a fallacy to believe 3D mapping needs to wait until you can integrate the latest geophysical data, the newest allostratigraphic framework, or have resources to acquire a new 3D GIS modelling package.

5. ACKNOWLEDGMENTS

Reviews by M. Hinton and M. Pyne of the Geological Survey of Canada are much appreciated. This is ESS contribution.
REFERENCES


Airborne Electromagnetic (AEM) surveys have found use in the development of many geological frameworks. AEM is a geophysical tool capable of rapid acquisition over large areas. Consequently, the method has been increasingly applied to regional-scale hydrogeologic studies of groundwater aquifers and 3D geological frameworks such as Fitterman and Deszcz-Pan (1998); Auken et al. (2009a); Abraham et al. (2012), and Jørgensen et al. (2012). These and many more successful projects have been accomplished using AEM. While there are many published works on the successes, what about the failures? Physics does not fail, so what are the potential problems with AEM? Do the systems not work all the time? No, they do work within the bounds they were designed to operate. Factors influencing a successful AEM 3D mapping project come down to several key points in the use of the AEM technique: 1) Electrical conductivity of the geological materials; 2) The electrical conductivity contrasts between the geological materials that we want to map; 3) The depth of the materials; 4) The thickness and extent of the materials; and 5) the inherent limitations of the AEM systems that we use. These can all be summed up as physical properties and AEM system design.

The Danish have made the best effort at putting together standards for calibration, acquisition, processing, and inversion of AEM data (Aarhus Geophysics, 2010). Through mapping the 3D geology of Denmark, they have produced many papers on the use of AEM techniques (Christiansen, and Christensen, 2003; Auken et al., 2008; Auken et al., 2009b). Can these techniques be applied in North America and throughout the rest of the world? Perhaps they should be. Is this a feasible approach? Processing of the data can be a technical challenge for the inexperienced, leading to many consequences that can adversely impact data quality and the resulting product (Viezzoli et al., 2013).

One important concept that is typically missed in planning AEM surveys is the development of simple forward models of the electrical properties of the targets of interest and the AEM system that is proposed to map the area. These forward models, when an appropriate level of system noise is added, can be priceless in determining the usefulness of AEM and a specific AEM system as it relates to mapping the target of interest. There are several free or relatively inexpensive electromagnetic modeling programs that can provide informative forward models to the potential user. However, these forward models only provide information as good as the input. So what is good information? Basically, it is a good understanding of the electrical properties of the materials of interest. Those can be obtained through geophysical well logs or ground geophysical surveys. Coupling this information with a good description of the AEM system is critical. Note that not all AEM vendors want to provide this information.

In the end, as with everything else in life, there is no simple answer that does not include doing careful homework and gathering as much information as possible about the area of interest. The lessons learned are that if a shortcut is taken at any step in the process, the end product usually suffers. Remember that the success of an AEM 3D mapping project is dramatically impacted by everything from careful calibration and acquisition to the color scale in final reports.

References


APPLICATION OF SHALLOW GEOPHYSICAL METHODS FOR 3-DIMENSIONAL MAPPING OF QUATERNARY DEPOSITS, SOUTH SIMCOE COUNTY, SOUTHERN ONTARIO

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ABSTRACT

Near surface geophysical methods are actively being employed by the Ontario Geological Survey to assist with its program of 3-dimensional mapping of Quaternary deposits. A number of widely used methods including ground-based gravity, airborne time-domain electromagnetics, borehole geophysics and seismic reflection have been undertaken at varying scales and extents within the South Simcoe area of southern Ontario to obtain a refined understanding of bedrock topography and an improved conceptualization of the subsurface architecture of major hydrostratigraphic units that overlie bedrock. The successful interpretation of the geophysical datasets within this area of thick Quaternary cover and abundant cultural interferences requires an approach that involves not only their full integration with existing and newly-acquired high quality subsurface information but an appreciation of the limitations of each method on their own. The examples highlighted in this paper demonstrate some of the successes and challenges of using shallow geophysical methods as part of the 3-D mapping toolbox.

1. INTRODUCTION

The Clean Water Act was introduced by the Province of Ontario to ensure sustainable and safe drinking water for all municipal drinking water supplies across the province. This is being achieved by the development of locally driven, watershed-based, source water protection plans. A good understanding of geology and its effect on both surface and groundwater flow systems is essential for the successful development and implementation of these plans. The Ontario Geological Survey (OGS) has developed a program that delivers baseline geoscience information and products that act as a foundation for and upon which these plans can be developed. Three-dimensional (3D) mapping of both bedrock and surficial aquifers is an important component of this program. The mapping and characterization of Quaternary aquifers and aquitards has been ongoing since 2002 with projects either completed or ongoing in the Waterloo (Bajc and Shirota 2007), Brantford–Woodstock (Bajc and Dodge 2011), Barrie–Oro (Burt and Dodge 2011), Orangeville–Fergus (Burt and Webb 2013), Niagara Peninsula and South Simcoe areas.

Lying almost exclusively outside of Ontario’s Greenbelt (Ontario Ministry of Municipal Affairs and Housing 2005), the South Simcoe area is well poised to receive accelerated population growth in years to come. With the exception of the towns of Alliston and Beeton, the water supply needs of this area are serviced almost exclusively by groundwater. Increased pressures related to growth may strongly impact on water quantity and quality within the aquifers, as well as on surface waterways and sensitive ecosystems tied to them. Intensive agricultural practices, heavily dependent upon irrigation, have also placed significant stresses on both the surface and groundwater resources of this region. In response to the need for high-quality information on the distribution and characteristics of subsurface hydrostratigraphic units, the OGS initiated a 3D mapping project in south Simcoe County during the summer of 2010. The objectives of this project are to develop interactive 3D models of the Quaternary geology that can 1) aid in studies involving groundwater extraction, protection and remediation; 2) assist with the development of policies surrounding land use and nutrient management; and 3) help to better understand the interaction between ground and surface waters.

2. GEOLOGIC SETTING

The irregularly-shaped South Simcoe study area is roughly 1450 km² in area measuring 50 km north-south by 40 km east-west. Topographically, the area consists of a broad till upland incised by a series of south- to southwest-trending valleys measuring 3-5 km wide and 75-85 m deep. The valleys are flat-bottomed and partially
backfilled with clayey to sandy glaciolacustrine deposits. Hummocky sandy knolls of the Oak Ridges Moraine characterize the southwestern corner of the survey area. The moraine abuts up against the partially buried brow of the Niagara Escarpment which fringes the western margin of the survey area. Drift thickness along the western margin is generally less than 10-20 m but increases locally in narrow re-entrant valleys cut into the escarpment (e.g. Hockley Valley). To the east, the bedrock surface drops off dramatically into the Laurentian trough, a broad bedrock depression extending from the south end of Georgian Bay to Lake Ontario resulting in drift thicknesses that commonly exceed 150 m. Locating deep, narrow channels incised into this bedrock trough may be of interest from a hydrogeological perspective as they may host significant aquifer bodies.

Uplands are veneered by 5-40 m of pebbly, silty to sandy Late Wisconsinan Newmarket Till and underlain by up to 120 m of Thorncliffe Formation silty to clayey glaciolacustrine rhythmites with lesser sand (Middle Wisconsinan). The glaciolacustrine deposits occur as a series of coarsening-upward cycles that grade from highly-bioturbated clay into silt and clay rhythmites then ripple- and planar-laminated sands. These sequences can be traced in the subsurface for several tens of kilometers and may reflect basin-wide changes in base level. The base of the Thorncliffe Formation is marked by a basin-wide unconformity developed on an older sediment sequence consisting of an upper, stone-poor, fine-textured diamicton interbedded with glaciolacustrine silts and clays and a lower cobbly silty to sandy diamicton. AMS radiocarbon dating of terrestrial leaves and wood recovered from the unconformable surface suggest an age of less than 40 ka BP for the subaerial exposure. Detrital plant debris contained within the overlying Thorncliffe Formation deposits have returned ages as young as 28 ka BP.

The broad, southwest- to south-trending valleys are interpreted to be tunnel channels incised by the rapid release of subglacial meltwaters following deposition of Newmarket Till. The channel fills generally comprise of a single, fining-upward sequence consisting of a lower sandy to gravelly waning flow facies overlain by variably-textured diamictons that were deposited as either debris flows originating from newly eroded, highly unstable valley walls following the removal of glacier ice or as flow tills deposited either adjacent or under the retreating ice margin. These diamictons transition quickly into rhythmically-laminated, fine-grained glaciolacustrine deposits that are in turn veneered by sandy regressive facies.

3. GROUND GRAVITY

A regional gravity survey was conducted over the South Simcoe study area in 2010 and 2011 to better understand the location and geometry of buried bedrock valleys beneath the thick Quaternary cover. The valleys can often be well delineated using gravity due to the density contrast between the lower density valley-fill material and the higher density bedrock. As a result, bedrocks valleys can often be delineated using their associated negative gravity anomalies. Approximately 3600 stations spaced at 200 m were collected along 22 road traverses. Standard data reduction procedures, including terrain correction, were applied to the gravity results and the Bouguer gravity anomaly was calculated using a density of 2.1 g/cm$^3$. Additional details regarding data collection and post-processing methods can be found in Bajc and Rainsford (2010, 2011).

Figure 1 provides a comparison of the bedrock topography, modelled primarily from water-well data, against an image of the residual gravity obtained by subtracting a 500 m upward-continued regional field. As expected, there is a good correlation between the bedrock topography interpolated from water-well data and the gravity results. In areas where deep water-well information is sparse, the gravity profile data is able to define valley thalwegs with greater precision. Strong positive residual gravity features (highlighted by the thin white dashed line) show no correlation with the interpolated bedrock surface. They do, however, appear to be associated with magnetic low features in the basement defined by the regional aeromagnetic coverage. These were incompletely removed as part of the regional-residual field separation. As the drift cover and underlying carbonate rocks are essentially non-magnetic, it is inferred that these features are the expressions of higher density rocks within the crystalline basement, possibly remanently-magnetized mafic intrusions.

Valley thalwegs were interpreted by examining the individual residual gravity profiles and identifying “lows”, which were then evaluated according to amplitude and shape. These picks were then verified by correlating with trends of known bedrock valley thalwegs interpreted from water-well records. Unable to differentiate between aquifers and aquitards, the gravity results were used along with the lithologic logs of water wells to infer areas where
interpreted thalwegs were more likely to host significant groundwater resources. Some of these areas were selected as drill targets for the ensuing drilling campaigns. In several cases, significant aquifers were encountered at the bases of boreholes drilled along interpreted thalwegs.

4. AIRBORNE TIME-DOMAIN ELECTROMAGNETIC SURVEY

A 1,898 line km Aerotem IV time domain electromagnetic (TDEM) survey was flown at 200 m flight line spacing over a 328 sq. km area in the south-central part of the study area in order to test whether the airborne TDEM method could be an effective tool for detecting and delineating buried bedrock valleys and important hydrostratigraphic units in the overlying Quaternary sequence. In addition to the standard EM products such as decay constant and apparent conductance, the project deliverables included laterally constrained 1-D inversions of the EM data. The inversions resulted in a 3-D database of electrical conductivity which can be imaged in plan and section form. The results of this survey have been published as Geophysical Data Set 1070 (Ontario Geological Survey 2012).

![Figure 1. Comparison between bedrock topography, residual gravity and regional magnetics in the South Simcoe Survey area. Major thalwegs interpreted from residual gravity results highlighted in thick white dashed line. Possible remanently magnetized mafic intrusion highlighted by thin white dashed line.](image)

The objectives of the TDEM test survey are to determine:
- whether buried bedrock valleys and channels within surficial materials are detectable
- whether important hydrostratigraphic units are mappable in the subsurface
- the optimum flight line spacing and orientation
- whether the TDEM data provides more information than ground gravity
- the effect of cultural sources on the survey results

Surficial geology maps, continuously-cored borehole logs, ground gravity data, downhole geophysical logging and water well records are available to help address these questions. It was clear from the preliminary survey results that man-made cultural interferences such as power lines, telephone cables, pipelines, rail lines and metal fences had a deleterious effect on the data. This outcome was not unexpected and resulted in about a 50% loss of useable data. Such challenges have previously been noted with similar surveys elsewhere (Viezzoli et al., 2011). The effect could have been mitigated somewhat by orienting the flight lines oblique to the road network along which most of the cultural infrastructure is situated rather than parallel with it.

From an inspection of the inverted EM conductivity sections, a good deal of vertical variation coupled with continuity in the horizontal direction (along the flight line) is observed. The vertical variations suggest the presence of
mappable electrical conductivity contrasts within the geologic layers, and the lateral continuity implies consistency of the inversions. The majority of the electrical conductivity sections display a 3 layer model (Figure 2b) consisting of a lower conductive unit (>30 mS/m), possibly up to 100 m thick, overlain by a more resistive unit (<15 mS/m) ranging between 75 and 100 m thick and an upper discontinuous unit of higher conductivity. The validity of this upper layer is open to question as it is generally expressed in the upper 30 m of the conductivity sections where there is little early-time EM data to support it.

Together the 5 boreholes drilled by the OGS within the EM test area and the 11 boreholes geophysically logged from the broader South Simcoe area provide high quality geological logs as well as downhole electrical conductivity profiles of the Quaternary sequence and the upper part of the underlying Paleozoic bedrock. An assessment of the ranges of electrical conductivities of distinct lithologic units derived from borehole geophysical logging shows a total range of the medians of 77 mS/m with the majority of the facies falling into the range of 58 to 84 mS/m. The exception is organic-rich clay which has a median value approaching 135 mS/m. With limited information, bedrock conductivity values tends to be low with values ranging between 50 and 55 mS/m. With the exception of the organic-rich clay units, it is unclear whether the relatively small contrasts in conductivity observed between the various lithologic units are sufficient to map distinct hydrostratigraphic units in the overburden sequence.

![Figure 2](image_url). Example conductivity sections showing: a) a 2-layer model from the southern part of the survey area where shale bedrock is overlain by till then Oak Ridges Moraine sand and b) a 3-layer model from the northern part of the survey area where limestone is overlain by till then a thick sequence of fine-grained glaciolacustrine deposits then silty/sandy till. Black dashed lines mark significant breaks in conductivity.

Parts of two inverted conductivity sections are presented in Figure 2 in order to illustrate the correlation with the geological sections obtained from two cored boreholes. As is typical of many of the conductivity sections, the deeper parts are characterized by a region of higher conductivity (imaged as red) which, in many cases, is coincident with the bedrock surface. In areas of shale bedrock, as occurs in Figure 2a, this increase in conductivity is expected. In areas of limestone bedrock, one would expect a decrease in conductivity, not an increase as is observed in Figure 2b. It is possible that either shaley partings in the limestone succession or slightly saline formational waters are responsible for this increase in conductivity. Discontinuities in this higher conductivity unit may represent the locations of buried bedrock valleys. In at least one location, a prominent residual gravity low is coincident with one of these discontinuities. Further investigation is required to support this claim. Much of the overlying Quaternary sequence is
depicted as a relatively resistive unit in the EM sections. Whether it be sand-dominated (60-65 mS/m) as in Figure 2a or silt and clay-dominated (70-80 mS/m) as in Figure 2b there is very little difference in the apparent conductivities derived from the airborne survey. This observation is consistent with the results of the borehole logging. Sand layers approaching 10 m in thickness within a predominantly fine-grained succession are too thin to resolve using the current instrumentation. The upper higher conductivity layer in Figure 2b is enigmatic as it does not appear to be associated with a unit that would be perceived as conductive. Most uplands are capped by a layer of pebbly, silty to sandy till which in some of the geophysically logged boreholes has returned highly variable EM readings with a range of 44-294 mS/m. Alternatively, the response may simply reflect cultural effects associated with near-surface infrastructure.

5. SEISMIC REFLECTION

A 20 km seismic reflection survey is planned for the fall of 2013 in collaboration with the Geological Survey of Canada to assist with the interpretation of the airborne time-domain EM survey data. The main objectives of this survey are to image the bedrock surface and produce an improved architectural framework for the overlying Quaternary units. This information will also enable a refined conceptualization of the main hydrostratigraphic units and their contact relationships.

6. REFERENCES


Ontario Geological Survey 2012. Ontario airborne geophysical surveys, Magnetic and Electromagnetic Data, Grid and Profile Data (ASCII and Geosoft® Formats) and Vector Data, South Simcoe County Area; Ontario Geological Survey. Geophysical Data Set 1070.

THREE-DIMENSIONAL GEOLOGIC MAPPING OF LAKE COUNTY, ILLINOIS: NO SMALL TASK

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ABSTRACT
A three-dimensional geologic model for Lake County, Illinois has been made by the Illinois State Geological Survey (ISGS) based on analysis of data from more than 200 exploration boreholes, 24,000 water-well and engineering borehole records, and several miles of geophysical transect data. A data-sharing agreement with the county has facilitated the exchange of digital data, including access to county-wide, high-accuracy datasets that facilitate mapping and quality control of public domain information, such as water-well records. In Lake County, the variability of the continuity and physical characteristics of deposits, typically associated with a number of inset proglacial depositional sequences, necessitates application of both lithostratigraphy and allostratigraphy to map and model geologic surfaces. A number of map units are defined based on genesis, as a practical matter, where bounding surfaces are more readily identified than the boundaries of discrete lithologic units. Throughout the mapping process, ISGS staff have interacted with local decision makers for them to gain an understanding of local natural resource issues, and to provide geologic information to those making decisions. Interactions have included presentations to the county board, local municipalities, industry, and the general public. Future challenges include the design and presentation of the three-dimensional model for the end users.

1. INTRODUCTION
Lake County, Illinois, is bounded by Wisconsin along its northern border and Lake Michigan along its eastern border (Figure 1). As an extension of the Chicago Metropolitan area, the county has a population of more than 700,000 in about 445 square miles of land (nearly 1600 persons/square mile) that use both surface water from Lake Michigan and groundwater from both glacial deposits and carbonate and sandstone bedrock.

Lake County contains fifty-five individual villages, towns, and cities, as well as a number of other unincorporated entities. The large number of individual government units, large population, and mix of urban, suburban, rural, agricultural, and unique natural areas has presented a challenge to planning for long-term management and supply of water to the residents of the county. In part, geologic mapping has been driven by the need to determine the viability of developing further the groundwater resource, compared to the cost of building infrastructure to withdraw, treat, and transport additional quantities of surface water from Lake Michigan to more distant communities.

Mapping the three dimensional geology of the county can be categorized as three broad components: 1. discovery of a geologic framework; 2. classification of mappable geologic entities from that framework (lithostratigraphic units and allostratigraphic units); and 3. implementation of technological steps and the use of software components to carry out geologic mapping.

2. GEOLOGIC FRAMEWORK
Lake County, Illinois is underlain by a number of glacigenic sequences that record the fluctuations of the Lake Michigan lobe ice margin in and out of the Lake Michigan basin (Figure 1) during the lobe’s last occupation of northeast Illinois between about 18,300 and 16,700 cal yr BP (15000 and 13500 14C yr BP). In Lake County, the variability of the continuity and physical characteristics of deposits, typically associated with a number of inset proglacial depositional sequences, necessitates application of both lithostratigraphy and allostratigraphy to map and model geologic units. A number of map units are defined based on genesis, as a practical matter, where bounding surfaces (primary depositional contacts or erosion surfaces) are more readily identified than the boundaries of discrete lithologic units. There are facies changes within the units, with considerable lithologic variation in some places.

Importantly, the glacier was constrained by the geometry of the depositional basin—the surface of which includes both bedrock and older glacial deposits. Like other places around the Great Lakes where the ice margins of outlet lobes were constrained in basins, the primary depositional environments were associated with local to regional glacial
lakes. These settings differ from others on a continental scale where meltwater could drain away from ice margins. Differences in these two contrasting situations dictate how a geologist approaches subsurface geologic mapping in glacial terrain. For settings where lacustrine deposits are dominant (local to large glacial lakes), allostratigraphy is a viable approach to mapping units. In these cases, mapping units based on depositional environments is necessary where bounding surfaces become the primary mappable attribute. Because most to all of the sediment shed from the glacier is trapped in the depositional environment(s), sediment variation (e.g. thickness of sediment bodies, grain size of discrete bodies, etc.) is great. This is the case for Lake County. This contrasts to areas where meltwater drains away from the ice margin in constrained channels, and where fine-grained sediment is transported to flood plains and ocean floors via large continental drainage systems. In these environments, lithostratigraphy is more applicable where diamictons, for example, are more uniform in physical characteristics and seemingly are mappable over large areas.

![Figure 1](image_url)

**Figure 1.** Area of Lake County, Illinois, illustrating the creation of a depositional sequence in a glacial lake and outlining bounding surfaces that define allostratigraphic units.

### 3. METHODS

**Field data collection**

More than 200 boreholes were drilled by wire-line and direct push methods in which more than 24,000 feet of continuous core was recovered. Down-hole natural gamma-ray logs were obtained from each borehole. By working cooperatively with private water-well drillers, more than 400 additional natural gamma-ray logs were obtained from
cased private water wells during construction of the wells. More than 21 miles of surface geophysical transects were
made using radar, electrical resistivity, and seismic reflection. Outcrops are rare, revealed in only a few gravel pits
and small road-side cuts, but nevertheless provided some information on local depositional settings.

Data standardization
The lithologic and descriptive logs for location-verified geologic, engineering, and water-well records were
standardized so that the descriptive data could be logically analyzed and displayed graphically (Figure 2).
Importantly, standardization does not mean simplification. Replication of short to long verbose descriptions were
mapped to five separate database fields, corresponding to a primary lithology, color, textural modifiers, and
consistency of the material being recorded. To ensure quality control, the standardization process relies on look-up
tables for allowable terms in each field; additional terms were added look-up tables as needed. Geologic logs and
water-well logs had some differences in data structure and accompanying descriptive terms because there is both a
different precision in geologic logs as well as fundamental differences in terminology (driller vs. geologist). For
example, geologic logs typically contain both a material and a texture (e.g. diamicton and loam, respectively); terms
that absent on most water-well logs. Geologic logs also often contain an interpretation. Therefore, a different set of
look-up tables and different application of fields were used to accommodate different terminologies. In the water-well
record database for the project, approximately 132,000 individual descriptions (more than 25,000 unique) were
parsed into about 40 primary lithologies with accompanying color and other modifiers.

![Figure 2](image.png)

Figure 2. Lithology standardization database windows viewed in Microsoft Access. An easy to use graphic interface
(a.) for filtering data provides advanced query options to group similar descriptions for standardization. The user does
not need to know a query language or query functions. The “Edit” function on the interface returns the result of the
filter in a table (b.) for editing. The table (b.) shows the original drillers’ description in the “Description” field (left) and
new standardized terms in the “Lithology”, “Color”, “Consistency”, “Mod1”, and “Mod2” fields (right). Editing takes
place by selecting one or more cells in a field, and choosing a value in the drop-down list of terms (c.) available for
that field. The available terms are provided in a lookup table. The example drop-down list (c.) shows some of the
terms available to populate the “Lithology” field.
Borehole location verification
A full-time staff position was dedicated to location verification of all borehole records. Through data-sharing agreements with local units of government (typically counties or county GIS consortiums) we obtain detailed property parcel layers and other vector and raster map layers that help us identify the location of water wells or engineering boreholes on the ground. A code was applied to each borehole record in the database that indicated the level of confidence in the location, which in turn was used to determine if the record would be included in the mapping. For this project, 15,000 water-well records (~38%) were rejected from a total set of 39,000 because of inadequate locational information.

Interactive 3D analysis in ArcGIS
The standardized descriptions for the lithologic logs provided the ability to analyze the records statistically or visually. To analyze the data visually, we developed our own scripts* for ArcScene that created three-dimensional (3D) shapes of the boreholes. The 3D representations of the borehole data are 3D multipatch features in shapefile format. Importantly, the multipatch features have all of the attributes included in the borehole database (elevation, thickness, standardized term fields, original description, etc.) (Carrell 2013, DeMeritt 2012). Geologic cross sections, geophysical profiles, and any other kind of 2D and 3D profile, object, or data can be added to the 3D Scene.

The visual display in ArcScene and the ability to navigate around and through all datasets in three-dimensional space facilitated the discovery of geologic features and the interpretation process. The scripts provided the ability to easily populate an attribute table with interpretations based on mass selections of intervals for multiple borehole or water-well records (Figure 3). This workflow allowed for mapping in small discrete areas for testing hypotheses about trends of geologic or depositional features. Surface interpolation and creation of structure contour surfaces then proceeded based on the elevation values of the top or bottom of the attributed record intervals (Figure 3).

Figure 3. Screen capture of a ArcScene window showing elements of the 3D geologic mapping workflow. a.) Custom toolbar with buttons that execute custom scripts; b.) selected intervals (highlighted in light blue) of 3D multipatch features that represent lithologic records, note that only intervals that represent sorted sediment are shown; c.) natural gamma-ray log traces; d.) exploration test hole shown in larger diameter to highlight better quality information, displayed as a separate dataset; e.) selected multipatch features highlighted as attribute table records, interpretation for geologic unit identified in field by red arrow; f.) “Create Surface” script executes the TopotoRaster geoprocessing tool based on tops or bottoms of selected intervals (user choice); g.) raster surface rendered from selection of interpreted record intervals using the “Create Surface” window shown in f.) and h.) key to 3D borehole representations, based on standardized terms.
Creation of mapped surfaces

Once data were attributed with interpretations in ArcScene, as shown in Figure 3, geologic surfaces were interpolated using the ArcGIS TopotoRaster geoprocessing tool. A draft surface for each map unit was rendered to validate interpretations, first in patches or small local areas (example Figure 3g) then as regional layers. However, a necessary component to the mapping is shaping the geometries of features (noting that much of mapping done here was based on depositional units defined by bounding surfaces), which is a limitation of most interpolation software. Hand-drawn structure contour lines were made to control the shape of ice-contact faces, control placement of edges of braided stream deposits, control the orientation and shape of depositional slopes, or otherwise create the lateral boundary or edge of the map unit. The software application of choice for the process of drawing shapes and lines was Adobe Illustrator with the MAPublisher plug-in (Figure 4) MAPublisher applies world coordinates to the Adobe Illustrator art board, allowing for the creation of georeferenced artwork. Importantly, the Adobe Illustrator drawing tools provided for efficient creation of lines and shapes with attributes that could be exported in a variety of geospatial formats. As a productivity tool, this workflow outpaced the labor intensive digitizing, attributing, and editing of the ArcGIS software suite. The structure contour lines created in Adobe Illustrator were exported in shape file format, then included with the interpreted borehole point data for geoprocessing with the ArcGIS TopotoRaster interpolation tool (Figure 5).

4. SUMMARY

Geologic contacts between regional depositional sequences and erosional surfaces are primary subsurface mappable surfaces in Lake County, Illinois. The contacts are bounding surfaces, and define allostratigraphic units. Other mapped units or surfaces are defined by lithostratigraphic properties. Therefore, both allostratigraphic and lithostratigraphic characteristics define the mappable units within the geologic framework. Mapping the geologic surfaces within the framework was facilitated by using custom scripts and software utilities developed by the Illinois State Geological Survey for Microsoft Access and ArcGIS software. In addition, the Adobe Illustrator drawing tools coupled with the MAPublisher plug-in that enables georeferenced and attributed features in Illustrator, provided for
efficient creation of structure contour lines and other features that could be exported in a variety of GIS formats for use in the surface interpolation process or 3D viewing in ArcScene.

The large and dense population of this county has created a need for detailed geologic information. The large population has also created a prolific number of subsurface geologic records in the form of water-well and engineering borehole records, which has, in part, enabled detailed, 3D geologic mapping. The data within the large number of subsurface records revealed some of the variation associated with the inset lacustrine sequences, but did not replace the need for exploration test holes. Further, even though we drilled more than 200 exploration holes, that number was just enough to sample the wide array of landforms and sediment packages, and to provide us an understanding of characteristics of the subsurface geology. This understanding has enabled us to provide counsel to the local officials, and their hydrogeologic consultants, about development of groundwater resources. In particular, we have been able to explain why some communities have not been able to find suitable aquifer material in areas near existing groundwater production wells. For planning purposes, dramatic changes in geology over short distances has weakened confidence in long-term reliance on groundwater.

Importantly, the geologic mapping, and our knowledge that we export from the mapping process, has aided in the decision making about planning for additional water withdrawal from Lake Michigan. There are two very important parts to this planning. First, the State of Illinois is limited by an U.S. Supreme Court decision on the quantity of water that the State can withdraw from Lake Michigan. Therefore, each additional allocation for some Illinois communities impacts the potential future use of that resource for other communities. Second, the cost for development of the infrastructure to pump, treat and transport water from Lake Michigan to communities in western Lake County is estimated to be more than $200 million. The stakes are high, so we better understand the details of the geologic framework.

* links to the scripts for ArcGIS that were used in the geologic mapping:
  http://resources.arcgis.com/gallery/file/geoprocessing/details?entryID=C83CC388-1422-2418-7F10-B4D3DF5F1EE6
  http://resources.arcgis.com/gallery/file/geoprocessing/details?entryID=3CB0669C-1422-2418-7F29-072DB9AA0AE3
  http://resources.arcgis.com/gallery/file/3dgis/details?entryID=471521CC-1422-2418-34BA-6D2E07EB617

5. REFERENCES


1. INTRODUCTION

Alpine Foreland Basins, due to their geological evolution, feature a unique geological inventory which can contribute substantially to meet Europe’s ambitious targets for carbon emission reduction. The more than 5000 m deep sedimentary ‘Molasse’ basins along the northern and southern fringes of the Alpine mountain range (Fig. 1) offer abundant deep geothermal potential, storage capacity to attenuate intermittency of weather dependent wind and solar energy, and space for underground storage of gas or CO₂.

Figure 1: Map of the Alpine Foreland Basins, the GeoMol project area covering overall 89,000 km², and the GeoMol pilot areas for a more detailed assessment of specific geopotentials and the geological risks restricting their utilization.

Exploiting these subsurface potentials requires considering existing oil and gas claims as well as groundwater rights and, thus, must be based on a sound and holistic 3-dimensional assessment of the fundamentals: An adequate comprehensive understanding of the deep subsurface is a pre-requisite for the sustainable management and efficient use of geopotentials and reduces the financial risks. Avoiding usage conflicts and areas at risk demand cross-border coherent information on the structures and features of the subsurface based on 3D geological models.

Figure 2: N–S cross-section of the North Alpine Molasse Basin east of Munich (after Lemcke 1988, from Diepolder and Schulz 2011) exemplifying two geopotentials: Temperatures up to more than 150°C in the Upper Jurassic (Malm) aquifer, giving rise to the most intensely used hydrothermal reservoir in Central Europe, and the typical setting of hydrocarbon structural traps.

The increasing relevance of geological information for policy and economy at transnational level has recently been recognized by the European Commission, who demanded a common European geological knowledge base. GeoMol’s transnational approach responds to that, providing consistent information via an infrastructure for multi-dimensional subsurface data ensuring full interoperability among the involved GSOs “as the natural custodians of the subsurface (…) assisting governments, industry, and the general public to manage the subsurface in an integrated, holistic, and sustainable manner” (Kessler et al. 2009).
2. PUTTING UP THE SCAFFOLDING: DATA PREPARATION AND HARMONIZATION

An ongoing challenge in 3D modeling down to great depths is the availability of data with an adequate distribution and resolution to address issues trustworthy. GeoMol’s 3D geological models are based on seismic data, scattered and clustered borehole evidence and the conceptual models of the basin evolution. By far the largest data pool are seismic sections and, lately, 3D seismic surveys. More than 28,000 km seismic lines have been selected as the basis for structural 3D modeling and to interconnect existing 3D models in their true spatial relation. Originating from multiple sources and various dates of origin these data are subject to heterogeneous interpretations which have gone through several paradigm shifts over the last decades. Thus, it is imperative to standardize the data with regards to technical parameters and content prior to further analysis, exploiting the technical advances in seismic processing:

An effort has been made to adjust all lines to the same reference level, amplitude and step of signal processing to avoid mismatching at intersections and at the country borders (cf. Capar et al. 2013). After applying the whole sequence of processing steps from scanned paper plots to filtered post-stack migrated SEG-Y files structural features can be identified more precisely and certain seismic pattern can be used in sedimentary facies interpretation. Both features are critical parameters for the existence of geopotentials: the fault network determines the rock mass permeability and the occurrence of structural traps, facies distribution controls the hydraulic conductivity of aquifers. To improve the accuracy and reach of correlating lithologies and their seismic signature, several synthetic seismograms based on drill hole measurements have been generated and parallelized with the bore logs.

The stratigraphic subdivision of the Alpine foreland basins has evolved from regional approaches and reflects the complex basin evolution featuring laterally varying sedimentary cycles. Grown historically different nomenclatures and subdivisions on the detailed scale are used. Thus, working cross-border requires also a semantic harmonization and the alignment of stratigraphic peculiarities to allow the correlation of a uniform litho-stratigraphic column with the prominent seismic reflectors traceable over the entire basins.

![Figure 3: A pile of seismic reflectors, conspicuous after reprocessing, correlated with borehole evidence and the cross-border harmonized stratigraphic column of the Northern Molasse Basin.](image-url)

As many data sets used in 3D modeling are classified data, access restrictions require that all model building may be implemented at the legally mandated regional or national GSO only. For a transnational project this means a maximum of coordination from the very beginning of the data preparation and the 3D modeling processes. GeoMol’s 3D modeling procedure consists of several workflows customized to the specific needs of each partner, depending on the 3D modeling software used, and if modeled in time or depth domain (cf. Rupf et al. 2013). If modeling in time-domain, calibration of layer surfaces is done by borehole data re-converted into time-domain based on check shot data available for many hydrocarbon exploration drillings. Regionalized velocity models for time-depth conversion are applied at a late stage of modeling only, to facilitate later model refinement by additional seismic sections where needed. Trans-border accuracy of fit of the evolving 3D models and their intermediary products is verified by periodic check-up of all adjacent sub-territories during the whole modeling period. Since recently, with the deployment of the first modules of GST (cf. Chapter 4), the necessary transformation of country-specific coordinate systems for this cross-check runs real-time adapting the partners’ reference system on the fly and does no longer require the cumbersome bilateral file exchange.
3. 3D MODELLING AND GEOPOTENTIAL ASSESSMENT

Most of the geopotentials in the tilted sedimentary sequences of Alpine Foreland Basins are bound to structural features such as faults (fault traps, increased permeability) or anticlines (anticline traps). On the other hand, seismo-genetic structures like the buried Apenninic nappe fronts are the source of geo hazards – as recently evidenced by the magnitude 5.8 May 2012 earthquake in the Po Basin – and thus a strong limiting factor for the utilization of geopotentials. A chief purpose of 3D modeling therefore is the three-dimensional visualization of the structural setup and characterization of the fault network.

Core of the project GeoMol (and additional model building beyond the project area) is a structural 3D subsurface model of the principal units for the entire Northern Molasse Basin covering almost 55,000 km², providing the framework to fit in all existing and emerging models in their true spatial setting. Five detailed models in pilot areas (Fig. 1) will be built to cover specific questions of subsurface use and/or seismic risk which might inhibit the utilization of geopotentials. These models will consist of up to 13 litho-stratigraphic units ranging from the Cenozoic basin fill down to Mesozoic and late Paleozoic sedimentary rocks and the crystalline basement.

A principal challenge in multi-claim wide geopotential assessment is the inadequate availability of datasets which allow the interpolation of rock properties at regional scales. Geologists commonly address these gaps between hard data through implicit knowledge, conclusion by analogy and process-based conceptual models, e.g. depositional models based on the facies distribution. Thus, the regionalized facies interpretation using seismic signatures will add further information on rock properties to the 3D structural models. Thanks to the numerous activities in the field of deep geothermal energy providing well-log temperature data, an improved geo-statistical temperature model taking into account bulk rock properties and indicating uncertainties will be integrated into the 3D geological models.
Porosity and permeability data, however, the key data for assessing subsurface storage capacities and for numeric modeling e.g. of groundwater flow, can be regionalized in certain areas only, such as the pilot areas. Equally, hydrochemical and hydraulic properties of the deep (geothermal) aquifers will be regionalized in exceptional cases only. Like all widely spaced evidence these parameters are subject matter of the metadata catalogue (Chapter 4)

4. GEO DATA INFRASTRUCTURE AND INFORMATION CHANNELS

The successful implementation of a transnational project facing diverse data policy, data base systems and software solutions requires a sophisticated tool for 3D data interoperability and web visualization. Even though many data exchange and information systems as well as web accessible tools have been developed the 3D geological community still lacks the ability to exchange 3D geo data efficiently across the diverse systems (Diepolder 2011). Thus, to set up and deliver truly seamless 3D geological information, a key issue of GeoMol is to provide a geo data infrastructure complying with both, the data policy of the project’s member states (and beyond) and the European Commissions’ request for harmonized geological information to support policy and economy at transnational level. This development in the making called GST, Geo Sciences in Space and Time (Gabriel et al. 2011), might be also an important contribution to the future pan-European Geo Data Infrastructure as prepared and designed by the EGDI scoping study (http://www.egdi-scope.eu/).

Major technical characteristics and principal features of GST have been described previously (Diepolder 2011, Gabriel et al. 2011), the fundamental object-relational data model has been imparted in detail lately (Le et al. 2013). In summary, GST’s objective can be outlined as giving access to visualize and manipulate geoobjects using open standards, aimed at the generation of geomodels which will use thematic geo-information gathered at various scales to model and visualize the key spatial, geological, geophysical and geochemical parameters. A major concern is the management of large models, e.g. GeoMol’s framework model(s), and the ability of 3D tiling into spatially restricted models with refined resolution, i.e. models of GeoMol’s pilot areas.

GST will be the core of GeoMol’s web-based data share and analysis system designed to serve the GSOs concerned and the scientific community. Recently common users spaces have been installed providing a central accessing point to manage locally stored data at each of the project partners IT site. This distributed-organized system allows to keep all data locally and to share just cleared portions of the data, thus adhering to national regulations on geo data access. As GST also allows for a dynamic generation of virtual drilling profiles (and thus enables to deduce classified borehole data) a role based log in is required giving full access only to the legally mandated or licensed bodies.

It is generally acknowledged that 3D models provide the best information to tackle geological and environmental issues. However, the stakeholder analysis implemented within GeoMol’s work package ‘Users’ Needs’ clearly revealed that only a miniscule minority of potential users have the facilities and capability required to directly exploit 3D models. The majority of stakeholders strongly prefer 3D derived 2D information, such as digital maps implementable into GIS projects. To make sure that GeoMol’s outputs are also a benefit beyond the geological community and academia they have to be converted into ready-to-use information customized to the needs of the users. Thus, two further channels for information distribution are provided, (1) to serve the administration and decision makers, and (2) to raise the awareness of the general public and to provide educational material.

GeoMol incorporates a variety of stakeholders and advisors from different areas of expertise to assist in the appropriate design of its products. To satisfy the users’ demand for ready-to-use 2D products an interactive web mapping application will be implemented, where project results can be searched, spatially visualized and queried, also allowing for the dynamic generation of vertical and horizontal geological sections. In addition, web mapping services (WMS) will provide a metadata catalogue for information on the availability of spatial data, on the access to these services and their restrictions of use. This metadata database has to comply with both the requirements of the EU directive INSPIRE and national spatial data infrastructures.

To meet the societal needs for information and the citizen’s concerns about the impact of geopotential utilizations, GeoMol’s website www.geomol.eu, now providing just static textual information, will be extended by a GST-based interactive visualization tool which enables the general public to slice through, explode and virtually pierce through the subsurface of the Alpine Foreland Basins – however, at a scaled down overview 3D framework model only.
5. REFERENCES


6. ACKNOWLEDGEMENT

The project GeoMol integrates partners from Austria, France, Germany, Italy, Slovenia and Switzerland and runs from September 2012 to June 2015. The project is co-funded by the Alpine Space Programme www.alpine-space.eu as part of the European Territorial Cooperation 2007-2013. For further information please refer to www.geomol.eu.
1. INTRODUCTION

The Geological Survey of the Netherlands builds and maintains two different types of nation-wide models: (1) layer-based models in which the subsurface is represented as a series of tops and bases of geological or hydrogeological units and (2) voxel models in which the subsurface is subdivided in a regular grid of voxels containing several geological properties. Layer-based models include the geological framework model DGM (Digital Geological Model, Gunnink et al., 2013) and the hydrogeological model REGIS II (Regional Geohydrological Information System, Vernes and Van Doorn, 2005). Voxel models include NL3D with voxels of 250 by 250 by 1 m, and the detailed GeoTOP model with voxels measuring 100 by 100 by 0.5 m (Stafleu et al., 2011).

Modeling typically starts with a geological framework and this is then further refined to include user-specific parameters. In geohydrological applications, the geological framework model is used to distinguish geological units that act either as aquifer or as aquitard and to further parameterize these units with hydrological parameters, like porosity and hydraulic conductivity.

This extended abstract describes the parameterization for geohydrological applications of both the layer-based model REGIS II and the voxel model GeoTOP. The main emphasis is on building spatially distributed models of hydraulic conductivity, which are consistent with the geological model and can be used in groundwater flow modeling.

Hydraulic conductivity is a key parameter in geohydrological modeling. Direct measurements of hydraulic conductivity at the model-scale are often not available. Instead, hydraulic conductivity measurements are derived from pump-tests (which are costly and often multi-interpretable), from empirically derived relationships with grain-size distributions or by measuring hydraulic conductivity of small volumes of sediments that are extracted from boreholes. This results in the concept of “the missing scale” (Tran, 1996), and upscaling is necessary to derive meaningful parameters at the model-scale.

2. REGIS II: PARAMETERIZATION OF A LAYER-BASED HYDROGEOLOGICAL MODEL

The layer-based models DGM and REGIS II cover the entire country of the Netherlands and subdivide the subsurface in geological units (DGM), while REGIS II further subdivides the geological units into aquifers and aquitards. The models are based on a dataset of some 16,500 boreholes, evenly distributed over the country. Each interval in the boreholes is classified into one of 7 lithological classes (peat, clay, sandy-clay, fine sand, medium sand, coarse sand and gravel), which form the basis for the parameterization of the aquifers and aquitards in the REGIS II model. Hydraulic conductivity measurements are only sparsely available, and therefore hydraulic conductivity was correlated with the lithological classes and then interpolated to populate the entire volume of the geohydrological unit.

The procedure is as follows:

1. For each interval in the borehole, the sediment is classified into geological unit (at Formation or Member level) and into one of 7 lithological classes.
2. In each borehole, aquifers and aquitards are distinguished, based on the lithological classes. This distinction is applied separately for each geological unit; thus, individual aquifers and aquitards always belong to a single geological unit, and do not cross unit boundaries.
3. Representative minimum and maximum hydraulic conductivities (based on experience and literature) are extracted from a database and applied to each lithological interval; the database contains hydraulic conductivities for each combination of geological unit and lithological class.
4. All borehole intervals that belong to an individual aquifer or aquitard are grouped and upscaled to a representative hydraulic conductivity for the aquifer or aquitard at the location of the borehole.
5. Interpolation using Kriging with uncertain data results in a raster layer for the entire aquifer or aquitard.

The upscaling in step 4 takes the thickness of each borehole interval into account and uses the arithmetic mean for horizontal, and the harmonic mean for vertical hydraulic conductivity. By assuming a log-normal distribution, the minimum and maximum conductivities are used to construct a probability density function (pdf) from which we repeatedly sample (at random) hydraulic conductivities for each borehole interval. The individual samples for each aquifer or aquitard are then processed to obtain the average hydraulic conductivity and the corresponding standard deviation. The Kriging interpolation uses the average and standard deviation for each aquifer or aquitard at the borehole location to calculate hydraulic conductivity for the entire aquifer or aquitard. Examples are given in Figure 1. In this way, the entire country is parameterized, resulting in 128 aquifers and aquitards.

![Figure 1. Two examples of hydraulic conductivity for the REGIS II model. Sandy aquifer with horizontal hydraulic conductivity (left); clayey aquitard with vertical hydraulic conductivity (right).](image)

3. GEOTOP: PARAMETERIZATION OF A VOXEL MODEL

GeoTOP schematizes the shallow subsurface in millions of voxels of 100 by 100 by 0.5 m up to a depth of 30-50 m. Each voxel contains estimates of the lithostratigraphical unit the voxel belongs to, the lithofacies, and the main lithological class (peat, clay, sandy clay, sand, and, if applicable, sand grain-size class). From a limited number of selected boreholes, undisturbed samples were collected to determine the hydraulic conductivity using either the constant head method (for sandy samples) or the falling head method (for clayey samples).

In order to link hydraulic conductivity, measured on the small-sized samples, to the GeoTOP voxel model, the samples were classified into lithostratigraphical unit, lithofacies and lithological class. This resulted in a unique dataset of geologically classified samples with hydraulic conductivities. Hydraulic conductivity is measured for a small volume: 0.0004 m³ for sandy samples and even smaller for clayey samples. The model block-scale of GeoTOP (5000 m³), however, is several orders of magnitude larger, making some kind of upscaling necessary (Figure 2, left). Several upscaling methods exist, but none of these take the internal heterogeneity at the model-scale into account. Especially lithofacies units with layered sediments and lithofacies units with short-scale variation (for instance rapid alternations of sand and clay in tidal deposits) are important to consider in the upscaling method (Figure 2, right).
Geological expert-knowledge about the spatial scale at which the alternations of sand and clay within a voxel occur, was used to determine the 3D spatial distribution of lithology within a voxel. The initial GeoTOP voxel (100 by 100 by 0.5 m) was subdivided into tiny voxels of 0.5 x 0.5 x 0.05 m. Using Sequential Indicator Simulations (SIS), we produced 50 spatially correlated models of sand-clay occurrence (Figure 3, left). The proportion of sand and clay was allowed to vary between 10% clay - 90% sand and 50% clay - 50% sand. Each of these models was then populated with spatially correlated hydraulic conductivities using Sequential Gaussian Simulations (SGS; Figure 3, right). The hydraulic conductivities that were used were derived from the distribution of measured hydraulic conductivities for the specific lithofacies and lithology.

For each proportion of clay-sand, the 50 3D models of hydraulic conductivities were then used to calculate an upscaled hydraulic conductivity. This was done by applying a ModFlow groundwater flow model to the 100 by 100 by 0.5 m size voxel, with a vertical head of 1 m and "no-flow"-conditions at the vertical boundaries of the voxel. This procedure resulted in 50 upscaled hydraulic conductivities, for each proportion of clay-sand, and for each spatial correlation that was used to generate the clay-sand models and the hydraulic conductivity models.
Figure 4 presents some results of the upscaling procedure. The upper row shows the vertical hydraulic conductivity, as were derived from the measurements on the small samples, while the bottom graph shows the upscaled vertical hydraulic conductivity, for a voxel containing 30% clay and 70% sand. This distribution of sand and clay within the voxel results in an upscaled conductivity that is considerable larger than the conductivity of the clay samples, but not as large as the sandy samples.

![Figure 4](image)

**Figure 4.** Vertical hydraulic conductivity (as measured from the samples) for sand and clay (top row) and upscaled vertical hydraulic conductivity for a voxel containing 30% clay and 70% sand.

Based on the lithofacies-model of GeoTOP, upscaled hydraulic conductivities were assigned to each lithofacies and the hydraulic resistance to vertical flow for each voxel was determined by multiplying the upscaled hydraulic conductivity by the thickness (in this case 0.5 m). This procedure resulted in a model of the hydraulic resistance of the Holocene deposits (Figure 5), which is an important input in regional groundwater flow modeling.
Figure 5. Hydraulic resistance for vertical flow in days for the province Zeeland, the Netherlands, based on upscaled vertical hydraulic conductivity.

4. REFERENCES


During the last 15 years a huge geophysical groundwater mapping project covering almost 40% of Denmark has led to a radical improvement in the geological understanding of the uppermost 300 m. The objective of this mapping is to produce detailed groundwater vulnerability maps and to get an overview of aquifer localization and interconnection. Detailed mapping requires spatially dense geophysical data combined with geological information from new boreholes. The spatial data coverage is obtained by using the SkyTEM system, while high resolution seismic profiling is acquired along selected transects. The result is 3D resistivity volumes geologically interpreted and modeled with support from the seismic data and stratigraphic and lithological information from boreholes. A new detailed stratigraphic framework for the Miocene, hitherto unknown buried tunnel valley systems and subsurface glaciotectonic complexes constitute examples of the new knowledge that has led to revision of old maps, models and interpretations. In order to handle this new geological knowledge and to be able to extract useful, targeted and updated geological information at any time a nationwide 3D geological model is planned to be constructed over the coming years.

1. Geological Survey of Denmark and Greenland (GEUS)

The Geological Survey of Denmark and Greenland (GEUS) is an independent research, consultancy and advisory institution in the Ministry of Climate and Energy. The Survey has a staff of about 350 people. The Survey has a national responsibility within field operations, mapping, data compilation, data storage and research. GEUS also monitors and acts in advisory capacity within water, petroleum and mineral resources as well as environment and coastal zone management. The institution was established in 1888 and has since conducted a large number of projects nationally and internationally. During the last two decades GEUS has carried out development projects worldwide with focus on institutional capacity building, training and technical assistance to government agencies. GEUS plays a central role within the groundwater mapping project by delivering guidelines for mapping, modeling and data handling activities as well as by developing methods and databases for use in the project.

2. Geological setting

The size of the Danish land area is 43,000 km². The topography is flat or slightly hilly, with a maximum elevation of only 172 m above sea level. Most of the country consists of glacial and interglacial sediments overlying marine and fluvial Tertiary sand and clay, Cretaceous chalk and limestone. The cover of glacial and interglacial sediments is in average about 50 m thick, but ranges between more than 300 in buried valleys to only few meters. The buried valleys are found in many cross-cutting generations and create a very complex structure and composition of the glacial part of the subsurface as well as for the incised substratum (Jørgensen and Sandersen 2006). The Miocene succession in Denmark include fluvial sand deposits and sand deposited in prograding deltas. In between the sandy units, marine mud-dominated deposits occur (Rasmussen et al. 2010). The Miocene succession ranges in thickness from a few meters to more than 200 m. A large part of Denmark was heavily deformed during successive ice advances. The consequence of this is that widespread deformation and many glaciotectonic complexes were frequently left in the subsurface (Jakobsen 1996); often impossible to recognize in the terrain.
3. Groundwater mapping
The geophysical mapping project was carried out because the drinking water supply is 100% groundwater based. The objective of the project is to obtain a detailed description of the aquifers with respect to localization, extension, distribution and interconnection as well as their vulnerability against contaminants. The mapping project covers areas administratively selected as particularly valuable water abstraction areas.

The national borehole database (JUPITER) contains information dating back to 1926 and has until recently been the principal source of geological information. This database contains more than 240,000 boreholes, corresponding to an average of about 6 boreholes per km². But this data density only allows for a very general description of the complex geological composition of the shallow subsurface. Geophysical data are therefore necessary in order to create the much more detailed geological maps and models needed to reach the goals of the groundwater mapping project.

The mapping involves heavily use of geophysical survey methods, but also drillings, well logging, water sampling, hydrological mapping and 3D geological and groundwater modeling. Due to the complex geology it is found important to obtain spatially dense geophysical data covering large continuous areas. The exact choice and combination of geophysical methods depends on the geological setting and different combinations are typically used to cover both the shallow and deeper parts of the subsurface.

Electrical and electromagnetic methods are the most important geophysical methods used. These are often combined with reflection seismic profiling and borehole logging at selected localities. Contrasting electrical properties between sandy and clayey sediments are essential for the use of electrical and electromagnetic methods, but the capability of seismic methods to provide detailed structural information is also important. The airborne transient electromagnetic method, SkyTEM (Sørensen and Auken 2004), is possibly the most prominent method developed as a part of the groundwater mapping project. The first SkyTEM survey was carried out in 2003, and since then the SkyTEM method has been further developed and has proved to be much faster, efficient and reliable than the previously used ground-based, TEM method. The SkyTEM method is used for mapping to a maximum depth of 250–300 m.

For reflection seismic data, the development of seismic landstreamers used in combination with high frequency mini-vibrators has provided considerable savings of manpower and increased productivity compared to using traditionally planted geophones and cable lay-outs. The landstreamer technique together with careful processing provides high-resolution seismic data to depths of 500-1500 m.

4. Data processing, data interpretation and data bases
Special, integrated management systems are required to manage the large mapping project. It is important that data can be easily stored, extracted, interpreted, recombined and reused one time after the other. During the last decade, a system for handling and optimized use of the large amounts of data covering large areas has been developed in Denmark (Møller et al. 2009) (Fig. 2). This system includes a comprehensive national database for geophysical data, the GERDA database, the national borehole database, the JUPITER database, a software tool, The Aarhus Workbench, for processing, interpretation and visualization of electrical and electromagnetic data as well as preparation of these data for upload to the GERDA database, and finally a 3D visualization and modeling tool for 3D geological modeling and data quality control. A new database for the national geological model will in the future also be a part of the system.
All electric, electromagnetic and seismic data are collected with respect to specified guidelines and standards and reported to the GERDA database, hosted by GEUS. GERDA contains measured data as well as a geophysical interpretation of the data. The geophysical data are from data processing until geological interpretation handled in the Aarhus Workbench (http://hgg.au.dk/software/aarhus-workbench/). This software package has modules for handling, processing, inverting, interpreting and visualizing electrical and electromagnetic data, all combined on a common GIS platform and a common database. The prepared data are entered into GeoScene3D for further exploitation (Geoscene3D, http://www.geoscene3d.com).

5. Modeling techniques in use

3D geological models for hydrogeological purposes have traditionally been constructed as ‘layer-cake’ models, where the layers have been defined as the volume between two surfaces. Elements in such models are thus defined by bounding surfaces. The surfaces are defined by digitized points on cross sections and boreholes and/or on interpolated grids from the digitized points. Such models do not require advanced modeling software, but critical restrictions arise in areas of more complex geology difficult or impossible to model (Turner 2006). As the geology in Denmark is rarely organized as well-defined layers and therefore cannot be properly described in a full layer based model, a different approach is needed. One approach to increase the level of detail in 3D geological models is voxel modeling. This approach is at the moment elaborated at GEUS. For this, we have developed a dedicated voxel modeling concept, where the modeler is able to incorporate his or her cognitive interpretations during model construction (Jørgensen et al. in press). The concept intends to fully utilize all geophysical information contained in 3D resistivity grids from SkyTEM data. The conversion into lithology, lithofacies or lithostratigraphy is iteratively executed by dedicated manual tools. These tools, developed as a part of the GeoScene3D software, are designed to handle voxels in a flexible way by using various spatial voxel sorting and selection strategies (Fig. 3). The voxel modeling is typically supplemented with surfaces representing layer boundaries, erosional unconformities, etc.

Figure 3: Example of a modeling tool developed for manual editing of voxel models. By selecting a seed voxel in the resistivity grid (upper image) all neighbouring voxels within a given resistivity interval is pre-selected (middle image) and finally attributed with at certain lithology (lower image). From Jørgensen et al. (in press).

Figure 4: Map with model area (black), SkyTEM data (blue) and high-resolution seisms (red). The size of the model area is app 30 x 20 km.
6. Case study: The Tønder 3D geological model

The following case is a 3D geological model constructed in an area representative for the geology in Denmark and the type and amount of geophysical data available for the modeling are what is typically collected within a particularly valuable water abstraction area. The collected geophysical data is mainly a large-scale airborne transient electromagnetic survey (SkyTEM) accompanied with 38 km high-resolution seismic data (Fig. 4). New borehole data and old hydrocarbon exploration data have also been available for the model construction. The data are unevenly distributed across the area; the SkyTEM survey does not cover the entire model area. Cross-cutting tunnel valleys, faults, erosional unconformities, delta lobes and glaciotectonic complexes are among the geological features identified in the area (Jørgensen et al. 2012). The complexity varies as a result of shifting geological environments across the model area.

A broad geological overview and understanding of the area is gained by cognitive co-interpretation of the geophysical and geological data (Fig. 5). To address the high level of detail in the SkyTEM data, the model is constructed as a voxel model with lithofacies attributes supplemented with surfaces (Fig. 6). The model is mainly constructed manually by cognitive interpretation, but a newly developed semi-automated inversion technique (Foged and Christiansen 2013) has also been used to distribute lithology to voxels within the very heterogeneous glaciotectonic complexes.

The resulting model consists of 24 layer units, 32 surfaces representing layer boundaries and erosional unconformities, 7.5 mill voxels in 125 voxel layers occupied by 48 lithofacies and lithostratigraphic units (Fig. 6). The model reaches down to a depth of 600 m.

The pre-Quaternary section is in the deepest part composed of limestone followed by marine clay. This deeper part is covered by Miocene marine and fluvial sand, silt and clay layers. The Miocene is frequently disturbed.
by the incised buried tunnel valleys (down to 450 m). The Quaternary section above the valleys is deformed by

glacio-tectonism with the result of a very heterogeneous structure. This is seen in the central upper part of the model
(Fig. 6), where colors varying from red to brown indicate sediments from 100 % sand to 100 % clay. Most of the area

is covered by Late Weichselian outwash sediments (yellow) and Post Glacial sediments (pink).

7. Plans for a detailed national 3D geological model

The Tønder model area comprises roughly all major facets of the Danish geology and the area is therefore

ideal for testing the setup of the national 3D geological model. The general geological elements that we expect to

include in the national model have been modeled here, and more technical issues have therefore been put to test.

The Tønder model experience has also illustrated the need for detailed procedures in data handling as well as interpretations.

At this point we have a sketch for the future national model because the experiences from the Tønder area

have enabled us to describe the content and the workflow of a future national 3D model. Selected geological

elements of the future national model have been described and potential problems have been outlined. However, as

the Tønder model itself is only a fraction of a nationwide model, there is a broad range of issues that has to be

addressed in the coming years. This work is currently being initiated as a series of projects that focuses on creating

the best possible starting point for setting up the national 3D geological model.

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1. INTRODUCTION

For almost two decades, the Manitoba Geological Survey (MGS) has been producing and working with 3D geological maps and data, stimulated by demand for groundwater and hydrocarbons, as well as a desire to broaden our knowledge of the subsurface. In doing so, the MGS has spent a considerable amount of time creating a workable infrastructure for data collection, integration and output as it relates to 3D modelling. To date, the MGS has successfully modelled over 600,000 square kilometres representing over 50 geological units. Currently, the MGS is working to complete a 3D geological model of the Phanerozoic succession in southern Manitoba, south of latitude 55°N. This model is based on waterwell, oil and stratigraphic drillhole databases, as well as bathymetric and seismic data and surface datasets such as surficial geology (Keller, et.al. 2009).

The MGS employs a modelling methodology that consists of a series of cross-sections representing a 5 km wide east-west transect across the model area. The sections contain all available data within 2.5 km either side of the line of the section; this includes a topographic profile, a Phanerozoic unit distribution map, a ‘strip’ of the surficial geology map representing the 5km swath, as well as drillhole location and distribution maps. The uninterpreted sections are digitally created, printed and then hand interpreted by a geologist. The data included on the sections aid the geologist in visualizing the 3D distribution of data, thus allowing an appropriate cross-section to be drawn at the midline. The interpretation is then captured as a series of points representing unit ‘tops’. The points are recorded at a 5 km east-west interval along the section, and then imported and modelled. A slight modification to this methodology is being used for the current southern Manitoba model in that sections from all previous MGS 3D models have been concatenated, reinterpreted collectively and digitized. These digitized sections are directly imported into our 3D modelling software as a set of 134 sections or ‘vertical maps’ (Fig. 1, 2). The MGS uses the term ‘vertical map’ in order to bring added emphasis to our determination to integrate the methods of plan-view mapping and 3D subsurface modelling in our work.

Figure 1: Transects 25 represented as vertical map (Matile and Keller, 2012).
2. SOUTHERN MANITOBA MODEL CONSTRUCTION

The MGS cross-section methodology is covered in detail in Keller et al. (2009). As discussed above, it was decided that southern Manitoba, as a whole, should not be modelled in increments as was done in previous projects; instead, all previously completed models were combined into one large southern Manitoba model south of 55°N. This methodology allowed us to compensate for subtle nomenclature differences from area to area and to resolve some modelling issues resulting from rock formation edges along escarpments plotting in 3D at elevations other than the projected trend of that particular formation.

Geological transects representing a 5 km wide east-west swath containing all available geological data for that area, along with hand-drawn rock and Quaternary (sediment) units from previously completed regions, have been combined into 134 province-wide georeferenced vertical maps. Hand drawn transects from all previous modelling endeavours were scanned, georeferenced and combined, in ArcGIS, along with computer generated transects containing predicted stratigraphy points (PSP’s) or virtual drillholes from the TGI Williston Basin project (TGI II working group 2009). The resulting province-wide transects were digitized and stored in an ArcGIS geodatabase as a series of attributed polygons. The digitized sections depict up to 41 rock formations and 35 sediment units (Fig. 2).

The MGS is considering several methodologies for completing the 3D model of the area. One option is to model using the cross-section polygons directly. This method introduces several complexities. The cross-sections were digitized with an X coordinate representing the UTM Easting along the line of the section and a Y coordinate representing the elevation with a 150x exaggeration. Because the UTM Northing is consistent and known for each cross-section, a simple calculation (Z = Y/150, Y = Northing of section, X = X) can be used to place the sections correctly in 3D (Fig. 3). Once the sections are loaded, they must be modelled; using this method, the imported units
are represented by closed polygons (a top, base and sides). Coaxing the 3D software to create a ‘correct’ envelope using the closed polygons is a challenge that we are still struggling with. The Southern Manitoba model is the MGS’ first attempt at using polygons in the modelling process. All previous models have been constructed from a regular grid of points (5km x 5km) representing unit tops, therefore, the second option is to model using points.

Figure 3: Cross-section polygons displayed in 3D space (150x exaggeration).

Typically, it is a fairly straightforward and simple matter to extract points from polygons in ArcGIS. In this case, it is a bit more of a complex issue. Only the points/nodes representing the top of the digitized unit are of interest. There must be a node at the beginning and terminus (unit edge) of each top as well as along the line. To manually extract these unit top points from 134 cross sections would be incredibly time consuming. To this end, we have written a custom Python script which examines each of the sections in the geodatabase. The script is written in such a manner that only the top polylines are extracted. Because we are not interested in the ‘sides’ of the polygons, the script also looks for nodes within the polyline that would create a segment along the line with an angle within 90° +/- a predetermined value (Fig. 4). The script then labels the nodes in the attribute table with a ‘check’ value enabling us to examine the flagged nodes and make a determination as to their validity. Once each section is complete, the nodes are extracted, en masse, and imported into our 3D software for modelling.

Both methodologies rely on a database of consistent unit ‘edges’ in order to properly model the strata, and have them ‘seal’ against the underlying unit. The MGS has an extensive digital database of unit edges which has been recently updated (Nicolas et al, 2010). This database of unit edges was consulted when creating the cross-sections, however some deviation was necessary in order to make ‘sense’ of the units when creating the vertical maps. This deviation was due to the increased availability of data when the sections were being produced. The existing unit edges must be manually modified to fit the sections in order to create the surface/solids in the 3D model. This is a tedious and time consuming process, however modelling cannot continue until this important step is complete.
Figure 4: Effect of Python script on single unit within cross-section polygons. (A) Target polygon selected from cross-section (B) Target polygon converted from polygon to polyline (C) Nodes from ‘top’ surface of polyline captured.

Finally, a network of pre-glacial/Tertiary buried valley aquifers has been cut into the bedrock surface in southern Manitoba, but has yet to be systematically mapped in detail. We have recognized these channels on some of the cross-sections, but not consistently enough to map them with confidence; they are recognizable only when the channel is orthogonal to the cross-section. This presents a problem when modelling the units between sections. The MGS is experiencing a similar issue as it relates to surface water. In some cases, the channels represented on the cross-sections do not coincide with digital linework from the best available base maps. Again, it becomes difficult to model major rivers and streams between the 5km spaced sections.

3. FINAL THOUGHTS

Tremendous progress has been made in 3D mapping of southern Manitoba’s Phanerozoic terrane; underlying the model is a basement map, depicting top of Precambrian. In order to produce hand-drawn cross-sections at a 5km resolution for the entire south – an area 450 x 650 km – required two decades of commitment toward this long-term objective. Huge strides were made in the first decade to carry out major drilling and geophysical campaigns, both onshore, and offshore in lakes that vary greatly in size (one of which is larger than Lake Ontario), and to assemble all data, especially drillhole databases and bathymetry. The second decade focused on model construction province-wide. Our current hurdle is to process the hand-drawn sections into satisfactory solids that will then be available for applications ranging from groundwater modelling and management to engineering design and industrial mineral planning. The following task will be to satisfactorily fill in the Phanerozoic terrane in the north, along Hudson Bay, resulting in province wide 3D mapping, into which areas of greater detail can then be nested as required.
4. REFERENCES


4.1 Additional Bibliography


1. INTRODUCTION

At the Pall Life Sciences (formerly Gelman Sciences) site in Ann Arbor, Michigan, USA, wastewater containing 1,4-dioxane was discharged into unlined seepage lagoons and spray irrigated across a 15-acre field from 1967 to 1985. 1,4-Dioxane is readily soluble in water but resistant to microbial degradation and adsorption to soil particles (USEPA 2006). Mapped contaminant plumes (Figure 1) extend several kilometers in different directions from the original source area and provide a tracer-like record of solute transport through 80 m of glacial drift underlying the site and surrounding area. Despite substantial attempts to contain and remove the 1,4-dioxane following its discovery nearly three decades ago, remediation activities continue to this day along with efforts to characterize and model the aquifer system beneath a groundwater Prohibition Zone established in 2005. An array of more than 175 monitoring wells and 20 extraction wells has been drilled in the area, where the deepest known plume appears to be advancing toward a municipal water supply well and the Huron River. The experience at this site underscores the need for improved models of complex glacial aquifer systems. This study employs hybridized models incorporating stochastic variability within a deterministic hydrostratigraphic framework to model spatial variability of physical hydrogeologic properties in western Ann Arbor. Such a hybrid approach, described below, is expected to expand the space of uncertainty associated with model-generated contaminant transport predictions in this complex glacial aquifer system.

Figure 1. Location of the Pall Life Sciences study site and monitoring well distribution. 1,4-Dioxane concentrations shown as mapped in 2004.

2. APPROACH

The Pall Life Sciences (PLS) site is a natural laboratory for investigating solute transport in a complex glacial aquifer system. It sits on the northwest flank of the northeast-southwest trending Fort Wayne terminal glacial moraine (Leverett and Taylor 1915). Multiple aquifers with contrasting hydraulic head gradients lie directly beneath the PLS property and glaciotectonic sediment deformation appears to be minimal there. Data include abundant subsurface well control along with more than two decades of static water level and 1,4-dioxane concentration data. A two-step approach was employed to model the distribution of aquifer materials and their physical properties in the study area.
First, a deterministic hydrostratigraphic framework was developed from an allostratigraphic interpretation defining the three-dimensional distribution of aquifer and aquitard units, constrained by available hydraulic head and contaminant concentration data. The resulting hydrostratigraphic architecture was transferred to a numerical flow and transport (MODFLOW) model. Second, stochastic modeling was employed to generate an ensemble of realizations defining three-dimensional hydraulic conductivity fields within that deterministic hydrogeologic framework.

### 2.1 Deterministic Hydrostratigraphic Modeling

The glacial stratigraphy is exposed within local sand and gravel pits located on the flank of the Fort Wayne Moraine (Figure 1). Ten stratigraphic sections were measured along the east and south face of a quarry across a composite thickness of approximately 30 meters (Frahm 2011). The measured sections were correlated using an exposed till contact as a datum. The base of the till is sharp, subhorizontal, and laterally continuous across 260 m of exposure. This surface delineates a macroscopic change from the fine-textured till above to coarse, clastic aquifer below. Below the contact, stratigraphic units were defined by erosive surfaces, abrupt changes in particle size, and 1-6 m thick fluvial fining-upward sequences. Most units contain coarse grained particles and are poorly sorted, ranging from fine sand to boulder size. Occasional lenses of moderately- and well sorted medium grained sand may provide preferential pathways for transmission of groundwater.

Monitoring wells, most of which were gamma logged, provide the basis for detailed subsurface correlation across the study area. In addition, available head and concentration time series data provide an important constraint on hydrogeologic interpretations. In contrast to a more conventional lithostratigraphic correlation methods, an allostratigraphic approach was employed to identify and correlate bounding surfaces that divided the glacial sediments into mappable ‘allohydrostratigraphic’ units. Based initially on gravel pit exposure observations, and subsequently upon correlation of identified allostratigraphic surfaces into the subsurface, recognition criteria were developed to identify discontinuities within the glacial sediments (Frahm 2011). These criteria included: 1) changes in gross lithology; 2) changes in texture; 3) changes in gamma response; and 4) truncation geometries of correlated surfaces. For example, abrupt vertical or horizontal changes in sediment textural lithology (coarse-grained to fine-grained, fine-grained to coarse-grained) were indicative of potential allostratigraphic surfaces. Sharp, laterally continuous basal diamict contact surfaces are associated with glacial readvance, and represent a distinct change in depositional energy. The incision and fill of large scale channelized sand and gravel units, including the presence of basal lag gravels suggest amplification of the flow regime and represent discontinuities within the glacial deposits. When they can be correlated across gravel pit exposures or subsurface cross sections, contacts like these are well suited for allostratigraphic definition of major hydrostratigraphic units.

![Figure 2. Subsurface cross section locations. Base map produced by Environmental Health Division, Department of Public Health, Washtenaw County, Michigan (Sources: MiGDL Pall/MDEQ Database, Washtenaw County GIS).](image-url)
Eight hydrostratigraphic cross sections (Figures 2, 3) were interpreted based on geologists' logs and gamma logs for lithological control. Available hydrogeologic data including hydraulic head and contaminant concentration data from the monitoring wells was used to interpret connectivity of aquifer units. Concentration data used were available through December 2010, and comparative hydraulic head data were drawn from the September 2010 comprehensive annual sampling event. Data were compiled into an extensive database and uploaded into RockWorks15 geological modeling software. The database includes well locations, depths, and relevant elevations, the depth of well screens, drillers' and geologists' logs describing the sediments encountered. Where available, contaminant concentrations or Simulprobe data were included, as well as digitized natural gamma logs. The Rockworks database was used to construct a 3D model of the hydrostratigraphic architecture based on the interpreted allostratigraphic surfaces. The resultant model constitutes an internally consistent hydrostratigraphic architecture for the aquifer system in the west Ann Arbor region.

Figure 3. Hydrostratigraphic cross section G-G’ (see Figure 2 for location). Interpreted aquifer units are shown in yellow, aquitard units green, bedrock surface gray. Allostratigraphic bounding surfaces are numbered 0 through 8.

The elevation of bounding surfaces was mapped using Surfer software. Adjacent surfaces were subtracted using grid arithmetic to generate isopach maps of succeeding aquifer and aquitard units. Isopach and structure contour map grids were then transferred to MODFLOW to define explicitly deterministic aquifer and aquitard units that were subsequently populated by stochastic realizations of hydraulic conductivity distributions.

2.2 Stochastic Modeling

Geostatistical simulation of aquifer properties (conditioned to gamma log observations) was employed to model smaller scale hydraulic conductivity variability within the larger deterministic hydrostratigraphic framework using a three step process. First, continuous random fields of natural gamma radiation response recorded in monitoring well logs located throughout the site were generated (Pappas and Lemke 2011). Natural gamma radiation counts were normalized to account for variation introduced by different logging and drilling equipment. Gamma values were also analyzed for variability related to changes in sediment texture and separate variograms were constructed for vertical and horizontal (omnidirectional) gamma variation. One hundred stochastic realizations of gamma values were then constructed using a Sequential Gaussian Simulation algorithm and conditioned to natural gamma radiation measurements for 77 wells in the study area. Depth intervals in each well were classified as aquifer or aquitard based on their position within the deterministic allohydrostratigraphic interpretation. Aquifer and aquitard simulations were generated separately (using independent variograms and conditioning data).

Second, an empirical relationship was used to transform simulated gamma values to K values (Figure 4). This relationship was established using laboratory hydraulic conductivity measurements on samples taken from a continuous rotosonic core at monitoring well MW-96. Hydraulic conductivity was assigned to 30x30x3m model cells throughout a 14km² area embedded within a regional groundwater model.
Finally, individual cells were extracted from paired aquifer and aquitard realizations in locations corresponding to the distribution of aquifer and aquitard units within the 3D hydrostratigraphic model and merged into a single 3D model honoring the original allohydrostratigraphic interpretation. In this way, 100 composite realizations containing spatially distributed parameters representative of aquifer and aquitard materials were generated (Figure 5). These procedures required the creation of two computer programs, DETERMINE.for, which interrogates the hydrostratigraphic model surface grids to determine which VMODFLOW grid cells correspond to aquifer/aquitard material; and GSL2VMF.for, which constructs the aquifer/aquitard composites and writes an output file in .VMP property file format for insertion into the MODFLOW model.

Figure 5. Distributions of hydraulic conductivity property values for: (a) aquifer material in model layer 20; and (b) aquitard material in model layer 20 in the study area in the central portion of the MODFLOW model. Note that VisualMODFLOW does not have the capacity to display K property colors along a color spectrum (i.e., from low to
high values); rather, property color values are assigned randomly. Thus the complimentary distribution of aquifer and aquitard units is shown separately here for a single layer to illustrate the stochastic infill of K values within the deterministic hydrostratigraphic architecture.

3. FUTURE INVESTIGATIONS

A priori ranking of the 100 stochastic realizations is underway using K value distributions for flow paths along the primary migration direction between the source area and the Huron River, a potential groundwater discharge location at the site. Relevant transport metrics (e.g., first arrivals and breakthrough times at the river calculated using MODPATH and MT3D) will be compared among realizations to evaluate the degree to which stochastic variability influences transport and whether a priori rankings can be used to identify realizations representing the range of transport behavior uncertainty predicted using the full ensemble.

4. REFERENCES


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1. INTRODUCTION

The Alberta Geological Survey (AGS) has been tasked with integrating digital stratigraphic data from a variety of sources to produce a regional 3-dimensional geological model of Alberta, often referred to as ‘The Framework’. This is a suitable model name, as it has been widely recognized that this model provides a framework to integrate our data and evaluate multidisciplinary correlations. The Framework will be delivered as a multi-scale geocellular model based on the properties of each stratigraphic unit within the regional modelling domain. However the success of this model is contingent on well documented and transparent processes to generate reproducible and scientifically credible predictions, as well ensure that users are properly informed as to the model limitations and uncertainties. This presentation will provide an overview of the processes used to build ‘The Framework’ including a look at the good, bad, and ugly aspects of building a dynamically integrated, geostatistical model.

Figure 1. Three-dimensional view of 24 2.5D surfaces modelled to a 500m grid cell resolution within the province of Alberta (approximately 661,000 km²).

2. BUILDING THE FRAMEWORK

Building a fully-integrated, interdisciplinary model that can allow individual surfaces to evolve and improve independently is a difficult task that has required a significant amount of up-front planning. This included developing an input data documentation form and a grid metadata system to ensure that essential information about the input data, modelling procedures, and output model results are tied to each stratigraphic unit. For the Framework to provide the geologic foundation for other smaller-scale projects by enabling them to extract individual surfaces/unit models or stratigraphic packages (assemblages of units) as data, requires extensive documentation of both the input data used to create the model units and the output model results.
3. THE GOOD (BENEFITS)

There are many positive attributes of the Framework such as; 1) the geostatistical approach, 2) the procedures for analyzing output statistics and feedback mechanisms with geologists, and 3) the flexibility and adaptability of the model.

The Framework was built using a fully documented geostatistical approach. The Grid Metadata system catalogues all the details necessary to reconstruct the model surfaces if required, as well as all the pertinent information derived from every model cross-validation run. Retaining this information allows us to plot the statistics and compare improvements to model with each successive cross-validation run to determine the point at which we have most effectively characterized the currently available data, beyond which additional runs would become superfluous. The benefits of analyzing the cross-validation results are two fold; 1) it allows us to improve the efficiency of our modelling efforts by identifying when the drop in model RMSE has stabilized, and 2) by identifying the number and location of potential outliers, we can alert the geologist to potentially unidentified issues within a dataset, or that there may be unexplained variability that requires additional characterization.

Figure 2. A version of the Framework Model workflow.

The grid metadata and catalogue system also allows us to keep all previous versions of a surface/unit so that we can document the changes both spatially and with respect to regional parameter distributions. This functionality can also be used to help the model evolve, as it incorporates optimized parameters based on previous model runs. More importantly, the grid metadata system requires that all anomalous/potential outlier data is recorded. This process has also helped identify regions of the province that require further investigation by geologists (eg. Leduc Reefs; Figure 3A), allowing us to revisit these data at different scales, or utilize additional information assess whether the data are truly anomalous or represent undefined true variability. Areas of outliers are
often the most interesting and geologically significant and therefore should not be deleted if they do not seemingly fit in the context of the current model.

Figure 3: A) East-West transect through the Geological Framework model of Alberta showing a slice through the relatively small scale Leduc Reefs. B) Location of the transect through the Framework.

Another positive attribute of the Framework is that the workflow has an adaptable design, which allows individual surfaces to be updated. The need to update and remodel these surfaces include both internal or external triggers such as: 1) a significant amount of new data becomes available for a particular stratigraphic unit, 2) the results of an external project conflict with a current surface, or 3) that a unit has not been updated for a long period of time and should be reassessed (Figure 2). This allows us to develop the Framework on an 'as needed' basis, by integrating units of varying quality and refinement, thereby allowing modelling tasks to be triaged and focused on those units that have the greatest priority.

4. THE BAD (CHALLENGES)

Developing the Framework has resulted in numerous challenges, each requiring careful consideration to overcome. The main issues to date have been related to software, model scale, and grid storage and documentation. Finding a software package capable of integrating up to 100,000 data points per surface without requiring significant manual manipulation of the surface has been difficult. A number of good software packages are available to produce reasonable 3D models. However, they have not been able to handle our volume of data at the required resolution. Other programs were able to produce the surfaces individually, but were unable to integrate them within a geometrically correct 3D model without significant manual manipulation. Such manipulation produces a model that is no longer reproducible and calculating uncertainty becomes impractical.

Another challenge has been developing the grid metadata system, which was designed to store and catalogue all final grids and relevant metadata and model parameters. This required designing a new database to facilitate the acquisition and storage of model metadata within a searchable system based on name and spatial location. These surfaces are now being extracted and used as data themselves; therefore the grid metadata system will enable end-users to search for the most current grids, and ensure the necessary documentation is tagged to each surface.

5. THE UGLY (ISSUES TO BE RESOLVED)

The initial Framework surfaces were created using ArcGIS 10.1 to geostatistically interpolate the data. These resulting surfaces were then imported into GoCad/SKUA to integrate them into a geocellular 3D model. Both of these programs were able to produce independently generated surfaces; however, they both had significant problems integrating the surfaces into a single coherent and realistic model. Two examples of surface mismatch occurred in the Peace River and Bow Island arch regions (Figure 4A). The individual units surrounding the Peace River Arch were difficult to model because the entire area transitioned between being a topographically-high to a
topographically-low feature (Figure 4B). Modelling the Bow Island Arch was hampered by relatively sparse data points, which made individual units difficult to constrain, resulting in numerous surface cross-overs (Figure 4C). The solution was to identify the discrepancies to the geologist and have them provide additional data necessary to capture the structural complexities, as well as work with a software package capable of incorporating these complexities without requiring excessive manual surface manipulation.

Figure 4. A) Two examples where surface cross-overs occur in the Framework. B) Relatively minor surface cross-overs in Peace River Arch, and C) Bowl Island Arch regions. The surface cross-overs are highlighted inside the red circles.

6. THE FUTURE

The Framework is developing nicely and the future looks bright. Although this model is less than a year old, the usefulness of Framework surfaces have already been realized. Numerous grid surfaces are already being used by AGS, as well as other groups within the Alberta Energy Regulator. Uses include linking to the Framework model as a source of stratigraphic surface elevations and unit thicknesses to compare with data submitted to the AER as part of industry applications. Such links have already resulted in the incorporation of new data and information into the Framework, which in turn has been used to update and improve model accuracy.

Geostatistically modelling the entire province of Alberta at a 500m resolution requires a significant amount of computing power and time. By transitioning the model to become multi-scalar, we are allowing it to produce higher resolution detail in areas where there is a need or where sufficient data exists (eg. The Leduc Reefs; Figure 3), as well as lower resolution surfaces where there is little need for detail or where fewer data points exist. This approach will also facilitate the integration of multi-disciplinary data, such as probability ranges for stratigraphically associated geologic parameters.

We are well underway in producing a 3-dimensional, multi-scalar, geostatistically optimized, probabilistically parameterized, geocellular model of Alberta.
PROGRESS TOWARDS A NATIONAL GEOLOGICAL MODEL OF BRITAIN

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1. BACKGROUND

BGS has stopped its' systematic onshore geological surveying programme and the litho-printing of geological maps will cease after a final batch of completed maps are published. In future BGS will undertake integrated mapping and 3D modelling in user defined target areas considering all our available geospatial data (map, boreholes, geophysics etc) assessed in a single 3D workspace. The output will be 3D geological framework models that capture the understanding and interpretation of the survey geologist and honour all available data at the time. As well as building new models in these strategic areas, BGS is collating all existing models assembled over the last 25 years into a common framework to produce a multi-scaled National Geological Model of Britain (Mathers, 2011) comprising crustal, bedrock and Quaternary themes (http://www.bgs.ac.uk/research/UKGeology/nationalgeologicalmodel/home.html). Different to the traditional geological map, the national model will not be completed at any specific scale, but at every point in the model there may be a different geological resolution available, depending on the purpose of the original model or the strategic national need for subsurface information.

2. MODELLING SOFTWARE & WORKFLOWS

Over the last 30 years BGS has developed a strong capability in 3D geological modelling using a variety of methodologies and modelling software to produce geological framework models varying in resolution from national to site-specific. Currently BGS uses the following main software packages: 1) GOCAD/SKUA are mainly deployed to produce models of structurally complex and faulted bedrock geology drawing on datasets including seismic profiles and cubes, regional geophysical patterns, deep boreholes and surface geological surveying; 2) GSI3D is mainly deployed to model superficial, artificial and layer-cake bedrock geology to shallow depths (c.500m) through the use of cross-sections (Kessler, Mathers & Sobisch, 2009). The intuitive approach of the GSI3D software means that all our investigative geologists can use this package and it comprises an effective front end for the assembly of cross-sections of complex geology and fault network that can then be exported to the other more mathematically grounded packages for model calculation; 3) Petrel is increasingly used as our tool of choice for flow modelling but is not generally used for geological framework model construction.

In combination these packages enable the BGS to model almost all of Britain's geology at any resolution and evaluate all types of geoscience data in the production of these geological 3D framework models. In golf one needs a suite of tools (clubs) to play an effective round, the same holds for geological modelling. So imaginative and increasingly sophisticated workflows are now being used for many projects involving data exchange between packages and exploiting the strengths of the individual software methodologies (Kearsey et al. 2012). Interoperability, as ever, remains paramount.

Outputs from the modelling process are many and varied, they include screen grabs of models and 3D PDFs (Figure 1) used to illustrate reports, derived maps highlighting particular geological situations and answering particular user-defined questions, grids and tins for use in GIS systems. The models are also the delivered as fully attributed 3D block models using our bespoke Viewer-Browser, the LithoFrame Viewer. Using another BGS product, Geovisionary, 3D models and their components can be placed in a dynamic fly-through setting to demonstrate the interrelationship between terrain, surface geology and the sub-surface infrastructure.
3. THE MODELS

The National Geological Model has the following properties.

1. geospatially correct representation
2. scalar independence and varied resolution
3. national in coverage, seamless onshore and in time offshore

Existing datasets for incorporation include BGS's digital geological linework at all scales (the surface layer), subsurface, offshore and survey memoirs, reports and published literature containing useful contour and isopach maps, together with existing framework models and surfaces and geophysical data. The assembly of the framework models is also underpinned by key corporate databases, dictionaries and lexicons for boreholes, stratigraphic and rock terminology. A national sequence of lithostratigraphic units has also been developed. Framework model construction also relies on licenced national digital terrain and bathymetric models of ever improving resolution, air photography and remotely sensed imagery.

NATIONAL CRUSTAL MODEL

The national crustal model grew out of an initial collaborative study between the geological surveys of Britain, Northern Ireland and Ireland to construct a deep model of the Caledonian orogenic belt (Leslie et al. 2013). The model (Figure 2) clearly shows the tectonic grain of the orogenic belt and its division into distinct terranes separated by major bounding fault structures. Work is underway to extend this model southwards to include England. The model was constructed as a fence diagram in GS13D but it is intended to migrate the dataset to GOCAD in order to calculate a full, but simple, 3D block model. For further details on the development of this model please contact Graham Leslie agle@bgs.ac.uk.

NATIONAL BEDROCK MODEL

Construction of a national bedrock model began in 2009 with a commission from the Environment Agency of England and Wales (EA) to produce a simple fence diagram of 42 cross-sections for the onshore area of England and Wales extending to 1-1.5km depth. Subsequently sections were added by BGS to incorporate Scotland, insert bounding coastal sections and finally, with a second tranche of funding from the EA, many sections were deepened to capture the full vertical extent of potential shale gas sources. The model is available as a free download in varied formats from the BGS website http://www.bgs.ac.uk/research/ukgeology/nationalGeologicalModel/GB3D.html. The model GB3D_v2012 now comprises 121 sections with an aggregate length of over 22,000 km (Figure 3). The model adopts the geological classification and colour schema of the published BGS 625K scale bedrock geology maps. The component sections are also guided by various underpinning datasets, these include:
1. Existing regional 250K and tiled 50K resolution models (these in turn take into account seismic data, deep boreholes-wells, and regional geophysics),
2. Intercepts from BGS 1: 50K mapsheet cross sections,
3. Rasterised images of published maps (contoured surfaces, isopachs, subcrops), and cross sections, Surface Geology (625K bedrock linework)

Figure 2. Crustal fence diagram viewed from the southwest, sections are 15Km deep, fault planes in red.

Figure 3. The GB3D_V2012 Bedrock fence diagram of Great Britain. Vertical Exaggeration x15.
Utilising the 625K geological map and the cross sections the distributions of the 381 geological units in the model can be traced as shown in the example below (Figure 4). Distributions for key aquifers and potential shale gas sources have been compiled into a GIS to provide a risk screening tool for the EA to assess applications for shale gas exploration. The fence model can also be used to calculate low resolution 3D volumes for the youngest and structurally simplest bedrock units down to the base of the Permo-Trias. These have been used in regional and catchment scale hydrogeological modelling studies. Extracts from the fence model have also been utilised to communicate regional geology to the general public with respect to radioactive waste disposal and to illustrate BGS accounts of regional geology. A further phase of development of the fence is underway funded by the Nuclear Decommissioning Authority. This will key in 300 golden spike deep boreholes to enhance the model accuracy and provide a consistent national dataset to inform the public about regional geology in the context of the selection of a suitable site for location of a nuclear waste repository.

![Figure 4. The Cretaceous Grey Chalk Sub group of southeast England. Left, outcrop and extent of correlation in GB3D_V2012 dataset, right, the distribution of the unit (outcrop plus subcrop) defined by the dataset in GSI3D.](image)

**NATIONAL QUATERNARY MODEL**

Unlike the crustal and bedrock national models building an equivalent Quaternary version introduces certain difficulties:

1. Quaternary sediments tend to lack the extensive distributions of older geological units
2. Correlation is difficult or impossible over long distances and between regions or major catchments
3. Quaternary sediments are typically extremely variable in terms of their lithology

Therefore our approach to building a national Quaternary model is proceeding on the basis of constructing regional stratigraphies and consistent models that can be linked together for synthesis at a higher and often very fundamental level of classification (such as all the deposits of the last glaciation). This is a pragmatic approach and has been made more achievable by the recent production of a comprehensive stratigraphic classification and chart for the UK Quaternary (McMillan et al. 2005, Waters 2012).

Perhaps the most important output from the Quaternary model will be the production of an improved national model of the top bedrock-base Quaternary surface. This is of obvious importance in terms of engineering but also provides an important cap for bedrock modelling (Figure 5).
Figure 5. Part of the base Quaternary (rockhead) surface for the area around Reading, west of London, elevation in metres above Ordnance Datum.

4. METADATA & QA

The increasing use of models and model data demands proper recording of metadata and the introduction of rigorous QA procedures. To-date in BGS this has not been undertaken in a properly structured or systematic way. The creation of the National Geological Model programme has endeavoured to rectify this situation through:

1. The establishment of corporate rules and guidance for modelling projects
2. The introduction of systematic QA procedures and checking of all new models
3. The recording of detailed metadata on model construction and in particular sources of data evaluated, geological rules and assumptions and decisions taken
4. The assembly of corporate databases to hold the above information.
5. The gathering of metadata and checking of legacy models.

5. REFERENCES

THREE-DIMENSIONAL VISUALIZATION AND MODELING AT THE U.S. GEOLOGICAL SURVEY: EXAMPLES AND ISSUES

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1. INTRODUCTION

We need to use appropriate technologies and abilities to visualize, model, and work within the dynamic multi-dimensional earth. Natural processes are 3D/4D in character, yet scientists in the U.S. Geological Survey (USGS) often still research and share information of the natural world with 2D and 1D graphics and text. Current in-house 3D modeling and visualization efforts often consist of 2D map/GIS overlays stacked in 3D space. Static block diagrams and other 2D visuals do not allow efficient exploration of the rich multi-dimensional datasets and knowledge beyond the surfaces portrayed. Current capabilities and practice using 3D/4D tools vary widely across the USGS. Our research, science, and delivery efforts need to be brought up to date. This presentation considers several 3D/4D efforts within the USGS, and highlights important needs and challenges to be addressed.

2. SOME CURRENT PROJECTS

A geologic and hydrologic study with drill hole and field mapping data. A cooperative study between the USGS and the Camp Stanley Storage Activity (CSSA) military base, Bexar County, Texas, their cooperators, and the Environmental Protection Agency was conducted to define the framework geologic structure and the hydrostratigraphy of the area (Fig. 1). The basic regional geology and hydrology was not known sufficiently for the local management of resources. A detailed geologic study was conducted that defined previously unknown horst and graben structures. These structures were identified through both drill hole and surface mapping data and information. 3-D modeling was used to provide a visual framework for the information, improve understanding of the geologic framework, and to improve coordinated management of local resources, including groundwater. Understanding the geologic structure, such as local faults and fractures, provided an important first step to understanding the distribution of porosity and permeability, groundwater recharge, and migration pathways.

Figure 1: 3D visualization of the lowermost confining unit, structure, and cross section within the CSSA study area.
Volumetric regional geologic mapping for hazard and contaminant modeling. Surface geologic mapping to subsurface volumetric geologic mapping is well underway (Jacobsen and others, 2011), but fundamental challenges remain in mapping below-ground surfaces that cannot be directly observed. Volumetric geologic bodies are mapped indirectly both by extrapolating geologic structures observed at the surface and by estimating or inferring rock properties as proxies for direct geologic observation. Some proxies include: velocity for seismic data, density for gravity data, magnetism for magnetic data, and resistivity for electric data. Drill-hole information, when available, can be invaluable. However, study regions are often spatially undersampled, so that local structure observed in drill-hole data may be misinterpreted as regional structures. The objectives of geologic mapping dictates the methods used to address these challenges, as discussed below for two projects.

The Calico Hills Formation study is an effort to understand potentially contaminated groundwater flow through a heterogeneous sequence of overlapping and coalescing lava-flow aquifers and tuff confining units. The Calico Hills Formation within the study region is known only from drill-hole information. The information available is insufficient to resolve the number, extent, and connectivity of lava flows that occur between drill holes. The properties of these flows significantly affect the outcome of hydrologic flow models. A volumetric geologic map of the study region needs to match three types of data: geologic and lava flow configuration and estimated volumes, drill-hole data, and aquifer tests. Plausible volumetric lava and tuff configurations were created using a multi-point geostatistical approach. An idealized model of lava flows and tuffs, larger than the study region and free of drill-hole constraints, was generated using an automated object generator that was constrained using geologic knowledge and inferences from common lava flow dimensions and thicknesses. The proportion of lava to tuff, and the different shapes and distributions of lava flows relative to one another were quantified and stored in a pattern database. These patterns were correlated with drill-hole information resulting in a new plausible volumetric map of lava flows and tuffs for the study region. Hydrologic properties based on lithology were assigned to the volumes and used in a flow simulation, and the results compared with aquifer test data. A thousand volumetric maps were then made using the pattern database with drill-hole constraints; each map was equally likely given the available geologic and drill-hole information, and each map was compared with the aquifer test data. The subset of maps with flow simulation data that were consistent with aquifer test data was used to represent best guesses for the subsurface geologic configuration (Fig. 2). Volumetric maps in aggregate can be used to investigate general tendencies of the aquifer system. For example, one might learn that the presence of a large flow pathway along the eastern side of the study region is more likely than along the western side.

The San Andreas Fault project provides improved understanding of one of the world’s most dangerous fault systems by volumetrically mapping the San Andreas Fault and the surrounding geology, and by exploring the structural history of the fault. The study integrates mapping and modeling by field geologists and geophysicists who individually map structures and rock bodies to develop a volumetric map. At the scale of the study, structures such as local faulting or folding that would be important at the 24k scale are generalized in favor of structures important at approximately the 250K scale. Sparse drill-hole data are influenced by local structural features and are therefore not always honored exactly, but are honored regionally in a least-squares sense. Select portions of the volumetric map were examined both to better understand the fault history and to highlight problems with the mapping (Graymer and others, 2010). Portions of the map were discretized and used for predictive modeling of earthquake slip (Jachens and others, 2006). Final products are being published as volumetric spatial databases (e.g., Phelps and others, 2008).

Point clouds: novel multi-disciplinary uses. Dense point cloud datasets collected from airborne and ground-based LiDAR (LIght Detection And Ranging) geodetic techniques and photogrammetric analysis provide a unique opportunity to address a broad range of scientific questions that were unanswerable 5 years ago. These 3D and often 4D datasets are used in a wide range of scientific analyses including: identifying previously unrecognized fault zones in forested regions, measuring biomass and biomorphic characterization of vegetation, measuring glacial velocities, resolving the surface roughness of river beds, imaging near-shore bathymetry, and directly measuring decimeter scale 4D snow-water-equivalent changes within a snowpack over time. New 3D/4D approaches and methodologies are being developed to extend the analysis from traditional 2D GIS algorithms to comprehensive 3D point-cloud derived surface models. The data are in 3D, but many of the software approaches remain in 2D.
A cooperative study with the University of California Berkeley, the Sacramento Area Flood Control Authority, and the USGS injected grout into ground squirrel burrows on an active levee in California to assess the spatial extent of the burrow complex. The levee was slowly excavated to expose the grouted burrow. An ultra-high resolution ground-based Tripod LiDAR (T-LiDAR) system was then used to measure the 3D relations of the mammal burrows with the original levee surface. At the two sites excavated, one burrow was found that went from the water to the landside of
the levee at a depth of 45 cm. 3-D visualization and modeling was then used to find relations between the burrows, the integrity of the levee, and the volume of material removed from the levee by the ground squirrels. Removal of too much material would have potentially disastrous consequences.

3. RECENTLY INITIATED APPLICATIONS
Permian-, Pennsylvanian-, and Mississippian-age aquifers of the Appalachian Plateaus cover portions of seven states and contain large amounts of coal, oil, and gas reserves with long histories of production. The USGS Appalachian Plateau Groundwater Availability Study seeks to expand the regional geologic knowledge of subsurface resources to better define groundwater availability and vulnerability. A regional geologic model of the Plateaus aquifers is not available, yet is needed to understand locally driven groundwater-flow systems in the context of hydrostratigraphy at the regional scale. In addition to the water study a 4D petroleum system model of the Appalachian Basin is being built to model oil and gas generation, migration, and accumulation through time for contained petroleum reservoir and source rocks. The research focuses on unconventional (continuous) oil and gas reservoirs.

A cooperative study between the USGS, the Arizona Department of Water Resources, the Nogales city water planners, and the Department of Homeland Security was initiated to expand knowledge of the geologic framework of the Nogales area, to more accurately define the hydrostratigraphy of shallow aquifers, and to better understand water flow and groundwater recharge. Specifically, a 3-D study is being conducted to define the depth and geometry of the alluvial aquifers and the lower confining unit. There are no deep drill hole data available, except for water wells which are less than 500 feet in depth. Use of 3D technologies is helping make full use of the sparse geologic information at depth.

4. INSTITUTIONAL PROGRESS IN 3D VISUALIZATION AND MODELING
The USGS conducted a groundwater workshop in 2012 that provided a snapshot of current state-of-the-art USGS experience with 3D/4D visualization tools useful for groundwater studies and numerical modeling; and for the integration and assembly of geologic, hydrologic, geophysical, geochemical and other information used in these studies. The workshop presentations and panel/open discussions (1) increased awareness of relevant tools available and in use by USGS scientists; (2) provided an opportunity to discuss future directions and needs for 3D/4D groundwater science and research; and (3) create a USGS interest group to help the USGS move forward using 3D tools for groundwater studies.

The training and the workshop sought to elicit answers to the following questions:

• Why do we need 3D visualization tools? (Hint: we are naturally wired to see in 3D rather than 2D)
• How can the tools be used? How have you used them?
• How can the tools be afforded? (One option is collaboration with teams or individuals that have the skills and software available to them or in-house training for the software).
• How can we “publish” 3D products and associated information, for access by and communication to others both within and outside the USGS, while minimizing information loss and introduced biases (i.e. in transitions to 2D media)?
• How can more value be added to publications to make them more useable? (i.e. interactive, add user data, animations…)
• Have you had some scientific breakthroughs that came about because you used 3D visualization?
• When is 2D representation clearly insufficient? (e.g. information biasing, information loss, smearing, discontinuities).

The workshop outlined the following reasons for use of 3D visualization tools:

• QA/QC’ing of data, consistency tests, and other types of information checking.
• Quick construction of geologic, geophysical, hydrogeologic, or combined models.
• Easier integration of diverse geoscience data and associated information.
• Exploration and interpretation of diverse information, i.e. easier building of better conceptual models.
• Easier presentation of modeling results and implications.
• Collaborative engagement/facilitation, either between scientists (possibly with different expertise), or between scientists and cooperators/resource managers/policy makers.
Aside from discussing and formalizing the need for 3D/4D visualization and modeling tools, the workshop proved very useful in introducing members of the USGS groundwater community to a wide diversity of currently available commercial and open-source tools that could be used.

In addition to the 3D training mentioned above, the USGS has also made available a number of broadly used, relatively inexpensive software packages for constructing and interpreting (pseudo) 3D geologic models. Collaborative relations with other Geological Surveys such as the British Geological Survey have been highly beneficial in this endeavor.

5. ISSUES AND CHALLENGES FOR GREATER USE OF 3D VISUALIZATION AND MODELING

The USGS faces a number of important challenges that need to be overcome to facilitate greater access and use of 3D/4D visualization and modeling:

- Reward systems should encourage scientists to use currently available, and to research new 3D/4D technologies, tools, and media; for example by recognizing the value of innovative 3D/4D model publication outlets.
- Improved hardware and software capabilities, including immersive virtual reality rooms, need to be made more broadly available. This includes access to relatively inexpensive, open-source, multiplatform software that can be used to assemble and transform a wide diversity of data types. Access to immersive virtual reality workstations is needed to allow scientists to view and interact directly with their 3D/4D data. Hardware costs have dropped substantially over the past few years making these workstations affordable. Advancements in software that analyze and model 3D/4D geoscience data are not mainstream for our scientists and are a key missing step in the scientific discovery process. 3D data need to be analyzed and cross-validated in a 3D environment. Research and commercial software are available to view and manipulate 3D point clouds, and increasing functionality is being developed.
- To make best use of hardware and software resources, training must be provided to facilitate their introduction to scientists who have never used the available tools. Training can also be used to help scientists use 3D/4D tools for specific scientific projects and for improved communication with stakeholders and the public.
- Standards for data formats, procedures, and products need to be broadly adopted. These standards should provide robust descriptions and documentation on the source data used, the transformation and interpolation/extrapolation processes applied, and the final products developed. There is an especially strong need for standardization in data formats. These standards would greatly facilitate access by the geoscience community to source data and interpretations, both in current research and for unanticipated purposes for future research. The systematic nature of 2D studies, for example in geologic mapping over the past century, has produced a large body of information that is readily available for reuse in new studies. 3D/4D modeling and science in general, would greatly benefit from a large, ever-growing collection of subsurface information that could be used, and reused, to generate new studies. This implicitly requires that data repositories be available and managed.

6. REFERENCES


THREE DIMENSIONAL MAPPING FOR GROUNDWATER APPLICATIONS AT THE GEOLOGICAL SURVEY OF CANADA: 2011-2013 DEVELOPMENTS

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Introduction

The Geological Survey of Canada is charged with mapping the geology of Canada (Resources and Technical Surveys Act) in collaboration with provincial agencies. In the past ten years a number of national workshops (e.g. Rivera et al., 2003), national reviews (Council of Canadian Academies, 2009), and intergovernmental agreements have shaped the nature of the federal Groundwater Program. At present the focus is on completing work collaboratively with all levels of government agencies on 30 key Canadian Aquifers. Much of the work completed to date on these aquifers and regional issues is summarized in the book Groundwater Resources in Canada (Rivera, 2013). The emergence of new issues continues to impact the profile of groundwater work at the GSC. Notable amongst these issues is the concept of the water-energy nexus (e.g. Mass, 2010) and more specifically the environmental issues related to shale gas and hydrofracking (e.g. Parfitt, 2010). Related to this is the increasing concern regarding the potential environmental impacts of new petroleum pipelines etc. (e.g action plan, 2013). Hence there remains a need for three-dimensional geological mapping to support informed decision making in the face of widespread environmental and economic concerns. The scale, both geographically and economically, makes it essential that 3-D geological models have appropriate data support and are not simply the latest modelling iteration of low quality, low-resolution archival datasets. Energy issues will require greater emphasis on higher-resolution conceptual and digital models. There is a need to view data collection and model development as key component of the national infrastructure development that government agencies commonly fund to support economic development (e.g. Duke, 2010). How to achieve sustained funding for such activities was the focus of a recent workshop and working paper (Sturzik, 2013). It is essential that new data and model – model products be delivered to a broad user base, for this reason there is significant interest in data collection standards and online data delivery (e.g. Boisvert and Broderic, 2011).

Groundwater Program

A number of previous papers have provided an overview of the conceptual framework and methods employed to achieve program objectives and range of modelling approaches (Russell et al., 2011b). This abstract focuses on methods development, application and synthesis during the past two years and specifically geophysical and hydrogeophysical developments. Three-dimensional mapping in the GSC Groundwater Program is based on a traditional basin analysis methodology of understanding the geological history of the basin to inform future work and provide a predictive framework in areas of sparse data. This approach is being extended from the traditional subsurface basin context to encompass the hydrological cycle and understanding from atmosphere to aquifer.

Subsurface Methods Development and Applications

Seismic

Seismic stratigraphic and seismic facies data collection to support allostratigraphic basin analysis and model development (e.g., Sharpe et al., 2002) has been a cornerstone of GSC groundwater studies. For the past 8 years the GSC has operated a Minivibe as a seismic energy source. Recently an in-house ‘Microvibe’, has been developed as an alternative energy source. It is a 400 W, two-component (2C) vibrator that can vibrate in the vertical and horizontal directions (Pugin et al., 2013a). Constructed of twelve commercial transducers it sweeps from 20 Hz up to 800 Hz with ~15% of the power provided by an IVI Minivibe. To compensate for the reduced power level, the time...
length of the sweep is increased. This lightweight (70 kg) energy source is significantly reducing mobilization costs and time required for surveys and is maintaining a high quality data seismic reflection capacity.

Figure 1. A 5.5-km reflection line that reveals a buried esker feature. (a) Processed vertical shear wave component data plotted in two-way travel time (TWT) after corrections for surface topography. (b) Shear-wave velocity cross section. (c) The shear-wave section from (a) converted to an elevation section using the data shown in (b) with interpreted features shown in color. (d) The compressional (P-) wave elevation section. (e) Interpreted subsurface structure and stratigraphy based on the seismic data and available borehole information. Data from St Lawrence Lowlands, Richelieu River watershed, Quebec. Modified from Pugin et al. (2013b).
Multi-component data collection and processing was initiated with the Minivibe and has continued with the “Microvibe” (Pugin et al., 2013a). In the past 5 years over 800 km of data has been collected across Canada from a variety of geological terrains (Pugin et al., 2013a). Data from glacimarine, glaciolacustrine and till plain environments have provided an ability to assess the data quality and variety of processing approaches required to maximize the interpretation of the 3C(D) signal with a production of P-wave and S-wave seismic section using the same seismic source. P-wave seismic reflection is known for being very sensitive to liquid or gas phase variations in the porosity of sediments as S-wave reflection method is insensitive to porosity content providing essentially information on the lithology. In providing P-wave and S-wave data, multi-component seismic reflection is a tool that can show presence of gas or water within the sedimentary deposits with fluid escape through aquitards such as marine clays (e.g. Pugin et al. 2013b). The combination of P and S wave data can be used to enhance seismic facies interpretations. For example, poor S-wave returns with good P-wave reflection data is often an indication of very coarse-grained lithologies where large boulders act to disperse and scatter the shorter wavelength S-wave energy and induce incoherent S-wave returns (Pugin et al., 2013b). The presence of this aquifer esker feature was unknown prior to the acquisition of this seismic line, it was not interecepted and/or interpreted from borehole data.

Airborne geophysics

Airborne geophysics has the potential to provide high resolution, regionally extensive data for aquifer mapping and characterization. Successful applications of airborne electromagnetics (AEM) have been undertaken in Denmark (e.g. Germany and the United States. To test the applicability of AEM for the mapping and characterization of buried valley aquifers the GSC, in 2009, commissioned a helicopter time-domain electromagnetic (HTEM) survey over a 1062 km² region of the Spiritwood buried valley in southern Manitoba (Oldenborger et al., 2013a). The Spiritwood survey demonstrates the ability to map three-dimensional buried valley aquifer geometry at unprecedented levels of detail (Oldenborger et al. 2013a). Current work is focussed on 3D model building and involves constrained inversion of HTEM data (Sapia et al. 2012), classification of geophysical models and integration of geophysical results with water well records.

In addition to the HTEM data flown in 2009, the GSC collected supporting ground-based geophysical data along select transects. The level of data support resulted in the Spiritwood buried valley being flown by other Canadian airborne geophysics service providers as a means of testing system development and demonstrating capabilities. Comparison of the HTEM data sets and ground geophysics demonstrates that improved models can be obtained through system developments and constrained inversion of the data (Legault et al. 2012; Sapia et al. 2013). Continued work has seen the Spiritwood buried valley evolve into a de-facto Canadian test site for hydrogeological applications of AEM allowing data comparison and system testing.

Subsequent to the Spiritwood survey, the GSC has collected additional HTEM data over the Eastern Hatfield buried valley in southeastern Saskatchewan (Oldenborger et al., 2013b). The GSC has also provided technical support for HTEM surveys in Ontario (Bajc et al. 2012) and Manitoba (Manitoba Water Stewardship). Analysis and interpretation of these data are ongoing to support 3D numerical modelling.

Downhole geophysics

Over the past 20 years the GSC has collected a portfolio of ~250 downhole geophysical logs across the country consisting of natural gamma (gamma ray), inductive conductivity, magnetic susceptibility, active gamma, P and S wave velocity, and fluid temperature. Recently, a new high-resolution fluid temperature probe (sensitive to thousandths of a degree C) has been developed to infer small volumes of fluid movement behind casing, and identify very small volumes of flow entering/exiting the borehole from open bedrock fractures. This tool development is complimented by the acquistion of commercial televiewers (optical and acoustic) for imaging bedrock fractures in open holes, and a heat pulse flow meter to measure vertical fluid migration in the wellbore. Data from these tools are being used to assist in fractured bedrock aquifer assessments in large populated areas (Crow et al, 2013), and to help assess potential links between petroleum reservoirs and shallow fractured rock aquifer systems (Raynaud et al, 2013).
Borehole logs were collected in a variety of geological environments from glacimarine and glacilacustrine basins, eskers, moraines and thick till successions. Collected predominantly for the groundwater program, much of this data set is calibrated to the GSC test site in Ottawa. Work is currently being carried out to release all data in the Log ASCII Standard (LAS) format, the current international standard for borehole geophysical data exchange, which will give the public ready access to an updated and simplified compilation of the GSC downhole data. The LAS file contains all the logs collected in a single borehole with a common depth scale, the basic geological data, and the main metadata associated with each well site. This data is increasingly valuable for physical property assessment of 3D geological terrains, to develop technical specifications for surveys, and to constrain data interpretation of other geophysical data.

Figure 2. CDI model of HTEM data of Spiritwood Buried valley. The long blue-striped feature extending NW-SE is associated with a buried valley filled with less conductive material. Red is generally bedrock. Valley fill is diamicton, clay and sand and gravel. From Oldenborger et al., (2013).

Hydraulic methods development

Understanding of flow and solute transport requires the knowledge of hydraulic conductivity (K) and its anisotropy. Aquifer characterization generally involves conventional hydraulic tests (e.g., pumping tests, flowmeter profiles and slug tests), which induce predominantly horizontal flow patterns and therefore only estimate horizontal hydraulic conductivity (Kh). In aquifers where small-scale vertical variations in sediment stratification may induce large-scale anisotropy in K, and where the assumption of isotropy cannot be assumed at the scale of the characterization, K anisotropy (ratio of vertical (v) and horizontal (h) K, Kv/Kh) have to be considered. The lack of efficient laboratory or field testing methods for the assessment of Kv precludes the estimation of (Kv/Kh). This lack of capacity for the measurement of Kv/Kh may impact the understanding of an aquifer system at various scales, such as for the estimation of recharge through aquitards, the delineation of well capture zones, the prediction of the evolution of contaminant plumes and the definition of regional groundwater flow paths. Knowledge of the spatial distribution of
specific storage ($S_s$), is also critical in assessing groundwater storage in confined aquifers and is poorly estimated from conventional hydraulic tests.

The GSC is exploring new hydraulic field methods to quantify hydraulic parameters of aquifer systems (aquifers and aquitards). To date, two methods have been developed: (1) vertical interference slug tests (Paradis and Lefebvre, 2013); and (2) fully-transient tomographic slug tests (Paradis et al., in review). The former is carried out along a single-well, whereas the latter is completed between wells and thus hold the potential to 3D imaging of aquifers. Both methods have been proven to be efficient and can provide not only $K_h$, like conventional methods, but also $K_v$ and $S_s$ for roughly the same field effort of conventional approaches. The focus has been on unconsolidated aquifers; however, future work is planned to extend the range of applicability (e.g., other geological contexts, scale).

Hydrogeophysical data integration

Hydraulic tests are generally reliable sources of information on aquifer parameters, however, they are costly and time consuming and thus usually only available from a few wells. Accordingly, hydro-geophysics is increasingly recognized as an effective alternative to compensate for the lack in hydraulic data by attempting to translate geophysical data into hydraulic measurements (e.g. Pugin et al 2013b). The value of using geophysical data for hydrogeological characterization lies in the extensive spatial coverage generally offered by geophysical methods, which may be helpful to provide spatial continuity or discontinuity in aquifer heterogeneities. Reliable predictions in hydraulic parameters values, such as $K$, from geophysical data should however be based on sound relations that tied hydraulic measurements to geophysical data, which are usually subject to a large degree of uncertainty under field conditions.

In an effort to extrapolate hydraulic information away from wells using geophysical data, the GSC is also exploring hydro-geophysical data integration approaches that take advantage of both hydraulic and geophysical methods. A learning machine approach to predict aquifer $K$ at decimeter vertical scale from cone penetrometer tests (CPT) coupled with a soil moisture and resistivity probe (SMR) using relevance vector machines (RVMs) have been recently developed and applied for the characterization of a littoral aquifer at the sub-watershed scale (Paradis et al., in review). The use of conventional regression methods to predict $K$ in a littoral aquifer was not successful due to the strong nonlinearity in relations between $K$ and CPT/SMR mechanical and electrical parameters. The learning machine was developed from a training data set consisting of collocated $K$ measurements from slug tests in wells and CPT/SMR data upscaled at a vertical resolution of 15 cm. The learning machine was conditioned using fuzzy clustering and RVMs for classification and regression. Validation results show that $K$ predictions from the learning machine are consistent with actual well hydraulic tests. Future work is planned to extend the data assimilation approach with seismic data and thus provides efficient workflow for regional hydrogeological assessment.

3D geological modelling

Over the course of the past 2 years modelling has advanced on five aquifers (Nanaimo, Milk River, Spiritwood, Richelieu, St. Maurice). This geological modelling has two components, a conceptual model and the digital realisation of the model. The initial conceptual model is based on the interpreted stratigraphic architecture and depositional models developed from high quality data. The HTEM and seismic data highlight the nature of additional data support available for the Spiritwood buried valley in comparison with earlier studies of Prairie buried valleys (Fig. 2). Development of current geological models uses LeapFrog for data modelling, visualization and model export to FEFLOW for groundwater modelling.

Summary

The GSC is working on a national framework for groundwater assessments with an emphasis on technical methods development and technical transfer completed within a framework on specific aquifer studies. Geological model development is constrained to the extent possible by the collection of high-quality data to develop an interpretative framework for the integration of archival data. Emerging economic drivers and a maturing of data collection, processing and modelling approaches, along with strong efforts from provincial agencies, means it is feasible to develop a three-dimensional geological model for undeformed geological basins of Canada at a scale and quality relevant to support present and future challenges related to the groundwater sustainability of the country.
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DEVELOPMENT OF THREE-DIMENSIONAL MODELS OF SEDIMENTARY LITHOLOGIES AND PIEZOMETRIC LEVELS TO UNDERSTAND GROUNDWATER AND SURFACE WATER FLOWS, LOWER WAIRAU PLAIN, MARLBOROUGH, NEW ZEALAND WITH WEB AND SMART PHONE ACCESS TO MODEL DATA

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ABSTRACT

Holocene sediments are a key control on the groundwater hydrology and spring-fed stream flow in the lower Wairau Plain, New Zealand (Figure 1), as demonstrated by three-dimensional models of lithology and static groundwater level measured in wells and a groundwater budget. These models have provided significant new information about the lower Wairau Plain groundwater and surface water system, including the association of lithology with groundwater gradients in three dimensions and the controls on locations and flows in spring-fed streams.

In the west, Holocene Rapaura Formation gravel, deposited in a terrestrial environment, is common at the ground surface (Figure 1). Static groundwater levels (SGLs) typically decrease with depth indicating a vertically downwards component of groundwater flow.

The transition zone includes spring-fed streams (i.e., Spring Creek and Blenheim urban streams), Figure 1. Holocene Dillons Point Formation sediments (typically sands, silts and clays) deposited in a marine/estuarine environment and Rapaura Formation gravels crop out in this area. Groundwater inflow to the transition zone is approximately 8.2 m³/s, of which 8.1 m³/s flows in the Rapaura Formation aquifer. Most groundwater outflow from the transition zone (7.1 m³/s) is to the spring-fed streams, consistent with SGL gradients that are typically vertically upwards through Dillons Point Formation sediments in the area.

In the east, Holocene Dillons Point Formation sediments thicken towards the coast. Vertical SGL gradients are typically upwards indicating groundwater flow into the Rapaura Formation from the underlying Pleistocene formation.

In addition, a web-based interactive portal that provides instant access to information on groundwater systems and geology in three dimensions will be demonstrated.

1. INTRODUCTION

Groundwater is a very important water resource in the Wairau Plain, South Island, New Zealand (Figure 1). This resource provides the major supply for agricultural users, who are almost totally reliant on groundwater for large areas of vineyards, and the sole supply for the urban population in the main towns of Blenheim and Renwick (Davidson and Wilson, 2011). The Wairau Plain groundwater system also supplies flow to spring-fed streams. In Blenheim township, spring-fed streams are important amenities that are widely used for recreation and are navigable in part.

The geology of Wairau Plain includes Holocene formations (Rapaura Formation and Dillons Point Formation) and Pleistocene sediments (Brown, 1981), Figure 1. The Rapaura Formation, comprised of fluvial gravel, is the main aquifer in the area. Dillons Point Formation includes marine/estuarine sediments of the coastal Wairau Plain. Swamps (now largely drained), sands and silts were deposited in the east associated with a marine incursion that reached as far inland as Spring Creek and Blenheim (Brown, 1981; White and Tschritter, 2009; Raiber et al., 2012). Speargrass Formation is an outwash gravel of the last Pleistocene glaciation.
The boundary between Rapaura Formation and Dillons Point Formation, which generally coincides with the location of spring-fed streams, has been mapped at the ground surface. However, the three-dimensional distribution of key sediment types, and static groundwater levels, has not been mapped in detail to assess geological controls on the distribution of piezometric head, unconfined/confined conditions in aquifers and the location of spring-fed streams.

Figure 1. Geological map of Wairau Plain and environs (after Begg and Johnston, 2000) and depositional environments (after Brown, 1981) with contours of the base of Dillons Point Formation (after Ota et al., 1995).

Three-dimensional models were developed to represent the distributions of key sediments and static groundwater level in the lower Wairau Plain. These models are used to improve the understanding of Holocene deposition in the area. This paper will show how the distribution of sediments and the static groundwater level is relevant to the locations of, and flows in, spring-fed streams. Groundwater budgets, in association with Darcy flow measurements, will also be used to characterise Wairau Plain hydrogeology and hydrology.

In addition, this paper will outline a web-based system, including a smart phone application, that is used to access 3D geological model information.

2. METHOD
Marlborough District Council (MDC) holds geological data for 1165 wells located in the study area, with a total of approximately 22 km of lithologies logged, as of August 2012. Lithologies are generally described by drillers. Most of these wells (924) have their base in Holocene deposits. Data quality checks were completed during the process of 3D lithological property model development and poor-quality well logs were identified.
Three-dimensional models were developed in the lower Wairau Plain between the ground surface and 50 m depth to understand the distribution of three sediment classes described in well logs: 1) coarse sediments (predominantly where drillers describe gravel in a layer but also including other descriptions including "stones", "cobble", "shingle" and "boulders"); 2) sand; and 3) silt and clay (either singularly or together). Note that these classes of sediment are not exclusive, i.e. the models represent sediment occurrence where mixes of sediments are recorded in logs. For example, models separately represent gravel and sand fractions where a log describes "gravel and sand".

A 'property' code was assigned to the sediment descriptor in a well log with a second code used to mark the absence of that lithology. For example, the model of coarse sediments had gravel assigned a code of 200 and other lithologies assigned a code of 100 (White and Reeves, 1999). These codes were then combined into pseudo-logs, which are representations of the presence and absence of the sediment descriptor at an interval of 0.05 m over the depth of the well log. 3D lithological property models were generated from the pseudo-logs of all wells in the model domain by interpolation of pseudo-log property codes to a 3D grid, followed by 3D contour generation using EarthVision® software (Dynamic Graphics, Inc., USA); White and Reeves (1999); and Raiber et al. (2012). ‘Conformal’ lithological models were generated on a 100 m by 100 m grid mesh in the horizontal plane, deformed in the vertical plane by the pre-development DTM surface, between the ground surface and -50 m R.L. In this way, a continuous (3D) distribution of property codes was generated with the range of property codes indicating the likely presence of the sediment descriptor and the likely absence of the descriptor, i.e., the property code is a de-facto probability for sediment occurrence. For example, the presence of a sediment descriptor in the model volume is more likely with a property code of 150 or above.

Various 2D surfaces were developed to represent stratigraphic and chronological boundaries. For example, the top surface of the Speargrass Formation was the DTM where this formation is exposed at the ground surface. Below ground level, the Formation was estimated as a smoothed surface representing: elevations of selected clusters of wells with similar base elevations, the elevation of relatively fine Dillons Point Formation sediments and palaeoenvironmental indicators (e.g., shells and organics), White and Tschritter (2009). A 2D surface represented Holocene deposition at approximately 6,000 years B.P. with radiocarbon ages measured in Holocene samples and calculated elevations assuming constant sedimentation rates in the Holocene.

Static groundwater level (SGL) was calculated at each of the 1505 wells in the study area as the sum of ground-surface elevation at the well head, interpolated from the DTM, and the groundwater level mostly measured during drilling. The bases of most wells are located in the Rapaura Formation (31% of all wells with groundwater level measurements in the study area), Speargrass Formation (28%) and Dillons Point Formation (21%). Flowing artesian conditions are common near the coast and here the casing is commonly extended above ground level to measure static groundwater level.

Quality checks of SGL data were completed, primarily to identify measurements that were not representative of static conditions, i.e., due to the influence of pumping on groundwater level measurements. Groundwater level was below sea level in 24 wells located generally near the coast. These wells were removed from the data set because few of the SGL estimates were below sea level in the coastal area. Forty-five wells identified where the difference between SGL estimates in neighbouring wells was 2 m, or greater; 5 of these wells were removed from the data set where the original drillers’ logs indicated uncertainty in static groundwater conditions.

The 3D SGL model was calculated from measurements in 1475 wells using a conformal 3D grid and 3D contour generation between the water table and – 50 m R.L. with a 50 m by 50 m by approximately 1 m grid in the easting, northing and vertical directions, respectively. This model did not use control points to represent either the water table surface near the coast or the water surface elevation in spring-fed streams, so as not to impact the assessment of groundwater flow directions. Piezometric surfaces were calculated from this grid, and vertical SGL gradients across saturated Holocene sediments were represented by the difference between SGL at the water table surface and SGL at the base of the Holocene sediments, divided by the thickness of these sediments.

The three lithology models were merged in 3D plots to represent mixtures of major sediment types. Lithological and SGL models were combined to assess the controls on the location and flows of spring-fed streams in the Spring Creek and Blenheim urban area. A groundwater budget was developed to represent inflows to, and outflows from, the
Wairau Plain in three zones that largely follow the boundaries of Holocene sediments. Groundwater flows in formations at transition zone boundaries were then estimated with the water budget and the Darcy equation.

3. RESULTS
The transition of Holocene sediments from the west to the east is a key control on the groundwater hydrology and surface water flows in spring-fed Spring Creek and Blenheim urban streams in the lower Wairau Plain as demonstrated by 3D models of lithology and static groundwater levels (SGLs) that use available well log data from wells drilled since at least 1866.

In the west, Holocene Rapaura Formation gravel, deposited in a terrestrial environment, is common at the ground surface. Typically, SGL decreases with depth in the west indicating a downwards component of groundwater flow. The location of Spring Creek is possibly associated with pre-historic Wairau River channels as Holocene gravels are typically relatively shallow below the stream. Holocene gravels below Blenheim urban streams are mostly shallow in the west and associated with deposition by the Opawa, Omaka and Fairhall rivers.

Groundwater inflow to the transition zone, which is located between unconfined aquifers in the west and confined aquifers in the east, is an estimated 8.2 m³/s, including a flow from the west of 8.1 m³/s in the Rapaura Formation aquifer. Most of this flow (7.1 m³/s) discharges to Spring Creek and Blenheim urban streams. The predominant sediments at the ground surface near Spring Creek and Blenheim urban streams are sands, silts and clays. SGL gradients are typically vertically upwards in this area and the potential groundwater flow to surface water bodies, estimated with the Darcy equation, is similar to the flow to spring-fed streams. In the east, Dillons Point Formation sediments which are mainly sands, silts and clays form an aquiclude. SGL contours suggest the potential for vertically upwards groundwater flow which is consistent with the occurrence of artesian conditions in this area.

An interactive portal has been developed that provides instant access to information on groundwater systems and geology in three dimensions. It is possible to instantly call up relevant information by entering a street address, map coordinates or a smart phone’s GPS location. This information currently includes geological layer elevation, in the form of profiles and cross sections; the system is being expanded to include layer properties and uncertainty.

4. CONCLUSION
The results described in this paper were comparable with current knowledge (e.g., Davidson and Wilson, 2011). In addition, the lithology and SGL models have provided significant new information about the lower Wairau Plain groundwater system, including the association of lithology with groundwater gradients in three dimensions and the controls on locations and flows in spring-fed streams.

5. REFERENCES