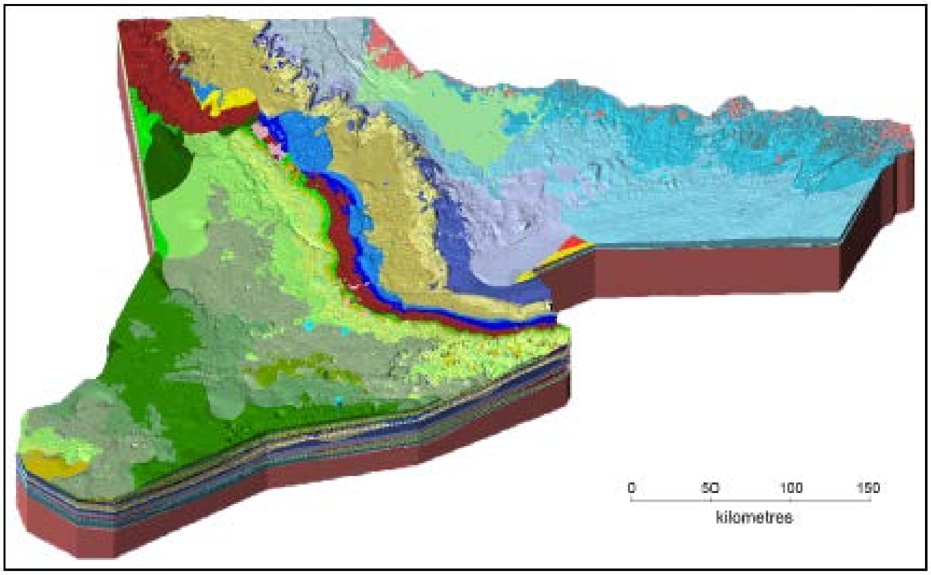
THREE-DIMENSIONAL GEOLOGICAL MAPPING

WORKSHOP EXTENDED ABSTRACTS

Conveners:

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



2018 Resources for Future Generations meeting
June 16–17, 2018
Vancouver, British Columbia CANADA

RFG2018

ILLINOIS STATE GEOLOGICAL SURVEY
Prairie Research Institute
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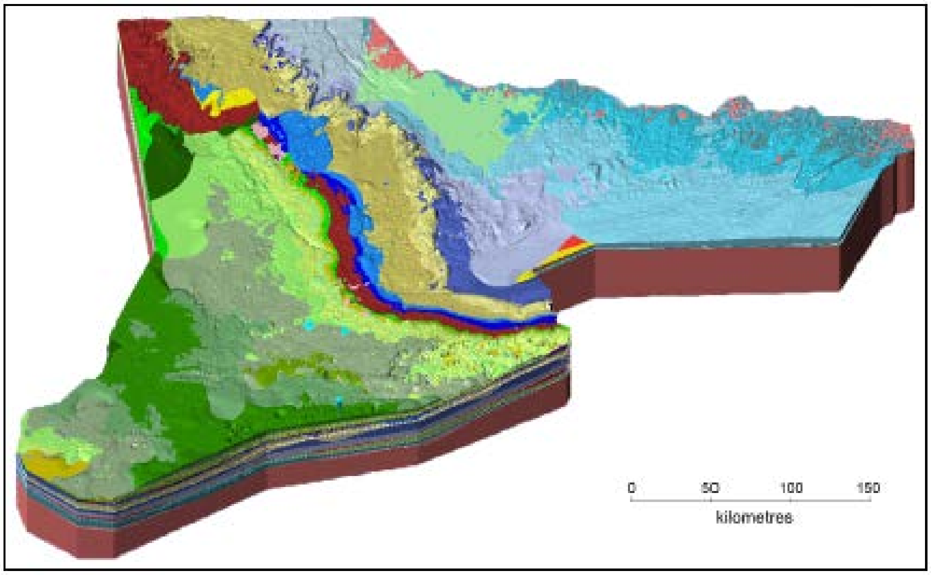

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Suggested citation:
Berg, R.C., K. MacCormack, H.A.J. Russell, and L.H. Thorleifson, conveners, 2018, Three-dimensional geological mapping: Workshop extended abstracts: Illinois State Geological Survey, Open File Series 2018-1, 95 p.

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ACKNOWLEDGEMENTS

The Workshop organizers thank Susan Krusemark and Michael Knapp and the Illinois State Geological Survey for assistance in publishing this Open-File Report. We thank the organizers of the Resources for Future Generations meeting for the opportunity to include our Workshop in the event. Finally, we thank all of our presenters and their respective funding agencies and sources for making this Workshop a success.

Day One Agenda – Saturday, June 16, 2018

Start	End	Min	Speaker, Affiliation	Title of Presentation
8:30	**8:40**	**10**	**INTRODUCTIONS**	
8:40	9:00	20	**Harvey Thorleifson**, Minnesota Geological Survey	Rationale and methods for jurisdiction-wide 3D geological mapping
9:00	9:20	20	**Richard C. Berg**, Illinois State Geological Survey	Synopsis of current 3D geological mapping and modeling in geological survey organizations – 2nd edition
9:20	9:50	30	**Keith Turner**, Colorado School of Mines	Geological models for infrastructure design: reducing geotechnical risk and supporting sustainability
9:50	**10:00**	**10**	***Discussion***	
10:00	**10:20**	**20**	**BREAK**	
			Program Rationale	
10:20	10:40	20	**Michiel J. van der Meulen**, Geological Survey of the Netherlands	Systematic subsurface mapping in the Netherlands: its future secured by a new law, and its funding because of a positive business case
10:40	11:00	20	**David R. Soller**, U.S. Geological Survey	Developing a three-dimensional geologic framework of the United States
11:00	11:20	20	**Kelsey MacCormack**, Alberta Geological Survey	Developing a 3D geological framework program at the Alberta Geological Survey; optimizing the integration of geologists, geomodellers, and geostatisticians to build multi-disciplinary, multi-scalar, geostatistical 3D geological models of Alberta
11:20	11:40	20	**Hazen A.J. Russell**, Geological Survey of Canada	Groundwater geoscience framework for southern Ontario: a status report
11:40	**12:00**	**20**	***Discussion***	
12:00	**13:00**	**60**	**LUNCH**	
			Data Infrastructure	
13:00	13:20	20	**François Robida**, BRGM, French Geological Survey	The need for standards to support 3D strategies of geological surveys
13:20	13:40	20	**Jay Hollingsworth,** Energistics	Vendor neutral transfer of unstructured grids using RESQML
			Complex Geology	
13:40	14:00	20	**Roland Baumberger**, Swiss Geological Survey	The National Geological Model: towards mastering the digital transformation in Switzerland
			Case Studies 1	
14:00	14:20	20	**Olivier Caron**, Illinois State Geological Survey	Will County geologic 3D mapping project: insights into the glacial history of northeastern Illinois by building a geologic model
14:20	**14:45**	**25**	***Demos***	
14:45	**15:00**	**15**	**BREAK**	
15:00	15:20	20	**Zbigniew Małolepszy**, Polish Geological Institute	New opportunities and challenges in 3-D geological mapping in Poland
			Modelling Approaches	
15:20	15:40	20	**Laurent Ailleres**, Monash University, Australia	Loop – a new open source platform for 3D geo-structural simulations
15:40	16:00	20	**Chaoling Li**, China Geological Survey	PRB 3D geological map modeling technology

16:00	16:20	20	**Holger Kessler**, British Geological Survey	Groundhog Desktop – a free software tool for geological studies
16:20	**16:30**	**10**	***Discussion***	
16:30			**Adjourn**	

Day Two Agenda – Sunday, June 17, 2018

Start	End	Min	Speaker, Affiliation	Title of Presentation
8:30	**9:00**	**30**	**ROUND TABLE DISCUSSION**	
9:00	9:20	20	**Peter B.E. Sandersen**, Geological Survey of Denmark and Greenland	Detailed 3D geological mapping intended for assessments of climate change impact and contaminant transport in groundwater
9:20	9:40	20	**Timothy Kearsey**, British Geological Survey	How accurate is your model between boreholes? Using shallow geophysics to test the best method to model buried tunnel valleys in Scotland, UK
9:40	**9:50**	**10**	***Discussion***	
9:50	**10:10**	**20**	**BREAK**	
10:10	10:30	20	**Boyan Brodaric**, Geological Survey of Canada	3D visualization of massive geo-models for Canada-3D
10:30	10:50	20	**Jan Stafleu**, Geological Survey of the Netherlands	An integrated modelling approach at TNO – Geological Survey of the Netherlands
10:50	**11:40**	**50**	***BREAKOUTS***	
11:40	**12:00**	**20**	***BREAKOUT REPORTS***	
12:00	**13:00**	**60**	**LUNCH**	
			Case Studies 2	
13:00	13:20	20	**Paul White**, GNS Science, New Zealand	Time-series facies models of sedimentary deposition in the last 20,000 years to identify pre-historic development of hydraulic properties of a coastal aquifer system, Wairau Plain, New Zealand
13:20	13:40	20	**Cath Cripps**, British Geological Survey	3D geological modelling of the UK onshore Chalk Group, for groundwater management purposes
			Delivering to the Client	
13:40	14:00	20	**Abigail Burt**, Ontario Geological Survey	The message is out!
14:00	14:20	20	**Christelle Loiselet**, BRGM, French Geological Survey	Storing and delivering numerical geological models on demand for earth sciences application
14:20	14:40	20	**Paulina Branscombe**, Alberta Geological Survey	Delivering to the client – communication and delivery for successful application of 3D models
14:40	**15:00**	**20**	***Discussion***	
15:00	**15:20**	**20**	**BREAK**	
15:20	**16:00**	**40**	**PANEL DISCUSSION**	
16:00	**16:30**	**30**	***Discussion***	
16:30			**Adjourn**	

THREE-DIMENSIONAL GEOLOGICAL MAPPING AND MODELING—WORKSHOP INTRODUCTION

Richard. C. Berg[1], Kelsey MacCormack[2], Hazen Russell[3], and Harvey Thorleifson[4]

[1]Illinois State Geological Survey, Champaign, IL USA, [2]Alberta Geological Survey, Edmonton, AB Canada, [3]Geological Survey of Canada, [4]Minnesota Geological Survey

In 1815, William Smith produced the geological map of England and Wales, which is considered to be the first formal geological map. This map could also be considered a three-dimensional (3D) map to the extent that it was accompanied by multiple cross-sections that depicted the subsurface. Since then, geological mapping has become a fundamental and core activity of the geoscience discipline, central to scientific understanding of landscape evolution, depositions of environment, and geologic history, and particularly its direct application to assessing water, energy, and mineral resources, engineering properties, hazard and risk assessments, and overall economic development potential.

A series of workshops designed to address the above application and facilitate sharing of best practices for 3D geologic mapping and modeling was initiated by Berg and Thorleifson in 2001, later joined by Russell and MacCormack. This RFG workshop is designed for those who are: (1) actively engaged in constructing sophisticated 3D geological maps and numerical models within their jurisdictions, (2) beginning the process of 3D geological mapping and modeling, and seeking guidance regarding best practices, and (3) interested in initiating a 3D mapping and modeling program within their institution and seeking guidance regarding not only the current state of best practices, but also seeking assistance in promoting the need for the program within their agency. The 2018 workshop will include presentations and discussions focusing on: (1) overall programmatic rationale, (2) developing methods and protocols necessary for model construction and validation, (3) managing large diverse data of variable quality that are required for 3D geological maps, (4) ensuring the interoperability of geologic maps and data, (5) developing visualization tools, (6) facilitating appropriate interaction between geological mappers, hydrogeologists, engineering geologists, engineers, and other scientists, and (7) delivering 3D mapping and modeling products to stakeholders, all of which will be “intertwined” with case study examples from across the globe.

Three-dimensional geologic mapping and modeling have long been a norm for oil and gas, as well as mineral resource exploration. However, its application to regional geology, groundwater, and engineering investigations is relatively new mainly because of the detail of mapping required to delineate subsurface materials, and the cost of obtaining the information (e.g., test-hole drilling and geophysical surveys). Advances in data collection and digital processing now permit the application of methodologies previously limited to the petroleum and mining industries, to mapping and modeling in 3D that can span from jurisdictional to more local geology. Particularly beginning in the late 1990s, geological survey organizations (GSOs) began to more comprehensively map the thickness, extent, and properties of multiple strata, as well as selected deformed structures, in a 3D GIS environment. Developments were driven by considerable progress in digital methods, large databases of water-well and engineering boring logs, and new drilling and geophysical tools to acquire subsurface information.

Advances in computer technology was coupled concurrently with escalating societal needs driven by land-use pressures requiring planners and health officials to make increasingly difficult decisions commonly revolving around groundwater resource evaluations and protection strategies. The situation can be particularly important in urban settings or expanding suburban areas, where there are thousands of data locations (e.g., water-well logs and engineering borings) that must be managed, evaluated, and compiled to construct accurate 3D geological maps and models at large scales. 3D geological models are quickly becoming the standard for assessing water and mineral resource potential, geological risk for both industry and government agencies, and economic development because they are effective tools to more easily explain and portray the often complex subsurface. They are also used frequently and successfully to assist with stakeholder engagement and communication.

With the advent of powerful computers (past 25 years) to manage large data sets and manipulate the data to portray complex relationships, it has been feasible to map, model, and display geology in 3D. It is imperative that geoscientists understand what these tools can do to provide insight on sedimentary environments, stratigraphy, and geologic history, and more importantly, to better explain the complexity of geological information to non-geologists. Users also typically request the input data that was used to make the maps and models. Therefore, robust yet user-friendly data bases with full metadata are also required, often along with a suite of interpretive or derivative products, as well as “user guides.”

The main focus of the workshop is to bring together geoscientists and technical staff who manage large data sets, and who need to integrate data of variable quality (such as logs from water wells) with crucial high-quality data (such as from test holes and geophysics) to construct 3D geological models of appropriate detail that can/may be used for a multitude of applications. This will be an opportunity to share new ideas and findings with people from other states, provinces, and countries who are dealing with similar challenges, and to provide updates from our previous nine workshops. Particularly important will be discussions of (1) program rationale, (2) institutional work flows, (3) how various geological surveys have dealt with various jurisdictional scientific and mapping issues, (4) the emphasis and need for jurisdiction-wide 3D geological mapping and modeling, and (5) delivering mapping and modeling products to stakeholders. For the latter, GSOs have become increasingly aware that their often "high-end" computing, visualization, and output/information delivery capabilities far exceed the capabilities of the majority of their intended users, which are often local governments. Therefore, ensuring that GSOs are able to allocate their resources appropriately to delivering this information in a format that their stakeholders want and can use is of paramount importance.

Participants are from: (1) the academic community – particularly hydrogeologists – who can benefit most from knowing that the 3D models discussed in the workshop are truly integrated and internally consistent solids models that represent the geometry, stratigraphy, hydrostratigraphy, and sedimentology of aquifer and aquiclude units, and their interrelationships, and therefore provides a sophisticated conceptual model for eventual groundwater flow modeling and estimating groundwater resource availability and yields, (2) state and national geological surveys that have been conducting geological mapping and groundwater investigations as part of their mandates, and (3) private industry that has been developing geological mapping and modeling software.

The workshop series has become an international forum regularly attended by geological survey practitioners and interested academic and industry persons. Beginning in 2001, nine previous workshops have been held in Normal, Illinois, Denver, Colorado, St. Catharines, Ontario, Salt Lake, Utah, Portland, Oregon, Minneapolis, Minnesota, and Baltimore, Maryland. The 10^{th} workshop, at the Resources for Future Generations meeting in Vancouver, British Columbia, has multiple speakers from North America, Europe, New Zealand, and China, and for the first time will be conducted over two full days.

This RFG workshop will be the 10^{th} in the series that previously have been hosted by, or conducted in parallel, with the Geological Society of America and the Geological Association of Canada meeting. It has truly become an international meeting on 3D mapping and modeling, with participants from Australia, Canada, China, Denmark, Finland, France, Germany, Italy, the Netherlands, New Zealand, Poland, Switzerland, the United Kingdom, and the United States.

The North American 3D mapping and modeling workshop concept has expanded to Europe and Australia. The European 3D GeoModelling Community has now conducted four workshops beginning in 2013. Workshops have been in Utrecht, the Netherlands, Edinburgh, Scotland UK, Wiesbaden, Germany, and Orléans, France. A 3D Hydrogeology Workshop was conducted in 2009 in Canberra, Australia.

There has been incredible growth and development over the 17-year course of these 3D workshops beginning with connecting the GSOs trying to build 3D modelling programs, to development of sophisticated workflows and elegant client-driven maps and models, to the need for jurisdiction-wide mapping and modeling, to the integration of 3D models to support decision making. It is this latter and most recent effort that requires an even more dedicated and focused effort, particularly within larger jurisdictions where funding and staffing issues are limited, and/or there are many competing interests for government funds. Therefore, the more that we can learn from each other's successes and failures, and report on the benefits and costs of 3D mapping and modeling, and support each other's efforts to initiate 3D modeling programs, the better we can "make the case" for a global and detailed 3D geological model.

RATIONALE AND METHODS FOR JURISDICTION-WIDE 3D GEOLOGICAL MAPPING

L.H. Thorleifson

Minnesota Geological Survey, St. Paul, Minnesota, USA

thorleif@umn.edu

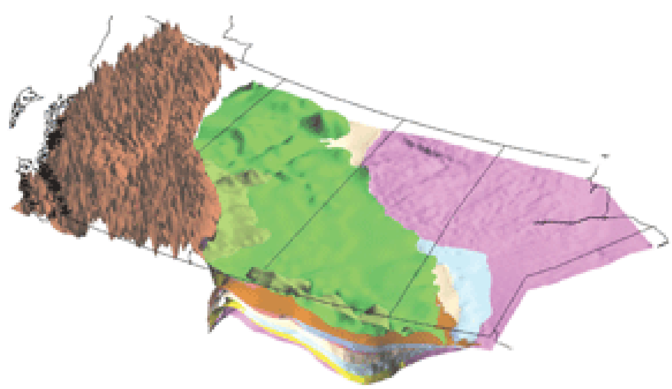
Abstract

Nations, states, provinces, and territories have completed or have observed three-dimensional (3D) geological mapping pilots and are now transitioning to jurisdiction-wide, multiple-resolution 3D geological mapping that will provide a spatial context for all georeferenced and vertically positioned geoscience information that is maintained to support the interests of society. This 3D geological mapping by geological survey agencies and partners is an extension of well-established 2D methods that is focused on depiction and prediction of the extent, thickness, and properties of all mappable lithologic strata in a jurisdiction, and it is being conducted to support applications such as groundwater management, infrastructure design, hazards mitigation, resource management, sedimentary basin assessments, and research. Development of programs in this field requires an adequate grasp of rationale; background; data compilation; data acquisition; model construction; geostatistical methods; properties, heterogeneity, and uncertainty; delivery and applications; examples; and strategies.

Introduction

Pressing issues related to energy, minerals, water, hazards, climate change, environment, waste, and engineering, as well as research priorities, call for accelerated progress on national, regularly updated, well-coordinated, multi-resolution, seamless, 3D, material-properties-based geological mapping databases.

Rationale—*Why do I need to do this?*



Geological survey agencies are unique and essential services that maintain knowledge of subsurface conditions throughout a jurisdiction, thus allowing governments, economies, and societies to function in an informed manner and stimulating benefits related to resources, safety, public health, and natural heritage (Häggquist and Söderholm, 2015; Riddick et al., 2017). Geological mapping, along with jurisdiction-wide geophysical, geochemical, and other surveys, and underpinned by a comprehensive and influential grasp of geological research, is a core activity of these agencies and their partners. For two centuries, geological maps have utilized the printing press to communicate observations and predictions of the lithology and other attributes of sediments and rocks. Pressing societal needs and accelerating capabilities in the form of methods and data are causing an accelerating shift to queryable 3D mapping that is ready for application to modeling, where achievable (Culshaw, 2005; Turner, 2006; Thorleifson et al., 2010; Smith and Howard, 2012; Pavlis and Mason, 2017).

Geological mapping is a mature field (Lisle et al., 2011), and analyses show that the activity returns large positive economic returns (Bernknopf et al., 1997; Bhagwat and Ipe, 2000). National, multi-resolution, updated 2D mapping remains needed. A cross section commonly accompanies a 2D map, while a 3D map can consist of a sufficient number of cross sections. All principles that apply to plan view apply to section view, so 3D mapping is thus an extension of well-established 2D mapping methods. In the context of these well-established roles for geological survey agencies, and well-developed methods for geological mapping, societal needs that rely on geological mapping are escalating in importance—in areas such as anticipation of ground conditions in engineering, groundwater capacity and vulnerability, assessment of sedimentary basins regarding energy and waste injection, mineral resources, hazards, and fundamental understanding of earth materials, processes, and history.

Geological survey agencies worldwide therefore are responding to these pressing societal priorities and exciting research opportunities by accelerating progress on national, regularly updated, well-coordinated, multi-resolution, seamless, 3D, material-properties-based geological mapping databases because of increased data availability, improved technology, intensified land use, and escalating societal expectations (e.g. Berg et al., 2011; Boyd and Shah, 2016; Berry et al., 2017; Soller and Garrity, 2018).

Background—*What do I need to understand?*

Geological mapping programs need to be sufficiently broad to support unanticipated applications while being developed with a grasp of current applications, such as qualitative groundwater modeling (Payne and Woessner, 2010), aquifer sensitivity (Berg, 2001; Hansen et al., 2016), wellhead protection (EPA, 1998), hydrogeological conceptual modeling (Anderson and Woessner, 1992; LeGrand and Rosen, 2000; Bredehoeft, 2005; Kresic, 2007; Royse et al., 2010; Cavero et al., 2016), hydrogeological property attribution (Fan et al., 2015; Maliva, 2016; Bayless et al., 2017), quantitative groundwater modeling (Anderson et al., 2015; Gleeson et al., 2015), engineering (Fookes, 1997; Gaich et al., 2017), sedimentary basin assessments, mineral resources assessment, hazards, and fundamental research (e.g., Maxwell and Condon, 2016; LaRowe et al., 2017; Shangguan et al., 2017).

Geological mapping is guided by well-established stratigraphic principles. Facies models and basin analysis (Miall, 2000, 2016; Sharpe et al., 2002) guide all work, while inferred lithology is needed as a basis for property attribution. Users need continuous tracing of the extent, thickness, and properties of lithologic units. Combined allostratigraphic and lithostratigraphic approaches may apply, naming should be orderly and minimized (NACSN, 2005), and the work needs to extend to hydrostratigraphy (Maxey, 1964; Weiss and Williamson, 1985; Seaber, 1988).

Geological mapping has been 3D since its inception, at least in the form of structure symbols, cross sections, structure contours, isopachs, and stack-units. Use of regularly spaced, orthogonal cross sections to build 3D geology was described by Mathers and Zalasiewicz (1985), while early principles of 3D GIS were outlined by Vinken (1988), Turner (1989), Raper (1989), and Vinken (1992). Bonham-Carter (1994) stressed that 2D GIS differs from 3D, in that 3D has x, y, and multiple z values, unlike plan view 2D, or perspective 2.5D methods based on a single z per site. A comprehensive conceptual structure for 3D GIS was presented by Houlding (1994), while Soller et al. (1998) worked out a method for regional 3D geological mapping based on geological maps, stratigraphic control points, and large public drillhole databases. Recent overviews have been published on 3D methods in the hydrocarbon industry (Zakrevsky, 2011) and in applied hydrogeology (Kresic and Mikszewski, 2012).

One approach is required for layers no more deformed than subsidence and normal faulting, where thickness can be inferred throughout their extent, and for which underlying geology can be drawn. Below these layers is basement, consisting of complexly deformed strata, as well as igneous and metamorphic rocks, which are depicted as a basement map, accompanied by increasing depiction of predicted 3D geometry of key structures, along with discretized basement physical properties (Groshong, 2006; Krantz et al., 2016; Laurent et al., 2016; Schetselaar et al., 2016).

The result is conveyed with the use of broadly accepted information standards (Ludascher et al., 2006; Howard et al., 2009; Asch et al., 2012; Kessler and Dearden, 2014).

Data compilation—*What do I need to compile?*

Much effort at the outset is required to assemble topography, bathymetry, soil mapping, 2D geological mapping, and public domain drillhole data. In the case of drillhole data, the steps are to acquire, digitize, georeference, and categorize by lithology (Thorleifson and Pyne, 2004; Dunkle et al., 2016).

Data acquisition—*What field work is needed?*

Some new field work will be required to benchmark the 3D mapping. Geophysical surveys (Pellerin et al., 2009; Styles, 2012; Everett, 2013; Binley et al., 2015) may include EM (Abraham et al., 2012; Jorgensen et al., 2013; Oldenborger et al., 2013; Hoyer et al., 2015; Sapia et al., 2015; Bedrosian et al., 2016), seismic (Pugin et al., 2009; Nastev et al., 2016; Oldenborger et al., 2016; Maesano and D'Ambrogi, 2017), passive seismic (Chandler and Lively, 2016), radar, borehole geophysical surveys, and marine geophysics (Todd et al., 1998). New drilling will be required in many programs to provide stratigraphic benchmarks that anchor the models.

Model construction—*How do I draw layers?*

Model construction proceeds first with recognition of the resolution of the model and the 2D mapping to which it is associated, whether global, continental, state/national, or county/quadrangle. In the use of lithological data, the model is anchored at stratigraphic benchmarks, strata may be drawn by a geologist through lithological data, a facies model guides interpolation, and strata are drawn at a resolution supported by the data. In the case of stratigraphic data, modeling may proceed directly from regularly spaced, correlated data. Maps such as depth to bedrock and depth to basement motivate data compilation and clarify data collection priorities. Legacy stratigraphic models may require much effort, as many regions have stratigraphic atlases in need of digitizing. Cross sections drawn through lithologic data (Lemon and Jones, 2003; Patel and McCechan, 2003; Kaufmann and Martin, 2008; Jones et al., 2009; Tam et al., 2014) are used in a common scenario involving a region in which regional 3D mapping is needed to support groundwater management, and the available basis for modeling is scattered cores and geophysical surveys, along with an abundance of water well data. An approach in this case is data compilation, acquisition of stratigraphic control sites using coring and geophysics, and construction of cross sections, resulting in depiction of a fully plausible geology that conforms to the geological conceptual model and from which data issues have been filtered by the geologist, although incorporation of new data is challenging. In the case of interpolated stratigraphic data, well-distributed drillholes correlated by means such as micropaleontology or lithological trends may be ready for machine modelling, although expert-generated synthetic profiles may be required in data-poor areas for an acceptable result to be obtained—in this case new data are, however, more readily incorporated into iterations. A progression from surfaces to fully attributed solid volumes will be needed for applications. This may require data collection and transfer to another software platform, depending on the nature of the discretization and attribution. Solid models may also be constructed from geophysical data.

Geostatistical methods—*Can I use geostatistical methods to infer solids and their properties?*

Geostatistical methods will somehow play a role in all programs, to infer or to characterize solids models based on 3D data. In this field, literature is available at the introductory level (McKillup and Dyar, 2010), as well as overview (Houlding, 1994; Kresic and Mikszewski, 2012; Kim et al., 2017), while more comprehensive guides have been presented by several authors. Examples of methods include simple kriging, ordinary kriging, universal kriging, block kriging, training image-based multiple-point geostatistics, and support vector machines. Modeling also requires concepts such as cellular partitions, tessellations, discrete smooth interpolation, differential geometry, piecewise linear triangulated surfaces, curvilinear triangulated surfaces, stochastic modeling, and discrete smooth partitions (Mallet, 2002; Wang et al., 2016; Pellerin et al., 2017).

Properties, heterogeneity, and uncertainty—*How do I specify the characteristics of layers?*

Three-dimensional geological mapping initially seeks relatively homogeneous strata, to which representative properties are assigned. The strata are then revisited, to better recognize heterogeneity. With heterogeneity adequately considered, uncertainty can somehow be indicated. Properties are inferred from lithology, while measurements in hand guide this inference from lithology. Interpolation and extrapolation can also proceed from measurements such as hydraulic conductivity values while adequately respecting the geological model (Royse et al., 2009; Priebe et al., 2017).

Research on heterogeneity includes, for example, recognition of structure-imitating approaches, process-imitating models, and descriptive methods (Kolterman and Gorelick, 1996; Bianchi et al., 2015; Kitanidis, 2015; Siirila-Woodburn and Maxwell, 2015; Mawer et al., 2016; Meyer et al., 2016; Michael and Khan, 2016). Anderson (1997) concluded that most porous media are heterogeneous, that simulation of facies patterns using depositional models is appealing but difficult, and that indicator geostatistics with conditional stochastic simulations are a promising approach to quantifying connectivity, thereby inferring preferential flow paths. The topic has also been addressed by Weissmann and Fogg (1999) and by De Marsily et al. (2005).

Uncertainty in 3D geology varies inversely with data density, while data requirements vary with geological complexity. Uncertainty thus relates to data, complexity, and interpretation (Tacher et al., 2006; Lelliott et al., 2009; Lark et al., 2013; Bond, 2015; Malvić, 2017; MacCormack et al., 2018). Stochastic techniques may be used to compute the probability for each grid cell to belong to a specific lithostratigraphic unit and lithofacies.

Delivery and applications—*How do I ensure that my output will be readily discovered and used?*

Adoption of appropriate formats, and provision of adequate accessibility, with needed guidance to users, will ensure discovery and application of the mapping to societal priorities (de Mulder and Kooijman, 2003; Giles, 2006; Mathers et al., 2011b), while protocols such as Building Information Modeling (BIM; Bhuskade, 2015; Kerosuo et al., 2015), RESQML (Legg et al., 2015), or Geo3DML (Li et al., 2015b; Wang et al., 2017) may facilitate delivery to user communities, as will strategies to address, for example, the needs of urban design (Schokker et al., 2017).

Examples—*What have other people done?*

Examples of successful yet steadily evolving 3D geological mapping programs are available in areas such as China (Li et al., 2015a), Australia (Gill et al., 2011; Martinez et al., 2017), New Zealand (Raiber et al., 2012; White et al., 2016), Denmark (Thomsen et al., 2004; Møller et al., 2009; Jorgensen et al., 2012), Finland (Artimo et al., 2003), France (Castagnac et al., 2011), Germany (Pamer and Diepolder, 2010; Lehné et al., 2013; Diepolder and Lehné, 2016), Italy (De Donatis et al., 2009), the Netherlands (Stafleu et al., 2011; Kombrink et al., 2012; Gunnink et al., 2013; Meulen et al., 2013; Maljers et al., 2015; Kruiver et al., 2017), Poland (Małolepszy, 2005), the UK (Mathers et al., 2011a; 2014; Aldiss et al., 2012; Tame et al., 2013; Burke et al., 2015, 2017; Woods et al., 2015; Gakis et al., 2016), Canada (Ross et al., 2005; Sharpe et al., 2007; Tremblay et al., 2010; Burt and Dodge, 2011; Keller et al., 2011; Russell et al., 2011; Bajc et al., 2012; MacCormack and Banks, 2013; Frey et al., 2016; Carter et al., 2017; Crombez et al., 2017; Russell et al., 2017), and the United States (Thorleifson et al., 2005; Phelps et al., 2008; Faith et al., 2010; Jacobsen et al., 2011; Keefer et al., 2011; Pantea et al., 2011).

Strategies—*What should I do next?*

Successful progress in 3D geological mapping requires a focus on societal needs, assessment of the status of data and mapping, raising expectations among users, long-term planning, commitment to institutional databases, reconciliation of stratigraphy from onshore to offshore, gradual harmonization of seamless 2D mapping, geophysics and drilling, choice of an appropriate approach, development of an evolving plan, and building of support.

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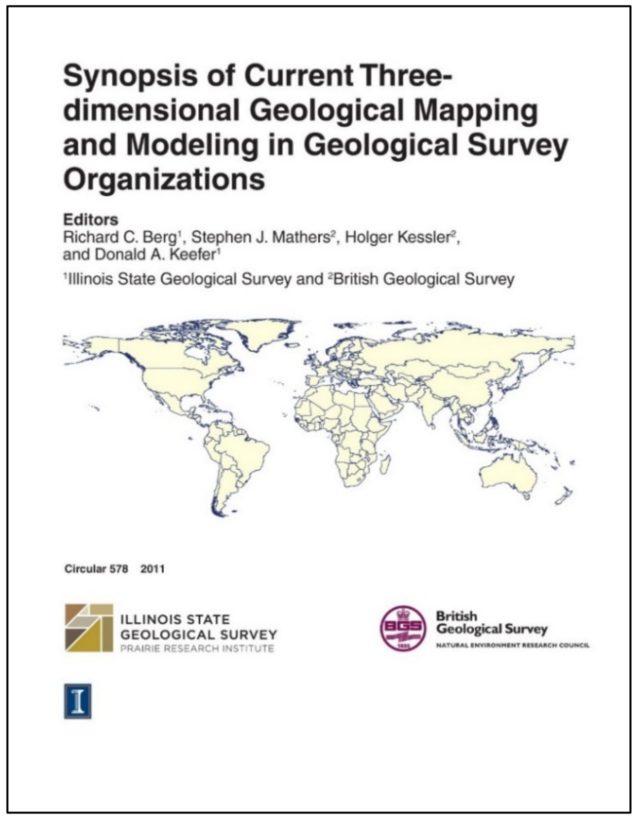
SYNOPSIS OF CURRENT THREE-DIMENSIONAL GEOLOGICAL MAPPING AND MODELING IN GEOLOGICAL SURVEY ORGANIZATIONS—2ND EDITION

Kelsey MacCormack[1], Richard C. Berg[2], Holger Kessler[3], Hazen A.J. Russell[4], and L. Harvey Thorleifson[5]

[1]Alberta Geological Survey, Edmonton, AB Canada, [2]Illinois State Geological Survey, Champaign, IL USA, [3]British Geological Survey, Keyworth, UK, [4]Geological Survey of Canada, Ottawa, ON Canada, [5]Minnesota Geological Survey, St. Paul, MN USA

Introduction

Since the publication in 2011 of the *Synopsis of Current Three-dimensional Geological Mapping and Modeling in Geological Survey Organizations* (http://library.isgs.illinois.edu/Pubs/pdfs/circulars/c578.pdf; Berg et al., 2011), there has been phenomenal uptake of 3D mapping and modelling methods at Geological Survey Organizations (GSOs) at the provincial, territorial, state, and federal levels. There is also an emerging interest globally through One Geology. This mirrors a growing recognition of the societal value of geoscience data management, geological mapping, visualization, and modelling applications to support science-based decision making for sustainable resource development and public safety.



As a consequence of differences in government organization, geographic scale, geological complexity, and economic development, GSOs have taken a variety of approaches to developing 3D modelling programs within their organizations. Multiple solutions have been implemented, with some organizations creating large modelling teams and developing multi-resolution models and other surveys working hard to gain support from their leaders or governments to initiate 3D modelling pilot studies.

This update to the 2011 publication will provide geoscience organizations with a guide highlighting the recent successes, accomplishments, and challenges experienced by GSOs in the development and deployment of their 3D programs. It will provide a context for organizations looking to gain support within their organizations to build 3D modelling programs by leveraging the business cases and approaches highlighted by international surveys with successful 3D modelling programs.

Objective

The objective is to produce a three-part publication by the Alberta Geological Survey that will serve as an updated best practices guide and case study overview of the state-of-the-art 3D modelling practices within GSOs. Part 1 will provide an overview of general requirements and operational necessities for supporting a 3D program. Part 2 will consist of organizational case studies based on a general template to capture information on the structure and mandate, recent successes, lessons learned, and current challenges of both well-established and newly formed 3D modelling programs, and particularly to provide insight and guidance to newly established programs as well as jurisdictions wishing to initiate 3D modelling programs. Part 3 will provide a brief summary and forward-looking prediction of the future state of 3D modelling within GSOs. Breakout, roundtable, and panel discussions from the 2018 RFG 3D Geologic Mapping Workshop, as well as RFG program abstracts and presentations, will all contribute to Parts 1 and 3.

Outline

Elements that will be discussed within the three parts shall include:

Part 1—Overview and Background

This introductory section will include the following:

- Mapping and modelling issues
- Overview of jurisdictional challenges and solutions
- Logistical considerations
- Overview of 3D mapping software
- Cost-benefit analysis for building 3D models

Part 2—Geological Survey Organizations Overview

This section will comprise most of this updated volume. Provincial, territorial, state, and federal GSOs will be submitting up to a 5000-word overview of their 3D mapping and modelling activities. Details on key areas of information to include in a template format will be provided later, but jurisdictional overviews should include the following:

- Organizational structure and business model
- Overview of 3D modelling activities
- Number of staff and budget resources allocated to 3D modelling activities
- Overview of regional geological setting
- Data issues (type, abundance, availability, confidentiality issues)
- 3D modelling approach (implicit vs. explicit, stochastic vs. empirical, etc.)
- Clients (degree of interaction, collaboration, support usage)
- Recent case studies showcasing application of 3D work
- Current challenges (organization, technological, conceptual)
- Lessons learned

Part 3—Discussion on the Future State of 3D Modelling within GSOs and Global Coordination Initiatives

This section will be based on the content provided in Parts 1 and 2. It will be summary statements and conclusions that bolster the urgency for an increased understanding of our subsurface to address myriad societal and economic development issues and to provide decision makers with scientifically defensible answers to critical earth resource and environmental questions.

We are asking GSOs to please confirm your contributions by June 29, 2018.

A 5000-word (maximum) contribution is due by December 5, 2018, with a June 2019 anticipated publication date by the Alberta Geological Survey.

Reference

Berg, R.C., S.J. Mathers, H. Kessler, and D.A. Keefer, eds., 2011, Synopsis of current three-dimensional geological mapping and modeling in geological survey organizations: Illinois State Geological Survey, Circular 578, 92 p.

LOOP—A NEW OPEN SOURCE PLATFORM FOR 3D GEO-STRUCTURAL SIMULATIONS

Laurent Ailleres[1], Lachlan Grose[1], Gautier Laurent[1,2], Robin Armit[1], Mark Jessell[3], Guillaume Caumon[2], Eric de Kemp[4], and Florian Wellmann[5]

[1]School of Earth, Atmosphere and Environment, Monash University, Australia, [2]RING-Georessources, Université de Lorraine, France, [3]Centre for Exploration Targeting, University of Western Australia, Australia, [4]Geological Survey of Canada, Canada, [5]RWTH Aachen University of Technology, Germany

Laurent.ailleres@monash.edu

Abstract

There is a critical technology gap in our 3D geological modelling workflow. Even with the advent of implicit techniques, 3D geological modelling of hard rock terranes (at any scale) is a highly specialized and costly task (both in time and computing resources) and often only adapted to “simpler” basin geometries. Importantly, usually only one model is built while uncertainty is high and non-quantified.

We present a new platform, *Loop*, which allows for the consideration of all types of structural information in the modelling workflow as well as the ability to enable simulations of different geological scenarios (e.g., change in topology due to changes in fault relationships) and characterizing uncertainty throughout the modelling process.

We present a forward modelling engine for modelling poly-deformed terranes and in particular folds and fold overprints. The method is based on producing scalar and vector fields of the different structural elements starting with the youngest in a time-aware process. For each event, a fold axis vector field is interpolated as well as the fold profile around the fold axis. We use structural geostatistics based on a new reference system based on the strain ellipsoid related to folding to analyze field data and extract geometrical information. The requirement to interpolate the fold profile around the fold axis means that at every data point, there is a need to estimate the fold axis at the same time as the fold profile. This lends to developing a structural data inversion scheme during which both fold axis vector fields and fold profiles are fitted to the data.

We present the inversion scheme based on probabilistic modelling (using Bayesian inference) and resulting in an inversion of the structural data and uncertainty characterization and a minimization of the uncertainty process. The results are shown in a real case study from the Northern Territory, Australia.

Introduction

One of the great challenges in both resources exploration and management and geological research is to predict and represent geology in 3D. Building 3D models, even with the advent of implicit techniques (Lajaunie et al., 1997; Cowan et al., 2002, 2003; Chiles et al., 2004; Moyen et al., 2004; Frank et al., 2007; Calcagno et al., 2008) is still a highly specialized and costly task (in both time and computing resources) and often only adapted to “simpler” basin geometries (Jessell et al., 2014). There is currently a critical technology gap in our 3D geological modelling workflow (Jessell et al., 2014):

1. Current platforms use only a subset of the geological information available, which makes building 3D geological models of hard-rock terranes very difficult (Jessell et al., 2010).
2. The integration with geophysical imaging is limited to the use of interpretative cross sections or the use of 3D models as reference models for a posteriori inversions that ignore geological data and information.
3. Finally, uncertainty is extremely high and usually neither quantified nor utilized.

The above three shortcomings in the modelling process conspire to promote the production of geological models with limited economic or scientific value. The new project aims to integrate all available data in the modelling process, develop enabling technologies that will combine probabilistic modelling with structural concepts to produce 3D structural geological models (integration of geological rules in the modelling workflow), and assess and characterize uncertainty throughout the modelling workflow to optimize data acquisition for future maximized uncertainty reduction.

Loop is a new platform (Figure 1) that enables field geologists, researchers from academia and government organizations, explorers, and resources modellers and managers to better define their 3D geological environment as well as to assess the requirement for optimized additional data/knowledge acquisition. The platform will be open source, scalable, and applicable to problems from the mine scale to the plate scale, in both data rich and poor environments. It will serve to solve problems related to urban geology, basins resources exploration and exploitation, as well as minerals and scientific exploration in poly-deformed metamorphosed terranes.

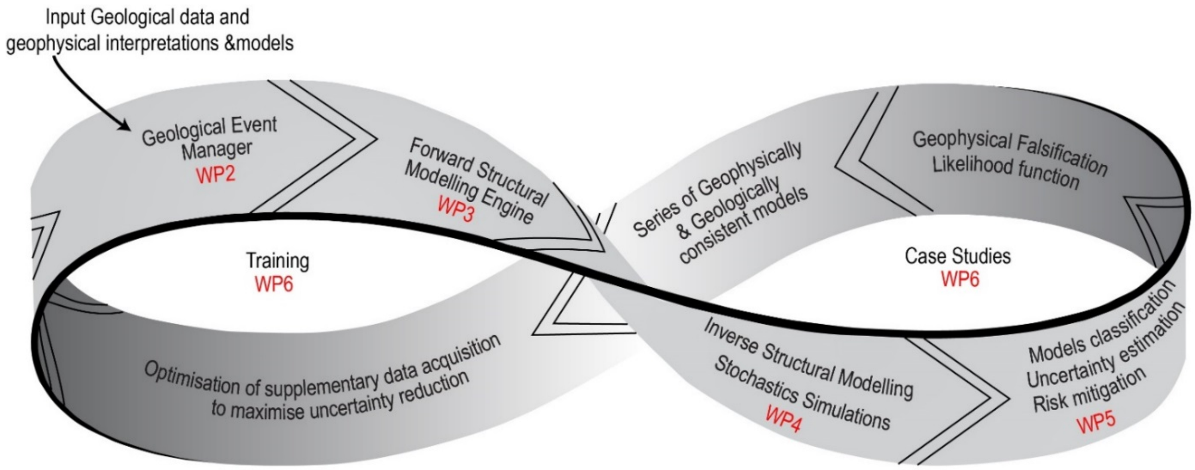


Figure 1. Newly proposed open source platform (called *Loop*) to solve 3D structural geological modelling problems from the mine scale to the plate scale and including geological problems, related resources exploration and management in urban geology settings, basins geology environment, and poly-deformed terranes.

Recent advances in 3D structural modelling

Although implicit modelling concepts were first developed 25 years ago (Stirewalt and Henderson, 1995; Lajaunie et al., 1997), the currently available methods' inputs are still limited to structural measurements of the primary foliation observed in the field (e.g., bedding, compositional layering). However, the concept of utilizing field structural data (Calcagno et al., 2008) is very important in enabling geologists to build 3D models and to use 3D models to guide further data acquisition. Jessell et al. (2010) provided a technological gap analysis of 3D modelling and uncertainty characterization techniques, demonstrating that only a limited subset of the structural observations are actually utilized.

The results presented build on recent developments by Laurent et al. (2016), who defined a "time-aware fold coordinate system" to allow modelling of overprinting of folding events, through interpolation of fold profiles and fold axes vector fields. This is a huge improvement on previous technologies, which provided limited capability to model one fold object and no capability to model poly-deformation (Maxelon et al., 2009; Massiot and Caumon, 2010).

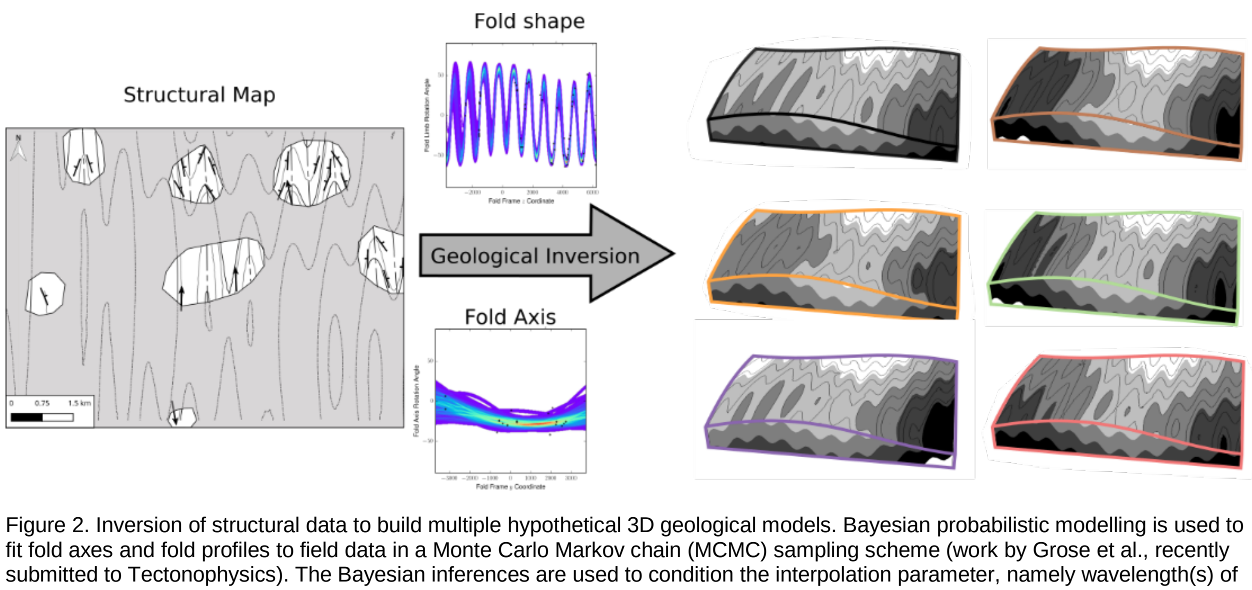


Figure 2. Inversion of structural data to build multiple hypothetical 3D geological models. Bayesian probabilistic modelling is used to fit fold axes and fold profiles to field data in a Monte Carlo Markov chain (MCMC) sampling scheme (work by Grose et al., recently submitted to Tectonophysics). The Bayesian inferences are used to condition the interpolation parameter, namely wavelength(s) of folds and parasitic folds, coefficient of the Fourier series used to fit the fold and fold axis profile to structural data. Using Bayesian inferences allows us to jointly invert for the fold axis and the fold profile in the entire model volume.

Grose et al. (2017) adapted the technique so that the fold profiles and fold axis fields can be derived from data (structural measurements) using spatially adapted statistical methods to the “fold coordinate system”. Current developments have led to the inversion of field structural data using Bayesian inferences (Grose et al., submitted to Tectonophysics) and classical inversion techniques (Monte Carlo Markov chain sampler) to jointly fit the fold axis vector field and the fold profile everywhere in the modelled volume, locally honoring the structural data (Figure 2). Complex fold geometries can be considered, including, for example, box and kink folds as well as parasitic folds using Fourier series. This method also automatically includes uncertainty characterization and sampling of the model space. This is the first time that inversion of structural data has been used to build 3D models and characterize uncertainty.

Recent advances in 3D uncertainty analysis

Uncertainty in geological data is high, and higher still in the third dimension. Model uncertainty derives from uncertainties in input data (Allmendinger et al., 2017), manual interpretations of geophysical data (Bond et al., 2007), natural geological variation (Lindsay et al., 2012), and the specificities of the interpolation schemes used in modelling schemes (Aug, 2004). We can simulate these uncertainties by applying Monte Carlo methods that perturb the input data to examine the resulting variability on the resultant models. This approach requires implicit codes, as manual model building is too slow to allow more than a few models to be constructed.

We can characterize 3D model uncertainty at the local scale by analyzing how lithological properties vary for each voxel in the model (Jessell et al., 2010; Wellmann et al, 2010; Lindsay et al., 2012; Pakyuz-Charrier, 2017).This provides important information on the spatial variability and local reliability of the models, and provides a pathway to undertaking sensitivity analyses that allow us to better understand the new data that needs to be collected to reduce model uncertainty. Alternatively we can derive a global estimate of model uncertainty by summing the local uncertainties, or by classifying the models according to derived parameters such as the volume of specific lithostratigraphic units, or the overall model topology (Lindsay et al., 2013a,b; Thiele et al., 2016b).

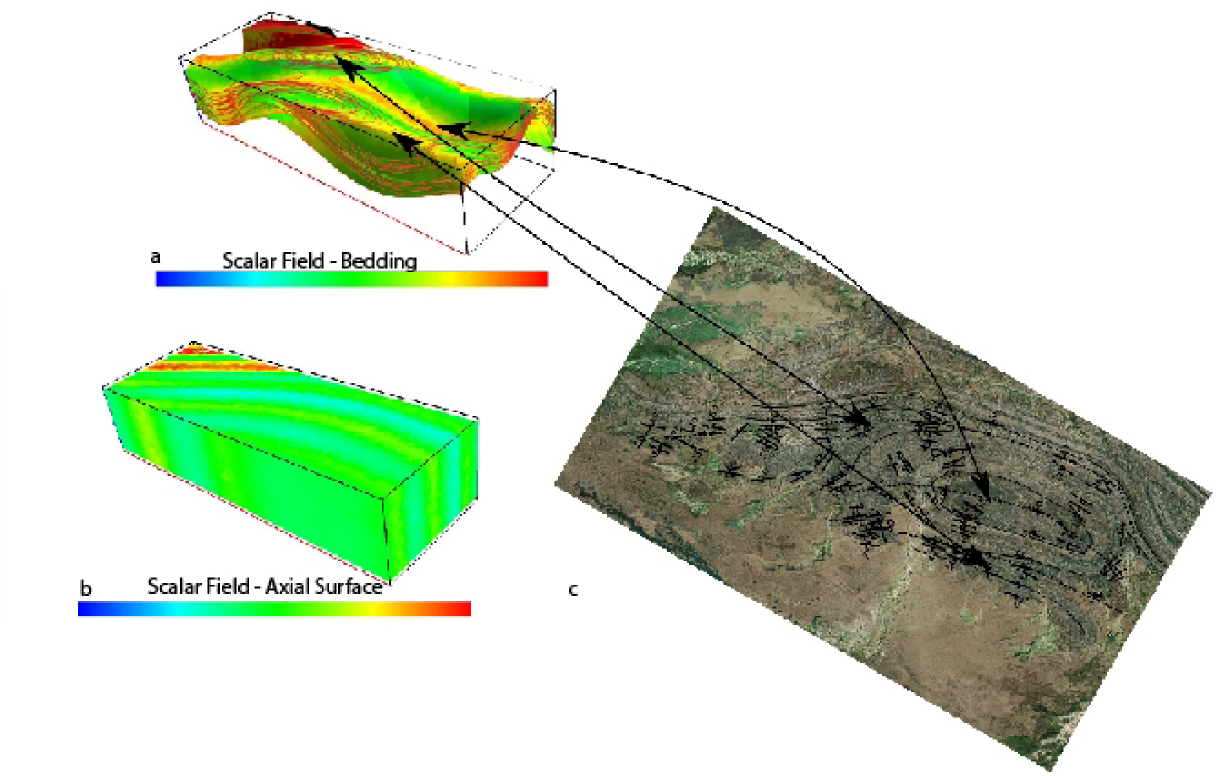


Figure 3. Results of the inversion of structural elements for implicit fold modelling. a) Resulting folded bedding from b) axial surface field of the axial surface of the folds and c) input data over satellite imagery of the Davenport area in the Northern Territory, Australia. Note that shear zones are present in the fields between each domal structure; however, they are ignored during the modelling process at this stage.

The major source of uncertainty in 3D models is related to the topology of the model. Here we define topology as the spatial and temporal relationships between lithological units (Thiele et al., 2016a); however it can be extended to include microstructural overprinting as well as metamorphic and alteration events (Burns, 1975, Potts and Reddy, 1999). The topology of a 3D geological volume is controlled by deposition, faulting, and structural and intrusion history, and is particularly sensitive to variations in discontinuous structures (faults, unconformities, and intrusions). Overprinting deformation events produce topologies that are very sensitive to small changes in the defining parameters of the events (Thiele et al., 2016b), and the topology of a model provides a method of comparing multiple models that go beyond local comparisons. Topology can also be extracted directly from existing 1D (drill-hole) and 2D (map and section) information, and this topological information potentially provides crucial constraints during the model-building process.

Characterizing uncertainty also provides a bridge to geophysical inversion, as multiple geological models can be directly used to calculate forward gravity models (Wellmann et al., 2017), or by combining the voxel-level uncertainty with the petrophysical probability density functions as constraints for joint gravity and magnetic inversion (Giraud et al., 2017).

Results

We present preliminary results on synthetic models where all structural parameters are known and subsampled, and a real case study from terrane in the Northern Territory, Australia (Figure 3).

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THE NATIONAL GEOLOGICAL MODEL: TOWARDS MASTERING THE DIGITAL TRANSFORMATION IN SWITZERLAND

Roland Baumberger and Nils Oesterling

Swiss Geological Survey, Seftigenstrasse 264, CH-3084 Wabern

roland.baumberger@swisstopo.ch

Abstract

The digital revolution affects economy and commerce and heavily influences structural change and economic growth all over the world. Geological Survey Organizations (GSO) cannot keep out of this change; the requirements of the digitization affect the way GSOs produce, supply, and publish their data. Whereas the technical aspects, the base for digitization, are mainly solved, new challenges, such as the digital transformation and communication to non-geologists, challenge GSOs in many respects. The adaptation of end-to-end processes and internal workflows to be fit for digital transformation will be more important than the development of new products or citation indices. This is not only to raise the awareness of the importance of geology and geological data in particular; it is also to increase the value of geological data to politics, the economy, and society and to create knowledge as well as for non-professionals to gain understanding. With the National Geological Model, the Swiss Geological Survey presents its approach to counter these challenges.

Introduction

Digitization and digital transformation have been dramatically changing the way information is produced, supplied, and consumed, as well as shared in both private and business life. Both topics have a big impact on Geological Survey Organizations (GSOs). The digitization can be treated mainly as a technical issue that aims for, e.g., the transformation of analogue borehole logs into an electronic metadata and storage format. The digitization of the subsurface by 3D geological models results from the availability of technical prerequisites (e.g., hardware, software) and the digitally available input data. On the other hand, digital transformation is an organizational issue. It is more than the contact form on the website or the publication of borehole logs on the map viewer. Digital transformation denotes a fundamental adaptation of existing end-to-end processes in, e.g., data management and production.

Free and simple access to geoinformation in digital format, everywhere, at any time, quickly and in high quality is today's standard, forced by digitization and digital transformation over the past few years. For GSOs, both digitization and digital transformation denote a paradigm change. There are at least four challenges: a) poor availability of geological information (not only data), b) long refresh periods (time-to-market), c) missing multidisciplinarity, and d) lacking enabling of non-experts. While the digitization is completed to a certain degree, the full consequences of the digital transformation have not yet been considered. Further, communication with the broad public becomes one of the most important mid-term key topics.

Consequently, the challenges mentioned above force GSOs to reconsider their role in society. It will change from product vendors to service providers, and from analogue-based administrative authorities to digital-focused key enablers. Even if the change sketched here may be a long-term topic, the preparation starts now.

The importance of geological data

Geological data is a niche product, and its production ties up resources to a high degree. However, Hughes (2011) showed that per year, only 0.002% of the population in Canada and the United Kingdom develop the ability to read, understand, or even interpret a geological map on a professional level. This fact underscores that the majority of the population does not understand geological data sets in general. Even though geology is an everyday topic, the broad public does not know the impact of geological data on our daily lives. Numbers in other countries do not differ, as can be shown in particular for Switzerland (FSO, 2008). A non-representative compilation shows that in Switzerland, geological data could contribute to an annual estimated value chain of CHF 14 billion in markets related to the subsurface—but they are not used. Geological data need to be transferred from a scientific niche-product, known and used only by geology experts, to a widely accepted and applied resource for solving societal and economic problems.

Consequently, GSOs must enforce their interaction with the public to highlight the importance of their activities. They need to enable non-geologists to understand and gain knowledge of geology and geological data.

The value of geological data

Today, little is still known about the economic potential of geological data in general. Spinatsch (2009) showed for Switzerland that the economic benefit of one published geological map sheet (Geological Atlas of Switzerland 1:25,000) is 6 to 8 times higher than the value of the input data, resulting in an economic benefit of around CHF 7 billion for maps only. Accounting for geological 3D models (including seismics and deep wells), one could add another CHF 4 billion, based on the same calculation (see Häggquist and Söderholm, 2015, for an international review). The market for geodata (products only, no services) in Switzerland has increased annually by 5% since 2003 (Frick et al., 2016), now standing at around CHF 0.9 billion in 2018.

Although Switzerland is a small country and lacks a traditional mining history, geological information represents an important economic factor. Yet its impact is not fully recognized.

The current situation in Switzerland

Because of the lack of mining history, political as well as public awareness regarding the subsurface was low for decades, a fact that has changed during the last few years. The increasing usage of the subsurface (e.g., geothermal energy, infrastructure, and waste storage) and related conflicting uses resulted in an increased awareness of the subsurface. Consequently, the interest in geological data and information, data access, and data utilization raised as well.

In terms of digitization, the Swiss Geological Survey (SGS) has consequently been working to increase the benefit of its data for the last decade. Besides the still ongoing geological mapping program, enormous efforts have been undertaken to validate the information stored in the existing geological maps, such as the vectorization of analogue maps, semantic and geometric harmonization of data sets, and the development of a new, nationwide 2D vector data set. Additionally, geological 3D models of the shallow and the deep subsurface have become another important component of the SGS product suite. Regarding the input data, most of the geological data of national interest stored in the archives has been digitized during the last five years. Despite these efforts, no systematic data recording of these digitized documents into, e.g., databases took place. Therefore, the availability of these data is restricted to (OCR-enabled) PDF files. With respect to the supply of data, the SGS endeavors to ease data exchange by describing its data by data models and to distribute its products using digital standard web viewers and shops.

Concerning digital transformation, the situation looks different. The fact that Switzerland is a federal directional republic consisting of 26 cantons, each of them having the sovereignty of the subsurface at their own disposal, results in the complete absence of standardized and binding specifications on how to survey and describe geological data. Although clearly defined and well-established end-to-end processes exist at the SGS, the political situation hinders a continuous digital and automated data acquisition workflow. Figure 1 shows the data management workflow at the SGS. While the production, storage, supply, and distribution sub-processes are mostly digital (but not automated), the preceding steps (survey, acquisition) still lack a truly digital background. To overcome this situation, the SGS develops minimal data models, providing at least a minimum set of attributes to describe and ease data exchange.

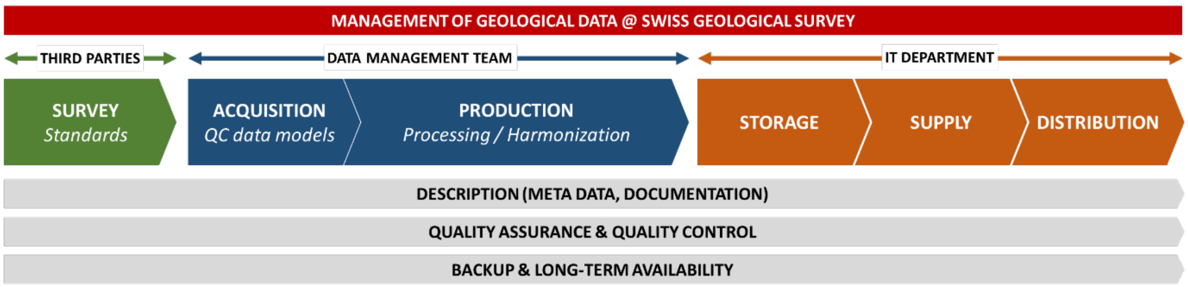

Figure 1. Data management workflow at the Swiss Geological Survey.

Present-day data delivery

Regarding the delivery process, the SGS separates its products from the input data needed to develop the data and models. Systematic data delivery (e.g., data storage in a geodata warehouse, and standardized supply and distribution through a web-based service-oriented infrastructure; see Figure 1) is currently restricted to maps and 2D vector data. Input data as selected borehole logs and reports are downloadable from the geoportal of the Swiss Confederation (http://map.geo.admin.ch). Any other data, in particular 3D-data, is provided through ad hoc processes. Two additional facts add further complexity: Firstly, higher-ranking strategic guidelines do not allow the publication of subsurface data on the geoportal of the Swiss Confederation. Therefore, the SGS cannot publish its geological data in their spatial 3D context. Secondly, the political system of Switzerland favors 26 different solutions regarding the distribution of geological data rather than one common, standardized, and harmonized approach.

In consequence, the following facts hinder the efficient use of geological data in Switzerland:

1. Existing geological data sets and models are neither harmonized (within data sets and amongst themselves) nor are they available nationwide.
2. A comprehensive information system aiming at the spatially correct 3D visualization of geological and non-geological data, which allows the investigation, interrogation, and analysis of these data, does not exist today.
3. A central access to geological data of the SGS is missing. Clients must search for data specifically at different locations and need to download and visualize them separately.

The Swiss National Geological Model

The SGS is restructuring its core activities to cover the challenges mentioned above and is consolidating its activities in the Swiss National Geological Model (SNGM). The SNGM is not a 3D geological model; it is a mid- to long-term strategic program (2018–2026) to implement the digital transition at the SGS. It supports the vision of the "integrated geological surveying," which actively changes the focus from previously discussed formats (analogue, digital) and products (maps, models) to primarily satisfying the client's requirements (based on existing products and formats). This paradigm change toward a one-stop service allows the SGS to focus quickly on topics relevant to society, politics, and research, as well as the fast derivation of new products needed by the clients, thus increasing the acceptance and value of geological data.

From a strategic point of view, the SGS aims at the nationwide and harmonized public availability of all products as well as input data (free, simple, digital format, everywhere, any time, fast, high quality). Further, the standardized description and storage of the data mentioned above, based on data models, shall ease the data exchange and analysis. Additionally, standardized interfaces will allow the interrogation and analysis of data available within the SNGM, and the single point of access to the data pool will simplify the supply of data and provide one-stop download possibilities (paid, free of charge). Lastly, the SGS demonstrates the willingness and organizational fitness to accept this change as inevitable.

The SNGM consists of at least four separate directions of action:

1. Acceleration of the production and achievement of nationwide coverage with 2D and 3D data. Mutual harmonization of SGS's data is according to existing data models.
2. Development of a 3D visualization platform (as a central public access) to visualize the geological data of the SGS and its partners, as well as the reference data (e.g., DEM, topographic maps, buildings) of the SGS's mother organization, the Federal Office of Topography (see Figure 2 for a sketch).
3. Development of a suite of services to investigate, interrogate, analyze, and process the data of the SGS and its partners. A guarantee of interoperability allows multidisciplinary use of the SGS's data, e.g., in combination with environmental data or engineering data.
4. Upgrading of 3D infrastructure, if needed and applicable.

Figure 2. A possible combination of data sets of different domains (geology, engineering, transportation, landscape), as will be possible within the NGM. (Source: thebimhub.com)

Cooperation with partners, data providers and users is key for the success of the SNGM. As mentioned above, geological data contribute to many branches and disciplines other than geology itself. Geological data may also be considered as, e.g., land use or infrastructure planning data. With the rise of GeoBIM, professionals working outside geology become systematically aware of the importance of geological data. Therefore, GSOs are in charge of supplying their data to support as many applications as possible.

GSOs are also in charge of facilitating the understanding, acceptance, and communication of geological complexity to non-geologists and the broad public. For Switzerland, therefore, the SNGM will help the SGS provide comprehensive services to the clients, supplying data with a higher accessibility and improved quality, as well as a fast update cycle.

From a conceptual point of view, the SNGM provides comprehensive access to and visualization of the geological data of the SGS, its partners, and clients, as well as to the reference data in Switzerland. As stated in The Economist (2017), “The world’s most valuable resource is no longer oil, but data.” The SGS wants to go further and additionally offer not only data, but also geoinformation to its clients. This means that the full potential of its data for comparison, combination, and analysis needs to be invoked—by offering standardized and harmonized data as well as corresponding tools to work with the data. The general data availability and the changed user behavior ask for information transparency, which will be one of the core demands by many actors regarding the subsurface in the future—and the GSOs are the main stakeholders contributing with their own data to fulfill this request.

Therefore, the SGS plans the SNGM as a web-based and open information platform and visualizes all available geological data (complete, harmonized, and nationwide) of the SGS and its partners, and makes them accessible and downloadable at one single location. From a technical point of view, the SNGM is based on standardized services and formats as, e.g., 3D-tiles, WMS, WFS, WMTS, and KML. Consequently, any data set that is already available in such formats, also from third parties, can be integrated into the SNGM. Third-party data sets will be transformed on the fly to one of the standards accepted.

By following this approach, the SNGM falls back to the already existing data management infrastructure of the 2D geoportal of the Swiss Confederation (Figure 3). Already proven workflows can be used to integrate data into the SNGM. Therefore, data sets can be published cross-platform with reduced functionalities.

The SNGM guarantees that the geological data (maps, cross sections, and 3D models, as well as the respective input data as wells, seismic data, etc.) as well as information (conditioned geological data) can be combined with data originating in other disciplines (e.g., engineering, the environment, and the economy). Consequently, this approach stimulates an interdisciplinary collaboration aimed at increasing the usability of geological data.

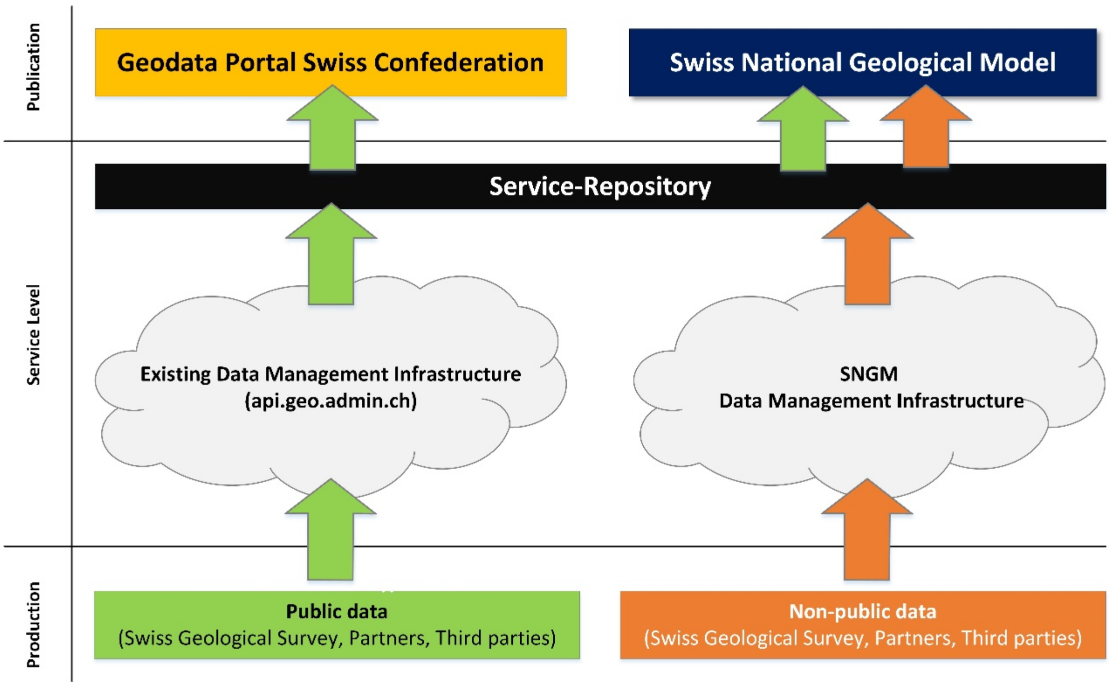

Figure 3. Schematic architecture of the SNGM, partly falling back to the existing data management infrastructure of the Swiss geodata portal.

After its overall completion, the SNGM will serve as the main tool for handling the digital transformation at the SGS. Therefore, the web platform will not only focus on the data visualization but on:

1. Services:
   a) Data capture tools, e.g., for boreholes (based on the corresponding data models) allow for standardized and thus harmonized data acquisition, including exporting this data into different file formats.

   b) QC: Already captured well logs or existing vector data can be checked against the up-to-date version of the corresponding data models.
2. The users will be able to register and upload their own data into a closed user group and to combine, interrogate, and analyze them with already available data.
3. Data integration: On a mid-term basis, automated integration of new data into the SNGM will serve to shorten data upgrade cycles and help keep the data up-to-date.
4. Data inquiry: The SNGM allows searching of the data available on an object-related basis, by crawling its meta-data. Registered users will be able to store the queries in their closed user group.
5. Data interrogation: Already well-established services as virtual borehole and cross section extraction from 3D geological models will cover parts of the interrogation services of the SNGM.
6. Data analysis: Spatial as well as attribute-based analysis is planned as a long-term development.
7. Data download: All available data will be downloadable while respecting data access policies and legal frameworks.
8. Data acquisition: The SNGM will be extended to serve as the single data acquisition platform of the SGS. Any data delivered to the SGS must be submitted through the SNGM.
9. App: Selected tools could be integrated into an app for mobile devices in the future.

In March 2018, the prototyping phase of the visualization platform of the SNGM started. This presentation on the SNGM will cover strategic and conceptual topics and will include a live demonstration of the current development status.

Conclusion

The SNGM focuses on the availability and delivery of data, its analysis, and applications. In the future, the relevance of available information, its description, content, and quality, gains importance. The plurality of data sources, available analysis instruments, and standardized and harmonized data is going to contribute to information transparency—an important asset in the context of the subsurface. GSOs are the main sources of this kind of data and therefore are in charge of supporting this evolution. According to Peebler (1996), geologists spend 20–30% of their working time searching, loading, and formatting data. The SGS attempts to significantly lower this number by offering an open, comprehensive, and easy-to-use 3D information and analysis system—not only to professional users, but also to the public—to highlight the importance and the value of geological data.

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DELIVERING TO THE CLIENT—COMMUNICATION AND DELIVERY FOR SUCCESSFUL APPLICATION OF 3D MODELS

Paulina Branscombe and Kelsey MacCormack

Alberta Geological Survey, 4999 98th Avenue, Edmonton Alberta, Canada T6B 2X3

paulina.branscombe@aer.ca

Introduction

3D geological models (structural, facies, and property) can help assess and describe subsurface information, interpretations, relationships, and complex geological settings to a variety of stakeholders with a range of geological knowledge. 3D geological models can support decision making by acting as tools that provide credible subsurface information needed to make informed science-based decisions, assess risk, and facilitate the management of subsurface resources.

The visual value of 3D geological modelling is obvious. Displaying a holistic and collective geological understanding in a 3D context is remarkable at all scales. Even basic manipulation of 3D geological models by rotating, slicing, and toggling data on and off can help communicate subsurface relationships and changes on a local and regional scale. The functional value of 3D geological models is recognized when they are communicated properly and delivered to the client in a format that can be easily adopted into the target application. Ideally, the stakeholder can access the model data with ease, take out information from it, and potentially put their own data into the model as well.

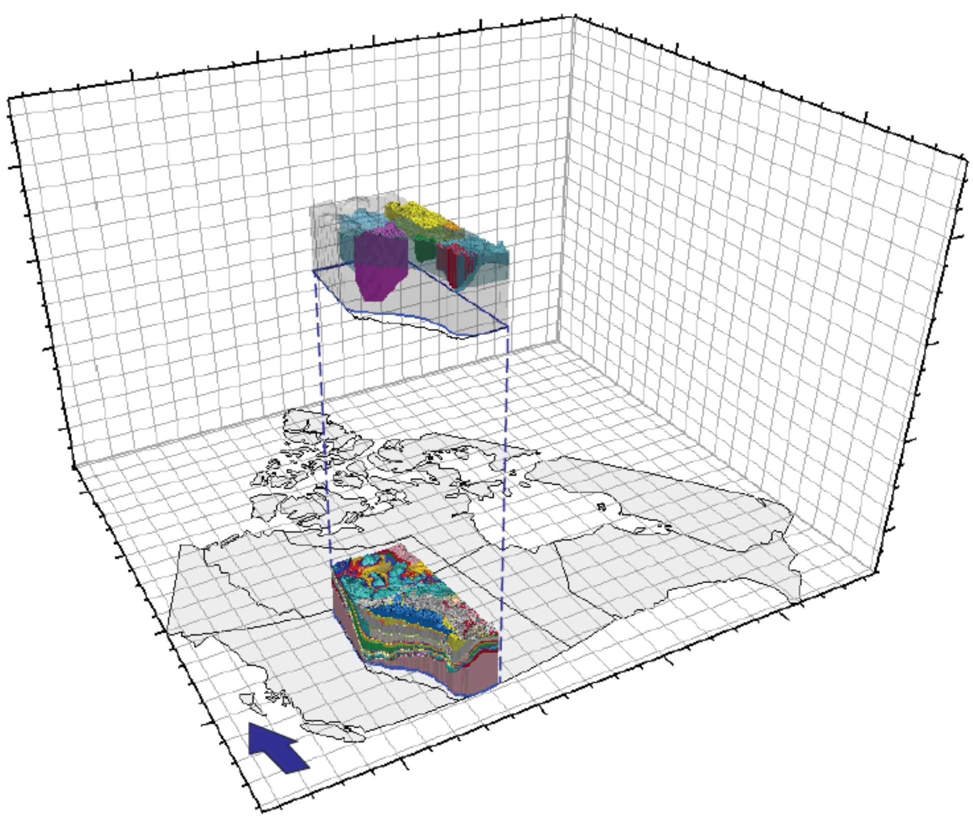

Figure 1. Location of the AER/AGS 3D Provincial Geological Framework Model of Alberta and sub-models within a partial outline of Canada (vertical exaggeration of 50×).

The Alberta Energy Regulator/Alberta Geological Survey (AER/AGS) has converted a number of its 3D geological models, including the most recent version of the 3D Provincial Geological Framework Model of Alberta (Branscombe et al., in process; Figure 1), into a non-proprietary format that can be visualized in iMOD, an open source 3D digital data-viewing software available for download from Deltares (n.d.). The models can be viewed in 2D and 3D and can be rotated, zones toggled on and off, or exploded for different visualization. Users can import any geospatial data into the model domain and quickly see how it relates, for example, to the 3D Provincial Geological Framework Model of Alberta.

Communication

Communicating 3D geological models properly is key to ensuring their acceptance and application. Model communication includes information on scale, limitations, model quality, and uncertainty of inputs, as well as discussion on delivery and application. 3D geological modelling facilitates the communication of subsurface characterization, risk, and uncertainty. Subsurface communication in a 3D context allows adjacent or related spatial relationships to be considered. This is helpful in identifying and communicating relationships and links between multiple subsurface entities or attributes.

Communicating the scale and resolution of a 3D geological model is necessary and is ideally decided during the front end of the modelling workflow. An appropriately scaled model ensures that the model can be used for the intended application (i.e., regional models are not used for local-scale investigations and local-scale models are not used for regional investigations). Transparency in communicating model limitations increases the credibility of the model.

Communicating uncertainty can be challenging because it is often perceived as a qualitative assignment. The uncertainty of model inputs can be quantified by completing an uncertainty analysis on the interpolated surfaces feeding into the model construction. Local and global uncertainty can be characterized by creating standard-deviation maps and computation of RMSE, respectively, using the methodology of Babakhani (2016). The errors within each interpolated geological surface are represented by the uncertainty at a local (standard deviation) and provincial (RMSE) scale. Uncertainty analyses can confirm whether each surface is acceptable for model input or highlight areas that need more interpretation or additional data. As such, the characterization of this uncertainty before the model construction phase of a geomodelling workflow is recommended.

Model quality can be described using a qualitative assessment approach for each zone (Anderson et al., 2015; Branscombe et al., in process). Uncertainty analyses and model quality assessment can identify areas that need improvement or focus for future iterations of the model.

Delivery

For successful delivery, 3D models should be delivered in a format that is appropriate and usable to the client. Entire models or models that are deconstructed into their various data components (i.e., point data, model horizons, model extents) need to be accessible to stakeholders. 3D models can be created in various 3D geomodelling software, but stakeholders need the models or model data in a format useable to them. Multiple 3D geological modelling software exists, but most stakeholders do not have access to it or any interest in procuring it. The dissemination of 3D geological models into non-proprietary format, such as AER/AGS's most recent 3D Provincial Geological Framework Model of Alberta and sub-models, allows users to access the models and visualize them in open source 3D digital data software such as iMOD. Delivering models and model data in non-proprietary formats allows the data to reach most, if not all, stakeholders.

Application

Geological modelling facilitates the transition from 2D subsurface characterization into interactive 3D geological models. The application of 3D models in science-based decision making is increasing. Regional and local-scale subsurface investigations and queries can be done easily with 3D geological models.

The AER/AGS 3D Provincial Geological Framework Model of Alberta and the sub-models within it were created to meet a variety of stakeholder requests. Recently, the 3D Provincial Geological Framework Model of Alberta was used to calculate 3D volumetrics for a regional groundwater yield-mapping project. The models at the AER/AGS were developed to characterize and integrate 3D data to support science-based decision making related to land-use planning, environmental sustainability, economic diversification, and public safety. Two regional-scale resource modelling projects were recently completed by the AER/AGS. The 3D Provincial Geological Framework Model of Alberta was used as a basis for recent property modelling (Figure 2) and unconventional hydrocarbon resource estimates of the Duvernay and Montney. 3D characterization of the subsurface and resources within it can improve resource management.

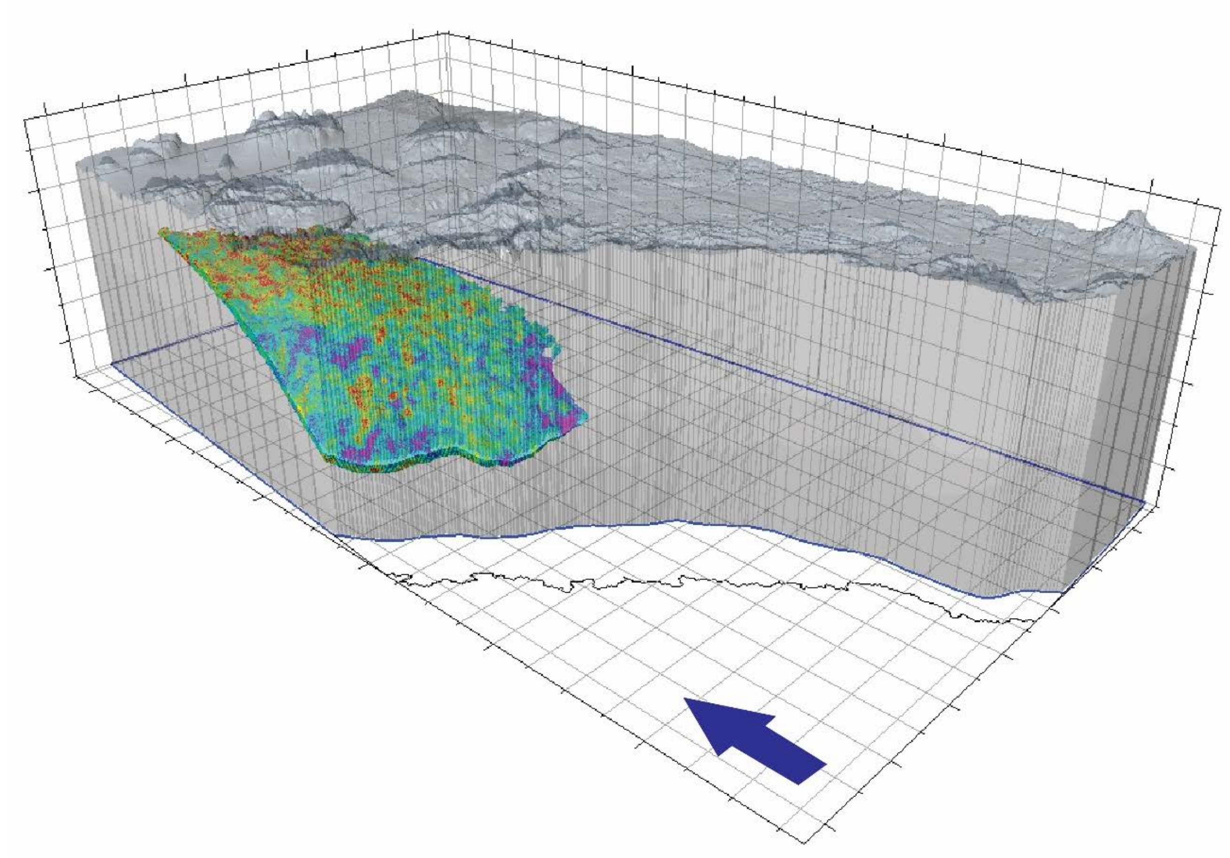

Figure 2. One porosity realization from the Montney 3D property model set within the 3D Provincial Geological Framework Model of Alberta (transparent gray and blue outline; province of Alberta outline in black) (vertical exaggeration of 50×).

3D geological models can reduce risks by providing a common subsurface framework. A single geological framework reduces inefficiencies caused by duplication of work and improves credibility and versioning issues. 3D geological models can facilitate risk assessments because the geospatial relationships of adjacent intervals and subsurface elements can be considered.

The AER/AGS Peace River Geological Model was built to facilitate the investigation (in response to a formal proceeding by the Alberta Energy Regulator) of odours and emissions from heavy oil and bitumen production in the Peace River Oil Sands Area in northwest Alberta.

3D geological models can facilitate the management of provincial/regional-scale resources. 3D subsurface and resource characterization provides more information than individually focused 2D subsurface interpretation. 3D geological and property models help to understand what is there, where it is, and how it is geospatially related to other subsurface entities, resources, or risks.

Conclusion

3D geological models can be used as common subsurface foundations that facilitate communication of subsurface characterization, risk assessment, and management of resources. These multi-dimensional models can support informed decision making by being single holistic geological frameworks for various applications and investigations at a variety of scales. When 3D geological models are designed and created fit-for-purpose and easily accessible to the client, the return on investment is realized.

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THE MESSAGE IS OUT!

Abigail Burt, Andy Bajc, and Riley Mulligan

Ontario Geological Survey, Sudbury, ON Canada

Three years ago, the Ontario Geological Survey (OGS) 3-D sediment mapping team delivered a presentation entitled “3-D Geological Modelling at the OGS—Products and Applications” (Burt et al., 2015). We described the diverse products that are generated throughout the life-cycle of a 3-D mapping project, focusing on their uses and the range of client feedback that we have received. Almost as an afterthought, we raised a series of questions.

> *One of the greatest challenges we face is getting our products into the hands of those that need it to do their job… How do we get the message out? Are we talking to the right people? Is it our job to “market” ourselves or should this be part of a broader organizational activity?*

These questions have not gone away. One could argue that in today’s climate of budget restrictions, being relevant and able to document that relevancy is critical to ensuring ongoing funding. This year we will delve into some of these questions, drawing on examples of interactions with clients and their usage of OGS products and data.

Who we are and what we do

The OGS is a provincial survey; our 3-D mapping activities are concentrated within the populated regions of the province, and our mandate is dictated by provincial government priorities. While the collection of geoscience data pertinent to understanding groundwater has been ongoing for more than 125 years, the pace has accelerated in the 18 years since the Walkerton contaminated water tragedy. In that time, we have migrated from a program area to an award-winning, permanently funded initiative encompassing 3-D Paleozoic bedrock mapping, 3-D sediment mapping, and ambient groundwater geochemistry mapping across southern Ontario.

The 3-D sediment mapping team serves a diverse range of client groups, including:

- Conservation authorities (responsible for protecting Ontario’s groundwater resource as part of Source Water Protection planning)
- Geoscience consultants (contracted to produce groundwater flow models and water budget assessments for conservation authorities)
- Towns and municipalities (groundwater quantity and quality concerns and land-use planning)
- Provincial and federal government agencies (for example, Ministry of Environment and Climate Change, Ministry of Natural Resources and Forestry, Ministry of Municipal Affairs and Housing)
- Academia

For each project area (Figure 1), we follow a standardized, well-established workflow from project inception to final products. Our core products, available as free downloads or for purchase on CD/DVD at a nominal fee, include:

- Annual field summary reports (report of field activities, simplified borehole logs, and cross sections including preliminary interpretations)
- Geophysical data sets
- Borehole data releases (graphic and written logs, analytical data, core photos)
- Interactive maps
- Groundwater Resources Studies (bedrock surface, 3-D sediment model, report, plates, analytical data)
- Journal papers (available through open access on journal websites)
- Conference presentations and posters (uploaded on conference websites where available)

The goals of each project are to reconstruct the regional Quaternary histories, assemble standardized subsurface databases of new and legacy geological and geophysical information, develop 3-D models of regional-scale sediment packages, and generate technical and non-technical products. We have the ability to address topics pertinent to each area and respond to specific client needs. These needs may be identified either during routine gap analyses, through formal project proposals submitted by clients, during internal OGS project planning meetings, or communications with clients following project inception. Some examples of specific needs addressed are outlined below (Figure 1).

- Waterloo Moraine Project: The Regional Municipality of Waterloo required a better understanding of the internal architecture of the Waterloo Moraine. Aquifers within the moraine provide a significant proportion of the municipal water that the population relies on. The Region was specifically interested in identifying the locations of windows through regional aquitards and the locations of untapped aquifers that could support future needs.
- Dundas Buried Bedrock Valley Project: The Grand River Conservation Authority required information on the distribution and continuity of sediment aquifers within the buried bedrock valley network to improve water budget calculations, specifically, how much groundwater is entering and leaving the Grand River watershed along the valley system. The project also helped the Regional Municipality of Waterloo target bedrock valley-hosted aquifers that could augment current water supplies.
- Whiteman's Creek Tier 3 Study: The Grand River Conservation Authority required a geologic framework to assess and manage water taking within a subwatershed under stress. The OGS modeling efforts within the Brantford-Woodstock project area provided the geological framework for the groundwater modeling efforts.

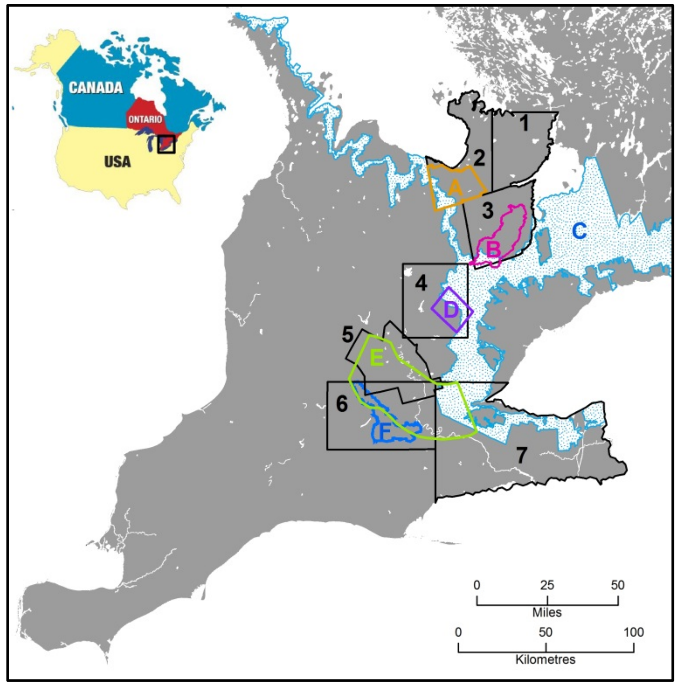

Figure 1. OGS 3-D project areas (1–7) and locations (A–F) mentioned in the text. 1) Barrie–Oro Moraine, 2) Central Simcoe, 3) South Simcoe, 4) Orangeville-Fergus, 5) Waterloo Moraine, 6) Brantford-Woodstock, 7) Niagara Peninsula, A) Township of Clearview, B) Innisfil Creek, C) Greenbelt, D) Town of Erin, E) Dundas buried bedrock valley, F) Whiteman's Creek.

- Innisfil Creek Drought Management Study: This study built on an OGS conceptual model coupled with new subsurface information to support development of a drought management plan that informs the development of policies related to irrigation best practices in an important agricultural region.
- Green Belt Expansion: The Ministry of Municipal Affairs and Housing and a number of partner land-based ministries required information on the subsurface extents of important aquifers contained within hydrologically significant moraines in the Greater Golden Horseshoe of southern Ontario. This information was used to inform decisions on the location of future growth of the Green Belt, an area of protected countryside within which future development is restricted. Growth of the Greenbelt is aimed at protecting important water features (cold water streams and wetlands) as well as the geology that supports its uninterrupted health.
- Town of Erin Municipal Water Supply: The Town of Erin required information on whether deep bedrock valley-hosted aquifers existed beneath decommissioned pumping stations, as part of a cost-saving exercise. OGS drilling and modeling efforts demonstrated that potential producing aquifers are located within a nearby buried bedrock valley.
- Central Simcoe Municipal Water Supply: The Township of Clearview required information on water quality in local aquifers, as well as possible new aquifer targets in sediment-hosted systems that have potential to supply the rapidly growing population. Select borehole and monitoring well locations were tailored to areas of interest within the municipality.
- Niagara Peninsula Monitoring Wells: The Niagara Peninsula Conservation Authority, the Grand River Conservation Authority, and the City of Hamilton required a geologic framework and monitoring wells to improve groundwater flow models and understanding of surface water–groundwater interactions within several subwatersheds. Twenty-nine monitoring wells, several later converted into nested wells, were installed in boreholes drilled to support 3-D mapping.

Getting the message out!

Reaching an audience that goes beyond primary contacts at project area conservation authorities or local municipalities and cities can be a challenge. The OGS has adopted a range of strategies, summarized below, that target different audiences.

- Groundwater Open House: Since 2014, the OGS, Geological Survey of Canada, and Conservation Ontario have collaborated to offer a free open house for conservation authority practitioners, policy makers, planners, consultants, and academics. The open house is a popular networking and educational opportunity for core client groups that features overview and project-specific talks and posters.
- Latornell Conservation Symposium: An annual symposium brings together practitioners from conservation authorities, policy makers, non-government organizations, academics, and businesses to discuss advancements, challenges, and opportunities in conservation. The OGS has offered 1-day workshops on our groundwater initiative, including program- and project-specific talks as well as a corporate booth at the meeting.
- OGS Earth: A web portal provides geoscience data, collected by the Mines and Minerals Division, which can be viewed in a widely available and free Google Earth platform.
- Geology Ontario: A search tool allows you to search and download from the Assessment File Research Image database, the Abandoned Mines Information System database, the Ontario Drill Hole database, the Mineral Deposit Inventory database, and the Ontario Geological Survey Publications database.
- Schools, colleges, and universities: Topical presentations at colleges and universities, and working with faculty to provide topical and geographically relevant teaching material, provides an excellent opportunity to reach a young technical audience. Monitoring wells installed within school and college grounds are effective teaching tools. Student recruitment sessions at universities and at the annual Prospectors and Developers Association of Canada meetings expose students to a broad range of OGS projects. Hiring students from universities within or close to project areas facilitates student learning and encourages future collaborations such as thesis work.
- Museums and local interest groups: This is an area that has great potential for reaching the general public, but it typically needs greater effort to make the initial contact (we need to be aware of them, and they need to be aware of us) and chance encounters often play a role. The Waterloo Region museum uses the Waterloo Moraine geologic model as part of its geology display. The Niagara Peninsula 3-D project came to the attention of the Royal Botanical Gardens when incorrect utility locations resulted in their water supply being shut down. This translated into a staff presentation and later developing a display and donating core for a winter exhibit and educational programming. Displays and information boards in development at local parks and tourist attractions, such as Martyr’s Shrine and Awenda Provincial Park, have a role to play in linking environment, ecosystems, and geology in a simple and easy-to-understand way that can be accessed by the general public.
- Media: Official press releases, articles in local newspapers, and conservation authority publications have featured both current field activities and project results. In recent years, OGS social media feeds, such as Facebook and Twitter, have highlighted groundwater and 3-D projects.
- Field visits and trips: Field visits and tours have proven popular with groundwater professionals from sister ministries, municipalities, conservation authorities, and project area consultants.
- Journal papers: Contributions to special volumes in academic journals expose aspects of 3-D mapping projects to an international audience. A paper in the *Canadian Water Resources Journal* established the geologic framework for groundwater studies that aim to inform decisions and policies regarding the use and management of groundwater resources in the Waterloo Moraine. Papers in a special volume of the *Canadian Journal of Earth Sciences*, focusing on new Quaternary research in southern Ontario and its applications to groundwater, present the results of 3-D mapping activities in Simcoe County, Orangeville-Fergus, and the Dundas Valley.

Is it working?

We have abundant evidence of product uptake within our core client groups. At the most recent groundwater open house, numerous presentations described the benefits and financial savings realised by municipalities, conservation authorities, and consultants that were a direct result of OGS 3-D mapping projects. The OGS groundwater initiative and 3-D sediment mapping group have received recognition in the form of an Ontario Public Service Amethyst Award and several conservation awards from local conservation authorities. Collaborations with universities have resulted in BSc, MSc, and PhD projects ranging from mapping to geomorphology to sedimentology. Sister ministries are using products and expertise to inform decision making. A recent request to provide expert knowledge on a soil science field trip demonstrates that at least some of our outreach efforts are effective.

What next?

OGS data and products provide the regional geologic framework for hydrogeological modelling and policy decisions in areas where 3-D sediment mapping studies have been completed. Our future challenges are to improve ease of data retrieval, address technological changes that impact product delivery, and expand uptake beyond our core client base to ensure that high-quality geoscience data remains a government priority now and in the future.

WILL COUNTY GEOLOGIC 3D MAPPING PROJECT: INSIGHTS INTO THE GLACIAL HISTORY OF NORTHEASTERN ILLINOIS BY BUILDING A GEOLOGIC MODEL

Olivier J. Caron

Illinois State Geological Survey, University of Illinois, Champaign, Illinois

caron @illinois.edu

Summary

The Illinois State Geological Survey (ISGS) has initiated its geologic mapping efforts in the suburban Chicago area, with the aim of producing large-scale, three-dimensional (3D) geologic maps of glacial deposits. The project addresses the overall goals of the State of Illinois, the Great Lakes Geologic Mapping Coalition (GLGMC), and the ISGS to map deposits both at the land surface and in the subsurface to gain a better understanding of the complex geology left behind by repeated glaciations and associated flooding events. Much of our drinking water, a significant amount of material for road building, and most natural lakes in Illinois have one thing in common: they are a legacy of the Ice Age glaciers that deposited the geologic materials that contain groundwater, are used in concrete, and form the containers that enclose lakes. Knowing the distribution and characteristics of these materials is essential for water-supply planning, economic development, and the sustainability of our recreational resources.

As a county with urban, suburban, and rural environments, Will County is located at the confluence of moraines of the Joliet sublobe, including the oldest (Minooka Moraine) as well as the outer Lake Border Moraine (the Tinley Moraine). The main objective was to reconstruct the complex successions of ice marginal and paraglacial outwash deposits by using a geomorphologic approach based on LiDAR DEM. In most cases, sediments and landforms are significant indicators of the extent of former ice-dammed lakes because their elevation is intimately linked to well-documented outlets. Their stratigraphic architecture is, however, complex and their subsurface extent poorly documented. Three-dimensional numeric geomodelization of surficial deposits is the next step in this study and is possible only with a thorough understanding of the regional glacial history, depositional environments, and as accurate as possible predictions regarding the thickness and distributions of subsurface units in regions of sparse data. This kind of model is based on the integration of surficial sediment maps and borehole logs with the use of GIS and 3D geomodeling. Most of the eastern portion of Will County is covered by the Valparaiso Morainic System. In the western part of the county, there are extensive areas of flat, level topography associated with an old lake plain formed by glacial Lake Wauponsee and a few lacustrine terraces and scarps associated with the former shorelines of this short-lived lake. Preliminary mapping, based on LiDAR-derived DEM, has identified evidence of two glacigenic successions, including some evidence of the Tiskilwa Member, the lowermost Wisconsin Episode diamicton. Ice-walled lake plains and ice-marginal lakes associated with the Tinley Moraine have been identified. The discovery of new outcrop sections should allow for a reassessment of depositional environments, their correlation, and the extent of the Haeger Member of the Lemont Formation (Wedron Group).

Introduction

The ISGS geologic mapping efforts in Will County address the mapping priorities of the GLGMC and the ISGS through the production of large-scale, 3-D geologic and hydrogeologic maps and framework models of glacial deposits. Will County is within the southwest and south metropolitan Chicago area, a region with a high population and industrial growth, critical groundwater issues, and a nationally significant intermodal freight and passenger transportation corridor (Illiana Corridor). Accordingly, the Illinois Geologic Mapping Advisory Committee (IGMAC) has denoted geologic mapping of Will County as a high priority. Will County has a population of about 680,000 people (the fourth most populous county in Illinois) and is projected to double in population by the year 2030 (U.S. Census Bureau). As a county with urban, suburban, and rural environments, 3D geologic maps will be used to guide planners and decision makers in sustainable economic development and environmental protection focusing on water supply management, storm water management, wetland preservation, and sand and gravel quarry development. Geologic maps and 3D geologic models will depict glacial materials several hundred feet under the ground.

The Will County geologic maps and models will provide a context for every decision that relies on information about the earth under homes, roads, and cities. These maps help us understand the availability of groundwater resources; help avoid building in areas that are susceptible to natural hazards, such as landslides; and help those entrusted with protecting our health and safety to make decisions. The long-term objective of this mapping effort in northeastern

Illinois is also to provide a context for evaluating aquifer yields, estimating recharge, and developing groundwater flow models. Will County is within a regional water supply planning area, which has been given special focus by the Illinois Department of Natural Resources and local constituents for planning long-term sustainability of both surface and groundwater resources. The Illiana Corridor includes one of the nation's largest inland freight depots, the location for a proposed South Suburban Airport, and a proposed west-to-east Illiana Expressway. Designed as a southern Chicago bypass, this proposed four-lane expressway crosses southern Will County and will link I-55 and I-57 in Illinois with I-65 in northwestern Indiana.

Quaternary stratigraphic framework of Will County, Illinois

River valleys, lake plains, and moraines dominate the landscape in Will County. Surface drainage flows to the Kankakee and Des Plaines Rivers; these rivers join less than a mile to the west in Grundy County, forming the headwaters of the Illinois River (Figure 1). Dolostone of Silurian age is present or buried by shallow alluvium in the lower parts of these major river valleys, as well as in the lower reaches of some tributaries, such as the DuPage River and Hickory Creek (Willman and Lineback, 1970). The glacial stratigraphy of Will County is dominated by sorted deposits of the Mason Group and glacigenic diamicton of the Wedron Formation (Hansel and Johnson, 1996; Figure 2). These units attain thicknesses of more than 185 ft (56.4 m) in the northern and northeastern parts of the county. Older units of the Wedron Group (Tiskilwa Formation and Batestown Member, Lemont Formation) are largely absent. Postglacial deposits are typically thin and include glacial and nonglacial lacustrine deposits (Equality Formation), glaciofluvial sand and gravel (Henry Formation), and postglacial peat (Grayslake Peat) and alluvium (Cahokia Formation). Eolian deposits of Peoria Silt, which cap most uplands of Illinois, are thin in this area, generally <3 ft (0.9 m; Fehrenbacher et al., 1986). The uplands of Will County are gently rolling, rising to about 800 ft (243.8 m). The oldest moraine in Will County, formed of the Yorkville Member (Lemont Formation), is the Minooka Moraine (Figure 1). The southern end of the moraine is truncated by the Des Plaines River just south of Channahon. The discontinuous Rockdale Moraine is the next oldest upland feature. Also formed of diamicton of the Yorkville Member, the Rockdale Moraine has been dissected by the Des Plaines River and by perched channels that formed and were abandoned during the last deglaciation.

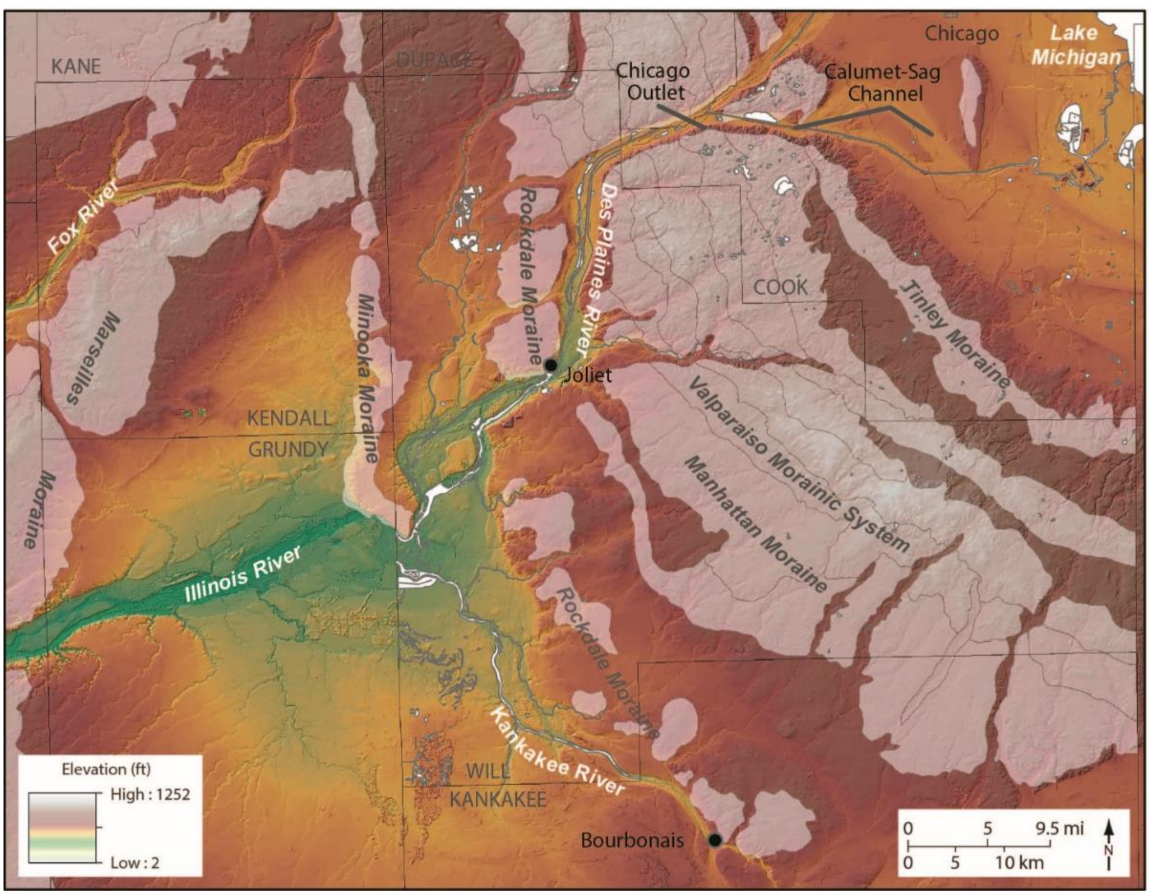

Figure 1. Locations and names of moraines in Will County.

The Haeger Member (Figure 2), known for its relatively coarse particle-size distribution (from boulders to silt) and high dolomite content, separates the finer-textured (silty and clayey) diamictons of the older Yorkville Member from the younger Wadsworth Formation. The Lemont section is a key locality of the Haeger unit and is found where the Des Plaines River enters Will County on the north (Johnson and Hansel, 1989). A vexing problem has been tracing the Haeger unit in the subsurface where it pinches out to the east and south of the Lemont section, and separation of the Yorkville and Wadsworth units may not be possible. The morphology of the Woodstock Moraine is atypical of moraines of the Lake Michigan lobe in Illinois. Instead of having a ridge-like form and being composed chiefly of diamicton, it is broad, marked by ice-contact channels, and composed of a mélange of diamicton and sorted sediment. These observations help explain the difficulty in mapping ice-marginal deposits of the Haeger in Will County. Recently obtained radiocarbon ages from the basal sediments of ice-walled lake plains on the Woodstock Moraine in McHenry County, Illinois, indicate a minimum age of the Haeger Member of about 20,600 calibrated years before present (cal yr BP; Curry et al., 2014). The Valparaiso Morainic System and Tinley Moraine form the uplands on the northeastern side of Will County, including (from oldest to youngest) the West Chicago, Wheaton, Keeneyville, Westmont, and Clarendon moraines (Willman and Lineback, 1970; Willman, 1971; Figure 1). These moraines are well defined topographically in some areas and less so in other places. Diamicton of the Wadsworth Formation, the surficial till unit found within these moraines, is characterized by a nonuniform lithology that includes beds of variably textured diamicton (matrix textures of loam, silty clay loam, and silt loam) and common interbeds of sand and gravel from about 3 to 25 ft (0.9 to 7.6 m) thick.

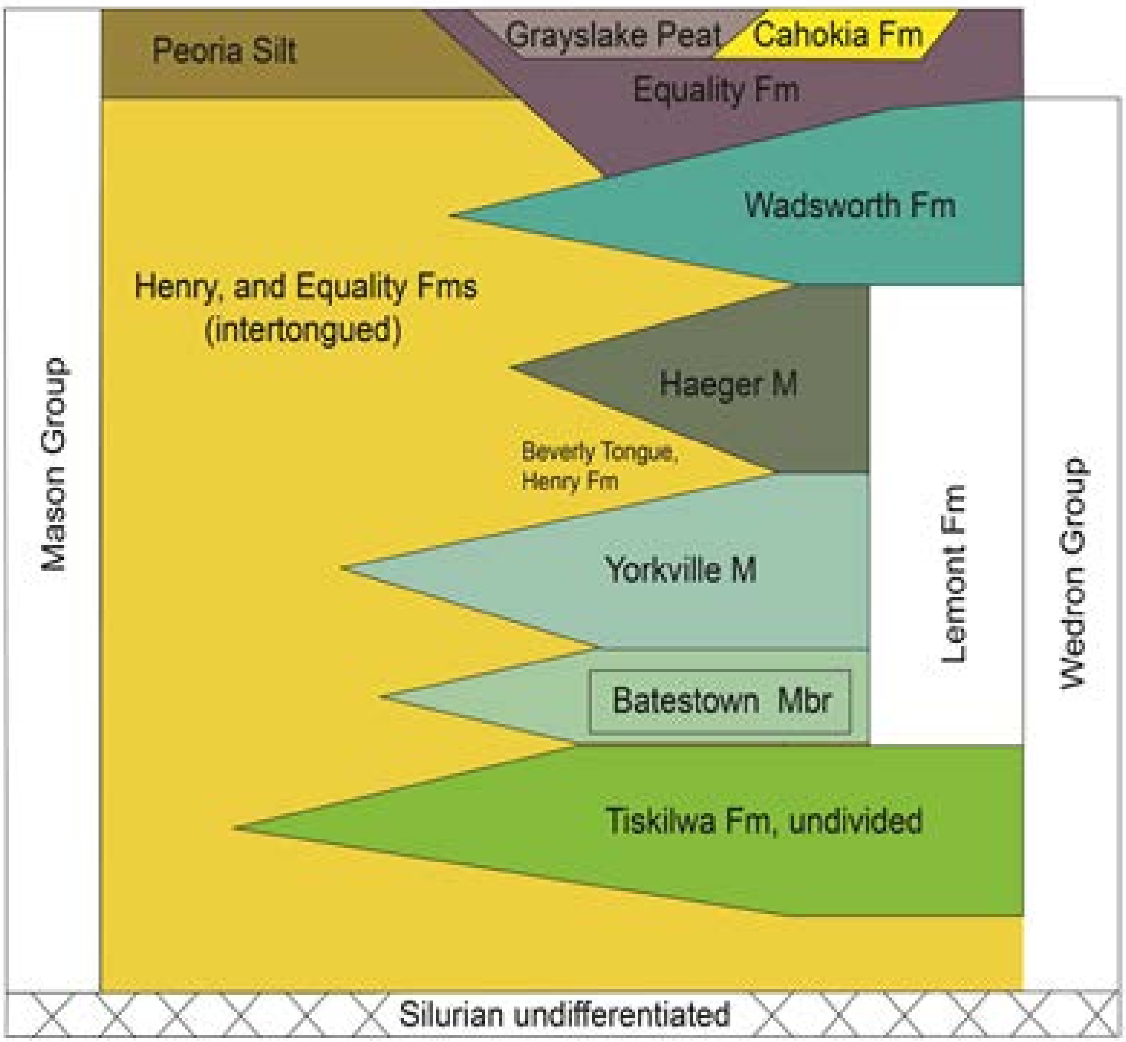

Figure 2. Lithostratigraphy of Will County and environs.

Approach and methods

Several local and regional-scale maps and studies have been completed for parts or all of Will County. Bretz (1939, 1955) mapped the surficial geology of the Chicago area at 1:24,000 scale. This work included two reports and all or parts of twenty-four 7.5-minute quadrangles in parts of Lake, Cook, DuPage, and Will Counties. This detailed mapping included the geology and stratigraphy of the bedrock and the characterization of Quaternary sediments but did not include cross sections or any information about the subsurface. Willman (1971) followed with a report and 1:250,000-scale map of northeastern Illinois, which included the area covered by Bretz and all of Will County. Again, no cross sections were prepared. Abert et al. (1993) created a series of 1:100,000-scale maps of the bedrock topography, sand thickness, and the thickness of Quaternary deposits that cover the southern portion of Will County. More recently, Curry and Grimley (2001), Curry and Bruegger (2014), Caron and Phillips (2015), and Caron (2016) mapped Quaternary deposits of parts of the Beecher West, Steger, Illiana Heights, Frankfort, and Mokena 7.5-minute quadrangles in response to discussions about the Illiana Expressway interstate corridor and the proposed South Suburban Airport. Regional groundwater studies have been conducted in Will County (Woller et al., 1983; Roadcap et al., 1993).

Reconstructing and mapping the paleoenvironment of Will County, based on a LiDAR-derived digital terrain model (DTM), represented an important challenge, mostly due to the complexity of the subsurface. The lithostratigraphy of this area can be better understood by using the concepts of sequence stratigraphy. In particular, sediment accommodation space is seen as a critical element in stratigraphic analysis. Therefore, geomodeling will be a very powerful tool to reconstruct the subsurface architecture and quantify the volume of sediment. The next step is the development of a methodology for 3D numeric geomodelization of surficial deposits for this county of more than 2,199 km^2. This kind of model is based on the integration of the surficial sediment maps and boreholes logs with the use of GIS and 3D geomodeling.

A database has been developed consisting of ISGS test holes and archival water-well borehole logs from ISGS holdings and from private firms. Data from ~29,000 boreholes have been reviewed and compiled (ISGS boreholes database), properly located, and used to help develop the 3D geologic framework and to identify potential aquifers. All records in the database are spatially referenced by UTM coordinates and most by elevation. In addition, earth electrical resistivity (EER) totaling 8.4 miles (13.5 km) was acquired along 8 lines within Will County, mostly across the Valparaiso Morainic System. Siting resistivity targets was difficult because of the extensive subsurface oil pipeline network in the area. The subsurface data include detailed studies of 105 stratigraphic test holes drilled by the ISGS. We acquired a total of 2,177 ft (664 m) of core at 70 locations by using hydraulic push methods and 3,925 ft (1,196 m) of core at 35 locations by using continuous wireline coring. The 35 wireline cores reached bedrock and have natural gamma-ray logs. A total of 30 new cross sections have been built across Will County. The cross sections together with geologic map contacts are used here as the main expert knowledge constraints, but other constraints will also be used to take into account reliable data between cross sections and to increase the accuracy of interpolated surfaces.

Among the most significant features of the bedrock topography of Will County are the Des Plaines (500–550 ft MSL) and Spring Creek Bedrock Valleys (525–550 ft MSL). The glacial sediments filling this tributary of the Des Plaines River include thick deposits of diamicton and sand and gravel, which extend northeastward from Joliet for a distance of at least 10 miles (16.1 km). This bedrock valley coincides with the present valleys of Spring Creek and Hickory Creek (Figure 3). The bedrock valleys below Spring Creek and Hickory Creek are about 1 mile (1.6 km) wide, have relatively steep walls, average 150 ft (46 m) in depth, and bifurcate around a bedrock island. The surface elevations of water wells, engineering borings, stratigraphic borings, and gamma logs were interpolated from the Will County LiDAR. Preliminary elevation contours were derived from a surface calculated by subtracting the thickness of consolidated materials from the ground elevation. A smoother bedrock surface was created from the contours by the ArcGIS Topo-to-Raster interpolation method. Finally, the contours were adjusted to honor all of the data points on the final bedrock topography map.

During the first five years of this project, we remained in contact with local map users throughout the duration of the project. During mapping and after completion of the maps, ISGS staff worked with county representatives to explore the development of additional interpretive geologic maps. Extensive fieldwork descriptions of outcrops were conducted, all with the goal of providing detailed information related to surficial and subsurface mapping of the various deposits in the county. More than 37 exposures of glacial sediments were investigated, and 21 new gravel pits and quarries containing exposures were also visited. The geological model that is being developed is based on the integration of the surficial map and boreholes logs. The geomodeling defines the thicknesses and stratigraphic distribution of Quaternary deposits and is based on strict coherence between the surface distribution deduced from the geologic maps and the borehole stratigraphy. Data processing will be achieved by using GeoScene 3D. This software permits an integration of varied data and has a very powerful calculation capacity.

It is anticipated that at least 12 surfaces will be developed as part of the geologic modeling exercise. However, considering the extreme complexity of this glacial environment and distribution of sediments, prior to construction of a solids model, there will be one final evaluation of subsurface data to reveal any portions of the county that will require additional data gathering. This will be based on the distribution of multiple cross sections cross-checked with the distribution of stratigraphic, water-well, and engineering boreholes and lines of geophysics. The anticipated use of the geological information by county and regional planning, zoning, and water-resource agencies warrants as accurate a 3D depiction as possible.

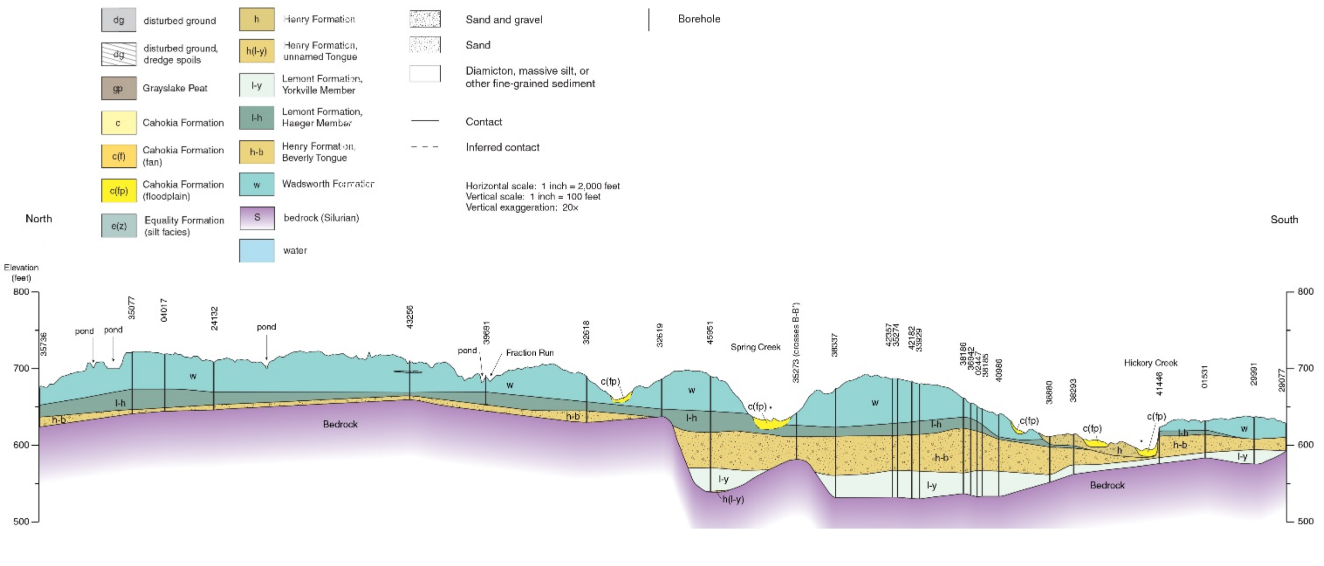

Figure 3. Schematic example of the bedrock valleys below Spring Creek and Hickory Creek showing how cross section building was used for data quality control and correlation.

Conclusions

Classical science-based geologic mapping combined with modern 3D geologic modeling and hydrostratigraphic analysis generate a definite lithosome geometry for Will County. This is a region of projected high population growth within the Chicago metropolitan area where detailed subsurface information is required to implement sustainable water- and land-use resource-based planning efforts. The mapping and modeling study shows that first using LiDAR DEM provides unique information about depositional processes and extrapolation of surface conditions to the subsurface. Further work focuses on the integration of the sedimentary record from water-well logs and test drilling, particularly in the northwestern part of Will County, based on various criteria such as the nature of sediments, dimensions, elevation, texture, orientation, spatial relationships, and chronology. Paleoecological investigations will be conducted on the different facies to gain information on environmental conditions and to derive paleoclimatic interpretations of the lithostratigraphic units. In addition, a stratigraphic problem has been tracing the Haeger unit in the subsurface. In places where it pinches out to the east and south of the well-known Lemont Section, separating the Yorkville from the Wadsworth units may not be possible. Determining the southern boundary of the Haeger Member and its associated sorted sediment is an important aim of this 3D geologic mapping program.

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3D GEOLOGICAL MODELLING OF THE UK ONSHORE CHALK GROUP, FOR GROUNDWATER MANAGEMENT PURPOSES

Catherine Cripps, Andy Farrant, Jo Thompson, and Mark Woods

British Geological Survey, Nottingham, NG125GG, UK

caip@bgs.ac.uk

The Upper Cretaceous Chalk Group outcrops and underlies the surface predominately in southeastern England and forms the region's most important aquifer, supplying industry and approximately 18 million people, including the megacity of London. As such, the Chalk is becoming increasingly water-stressed, with multiple pressures of population growth, groundwater pollution, and extremes in weather and climate, producing events such as droughts and/or groundwater flooding. Against this backdrop, the UK's environmental regulatory body, the Environment Agency, is having to balance the needs of multiple stakeholders in the region with maintaining a sustainable abstraction regime, and to help preserve the Chalk's unique ecological environment. Since the 1970s, when all Chalk was treated as a single homogenous unit, there has been a quiet revolution in Chalk Group stratigraphy, whereby major gross characteristics of the Chalk have been used to differentiate the Chalk into a high-resolution lithostratigraphy (Figure 1). Nine formations make up the basic framework of the lithostratigraphy, supplemented by named marl seams, flint bands, and hardgrounds; moreover, this new lithostratigraphy can be applied to a conceptual hydrostratigraphy. The British Geological Survey, in our role as the UK's geological surveyor, was commissioned by the Environment Agency to instigate a mapping and 3D explicit geological modelling programme that incorporates this "new" stratigraphic framework covering large areas of Chalk Group outcrop. This recent mapping and modelling programme not only has enabled new structures and variations in the Chalk to be discovered (Figure 2), but has also significantly improved the hydrogeological conceptual understanding of the Chalk aquifer properties and flow regimes. Consequently, this has enabled the Environment Agency to make expert-informed planning and management strategies regarding the regulatory management of these precious groundwater resources.

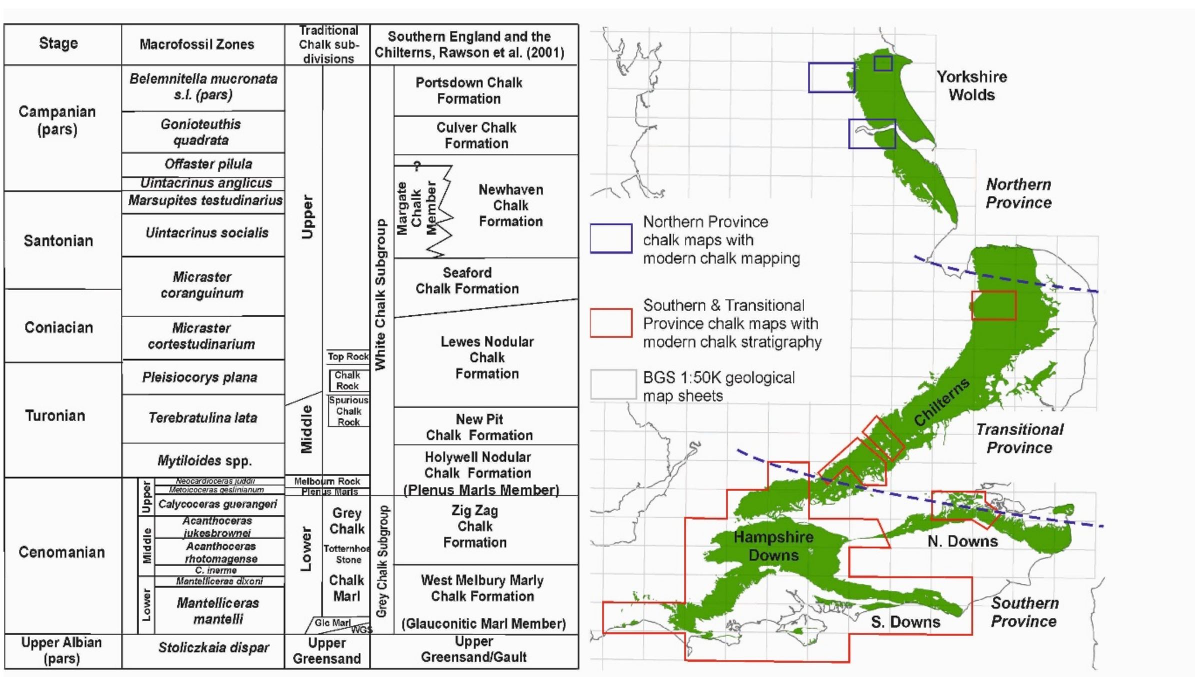

Figure 1. Southern England and Chilterns Chalk Group lithostratigraphy on the left, and areas of Chalk Group outcrop (in green) with new lithostratigraphic mapping outlined in red.

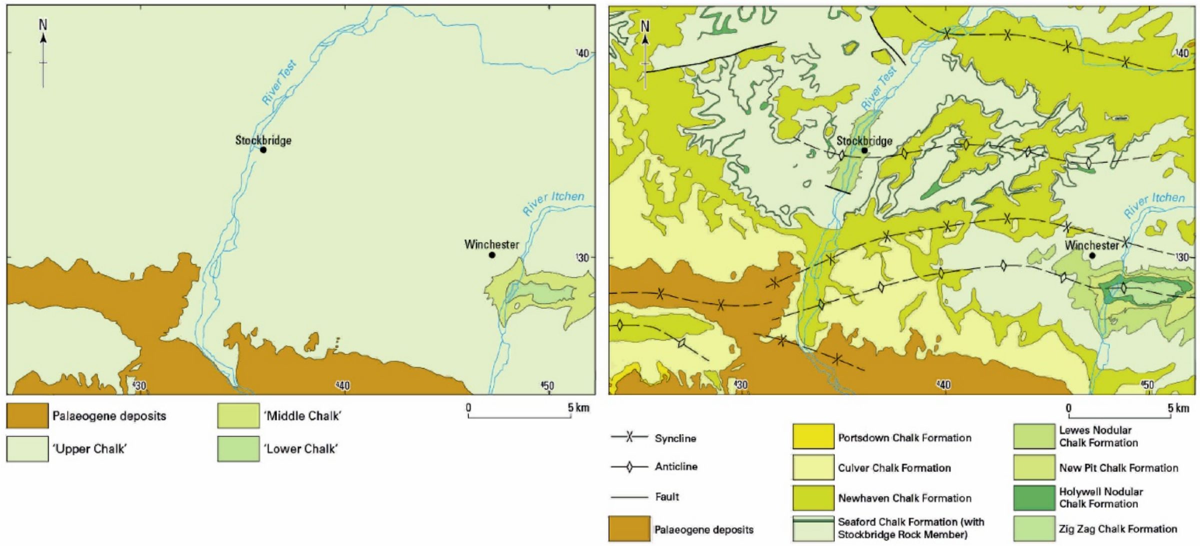

Figure 2. An example bedrock geological map (Winchester district, BGS 1:50,000 scale, geological sheet 299) showing the difference between the traditional classification of the Chalk (left), and the new detailed lithostratigraphy (right). Using the new lithostratigraphic mapping, faults and fold structures can be identified clearly.

HOW ACCURATE IS YOUR MODEL BETWEEN BOREHOLES? USING SHALLOW GEOPHYSICS TO TEST THE BEST METHOD TO MODEL BURIED TUNNEL VALLEYS IN SCOTLAND, UK

Tim Kearsey[1], Katie Whitbread[1], Sarah Arkley[1], David Morgan[2], David Boon[2], and Mike Raines[2]

[1]British Geological Survey, The Lyell Centre, Research Avenue South, Edinburgh EH14 4AP, UK, [2]British Geological Survey, Nicker Hill, Keyworth, NG12 5GG, UK

timk1@bgs.ac.uk

3D geological models are fast supplanting 2D maps as the primary way for geological surveys to deliver subsurface understanding. In parallel, there is an increasing interest in the accuracy and uncertainty of geological models as more and more end users rely on them for subsurface prediction. This is putting geological reasoning under a degree of scrutiny that it previously has not been subjected to (Bond 2015). The problem is enhanced when the feature of interest has no surface expression. Since 2001, the British Geological Survey (BGS) has published a National Superficial Deposit Thickness Model (SDTM) derived by interpolation of borehole data (Figure 1). This shows variations in the thickness of unconsolidated deposits less than 2.6 million years old (Quaternary System). It includes all deposits of fluvial, glacial, marine, residual, aeolian, or anthropogenic origin (Lawley and Garcia-Bajo 2010). The borehole data used in the derivation of SDTM comes largely from third-party sources, stored in the BGS digital borehole archive. The characterisation of superficial thickness is thus affected by the irregular distribution of the borehole data, with potential implications for the accuracy of the SDTM model, particularly in relation to complex features such as buried tunnel valleys and overfilled bedrock depressions (Figure 1). Here we explore the characterisation of these features using an example from central Scotland and test whether alternative modelling methodologies enhance our ability to predict the geometry of these features.

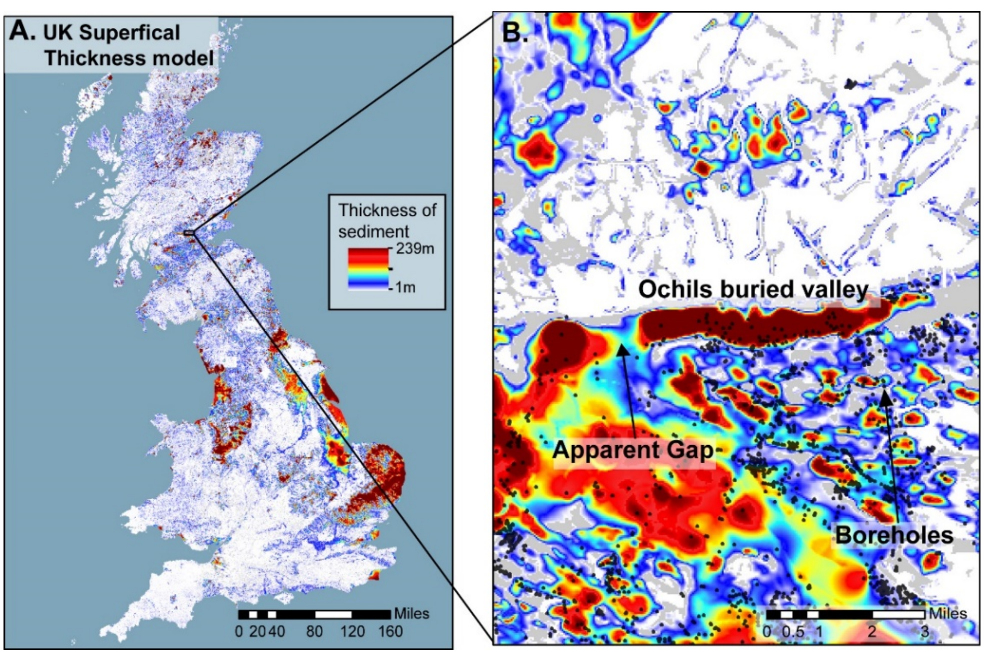

Figure 1. A) SDTM, the BGS national superficial thickness model. B) The Ochils buried tunnel valley as shown in SDTM. Black dots mark the positions of boreholes. The apparent gap may be caused by the interpolation method.

Work on uncertainty in 3D geological models has focused on the clustering of input data (MacCormack and Eyles 2012); the role of geologists' experience in the model accuracy (Lark et al. 2014); whether a regional approach improves accuracy (MacCormack et al. 2017); and the role of information entropy (Wellman and Regenauer-Lieb 2012). However, there has been less research into the role that the relief of buried surfaces has on the accuracy of 3D geological models.

In this study, we focus on the Ochils buried tunnel valley, located east of Stirling in central Scotland (Figure 1B). This feature has a maximum depth of 113 m, based on boreholes, and is the second deepest buried bedrock trough known in Scotland. In the UK Superficial Thickness model, the Ochils trough is not completely resolved; there are apparent gaps in the longitudinal continuity in areas with no borehole data (Figure 1B), and the cross-sectional geometry is variable along the length of the feature. These apparent characteristics of the feature may arise, at least in part, because of the way the SDTM was constructed. The model utilises all the boreholes that intersect the top of bedrock, and the depth to bedrock is extrapolated on a grid using a Natural Neighbourhood interpolation and area weighting of the Voronoi neighbourhood of each data point (Lawley and Garcia-Bajo 2010).

To examine the degree to which the method of interpolation has affected the surface morphology, two additional interpolation methods were applied to the SDTM borehole data set. The first was by direct triangulation using Delaunay-triangulation (Kessler et al. 2009) and the Paradigm SKUA Geological Grid (Scandinavian Oil-Gas Magazine 2008), which creates implicit surfaces using a 3D grid, which is parallel to original depositional normals (Mallet 2004).

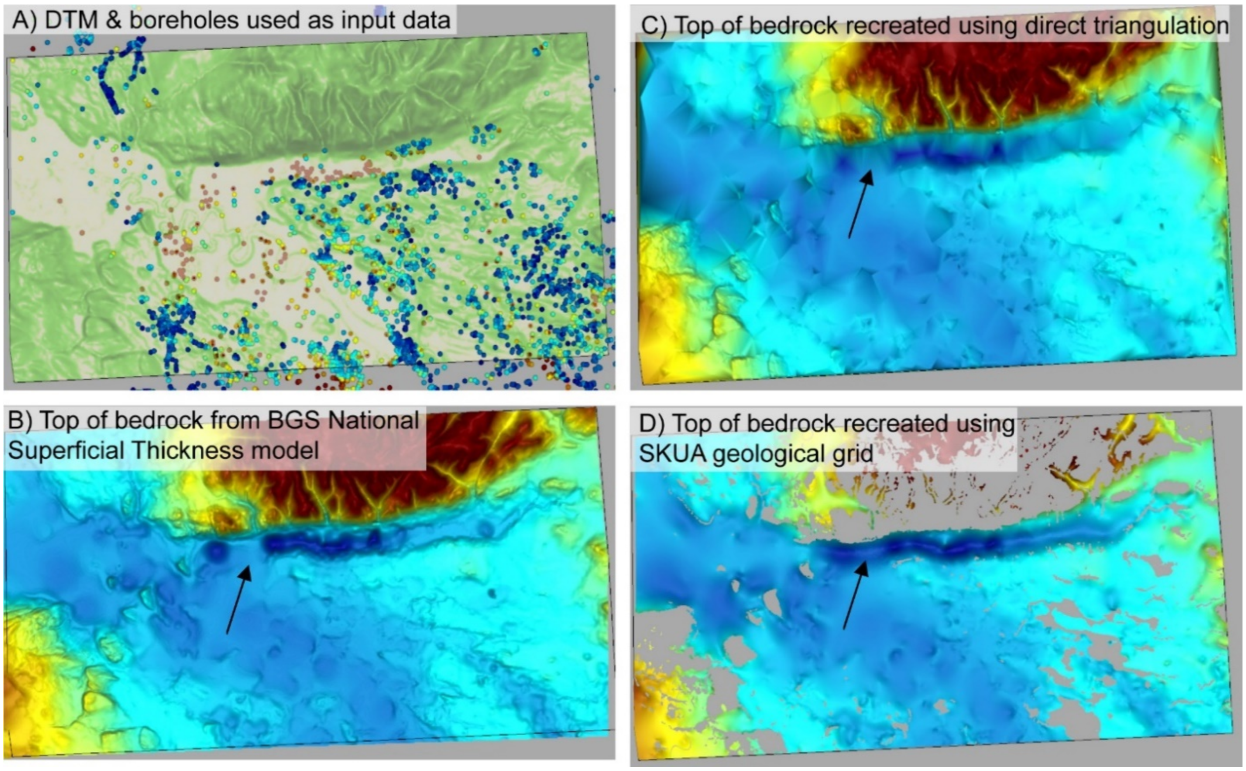

Figure 2. A) Distribution of borehole input data used in the test. B) Top bedrock surfaces from the current BGS superficial thickness model (SDTM). C) and D) The recreated surfaces using different methods. Note that only method D) does not contain the apparent (arrowed) gap in the buried valley.

The direct triangulation method (Figure 2C) creates a surface that differs from SDTM by an average of 2 m (max. 100 m above; min. 99 m below). The SKUA Geological Grid bedrock surface (Figure 2D) differs from SDTM by an average of 3 m (max. 63 m above; min. 36 m below). However, this SKUA method geological grid appears to resolve the Ochils buried valley as a continuous feature rather than creating the apparent gap, and it reduces the localised deepenings ("bull's eyes"). All methods are using exactly the same input data, so all the differences between the surfaces are a product of the algorithms that were used.

To test the accuracy of the different interpolation methods, we tried to resolve which of these methods provided the most accurate prediction that we needed to collect more data. Drilling new boreholes was too expensive given the >90 m thickness of Quaternary sediments in the Ochils buried valley. Instead, we used a TROMINO® passive seismic instrument to provide geophysical constraints on the bedrock surface. Two separate survey lines were selected: line 1 was targeted on an area of the Ochils buried valley with good borehole control; the second was targeted on a section of the feature with no boreholes and that some methods interpret as a high (Figure 3). Each survey line consisted of an individual measurement of depth to bedrock every 100 m along the survey line.

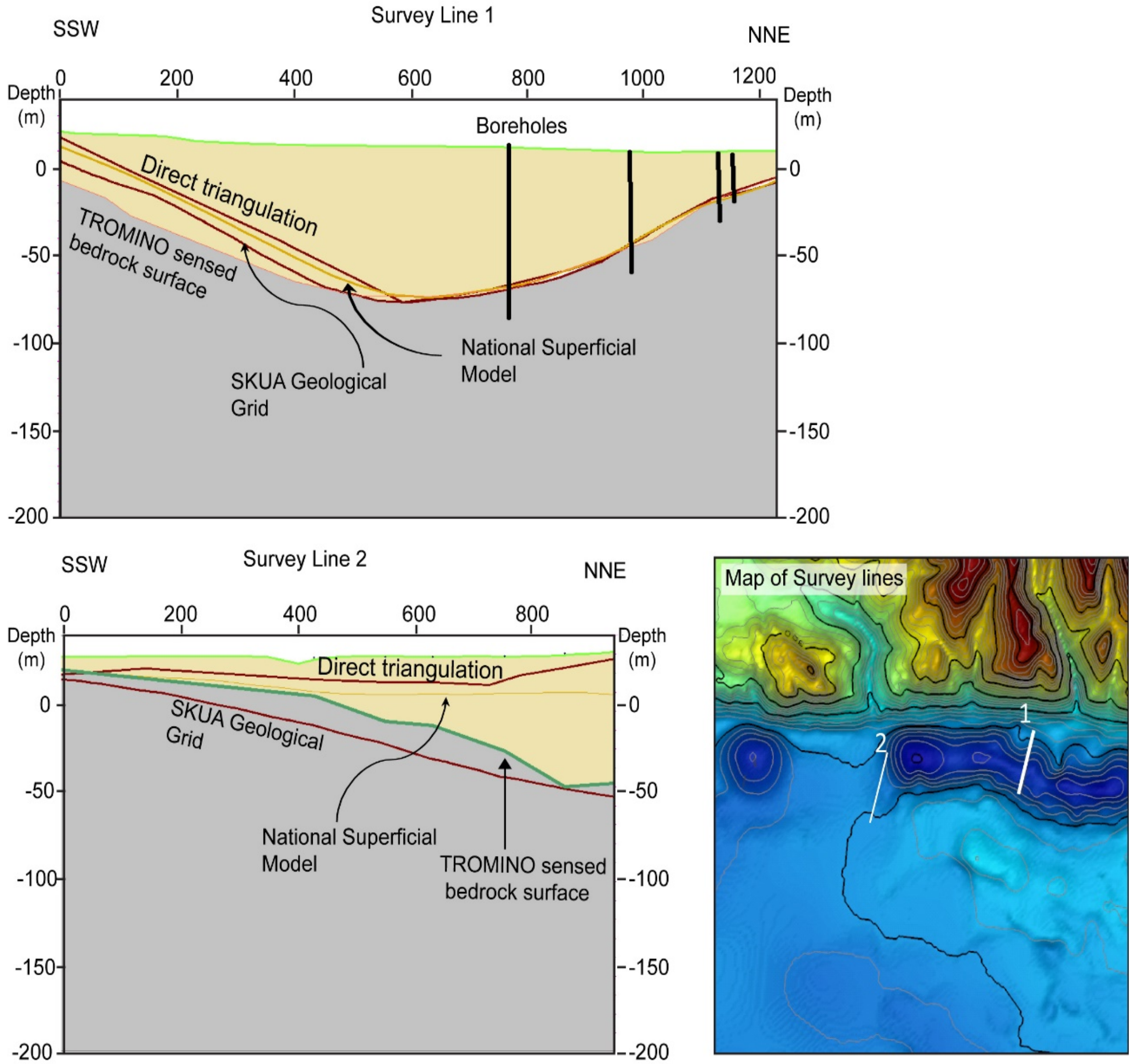

Figure 3. The results from the two passive seismic lines compared to the surfaces created by the different methods described in Figure 2. Survey line 2 shows that the apparent gap in the valley predicted by SDTM and the direct triangulation method is likely to be an artifact of the interpolation.

The results revealed that along survey line 1, in an area of good borehole control, all the methods proved to be accurate within a distance of 200 m of boreholes (Figure 3). Away from the boreholes, all methods underestimated the thickness of superficial deposits, with direct triangulation being the worst performing method, followed by the SDTM model, and then the SKUA Geological Grid. Survey line 2 focused on an area that SDTM and the direct triangulation method suggested may be a bedrock high. The results showed that this is actually an artifact of the interpolation and that these two methods underestimated the thickness of superficial deposits by 50 to 60 m (Figure 3). The SKUA Geological Grid, on the other hand, overestimated the thickness of superficial deposits by up to 16 m.

The results suggest that for modelling buried valleys using scattered data points, the SKUA Geological Grid model produces the most predictive result. Furthermore, using Natural Neighbourhood interpolation or direct triangulation can lead to a substantial underestimation of the geometry and thickness in linear features such as buried valleys. It also suggests that when modelling buried geological surfaces with a substantial degree of relief, the method used to interpolate between data points can have a significant impact on how predictive that surface is. It also highlights the utility of targeted shallow geophysical methods in improving the accuracy of 3D geological models.

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3D VISUALIZATION OF MASSIVE GEO-MODELS FOR CANADA-3D

Michael Hillier and Boyan Brodaric

Geological Survey of Canada, Ottawa, Canada

michael.hillier@canada.ca, boyan.brodaric@canada.ca

Abstract

The development of national 3D geological models involves enormous amounts of data and requires new approaches to information management and visualization. Visualization in particular requires a hierarchical method in which data are viewed efficiently at various levels of generalization. We present an octree-based method and system for massive 3D model visualization as part of an initiative to build a national 3D geological model for Canada.

Introduction

Government organizations are under increasing pressure to provide open access to the data they collect and manage. Coincidently, many geological agencies are building 3D geological models (Berg et al. 2011), here called geo-models, often in synergy with the 3D activities of international consortia such as OneGeology (OneGeology 2018). A requirement resulting from these trends is the need to manage and visualize massive geo-models in desktop and web environments, enabling the discovery of relationships and patterns that might otherwise be hidden. Information obtained from such an environment directly benefits scientific research, education, and various forms of engineering and resource development.

The Canada-3D (C3D) project at the Geological Survey of Canada is developing a national scale geo-model of Canada, from surface to crustal depths, to provide an authoritative synthesis of the geology of Canada. An integral part of this effort is an efficient visualization mechanism. Visualization of such geo-models is challenged by several factors: (1) massive geo-model sizes, (2) file-based data management that treats geo-models as single entities, (3) the inability of popular geo-modelling software to calculate and render massive models, (4) variability in 3D geometry structures, as key 3D data types are often unsupported, and (5) efficient and effective web-based access to large geo-models.

In this paper, we address these challenges through the development of an octree-based method in which 3D geographical space is decomposed hierarchically into blocks, each containing an appropriately generalized portion of the national geo-model. Each block is stored in distinct files, accessed efficiently through a relational database, and optimized for viewing with ParaView open source software (ParaView 2018), which can be run in desktop and web environments. The novelty of this solution rests in its use of a database-driven approach to visualize both vector and grid-based entities from geo-models. The paper is structured as follows: section 2 discusses related work; section 3 describes the hierarchical visualization method and section 4 its implementation; section 5 evaluates the approach; and section 6 concludes with a brief summary.

Related work

Myriad software packages carry out 3D visualization, although the application of hierarchical octree approaches is limited to a very few that currently do not natively support unstructured meshes. More than 30 different commercial and research geo-model visualization packages were evaluated against five key criteria: (1) database support, (2) open source code, (3) comprehensive geometry data types, (4) desktop and web support, and (5) real-time visualization of massive data. A database-driven modelling and visualization environment is required to efficiently discover and retrieve selected portions of geo-models. Open source code is also desirable to share and improve the results within the community. A comprehensive suite of geometry data types is essential to handle the large variety of complex geometries used in geo-models, whereas both desktop and web support are required to allow both offline and online access to geo-models. Finally, the visualization environment must operate efficiently over very large volumes of data (potentially billions of objects), allowing real-time exploration of geo-models. Results of the evaluation show that none of the systems met all five criteria.

Use of multi-resolution hierarchical octree approaches for geo-models is also limited thus far. The PolarGlobe cyberinfrastructure solution adapts the open source Cesium visualization engine to view climate simulation data using optimized filters and volume rendering on point cloud data (Wang et al. 2017). NASA's open source system WorldWind (Hogan and Couglan 2006) is used to visualize time-varying point data that samples a volume to better understand the Earth's dynamic phenomena more intuitively (Li et al. 2011). Though both systems are promising, they have at present a geometry data model that is neither comprehensive nor easily extensible, and they omit visualization of vector-based geometries such as unstructured meshes, which are often used to depict geological volumes. Ongoing work suggests that these gaps are being actively addressed.

The Hierarchical Visualization Method

Four elements are needed for interactive visualization of massive geo-models: (1) spatial decomposition, (2) storage of geo-models (3) generalization of geo-models, and (4) retrieval and streaming of selected geo-model portions.

Spatial decomposition

Spatial decomposition is the process of recursively partitioning a 3D volume into successively finer blocks. These are organized in this work as a classical octree (Figure 1a). The base of the tree, called the root, contains the block corresponding to the full volume of interest. The first level can partition this volume up to eight equally sized blocks. Each subsequent level can further subdivide each block into at most eight more blocks. Each child block is connected to a parent block to form the tree, such that each child block is an eighth the size of its parent. The number of blocks increases at each successive level, with blocks at the same level having the same size. To enable geographically targeted and scale-dependent visualization, each block is filled with geo-model data generalized to an appropriate scale for the level. Note that variable partitioning is deployed, in that block subdivision occurs only when the amount of data within that block exceeds a specific threshold; thus, some blocks might be subdivided and others not (Figure 1b). For triangulated meshes, that threshold is approximately 1 million total triangles per block, which ensures loading and rendering speeds of less than 1 second. Also note that such variable partitioning enables the incorporation of multi-resolution parts of a geo-model, as more detailed parts will occupy deeper blocks and less detailed parts will occupy shallower blocks; empty blocks will not be segmented.

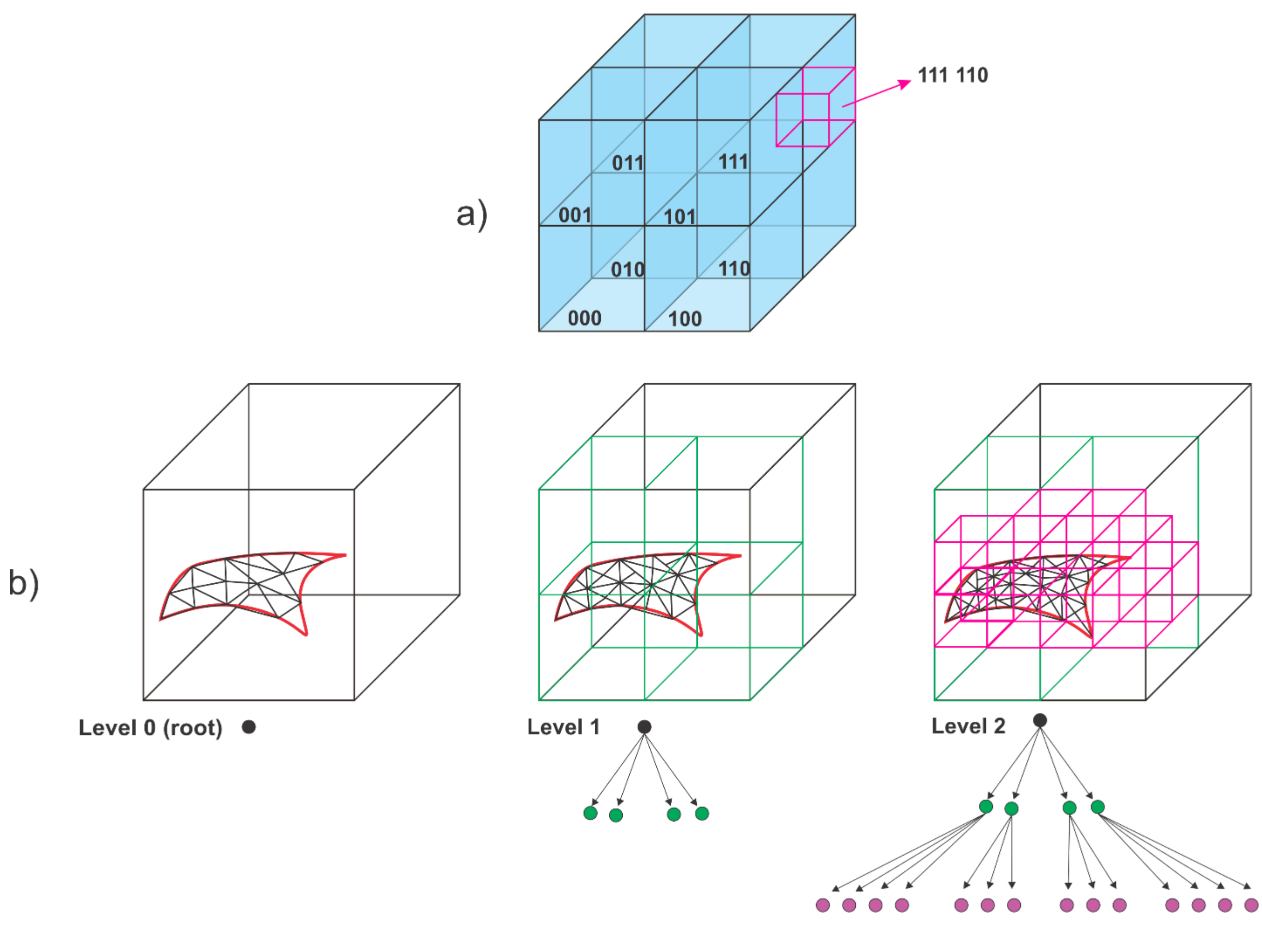

Figure 1. (a) Octree data structure and spatial indexing. (b) Variable subdivision of blocks.

A spatial index in the form of a bit string is assigned to each octree block. It serves as an identifier for the block and is used to retrieve block contents during interactive visualization. Each block has 3 bits associated with it that describe its relative location within its parent block. The first bit indicates the block's relative *x* position—left (0) or right (1). The second bit indicates the block's relative *y* position—bottom (0) or top (1). The third bit indicates the block's relative *z* position—down (0) or up (1). Encoding proceeds left to right, starting with the first level and ending with the target block. For example, encoding for the level 2 magenta block in Figure 1a begins with 111 (first level) and ends with 110 (second level). Thus, the hierarchical level of a block can be calculated by dividing the total length of the bit string by 3. The location of a block can be computed using its spatial index and the root block's corner points.

Storage

Storage of geo-models occurs in two parts: (1) a file system for geo-model contents and (2) a relational database (PostGRES) that maintains an index to those contents. The contents are stored in distinct files using a binary encoding of the VTK standard for geometry types (VTK 2018). Separate files are written for specific types of features, such as faults or geological units, for each block. The relational database then maintains a record for each file, including a record identifier, file locators for the generalized or original geo-model contents for the block, the spatial index of the block, and a designator for the feature type (i.e., id, gen_model, raw_model, spatial index, feature). This separation of index and geo-model contents avoids size issues that might result from the insertion of the content into the database, which could require billions of blocks for the whole of Canada.

Data processing

Block partitioning and storage of a geo-model involves two steps: (1) transformation into a common coordinate system to avoid the overhead of real-time projection, and (2) generalization of the data to meet the block threshold. For regular gridded data, generalization is routine and involves subsampling the grid to an appropriate amount for a particular scale. For vector-based geo-models, generalization is more complex and involves decimation of geometry primitives (e.g., triangles, tetrahedrals), such that consistent topology and continuity are maintained across block boundaries. Surface mesh generalization is achieved using a quadric error metrics technique (Garland and Heckbert 1997), and an algorithm was developed to insert surface-based geo-models into the hierarchical data structure. The algorithm first inserts the meshes into level 1 of the octree, writes the raw data to a file, and stores the location in the database. Next, recursive iteration through the octree is carried out to generalize, if needed, each octree block's data to remain under a threshold (1 million triangles per block). The generalized data are written to a file and their location is stored in the database. If a block's data is generalized, that block gets subdivided and the new blocks (with data) are pushed to the database and file system.

Retrieval and streaming

A streaming algorithm, refined in this work, links a view within the visualization system to the hierarchical model stored in the database and file system. The algorithm identifies the required blocks, retrieves them from the database and file system, and streams them to the viewing engine for scale-appropriate viewing. Upon start, the visualization system queries the database to obtain all unique spatial indices. From those indices, the octree data structure is built as shown in Figure 1. Any update to the camera's view causes the octree structure to be analyzed: starting at the first level, each block is checked to determine its intersection with the view frustum, which denotes the region of space in the field of view of the camera as shown in Figure 2. For each intersecting block, the amount of space it occupies on the screen (measured in terms of pixels) is compared with the total space of the screen. If a block's size is much larger than the screen, then its children are analyzed; if not, then that block's spatial index is added to a visualization list. This list is compared with blocks already rendered to purge unnecessary blocks from the renderer. The final list is then sent to the renderer for display.

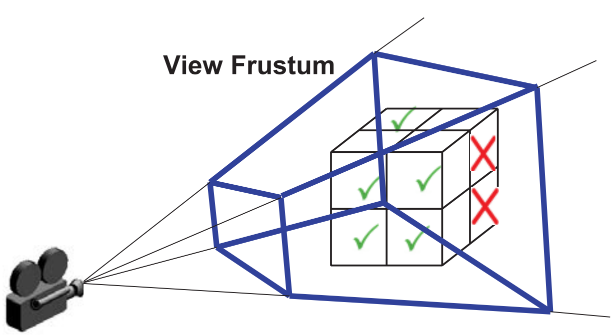

Figure 2. Only octree blocks that intersect the view frustum are loaded and rendered.

Implementation

Implementation was carried out in the ParaView open source multi-platform (Linux, Windows, Mac, and web) visualization system. ParaView meets our original criteria: it can be easily connected to a variety of databases (PostgreSQL in this case), has an active open source development community, uses the sophisticated VTK geometry data model, can be deployed in a distributed server environment and on the web, and results in efficient interactive visualization that can scale to massive volumes.

Three pieces of software were developed in C++ to support hierarchical 3D visualization of surface meshes in ParaView. The first piece is the data processing algorithm (Section 3.3) which inserts the data into the hierarchical data structure and generalizes the data for rendering. For a small region of topography, surface meshes at five different generalization levels are illustrated in Figure 3.

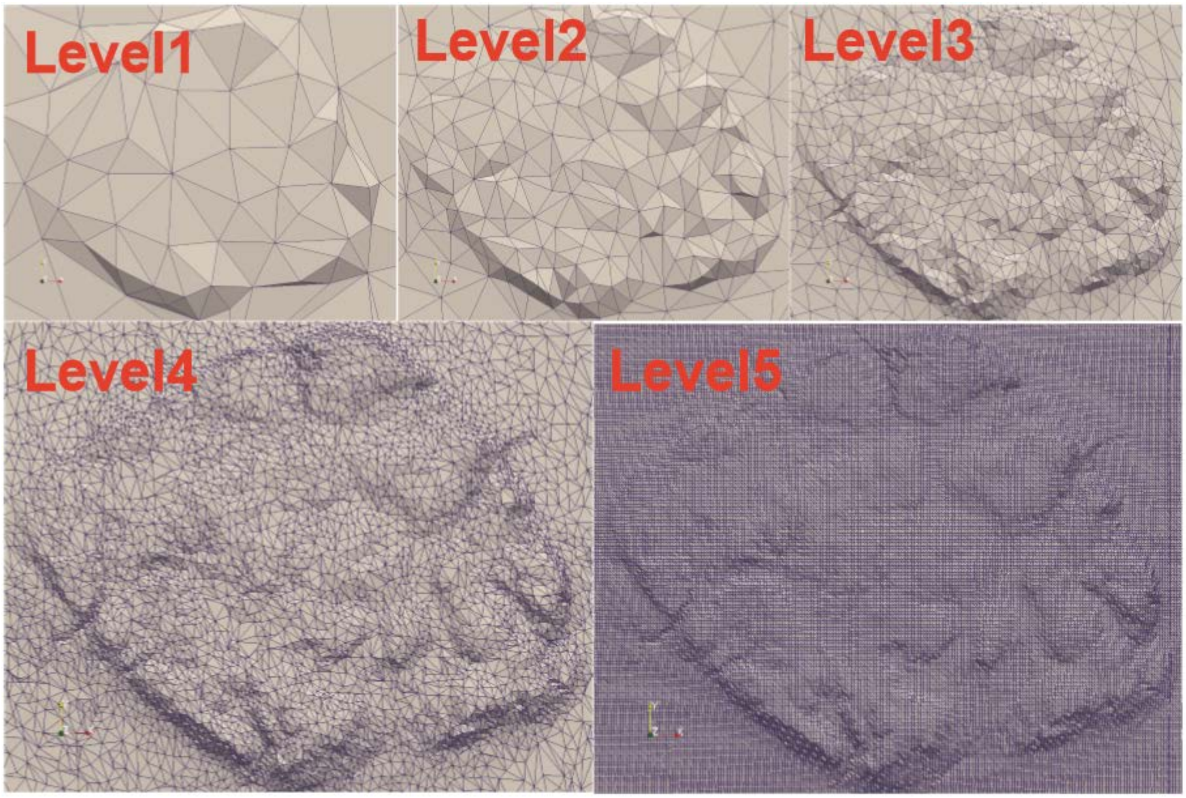

Figure 3. Five levels of generalization for a topography surface mesh feature.

The second and third pieces of developed software are ParaView plugins. The first plugin determines the appropriate blocks intersecting the view frustum and manages the list of blocks for rendering. The second plugin requests the required blocks from the database, builds the octree structure in memory, and assembles the data as well as clips it to fit the view. These plugins were first deployed using the desktop version of ParaView for proof of concept. They are demonstrated in Figure 4, where a small portion of the Canada-3D geo-model is visualized, including topography, a portion of the Williston Basin and the Precambrian-Phanerozoic contact surface. Subsequently, a working web prototype was also tested, and this will be the focus of future work. Development and testing occurred on a powerful HP z820 workstation containing a dual Intel Xeon E5-2650 2 GHz processor, 128 GB of DDR3 memory, and Nvidia Quadro 5000 GPU—this system hosted both the geo-model and visualization software.

Evaluation

Data loading times are compiled in Table 1 to assess the performance of the approach. The table shows times taken to load a variable number of triangles from the Canada-3D geo-model for the required blocks at increasing zoom levels. Initially, the camera is zoomed out with only level 1 data rendered. As the camera zooms in, higher resolution data are retrieved from deeper in the octree. Of note is that data loading times are roughly constant through the range of resolutions, demonstrating a scalable solution with no resolution limits. The time to render each level, that is, the key metric controlling the user's overall experience, is less than a second for all tested levels.

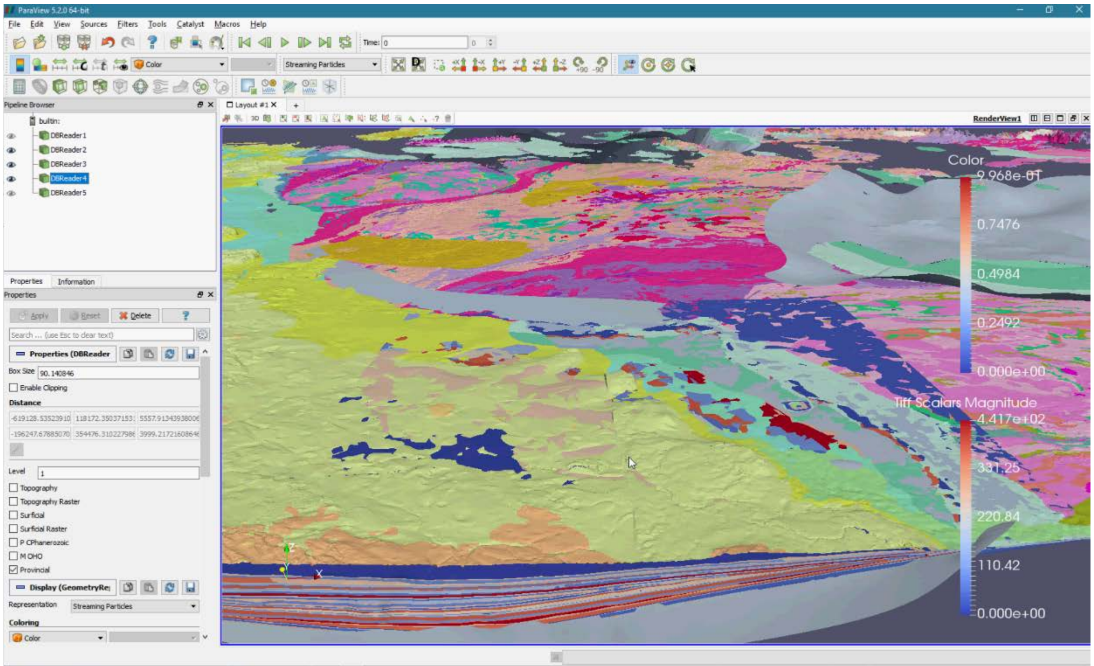

Figure 4. Hierarchical Canada-3D model streamed to ParaView using custom-developed plugins to facilitate big data visualization of vector and raster components of geo-models.

Table 1. Time to load data in preparation for the renderer. Display time for the user is <1 sec for all.

Level	Data loading time (s)	Total triangles viewed (generalized)	Total triangles (original)
1	0.124	299,934	56,884,668
2	0.065	149,940	56,884,668
3	0.202	399,802	57,640,611
4	0.112	225,051	38,567,602
5	0.108	209,896	19,774,527
6	0.147	242,613	21,993,839

Conclusion

Presented is a hierarchical visualization method and system for geo-models. The system consists of custom plugins for the ParaView visualization environment and utilizes view-dependent hierarchical strategies to permit efficient streaming of massive geo-model surfaces. To ensure an interactive visualization experience, an original geo-model—a test case for Canada—was generalized at various levels and partitioned into blocks within an octree structure, and metadata about each block was managed in a PostgreSQL database. Combined, these elements provide a foundation upon which functions such as volume rendering, 3D viewing, and interoperable data download are supported efficiently and effectively.

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VENDOR NEUTRAL TRANSFER OF UNSTRUCTURED GRIDS USING RESQML

Jay Hollingsworth and Jana Schey

CTO and COO, Energistics Consortium

Introduction

The oilfield of today and tomorrow is driven by digital data: real-time measurements that put eyes on drilling conditions miles underground; sensors streaming information related to hydrocarbon production; digital earth models being shared by teams across distant locations.

To really deliver the maximum benefit, information must flow through the organization quickly and seamlessly. To do this effectively requires standards that are built to ensure data integrity and protocols to move data rapidly to where they are needed. This is the mission of Energistics.

This abstract focuses on the RESQML standard, with the example of transferring unstructured grids.

About Energistics

Energistics is a global non-profit consortium dedicated to the development and adoption of open data exchange standards in the upstream oil and gas industry. We serve a wide spectrum of stakeholders: integrated oil companies, independent operators, national oil companies, oilfield service companies, software vendors and system integrators, regulatory agencies, and the global standards user community. We have more than 25 years of experience in modeling, developing, and delivering standardized protocols.

Energistics provides a forum to strategize the present and future of an interconnected industry, ensuring data integrity and reliable real-time transmittals.

Energistics standards

WITSML™ enables a seamless flow of well-related data between operators and service companies to help speed up and enhance decision making and reporting. It encompasses all aspects of wells, including drilling, completions, and interventions.

PRODML™ supports the exchange of hydrocarbon-related data from wellbore to custody transfer, together with field services results, engineering analyses, and other specialized data required in production operation workflows. PRODML can be used for fluid analyses, production operation reports, and downhole and surface flow networks.

RESQML™ allows earth-model data to be shared with complete fidelity between the many software packages used in an exploration and production (E&P) subsurface workflow. RESQML defines a rich set of subsurface data objects and metadata to capture and preserve asset team knowledge.

ETP (Energistics Transfer Protocol) is a proven data exchange specification that delivers true real-time data streaming and is capable of handling today's increasing volumes of data associated with real-time monitoring.

CTA (Common Technical Architecture) is the foundation that underpins all Energistics standards. It is now possible to deliver cross-functional transfers using any combination of the standards.

From drill bit to decision

Real-time data are critical to the remote monitoring of drilling activities. Data must travel instantly and continuously while being shared among numerous stakeholders. There needs to be total trust in the validity of the data. Energistics data transfer standards and protocols provide the foundation for well data transfers to work seamlessly around the globe.

Collaborative reservoir models

Modern workflows to build and simulate complex reservoir models involve different teams and many software packages. The reservoir models must retain all the knowledge created at each step. Energistics standards ensure that the model can be enriched at each step and moved on quickly to the next process.

Production data at your fingertips

Energistics standards can convey a large amount of metadata that informs on what has been done to the data over time, by whom, using which tool. Production data can feed with confidence into production monitoring and reporting systems.

About RESQML

RESQML is an XML- and HDF5-based data-exchange standard that facilitates reliable, automated exchange of data among software packages used in subsurface workflows. RESQML consists of a set of XML schemas (XSD files) and other standards-based technology, which developers implement into software packages. Software that has implemented RESQML can read and write the standard format (Figure 1).

RESQML has been developed by a global consortium of operators, service companies, software vendors, and government agencies under the umbrella of Energistics.

Subsurface workflow challenges

The E&P subsurface workflow is lengthy, iterative, and complex. It involves many people from different disciplines, sometimes different companies, and the use of many different software packages for complex analysis, interpretation, modeling, and simulation.

This multi-discipline, multi-company, multi-software environment is iterative and requires users to move data back and forth between different software packages. Many of these packages use different data formats, often proprietary and incompatible.

This inherently complex process and inability to easily exchange data means E&P companies and their people face challenges that include knowledge loss, rigid workflows, difficulty characterizing and sharing uncertainty, data loss, and productivity loss.

How RESQML helps address these challenges

RESQML-compliant software can read and write this standard, common format, eliminating data incompatibility and the need for reformatting. Figure 1 below is a high-level overview of how RESQML works and the workflows it supports. The newest capabilities help RESQML deliver these benefits:

- Delivers a "knowledge hierarchy" to organize data and transform it into knowledge.
- Increases workflow flexibility, for example, with partial model transfers that allow you to update or transfer only data that have changed.
- Supports traceability, with universally unique identifiers for each top-level data object and key metadata for data sources, updates, dates of change, etc.
- Supports uncertainty management through an increased ability to run more scenarios and realizations and reliably update models.
- Defines a rich set of subsurface data objects and enables transfer of detailed models and a variety of model types.
- Improves efficiency for both petro-technical and IT professionals.

Use cases

RESQML supports a variety of use cases, including but not limited to:

- Transferring unstructured reservoir modeling grids
- Transferring sealed 3D framework across applications
- Transferring non-cornerpoint simulation data
- Archiving earth-model data in a vendor-neutral format

RESQML Supported Workflows

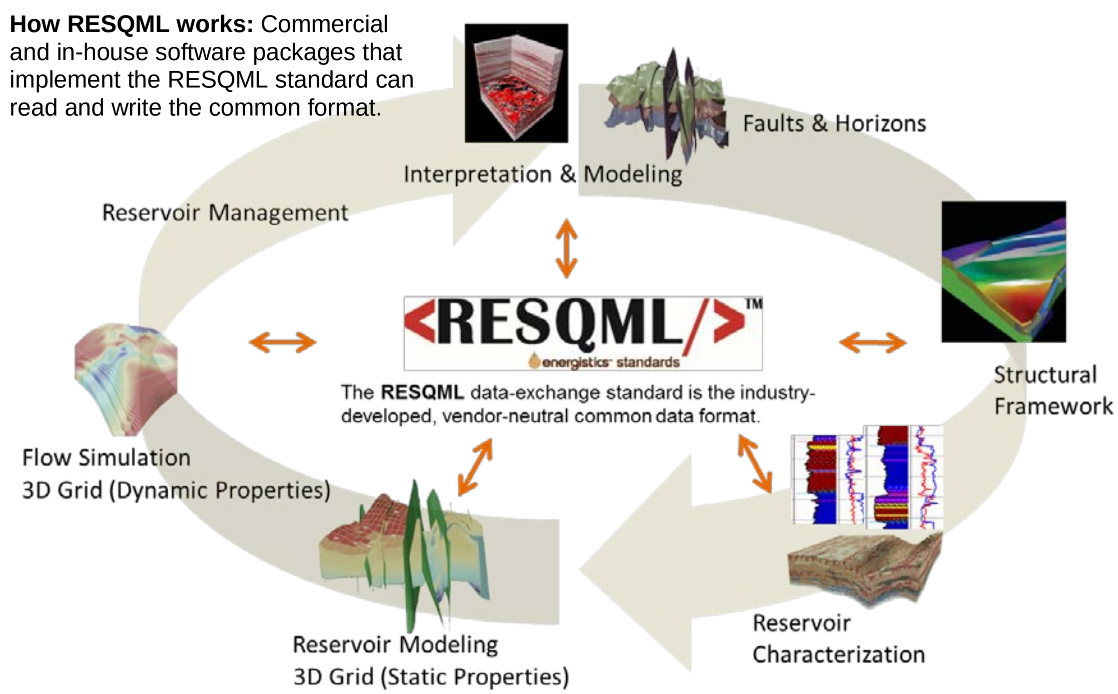

Figure 1. Implementing RESQML in software used in the E&P subsurface workflows streamlines data flow among the many different software packages used. The latest version supports more workflows and more flexible workflows. New capabilities provide a rich set of data objects, a well-defined knowledge hierarchy throughout the model, methods for specifying and transferring relationships among data objects, and the ability to group all the information into a single package.

Software packages that implement RESQML can read and write "comprehensive" subsurface models—that is, the model data and the relationships among the data that define how it "goes together" as a model—to this vendor-neutral, industry-defined, common data format. A "comprehensive" subsurface model could contain the structural and stratigraphic frameworks along with 3D grids and associated reservoir properties. It might also contain wells and seismic coordinate references. Conversely, to increase efficiency and support flexible workflows, RESQML also makes it possible to logically transfer only parts of models and associated data.

RESQML-enabled software continues to process and save data in the software's native environment. And when users need to move data and models to the next software package in their workflow, they can choose to export all the information to the RESQML format. That next software package may be a tool used by another discipline in the workflow or by a partner company in a joint venture. If that software is RESQML-enabled, it can read the RESQML format and process the data in its native environment.

RESQML supports the workflows shown in Figure 1. The following section provides a more detailed example of how it works.

RESQML workflow: A simple example

Figure 2 is an example of a very simple subsurface workflow using RESQML-enabled software. When users need to move data to the next software application in their workflow, they choose to write (export) data to the RESQML format. In this example, User A using Software A writes the data to the RESQML format, which is transported in an EPC file (for more information, see the *Energistics Packaging Conventions (EPC) Specification*). That next software application may be a tool used by another discipline in the workflow or by a partner company in a joint venture. If that software application is RESQML-enabled, it can read (import) the EPC file containing the RESMQL data and process the data in its native environment.

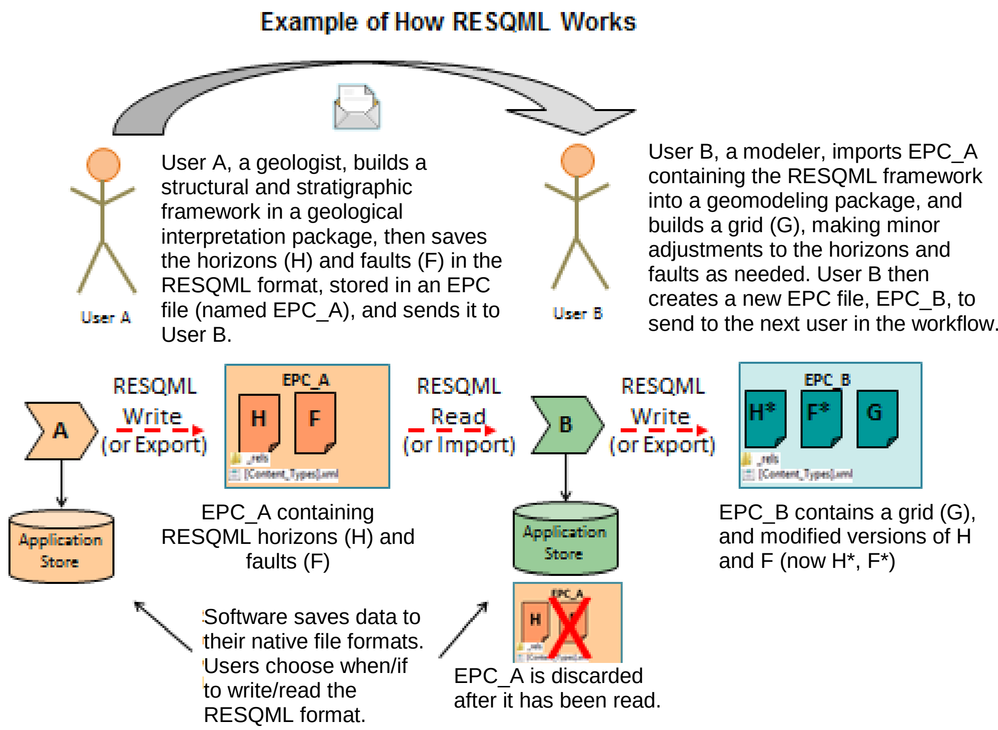

Figure 2. A user writes (exports) a file to the RESQML format, which is stored in an EPC file and may be read (imported) by other RESQML-enabled software.

More complex gridding situations

RESQML supports the transfer of information using modern gridding methods that are far more complex than traditional Cartesian 3D grids. It can move various styles of grids with truncated cells and grids that follow structural and stratigraphic features such as faults and surfaces, regular grids such as PEBI grids, any grids with local grid refinements around features of interest, or arbitrarily unstructured grids such as those in Figure 3 below (from SPE 106063, Usadi et al. 2007). It accomplishes this by creating general-purpose unstructured grids for any of these types and associating the appropriate descriptive metadata, which would allow a receiving application that supported these specific types to be able to reconstruct the original grid.

Properties can be associated with any topologic element of these grids (e.g., cell centers, faces, edges, and nodes).

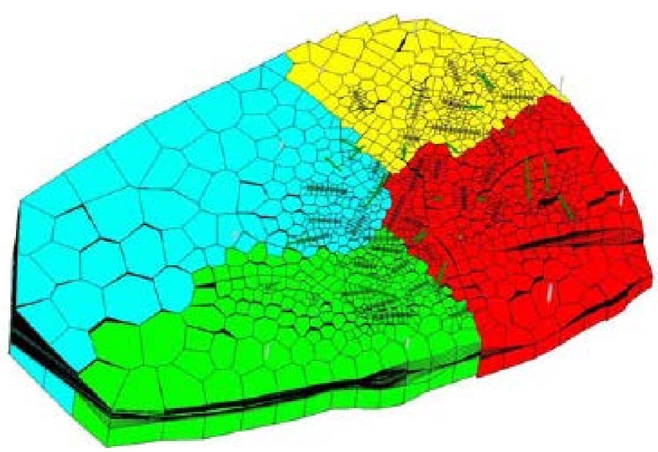

Figure 3. Arbitrarily unstructured grid.

Conclusion

RESQML improves workflows from interpretation to geomodeling to simulation. Version 2.0.1 leverages Energistics common technical architecture and other ML standards to support integrated operations, and it enables integrated decision making across multiple stakeholders. RESQML preserves data integrity throughout the asset life cycle to enable safer, more efficient operations. It enables a heterogeneous computing environment with multiple vendors, technologies, and platforms. Perhaps most important, RESQML is stable, provides robust functionality, and can support new capabilities as they are developed. And it is available now from vendors or is in the 2018–2020 planning stages.

GROUNDHOG DESKTOP—A FREE SOFTWARE TOOL FOR GEOLOGICAL STUDIES

Holger Kessler, Ben Wood, and Steve Thorpe

British Geological Survey, Nottingham, NG125GG, UK

hke@bgs.ac.uk

The British Geological Survey (BGS) has long pursued a policy of making as much data and information as open and accessible as possible; this is in line with the UK government's Digital Strategy (HM Government 2017). Our free on-line borehole scans are accessed more than 10,000 times per month, all of BGS' historic maps are now available on line and our iPhone app, iGeology, has been downloaded more than 300,000 times. However, the efficient delivery of 3D geological information to customers (see Kessler et al. 2005), in particular in the professional land, groundwater, and engineering sectors, has remained a challenge despite many technological advances over the past 15 years. The reasons for this are varied and range from cultural to technical; they will be highlighted with examples. Particularly working with the construction industry over the past few years (driven in part by increasing uptake of Building Information Modelling), it became clear that in order to deliver the complete package of geological information to clients in an efficient and usable form that was simple to use, free geological software needed to be available (see Gakis et al. 2016; Kessler 2017). What we identified is that there is a huge technology gap in the market between highly sophisticated solutions deployed on high-profile projects and traditional, often still paper-based workflows being deployed in the vast majority of construction and ground modelling projects. The BGS has now released Groundhog Desktop (Wood 2015) to fill exactly this technology gap. Groundhog can load geological data in common file formats and as web services. It enables the user to visualize and manipulate borehole, map, and cross-section data in an easy and interactive way. The interpreted map and section data can be exported as attributed linework or points for further use in other modelling and GIS tools. The BGS is continuously developing the software in cooperation with industry as well as major Geological Survey Organisations, and the current focus is the inclusion of time-related data, interpolation routines, 3D block model building, as well as the ability to annotate sections with features for conceptual site modelling and report building.

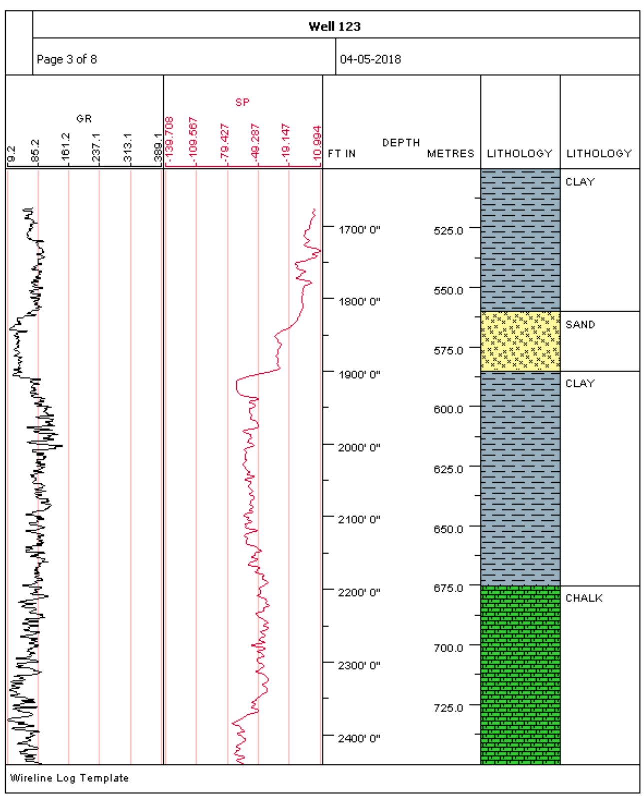

Figure 1. Groundhog Desktop borehole log, showing wireline log readings alongside traditional geological measurements.

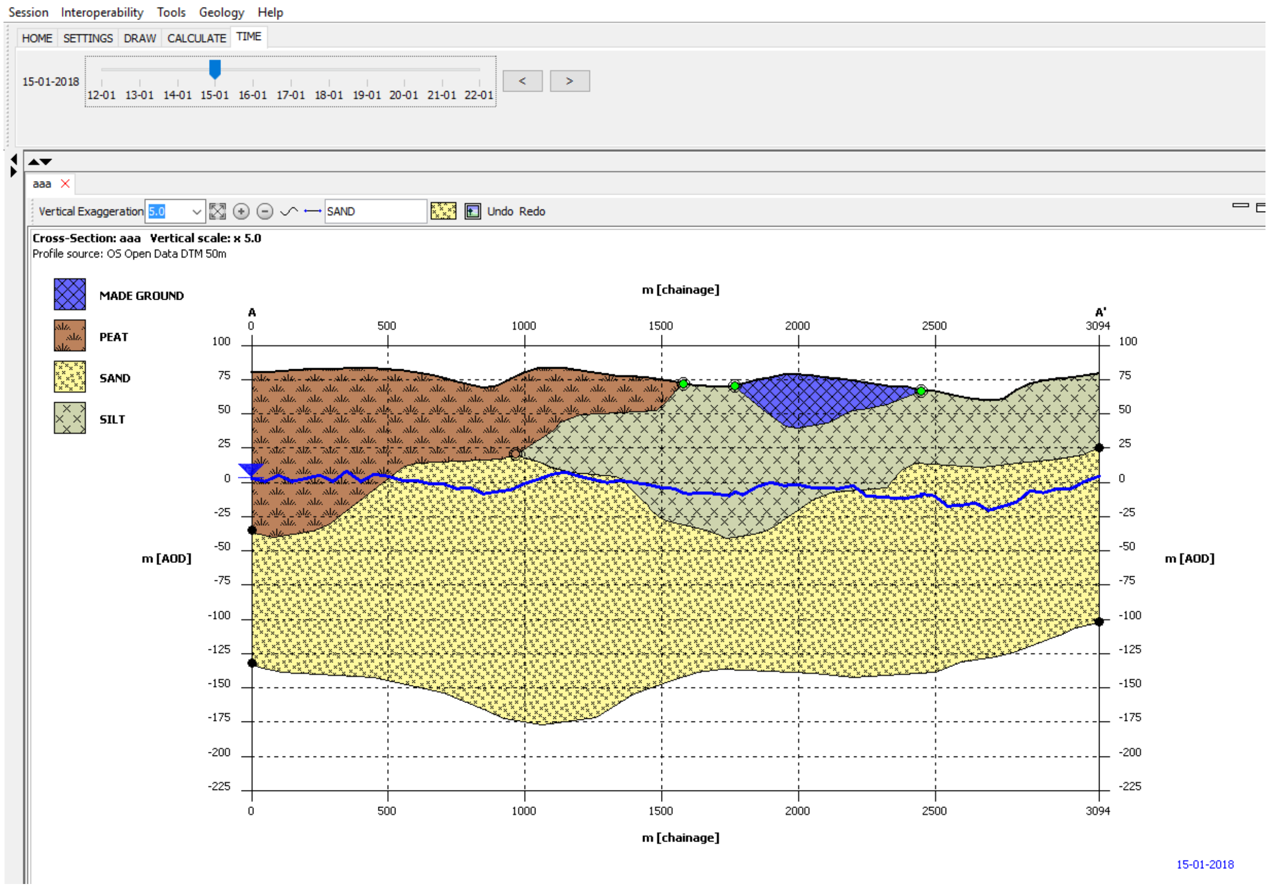

Figure 2. Current development of Groundhog Desktop includes time series visualization of, for example, groundwater levels.

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Kessler, H., G. McArdle, H. Burke, and D. Entwisle, 2017, Applications of digital ground models to support the maintenance and upgrading of rail infrastructure [speech], *in* Ground related risk to transportation infrastructure, London, UK, October 26–27, http://nora.nerc.ac.uk/id/eprint/517492/.

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PRB 3D GEOLOGICAL MAP MODELING TECHNOLOGY

Li Chaoling[1], Li Fengdang[1], Guo Jiateng[2], Liu Chang[1], Liu Yuanyuan[1], and Chen Feixiang[3]

[1]Development & Research Center of China Geological Survey, Beijing 10037,China, [2]College of Resources and Civil Engineering, Northeastern University, Shengyang,110819, China, [3]Beijing Forestry University, 100083

[1]lichaoling@126.com, [2]guojiateng@mail.neu.edu.cn, [3]frognose@163.com

Introduction

This paper presents the dual PRB 3D modeling technology of geological mapping. PRB (geological Point, geological Route, and geological Boundary) results in the dynamic and rapid modeling of geological maps from 2D to 3D during geological mapping. The PRB 3D modeling technology framework is shown on a regional geological map in Figure 1. It is mainly composed of the digital mapping technology and a database, the knowledge description framework for geological object modeling, and a modeling algorithm.

PRB is a field data acquisition model used in geological mapping. When the mapping precision of a geological route within the work area reaches the requirements, a planar geological map can be dynamically modeled and formed according to the geological route (PRB) information (surface). On this basis, if every route forms a detailed route profile, then under the double constraints of a plane geological map and route profile, we can dynamically and rapidly

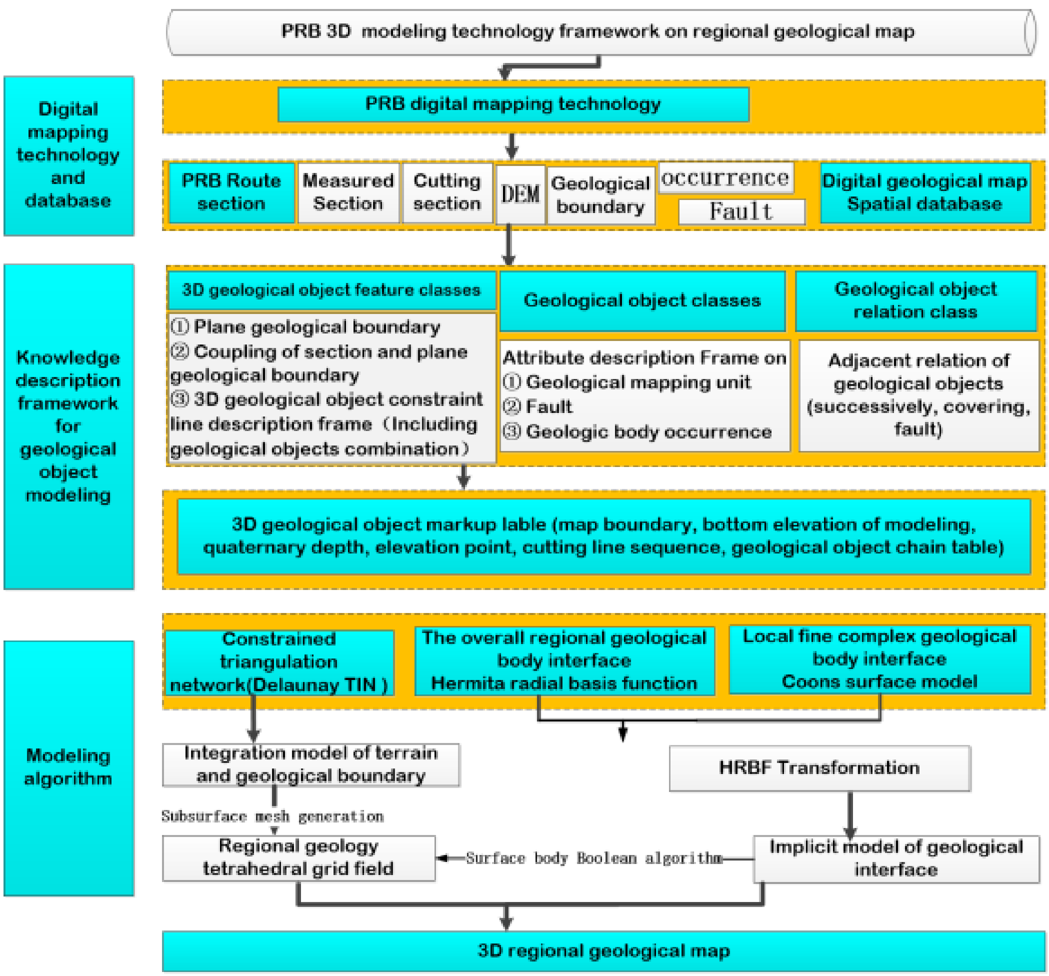

Figure 1. PRB 3D modeling technology for a regional geological map.

conduct 3D geological map modeling based on the geological map knowledge description framework and related algorithm. This method is called a geological route (PRB) dual dynamic 3D modeling technology. The following are described in accordance with the main contents of the technical framework.

PRB digital mapping technology and PRB data mode

PRB data mode and formation of plane geologic map

The geological point, geological observation route, and geological boundary are three key factors of the geological route. Figure 2 is a spatial specific representation of the PRB process. The PRB data model consists of eight entities: geological points, geological segmentation routes, geological boundaries, drawings, photographs, samples, fossils, and GPS locations.

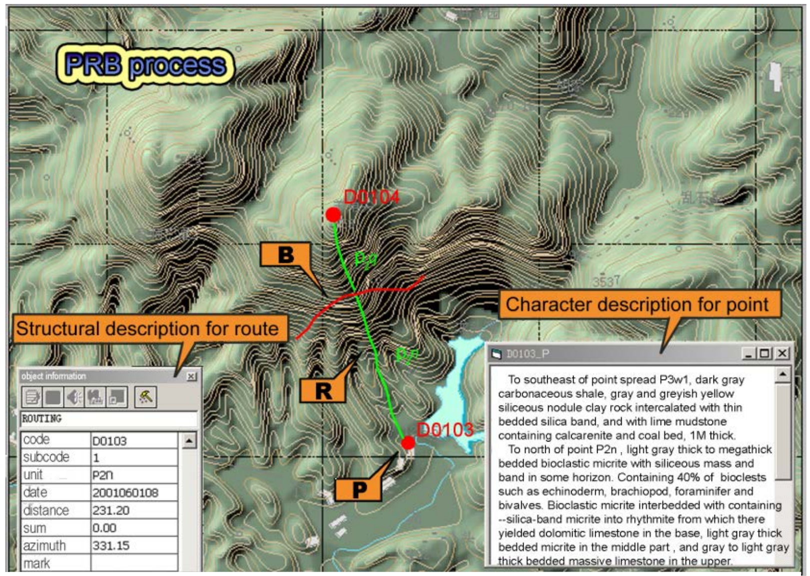

Figure 2. Concrete expression of the PRB process.

The data model can satisfy data acquisition from 1:1,000 to 1:250,000 scale geological mapping through the description framework and rule of the PRB syntax structure and mode. The PRB syntax structure and mode use the expression description: semantic granularity = geological mapping framework rules (syntax) + description precision content (semantics). The digital field geological survey PRB syntax structure is used mainly to build a digital model of the geological route observation and recording process. The PRB structured and unstructured description framework meets the degree of detail of data acquisition for different scales of geological mapping data collection. The spatial data structure of PRB meets the requirements of data acquisition of differently scaled geological mapping in geological location information and structured common attributes.

In the three core elements, and through the definition of the PRB data model, the basic process of PRB and PRB combination rules in the basic process, and the public mechanism of the PRB process, it can solve problems of semantics and can also describe the granularity associated with mapping precision. The whole process consistency and inheritance of the PRB data model also provides the computing conditions, and therefore can quickly form a plane geological map (Figure 3).

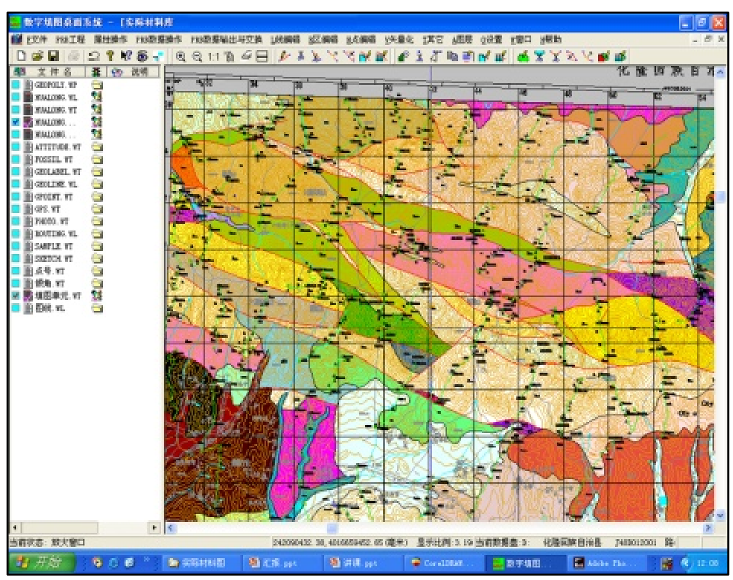
Figure 3. Geological map based on PRB technology.

Construction of a downward geological interface

The geological downward interface is constructed by double constraints of the section and plane geological map, and a 3D geological body model can be established accurately.

Based on comprehensive geological research, geological personnel can be more deeply aware of the shape of a surface geologic unit that extends to the subsurface, as well as the relationship between other geological bodies with a certain accuracy, and can edit the flat PRB data into the PRB profile data (Figure 4). The PRB geological section data are the basis of the vertical modeling accuracy of the 3D geological map.

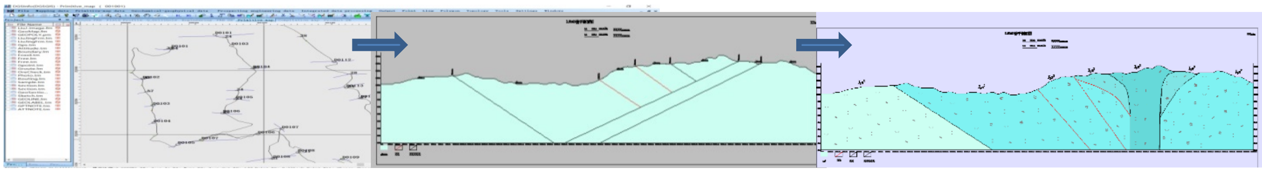

Figure 4. Left: The plane PRB route data. Middle: Automatically forms the PRB section by software. Right: The geological PRB section processed by geological personnel.

With the support of no depth information, a 3D geological map can be formed according to the geological map and the attitude information. We usually call this weak constraint 3D geological map modeling. According to the results of comprehensive geological survey research, if geological personnel turn each PRB geological route data into PRB profile data in the geological map, a 3D geological map with certain precision control can be formed according to the data of the PRB section, plane geological map, attitude occurrence information, and the geological knowledge established for the geological map. This is usually called strong constraint geological modeling. The core technology of strong constraint modeling is the PRB model + geological map knowledge description framework + implicit geological interface coupling modeling technology.

Knowledge description framework based on geological object modeling

For geological mapping, geological surveying by digital technology has formed a comprehensive field resulting in all kinds of databases, including the PRB geological route (including geological, geological boundary, occurrence) and freehand cross sections, surveyed geological cross sections, a DEM, and geological map and geological map spatial databases. To form a three-dimensional geological map accurately, efficiently, and intelligently, it is necessary to organize these data according to a certain agreement. In this paper, we propose a knowledge description framework based on geological object modeling in order to build data sets that can satisfy all types of 3D modeling algorithms. The knowledge description framework based on geological object modeling consists of two parts, as follows.

3D geological object description framework

1. 3D geological object feature classes: A combination of two-dimensional geometric data, such as a plane geological map, geological route, geological route section, and measured section, is used to describe the 3D geometric data set of geological spatial entities one by one. It is composed of three parts: (1) plane geological boundary, (2) coupling of section and plane geological boundary, and (3) a 3D geological object constraint line description frame that includes a simple geological object and a combination of geological objects, such as a monoclinic stratum, syncline, anticline, volcano, and dome, etc. Figure 5 is the line frame model expression of a 3D geological object feature element (red line, plane and profile geological boundary combination) in a 3D scene.

2. Geological object class: This expresses geospatial entity data sets with attribute characteristics, such as the geological mapping unit, fault and geologic body occurrence, etc.

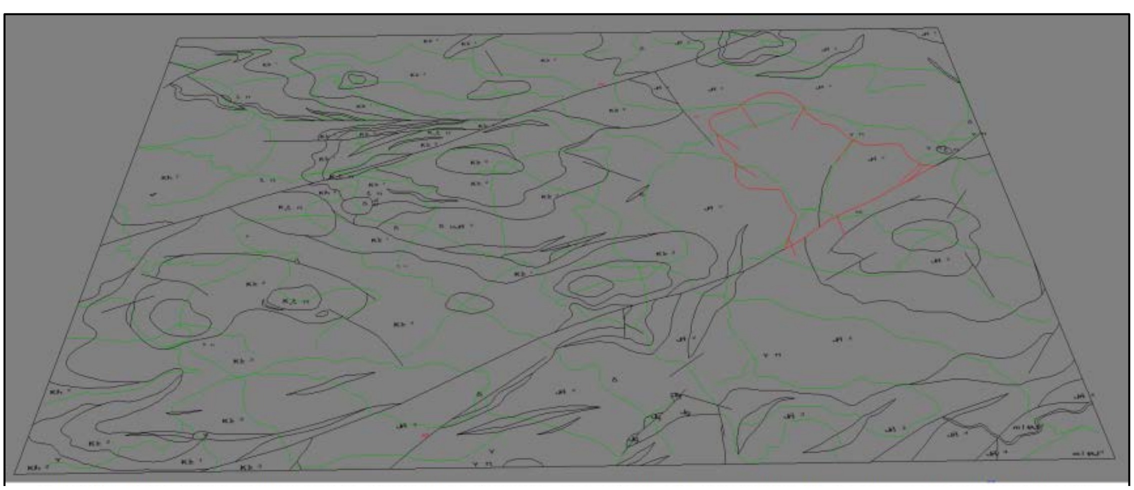

Figure 5. Line frame model expression of a 3D geological object feature element (red line, plane and profile geological boundary combination) in a 3D scene.

3. Geological object relationship classes: This describes the topological relationship of 3D geological data sets based on the description rule of geological contact relation, for example, successively, covering, fault, syncline, anticline, and so on, and it connects the data set of geological object classes with the 3D geological feature classes.

In the construction of 3D geological bodies, the sequence of geological body modeling should be given in accordance with the new and old sequence of faults and geological bodies and by spatial analysis and calculation.

Markup description rules of the 3D geological object as a whole

There is a specific description of the overall modeling parameters, the data entities of each geological object, and the topological relations. There is also an interface for data exchange. By using 3D geological body description rules, we can effectively describe the geological constraint interfaces and adjacency relations in the modeling area and facilitate modeling of all kinds of modeling algorithms. The rules for the description of the 3D geological body marks as a whole are as follows:

```
struct Mdl_3DGeoMap

{ // Input data

std::vector <Mdl_Point> MapRangePointList;// Modeling regional boundary point

std::vector <Mdl_Point> DEMPointList;// DEM altimetric point

std::vector < Mdl_CutLine > cutLineList;// Sequence of cutting lines or the order of modeling

std::vector < Mdl_Region > regionList;// the line frame model of 3D geological object feature classes chain list.

// input parameter

int numModelDemPoint;           //// The number of DEM points for modeling

double modelAltitude; //// Modeling bottom elevation

 double gridLen;       ////The distance of the parabolic point on the modeling of the bottom of the Quaternary
                       System

double q4depth; //// Quaternary depth

// output data

std::deque < Mdl_Body > bodyList;// The geological body

std::vector <Mdl_CutSection> cutSectionList;       //// cutting plane

};
```

PRB+ implicit geological interface coupling modeling technology and modeling algorithm

In brief, the modeling technique is to extend the surface triangulation to three prisms at a certain depth and to decompose the three prisms into tetrahedra, forming a grid field. The geological surface consisting of plane and section geological boundaries and production forms then cuts the grid field one by one, involving tetrahedral re-segmentation, defining the attributes and forming geological body units. Among them the key technologies are:

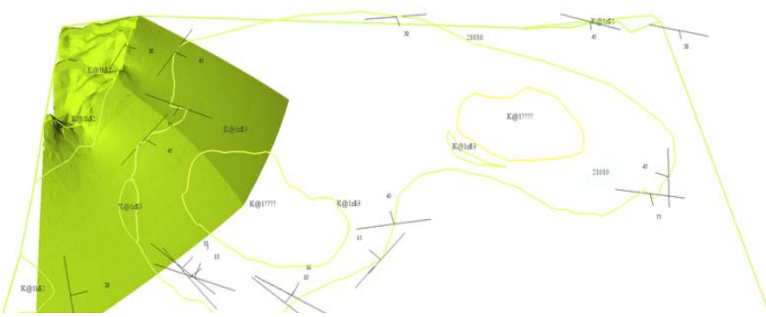

Figure 6. A 3D geological body established by the Hermite radial basis function method.

Coupling modeling technique of implicit geological interface based on grid field

The *Hermite radial basis function modeling method* (Figure 6) is used for modeling the overall regional geological boundary surface. The radial basis function implicit surface is the function surface, which takes the Euclidean distance from one point to the sampling points as independent variable structures. The radial basis function interpolation was taken full advantage of to construct the geological models based on the field effects of the geological boundary and the formation of the attitude location.

Using the PRB geological route profile and geological plan map as constraints of the geological surfaces, we solve the geological surface by a Hermite implicit function, and then the geological body unit is formed by attribute recognition.

The Coons surface model (Figure 7) is used for complex geological body interface modeling. Complex geological bodies mainly refer to the volcanic mechanism, salt mound structures, etc. For example, the volcano mechanism can reconstruct its surface through the Coons surface under constraints of the plane boundary and the section boundary and turn it into an implicit function model.

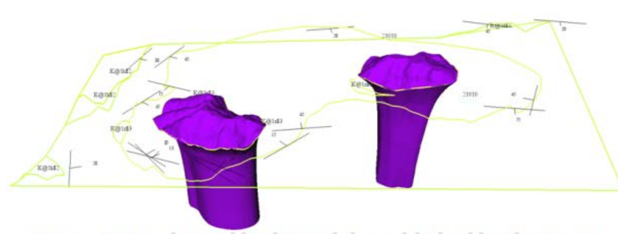

Figure 7. A 3D geological model established by the Coons surface method.

Fusion technology of the Hermite radial basis function and global modeling of the Coons surface model is shown in Figure 8. After the formation of a local complex structure model based on the Coons surface method, discrete point resampling on its surface is performed. These sampling points can be used as parameters to set up a linear equation set. By solving the undetermined coefficient of the surface equation of the Hermite radial basis function, a local complex structure model based on the Coons surface is converted to the same expression as the Hermite radial basis function. Finally, fusion modeling of the Hermite radial basis function and global modeling of the Coons surface model are realized. Figure 8 is a 3D geological body model established by this method.

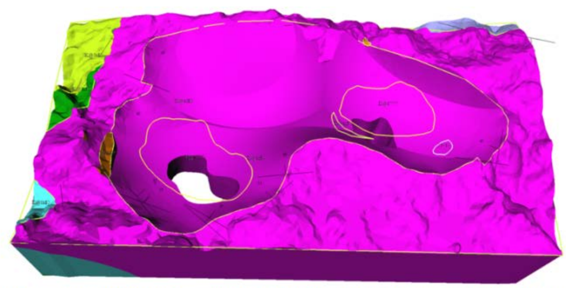

Figure 8. 3D geological bodies model established by the Fusion technology of the Hermite radial basis function and global modeling of the Coons surface model.

The main processes and steps of modeling

1. According to the set of cutting sequences, the general geological interface is directly reconstructed based on the radial basis function. As for the complex interfaces, the implicit 3D representation of geological interfaces is constructed by means of implicit 3D reconstruction of geological interfaces with the Coons surface and mesh implicit method.

2. Construction of a regional tetrahedron grid set: According to the elevation points, an unconstrained surface Delaunay triangulation network is constructed. The triangle is then extended downward to get a series of three prisms and the tetrahedron set is constructed by splitting the prism set.

3. Segmentation of the grid set by implicit geological interface: According to the order from new to old, all implicit geological interface models and the grid set model generated by the second step are used for cutting operations. The grid set model corresponding to each geological body model is then obtained.

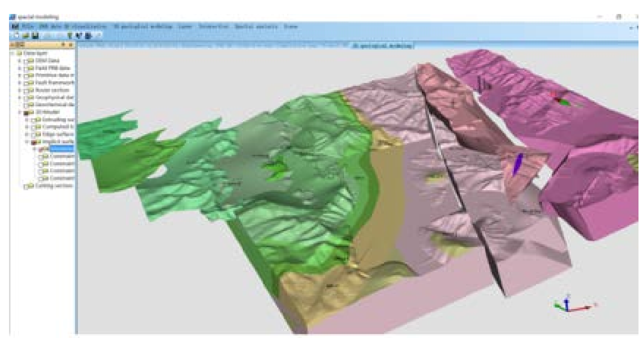

Figure 9. 3D geological map formed by the coupling modeling technique of implicit geological interface based on the grid field.

4. Boundary model extraction based on the grid model: From the grid set corresponding to each geological model, the tetrahedral boundary triangles located on the border are extracted, which form the boundary triangle model of the geological model. Figure 9 is a 3D geologic map formed by the coupling modeling technique of an implicit geological interface based on the grid field.

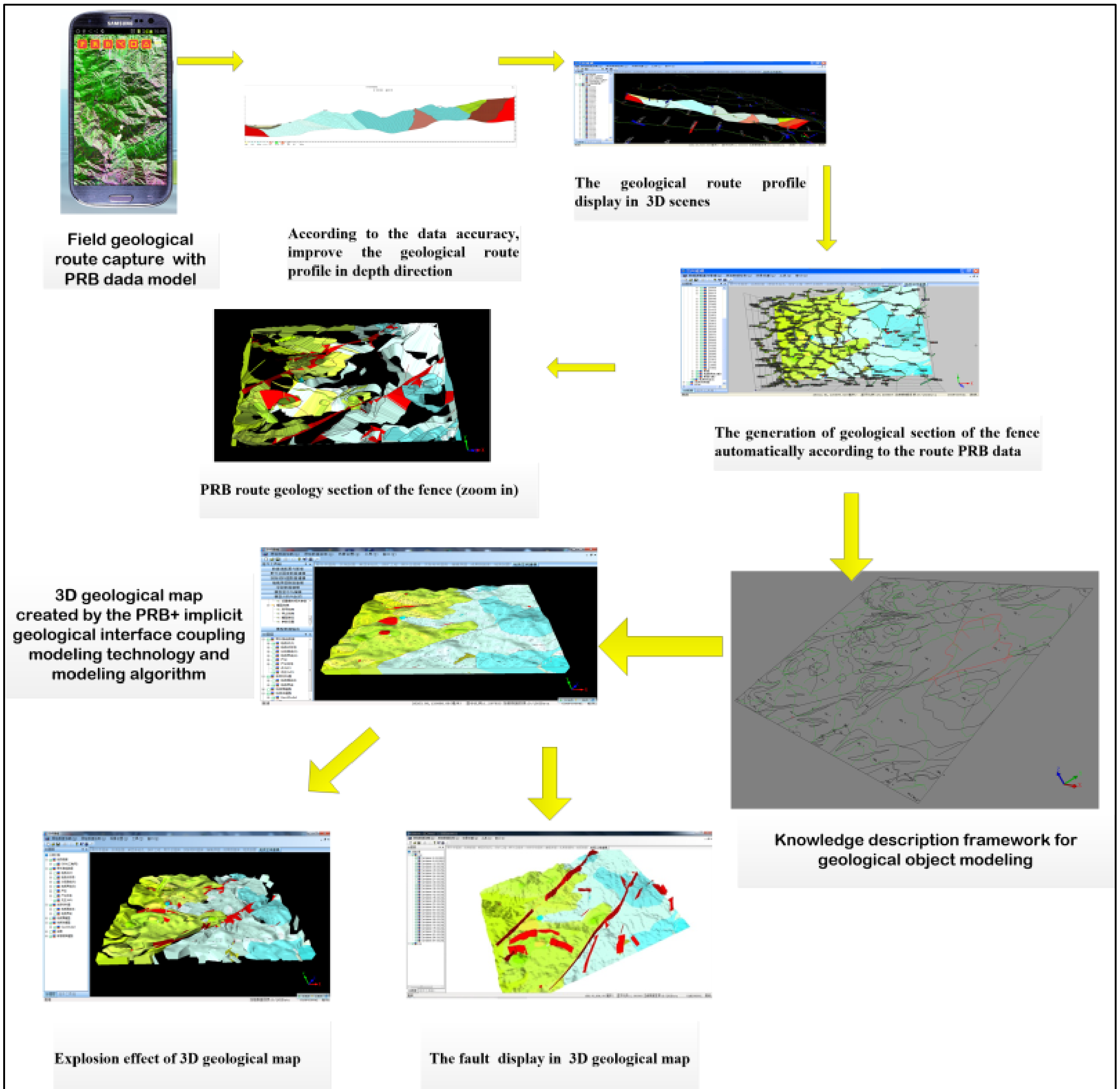

Figure 10. Modeling process of the PRB geological map.

Conclusion

Based on the demonstration application of several geological mapping projects in China, the PRB technique has obvious advantages: (1) The efficiency and accuracy of modeling are greatly improved. The modeling process of the PRB 3D geological is shown in Figure 10. The intelligence of modeling is high and the operation is simple. (2) Good consistency of geological body topology is maintained. (3) Data for 3D modeling is easy to obtain. (4) The 3D geological model can be reconstructed in real time with a change of geological route and geological map by using the technology of the knowledge description framework based on geological object modeling.

Reference

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STORING AND DELIVERING NUMERICAL GEOLOGICAL MODELS ON DEMAND FOR EARTH SCIENCES APPLICATION

Christelle Loiselet, Christian Bellier, Simon Lopez, Gabriel Courrioux, Jonathan Durand, and François Robida

BRGM, Bureau de Recherches Géologiques et Minières, Orléans France

c.loiselet@brgm.fr

Introduction of the problem

The BRGM (French geological survey) is a reference public institution for earth science applications. It manages and delivers geoscience data to help in decision making for spatial planning, mineral prospecting, groundwater prospecting and protection, pollution control, natural risk prevention, and the characterization of local areas. Some of these data are produced from 3D geological modelling, which is now a classical tool to better constrain geometries of complex geological systems and provide a continuous description of the subsurface from sparse and indirect data.

Moreover, accurate geological models are increasingly needed as inputs to (multi)physics dynamic simulations in a wide range of applications: flow simulations, seismic wave propagation, and subsurface resource exploration and exploitation. Since the early days of numerical geology, many methods and several commercial solutions have been developed to build such geometrical models of geological systems. For example, the BRGM develops and uses two geomodelling tools that rely on two different methods: *GDM Multilayer* (Bourgine et al. 2008) (http://www.gdm.brgm.eu) and *3DGeoModeller* (http://www.geomodeller.com). On the one hand, *GDM Multilayer* is based on an explicit description of geological surfaces with vertical faults. It can handle a large amount of well data and is well suited to model "basin type geology." On the other hand, *3D GeoModeller* is one of the first geomodelling software to use orientation data in implicit surfaces to describe subsurface geology in complex structural systems (Lajaunie et al. 1997; Calcagno et al. 2008). Yet there is no clearly identified unified open and shared format that describes what a "numerical geological model" should be.

Methods and results

Geological models need to be discretized to enter the production workflow. 3D meshes enriched with topological and geological information are built from lower dimensional objects—points, contact lines, surfaces—with their respective connections and geological regions. A possible option to generate these meshes is to use this additional solid modelling information as a starting point and provide both the mesh and the model (e.g., Pellerin et al. 2015). Here, we propose a new approach that consists of distinguishing the storage of the model from the representation of the model: models are stored using the native format of the tool that is used to generate it (software project files). This choice guarantees that there is neither loss of data nor loss of precision. This strategy requires that each tool must implement a common interface using only two predicates related to (1) the geological domain within which any point may reside, and (2) the geological contact (horizon or fault) that an arbitrary ray might intersect. Hence, answering only these two questions automatically allows for retrieval of all the topological information from the model and model representations to be generated on demand (logs, profiles, 3D gridding, etc.; Figure 1). Most of the interface has been designed independently from the geomodelling software. This requires that geomodelling tools implement only the two aforementioned predicates. This abstract interface relies on the implicit domain description used in the CGAL library (http://www.cgal.org).

Our approach implements an associated informatics architecture using an interoperable concept, allowing it to reference, store geo models, and access and deliver related information. We define metadata to describe 3D geological models and their representations. A standard profile is implemented to (i) allow a web application to edit and to manage data and (ii) ensure interoperability in the delivery. 3D geomodel metadata are indexed by a search engine and displayed in a geoscientific portal such as InfoTerre (http://infoterre.brgm.fr/viewer). This work is linked to international initiatives (such as (i) OGC (http://www.opengeospatial.org/)—Geoscience DWG; IUGS/CGI (http://www.cgi-iugs.org/) for standards, and (ii) OneGeology (http://www.onegeology.org/) and EPOS (https://www.epos-ip.org/) projects to test implementation) to define an interoperable model and to ensure common metadata for geological models. We also implement OGC standard web services to get different model representations delivered in GeoSciML format and, at the same time, that allow us to call the querying model interface that is based on common model representation components.

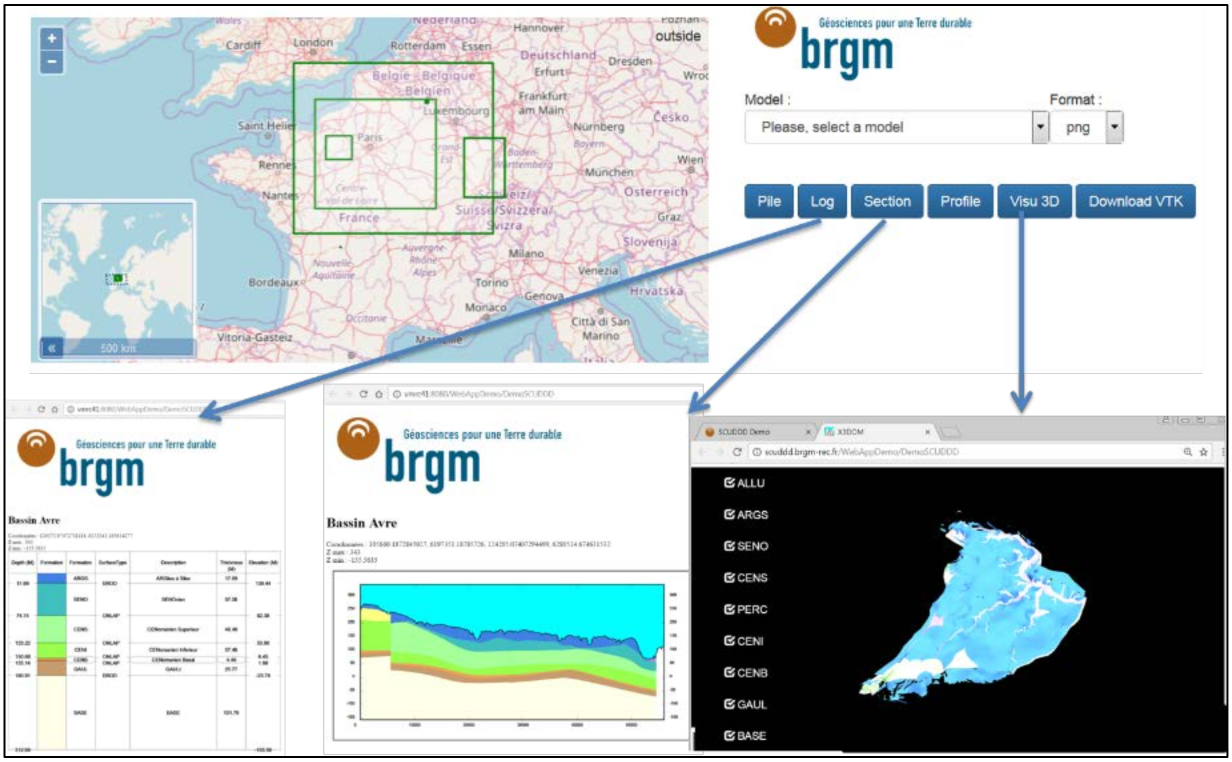

Figure 1. Representation of the Avre Basin geological model (Pennequin et al. 2017) in the web application using the generic interface and available services: knowledge geological architecture (geological pile), log, section/profile, and 3D visualization.

Conclusion and perspectives

The scheme proposed in this paper allows for providing geological information everywhere in the underground and not using geological data interoperability, but as an interoperable programming interface if and only if the geomodelling tools implement it. In perspective, we plan to develop in the same way an interoperable programming interface to query dynamic models and infrastructure models in order to deliver related information.

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DEVELOPING A 3D GEOLOGICAL FRAMEWORK PROGRAM AT THE ALBERTA GEOLOGICAL SURVEY; OPTIMIZING THE INTEGRATION OF GEOLOGISTS, GEOMODELLERS, AND GEOSTATISTICIANS TO BUILD MULTI-DISCIPLINARY, MULTI-SCALAR, GEOSTATISTICAL 3D GEOLOGICAL MODELS OF ALBERTA

Kelsey E. MacCormack

Alberta Geological Survey, Alberta Energy Regulator, 4999 98 Avenue, Edmonton Alberta, Canada

kelsey.maccormack@aer.ca

Introduction

The 3D geological modelling program at the Alberta Geological Survey (AGS) was initiated approximately 8 years ago and is called the 3D Geological Framework program. The path to building support to grow our 3D Geological Framework program was not easy and has required many discussions, presentations, and meetings to communicate the benefit of building 3D geological models to support science-based decision making, to better understand the geospatial relationship between surface and subsurface geology, and to provide a consistent and reliable geospatial context to enable a holistic understanding of the integrated nature of Alberta's diverse resources.

The AGS is responsible for describing the geology and resources in the province and provides information and knowledge to help resolve land-use, environmental, public health, and safety issues related to geosciences. Our vision is to be the internationally recognized source for credible, innovative, and integrated geoscience data, information, and knowledge for Alberta. The 3D Geological Framework has significantly improved our ability to effectively integrate and evaluate any type of geospatial data to provide science-based decisions in support of land-use planning, environmental sustainability, economic diversification, and public safety (Figure 1). The success of our 3D Geological Framework program is contingent on properly documented and transparent processes to generate reproducible and scientifically credible predictions, and to ensure that users are properly informed as to model limitations and uncertainties.

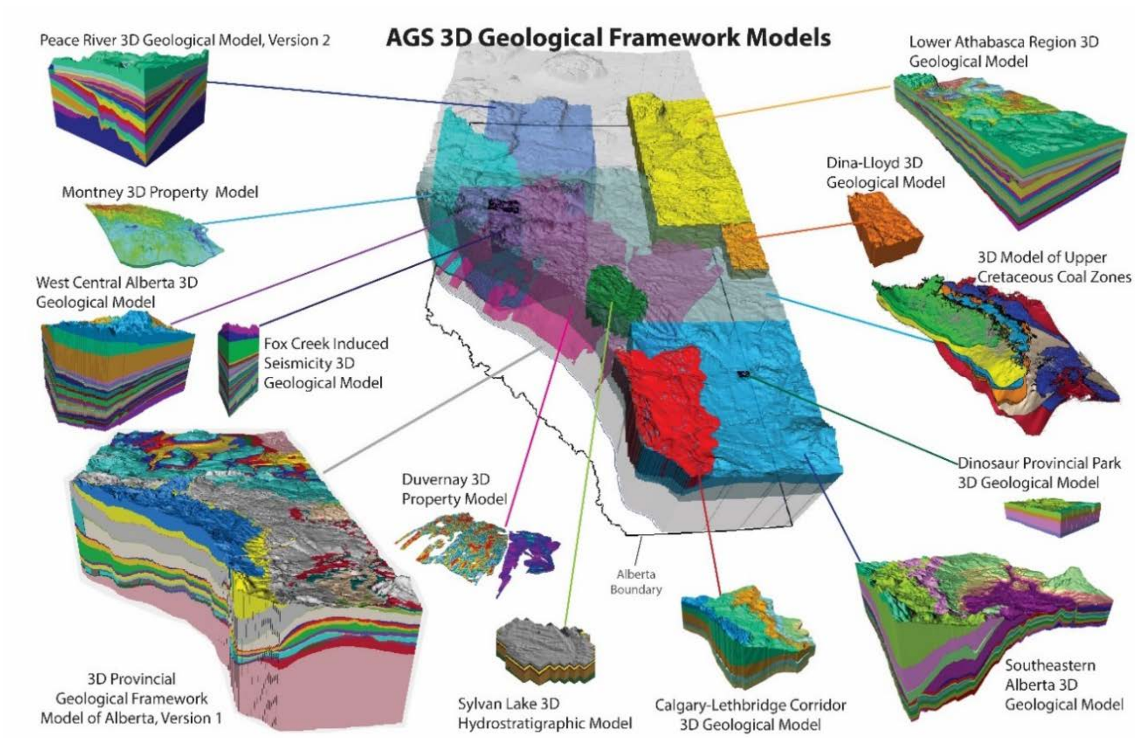

Figure 1. Collection of provincial and submodel-scale 3D models that form the Alberta Geological Survey's 3D Geological Framework.

Alberta Geological Survey's 3D Geological Modelling Program timeline

2010

The concept of building a 3D geological model for Alberta was initiated in 2010; however, construction of the 3D Geological Framework did not begin until 2011. The AGS declared that their goal was to create a 3D geological model of Alberta by the year 2020. Although many considered this to be an overly ambitious goal, a pilot study was initiated and resourced with a 0.5 FTE, which resulted in the creation of 8 independent 2.5D provincial-scale grids.

2012

In 2012, a geomodeller was hired to work full time (1.0 FTE) on the 3D Geological Framework, to determine the best approach for optimizing the available geological data. By 2013 the AGS had 35, 2.5D geostatistically modelled surfaces, of which 19 were used to test a variety of methods and approaches for building a consistent, reliable, and reproducible 3D geological model (Figure 2A).

2013

In early 2013, we were able to produce our first 3D provincial-scale model, referred to as the Provincial Geological Framework model version 0 (because it was never published), although it has been presented at numerous conferences and shown to regulatory and government officials to illustrate the vision for our 3D modelling program (Figure 2B). In late 2013, a deliberate decision was made to divert resources from our provincial-scale modelling efforts to focus on developing 3D geological models in smaller regions of the province to provide science-based evidence to support specific investigations for our parent organization, the Alberta Energy Regulator (AER). Two examples of submodels that were developed include an 83,334 km^2 model composed of 44 layers in the Lower Athabasca Regional area, and a 23-layer model covering 74,471 km^2 of the Peace River area to better understand the relationship between the production of heavy oil from certain geological units and the occurrence of hydrocarbon-related odors and emissions (Figure 1).

The development of these submodels was critical to demonstrating the usefulness of 3D geological models to support decision makers by providing science-based, tangible evidence that was easy to communicate and share with both subject matter experts and stakeholders with minimal background knowledge. The decision to focus on submodels that were used to support specific investigations was essential to gaining the support to acquire additional resources to allow the budding 3D Geological Framework program to continue growing.

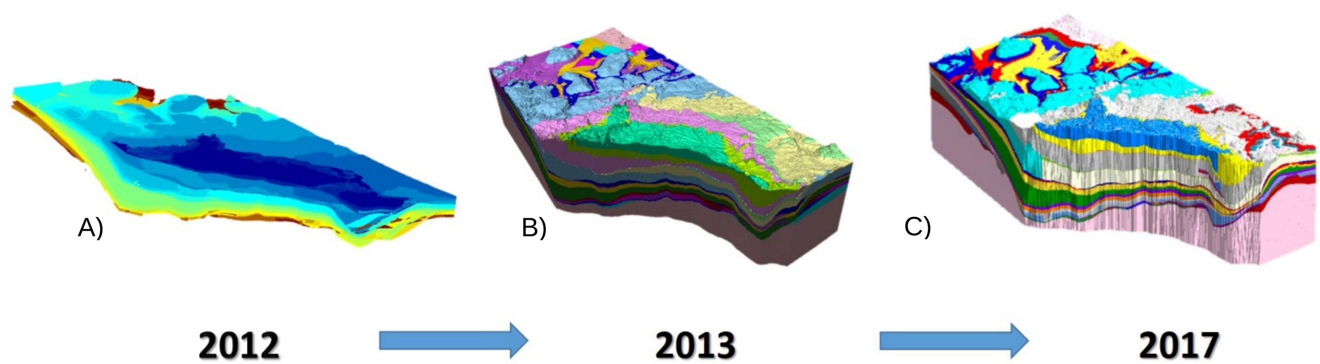

Figure 2. Development of the AGS Provincial Geological Framework model. A) In 2012, 35 2.5D provincial-scale grids were modelled, of which B) 19 geological units were modelled to create the first 3D provincial-scale geological model (version 0) in 2013. C) Provincial Geological Framework, version 1 was completed in 2017 and published online in 2018.

2014

In 2014, we received approval to hire a geomodeller and a geostatistician to support the growing demand for 3D geomodels to support projects within the AGS and the AER. During this time, the AGS 1) completed additional submodels to support an investigation into the geospatial relationship between induced seismicity and subsurface geological features, and 2) constructed a large 88,768 km^2 model in southeastern Alberta to better understand the geospatial relationship of regional groundwater and hydrocarbon resources (Figure 1).

2016

In 2016, the AGS underwent a restructuring to create a new Geological Modelling Team to house our geomodellers, geostatisticians, and petrophysicists to improve the coordination and efficiency of geomodelling efforts. The Geological Modelling Team sits within the Mapping and Modelling Group, which also contains two teams focused on geology: 1) the shallow geology of the human-interface surface (Surficial Mapping Team), and 2) the underlying Quaternary-Precambrian geological units (Subsurface Geology Team). The quality of our 3D geological models has significantly improved with the increased collaboration and communication among our geologists, geomodellers, and geostatisticians. It is important that the geologists are able to communicate to the geomodellers their knowledge and conceptual understanding of the geology for incorporation into the model construction process. Our approach to creating geological models has been specifically designed to optimize modelling efforts by promoting collaboration amoungst our geoscientists. This collaboration is especially important in large regional-scale modelling efforts, including unconventional resource exploration and development.

2018

As of 2018, 13 models have been completed as part of the 3D Geological Framework program and include both provincial-scale (602,825 km^2) and local-scale (47,471 km^2) models (Figure 1). These models have been constructed at a grid cell resolution of 500 m or less, and in the case of the Provincial Geological Framework (version 1) model, have been interpolated using more than 620,812 data points. Version 1 of the Provinvial Geological Framework, which was completed in 2017, contained 32 geological units (Figure 2C). However, some of the local-scale models, such as the West Central Alberta Model, have been built to characterize the form and geometry of as many as 54 geologic units (Figure 1). The Geological Modelling Team will be working on publishing the remaining submodels and version 2 of the Provincial Geological Framework as free downloads on our website (www.ags.aer.ca/3d-geological-framework).

Enhancing the application of our 3D models

To enhance the application of our 3D models to support investigations by the AGS and AER, we have begun integrating geospatial information (roads, pipelines, ecologically sensitive areas, etc.), resource information (such as groundwater, minerals, hydrocarbon, etc.), as well as parameterizing zones within our 3D models, with rock property data (porosity, permeability, TOC, etc.), to better assess the geospatial relationships of anthropogenic development and Alberta's natural resources. We have also enhanced our models by calculating uncertainty for every geological formation within our 3D models. This was done to ensure that users are aware of the uncertainty within the model so that they can make informed decisions considering the accuracy of the model and their level of risk tolerance. The uncertainty results can also be used to guide our modelling program by identifying areas of our models where uncertainty is high so that we can direct our geologists to look for additional data and information to refine the models.

Our models are intended to be “evergreen,” so it is important that we have the ability to update them easily and efficiently. Therefore, we have developed workflows for each of our models to reduce the chance of errors, and significantly decrease the time required to rebuild each model when new data become available. For some models, this has reduced the rebuild time from approximately 2 days to 2 hours.

Sharing and communicating our 3D models with stakeholders

A key component of our 3D Geological Framework program is to ensure that we are able to get our models into the hands of our stakeholders in formats that our stakeholders can use. We work with several teams within the AGS and AER to build consistent and reliable 3D geological models that allow for the effective integration and evaluation of any type of geospatial data to support science-based decision making in support of land-use planning, environmental sustainability, economic diversification, and public safety. We also ensure that our 3D geological models are available to users in a deconstructed format (points, extents, grids) in downloadable ASCII and shapefile format so they can be imported into another 3D viewer software. We have also provided our stakeholders with access to a free open-source 3D viewer software (iMOD, developed by Deltares) to ensure that everyone is able to interactively explore our 3D models even if they do not have access to the software. A link to download iMOD is available on our website (www.ags.aer.ca), as well as instructions for loading the models into the software. iMOD allows users to interact and explore our models by turning layers on and off, creating custom cross sections, and importing their own data into our models.

We have also leveraged the work done to create our robust geostatistical 3D geological models to develop simplified versions suitable for 3D printing and for developing Minecraft models. The 3D prints allow users to interact with our models in a tactile and tangible format, which they can physically take apart and rebuild. We also developed a methodology to transfer our geostatistical models into Minecraft format so that users of all ages can interactively explore Minecraft worlds containing actual geological units present within regions of Alberta. The Minecraft models have been very popular with our stakeholders, as evidenced by the number of views and downloads they have received on our website and the feedback we have received at local conferences and exhibitions. Even more exciting is the recent development of exhibits showcasing this work at the Telus Science Center and Dinosaur Provincial Park (a UNESCO World Heritage Site).

Future of the AGS 3D Geological Framework Program

Our 3D Geological Framework Program has come a long way in the past 6–8 years; however, (in my opinion) it is still within its infancy stage. There is still so much that can be done to continue to develop and integrate new information into the 3D Geological Framework. This is just the tip of the iceberg!! Below are a few items that we are working on developing within our 3D Geological Framework program:

The AGS released version 1 of the Provincial Geological Framework on May 4, 2018, and is in the process of publishing the remaining submodels as free downloads on our website (www.ags.aer.ca/3d-geological-framework). We are encouraging our stakeholders to check the website frequently as we release new models as well as updated versions of our currently available models.

We are connecting our detailed geological descriptions of the subsurface units with our 3D models (providing the geospatial form and geometry), and the Alberta Table of Formations (provides information on the geochronological deposition of the geological units). Thus, we are providing a modernized update to the popular Western Canadian Sedimentary Basin Atlas.

We are reaching out to our neighboring provinces, territories, and states to discuss the opportunity to collaborate on developing continuous geological models between neighboring jurisdictions.

We are working with international geological survey organizations looking to develop or enhance 3D geological modelling programs. These exchanges have often resulted in mutually beneficial development of each other's programs.

We are developing virtual-reality (VR) and augmented-reality (AR) applications to create new ways for people to engage with our geological modelling products. Our first VR proof-of-concept was a guided tour of the Peace River Minecraft model (www.age.aer.ca/geology-alberta-minecraft-edition), which has been very well received. We are planning to develop other VR and AR products to enhance the way that we share and communicate geoscience information about the province to our stakeholders.

The objective of our 3D Geological Framework program is to efficiently and effectively communicate consistent and reliable 3D surface and subsurface geosicence information to support science-based decision making to better understand the geospatial relationship between surface and subsurface geology, and to provide a consistent and reliable geospatial context to enable a holistic understanding of the integrated nature of Alberta's diverse resources. This presentation will focus on how AGS developed a 3D Geological Framework program to engage with stakeholders, government, and the public by facilitating transparent communication of complex geological and environmental issues using tangible graphics and visualizations, which are easy to understand and are based on scientific evidence.

NEW OPPORTUNITIES AND CHALLENGES IN 3-D GEOLOGICAL MAPPING IN POLAND

Zbigniew Małolepszy and Ewa Szynkaruk

Polish Geological Institute–National Research Institute, Poland

zmal@pgi.gov.pl, eszy@pgi.gov.pl

Introduction

Recent advances in 3-D map presentation over the web has resulted in a surge of interest from stakeholders and professionals seeking to employ the 3-D products that the Polish Geological Institute is offering as a state geological survey. This surge results in both opportunities and challenges. Very specific opportunities arise when more and more of our own colleagues and also professionals in a wider community are willing to make their products 3-D friendly in order to, in turn, take advantage of the possibilities that the third dimension offers for their own work. The challenges (that can also be turned into opportunities) arise from increased pressure to make our 3-D maps more suitable to sometimes conflicting needs and communicate them properly in a way that encourages reuse and accounts for both their strengths and limitations—uncertainties in particular. Below, we propose to have a closer look at these factors, with particular emphasis on how they play out in our everyday mapping practice at the Geological Survey of Poland (Figure 1).

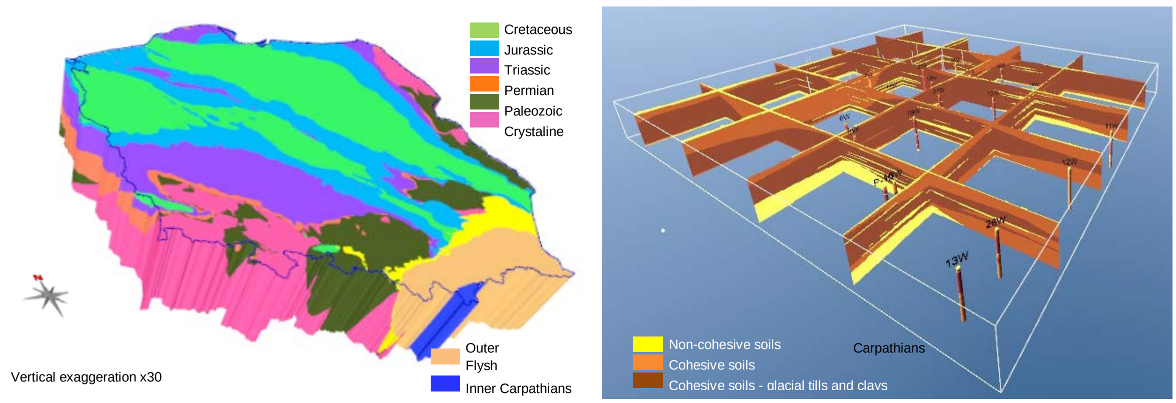

Figure 1. Multi-scale 3D geological mapping in Poland from country (A) to landfill scale (B) (Piotrowska et al. 2005; Ryżyński et al. 2016).

Country-scale geological framework model

After more than a decade of producing project-specific (and project-limited) 3-D models, we and the wider community are arriving at the conclusion that we need an accurate framework geology of Poland that will hold our existing and yet-to-be models together and provide a suite of country-wide geological information in itself. It is supposed to help our work in numerous ways, not the least in terms of access to digital 3-D geological data. It has also—and this seems to be the crucial point—brought on board colleagues from various departments and disciplines, both within and outside our organization, who noticed the need—and the benefits—of going 3-D. With this new project, we now have unprecedented support offered by simultaneous or preceding projects that collect, harmonize, and make available digital 3D data related to mineral resources, rock properties, formation temperature, hydrogeological data, etc. Furthermore, new 2-D geological mapping projects will now also directly supply modeling-ready data (Figure 2). And there is still more as our neighbors—Germany for a start—are interested in mutual cross-border adjustments and harmonization of our 3-D maps. All those manifest synergies are a powerful driver for a much more widespread application of 3-D methodologies and a rapid growth in 3-D model building, delivery, and use. Thus, the 3-D framework geology of Poland promises to be much more accurate, be more usable, and have a considerably wider and stronger impact than would be imaginable just a couple of years ago. Nonetheless, this also creates challenges that are not a small feat.

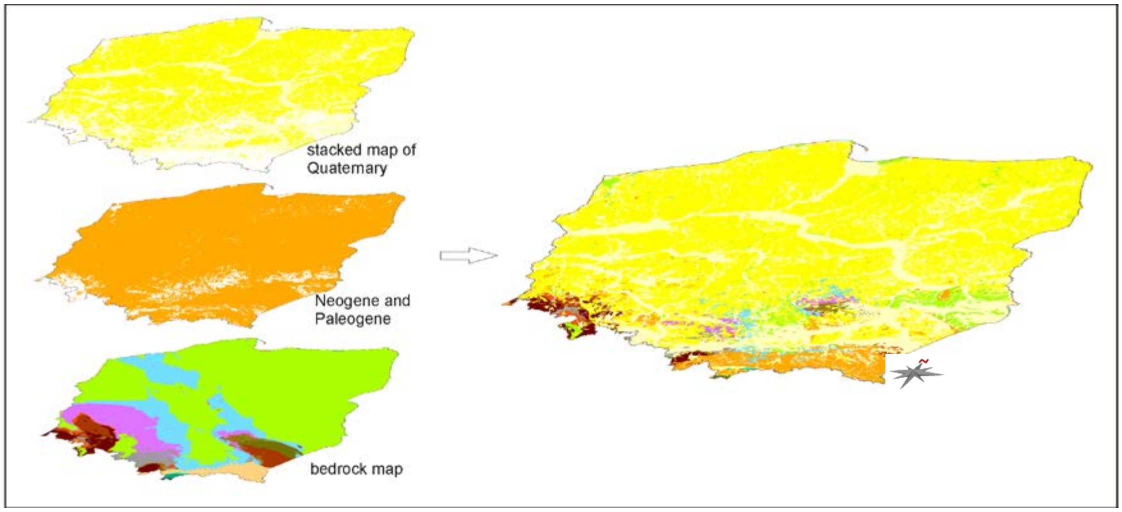

Figure 2. New 2-D layered country-scale Quaternary map in scale 1:500,000 (courtesy Stępień U.).

All the complexities of nation-scale bedrock modelling notwithstanding, they may still seem less of a hurdle compared to building the model of unconsolidated surficial deposits. 3-D mapping of some 300,000 km^2 of glacial tills and alluvial sands of the Quaternary, with thicknesses varying from several to up to 300–400 meters, make quite a daunting task. To tackle this, we employed a number of geological mappers working in 2-D to create, in the first step, a fully layered map of the Quaternary, generalized to 1:500,000 scale, where all geological units will have their real extent. The map will also include the layered map of Neogene and Paleogene sediments, as well as a bedrock map. Semi-automated generalization of large-scale 1:50,000 maps will be used and surficial geology will be fitted to the most recent LiDAR DEM. The morphology of subsurface horizons will be depicted and all of this work—carried out by our most experienced Quaternary geology specialists—will produce a 3-D model-ready geodatabase and printable map sheets at 1:500,000 scale, at the same time fulfilling all printed-map editor requirements.

3-D geological mapping of sedimentary basins: use, uncertainties and perspectives

Our now-systematic 3-D mapping of sedimentary basins of Poland, which focuses on areas that support the vast majority of human activity related to geo-resources, is seeing growing interest from the academic community wishing to use fragments of these models for their own research activities. These models, apart from mapping fault networks and stratigraphic horizons, also contain parametric grids that are populated with various rock properties such as lithology, lithostratigraphy, porosities, permeabilities, total mineralization, and other parameters, depending on data availability. We share them on request so that they can be further used, including a geometric framework for evaluating distributions of other parameters that are of user interest.

Although at basin scales we are still within the realm of so called "general mapping," there are two major issues that we urgently need to address: one is the selection of parameters that can be mapped at such scales and still convey useful information, and the other is the assessment and communication of uncertainties. With regard to selecting the right parameters, our looming task is to properly assess user needs: users might be interested in such models and their use. We are at the beginning of this avenue—teaming up with colleagues with backgrounds in social sciences and gathering ideas about how to properly survey our audience and thus tailor our models to that perspective model use. We believe that such tailoring will greatly promote and encourage use of our models. With regard to model uncertainties, which at the basin scale are significant but difficult to grasp for both specialists and the general public, there is an equal amount of work waiting for us. Although procedures for estimation of model uncertainties are already quite well documented in the literature (Wellman, 2014) and widely shared among the geomodelling community, we still struggle with communication of these uncertainties to the end user. In our everyday practice, we are currently trying to test a few approaches—such as point-based display in a 3-D viewer or error bars in a virtual borehole window. However, we are acutely aware that this is another point that needs to be first presented to end users for evaluation.

City geology: 3-D mapping on-demand

Very large scale 3-D geological maps and grids are produced at PGI on user demand for particular purposes, e.g., city geology, waste management, and other geo-engineering applications in subsurface management. Challenging modeling of complex shallow structures such as glacial deformations (Figure 3) may cause problems of 3-D grid layering for proper depiction of lithology and associated parameter distribution, what steers us toward wider usage of advanced modeling tools within the organization. Such large-scale, applied models are also an opportunity to test uncertainty-based modeling workflows and to check our ideas of communicating uncertainties. Given that the user is known, it is much more straightforward to ask which of our ideas transmit uncertainty clearly and which do not.

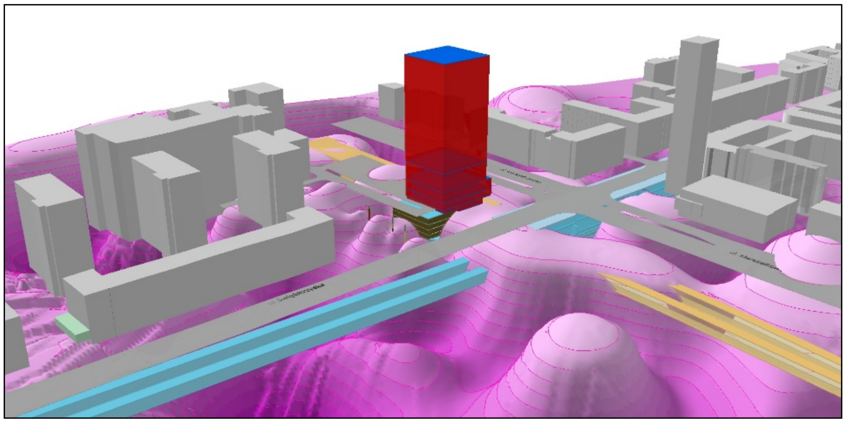

Figure 3. Shallow geological model of glacial deformations of Pliocene clays in Warsaw with two lines of the underground intersecting (courtesy Ryżyński G.).

Advanced web-visualization

All 3-D geological models developed in the last 13 years have been converted to web-accessible formats and soon will be available on-line. The 3-D geological models will be delivered with use of our in-house web viewer. We have developed two intuitive viewers of modelled geological structures, one on desktop and the other one in the web (http://webcad.pgi.gov.pl/geo3d/en/projects). Current functional versions allow the viewing of solid models, cross sections, horizontal section maps, and virtual boreholes. Layers of a visualized 3-D model can be switched on and off or "exploded"—that is, uplifted with mouse movements to see the top of the underlying layer. Viewer tools are being upgraded and we hope to have the following in the near future:

- a parametric 3-D grid viewer
- 3-D geological model uncertainty visualization
- streaming of large data sets of geological objects and 3-D grids
- tools to generate subsurface geological maps and cross sections for print-outs.

All modeling procedures and visualization is in accordance with the INSPIRE rules and standards of the GeoScience Domain Working Group (OGC).

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THE NEED FOR STANDARDS TO SUPPORT 3D STRATEGIES OF GEOLOGICAL SURVEYS

François Robida

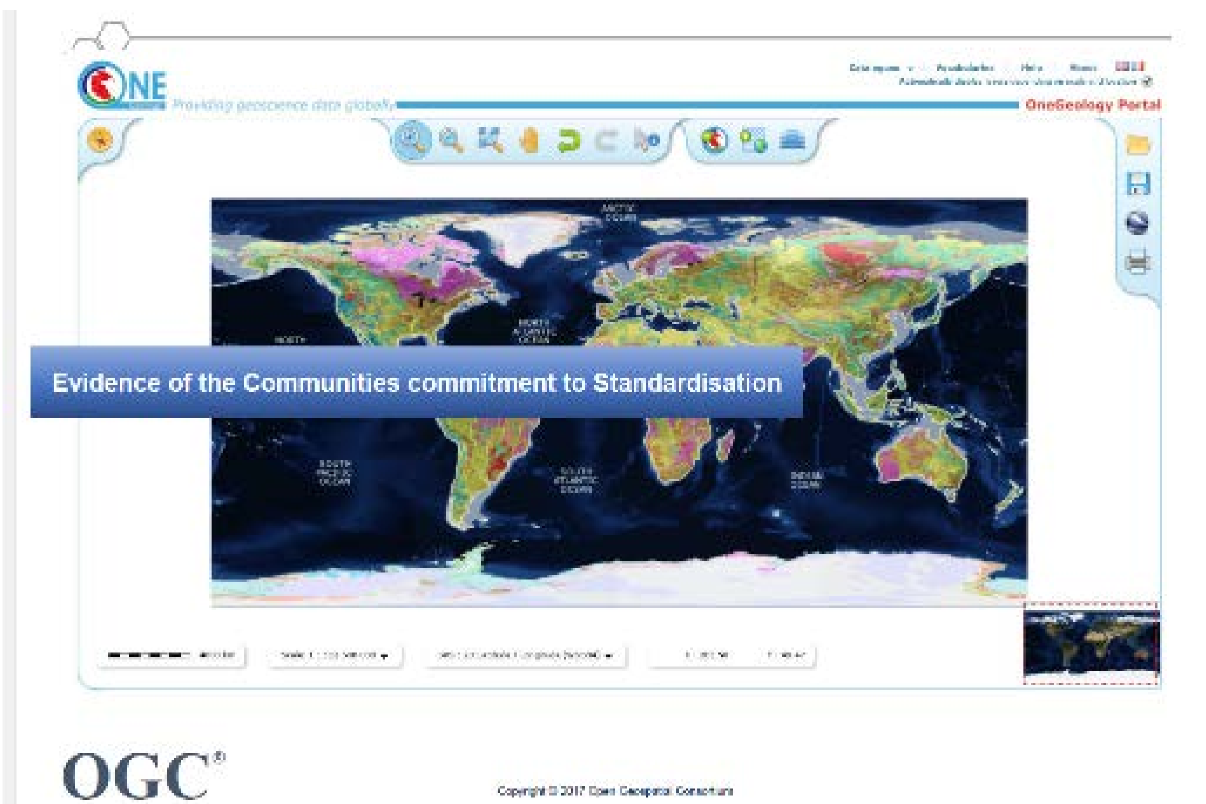
BRGM (French Geological Survey)–IUGS/CGI–OGC

Most geological surveys are developing ambitious 3D programs or strategies, such as the RGF in France. If those strategies vary from one survey to the other, all ambition to deliver new products goes beyond “traditional” 2D maps because they could serve more needs and more categories of users. Those new products should have some common features, such as being updated regularly, providing provenance and traceability, and having the ability to be delivered on demand.

Being based on 3D/4D data and models, they can be queried to provide different representations, such as virtual boreholes, sections, grids, and 3D meshes, all or some of which may be according to user requirements. To be easily integrated into different environments or workflows (including machine to machine), the deliveries should be provided according to standards that are usable by the different categories of users.

It is therefore of paramount importance to make sure that these standards exist, are implemented, and target the user’s environments. Given the diversity of potential users of 3D geological information, the openness and genericity of such standards are key. This is one of the reasons why the IUGS/CGI, which successfully produced standards such as GeoSciML, is partnering with OGC to create the joint Geoscience Domain Working Group, with the aim of addressing the exchange of 3D geological data (boreholes and 3D models in particular). Considering the growing demand for “usable” geological information for cities and infrastructure development, it is also important to address the interoperability issue with the standards of the built environment (BIM). This will be addressed in partnership with OGC and BSI (Building Smart International, which develops BIM).

In the same way that OneGeology served as a flagship project to demonstrate and democratize the use of CGI and OGC standards to deliver geological maps, it is now a new challenge for the OneGeology platform to do the same for 3D geology.



GROUNDWATER GEOSCIENCE FRAMEWORK FOR SOUTHERN ONTARIO: A STATUS REPORT

H.A.J. Russell, A.F. Bajc, F.R. Brunton, T.R. Carter, S. Frey, S. Hamilton, R.D. Knight, and D.R. Sharpe

Geological Survey of Canada, Ottawa, Ontario Canada

Introduction

The glaciated Phanerozoic basin of southern Ontario supports 40% of the Canadian GDP and has 87% of the Ontario population. More than 2 million people within this region, and significant components of the agricultural industry, rely on groundwater (e.g., Sharpe et al. 2014). The province has just completed a decade-long, $250 million drinking water source protection program focused on municipal wellhead protection and the identification of threats to drinking water. Nevertheless, there remains no regional framework for managing groundwater within the province, an element considered by many to be a necessary part of the infrastructure required to sustain a modern groundwater-dependent economy. Within the Canadian federal governance structure, groundwater and surface water are generally considered a provincial responsibility. In Ontario, provincial regulations are enforced by the Ministry of Environment and Climate Change (MOECC). Geoscience support for groundwater is provided by the Ontario Geological Survey (OGS). Under the Clean Water Act, Conservation Authorities have local responsibility for both groundwater and surface water at a watershed scale (commonly <7,000 km^2). A large amount of groundwater data is also managed by cities and municipalities through technical reports relating to municipal well fields and planning process documentation. This hierarchy of responsibilities has resulted in a fragmented groundwater management structure that lacks a unifying science-based framework.

The Geological Survey of Canada (GSC) collaborates with provincial geological surveys under the Interprovincial Geosciences Accord. The research discussed in this paper was completed as part of the 2014–2019 OGS–GSC collaborative groundwater project (e.g., Russell and Bajc 2015; Russell and Dyer 2016). The development of this project was in part guided by a gap analysis completed by the OGS and GSC in the winter of 2015 (Russell et al. 2015).

This paper reviews the development of regional geological 3-D models for the 110,000 km^2 area of southern Ontario. It highlights some of the initiatives by both the OGS and GSC on specific components of such a framework, for example, geochemistry and physical attributes.

Study area

Southern Ontario is bordered by three of the five Great Lakes, making it the largest USA and Canada trans-boundary groundwater–surface water resource. The Paleozoic sedimentary geology of the area unconformably overlies the Precambrian rocks of the Canadian Shield to the north and is part of the Michigan and Appalachian basins. The Paleozoic sedimentary sequence is up to 1,400 m thick and is overlain by up to 200 m of Quaternary sediment (Figure 1; Armstrong and Carter 2010; Sharpe et al. 2014).

Framework

The OGS and GSC have a critical role in providing geoscience knowledge for groundwater. A key component is the development of a 3-D data framework focused on a 3-D geological model and data support (Table 1). This includes research that was both ongoing by the OGS prior to 2014 under the OGS Groundwater Geoscience Initiative and continuing work under the collaborative project.

Bedrock model development

Southern Ontario is part of the earliest exploited petroleum province in North America. More than 160 years of exploration has contributed data to the Ontario Petroleum Data System (OPDS; Carter and Castillo 2006), which is maintained in an Oracle® database maintained by the Ministry of Natural Resources and Forestry. It contains records for approximately 26,700 wells, with depth and elevation information for nearly 600,000 formation picks (Figure 2). This data structure is supported by detailed geological knowledge on the formation character, depositional processes, and geological history (Armstrong and Carter 2010). The database management ensures versioning of information on formation picks, and as part of the project, extensive QA and QC was completed to enhance data integrity for information within the zone of potable water (e.g., Carter et al. 2017). The modelling initiative is currently on version 6

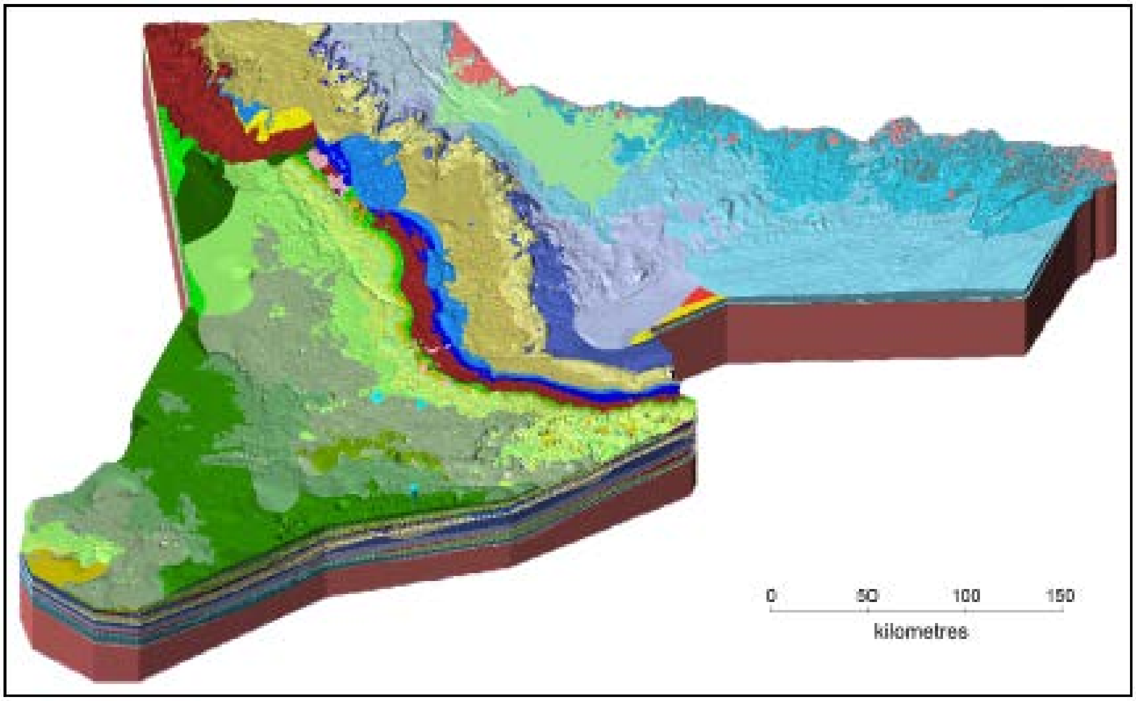


Figure 1. Southern Ontario bedrock model domain with subcropping–outcropping bedrock geology. Note the geology shown within the lake basins. Bedrock transitions stratigraphically upward from east to west, from Ordovician (blue, mauve) to Silurian (yellow, blue, brown) to Devonian (green).

Table 1. Illustrative data sets integrated into the regional geoscience framework for southern Ontario.

Initiative	Example reference
Regional groundwater model	Frey et al. 2016
Bedrock geological model	Carter et al. 2017
Bedrock topography	Gao et al. 2006
Seamless surficial geology	Ontario Geological Survey 2010
Karst map	Brunton and Dodge 2008
Surficial geological model	Russell et al. 2016
Surficial stratigraphic studies	Bajc et al. 2014
Surficial geochemistry	Sharpe et al. 2016
Ambient groundwater chemistry	Hamilton 2015
Chemostratigraphic data	Russell et al. 2017
Municipal well data consolidation	Russell et al. 2017
Attribute information on aquifers	Russell et al. 2017

of an iterative process of model development and refinement that has progressively advanced from a 3-layer model to the current iteration with 60 layers, including 58 Paleozoic formations. Work is ongoing to refine a hydrostratigraphic classification to permit the simplification of this formation-scale stratigraphic model to facilitate model utilization for groundwater modelling (e.g., Frey et al. 2016; Carter et al. 2017). A key component of the hydrostratigraphic rationalization is the challenge to capture information on the spatial heterogeneity and paleokarst of respective formations (e.g., Brunton and Dodge 2008). The bedrock model should be available for publication in the winter of 2019.

Surficial model development

A similar exercise is underway for the surficial geology of southern Ontario. Building on a series of semi-regional-scale models developed by the OGS (e.g., Bajc et al. 2014 and references therein) and GSC (Logan et al. 2006), a regional model is being constructed for the entire study area. Elements of the surficial geological map of southern Ontario (Ontario Geological Survey 2010) have been used to constrain the near-surface stratigraphic units of a 7-layer model for the complete area. A key input to the surficial geology modelling effort is the inclusion of knowledge gained from more than 300 continuously cored stratigraphic boreholes collected by the OGS (e.g., Bajc and Hunter

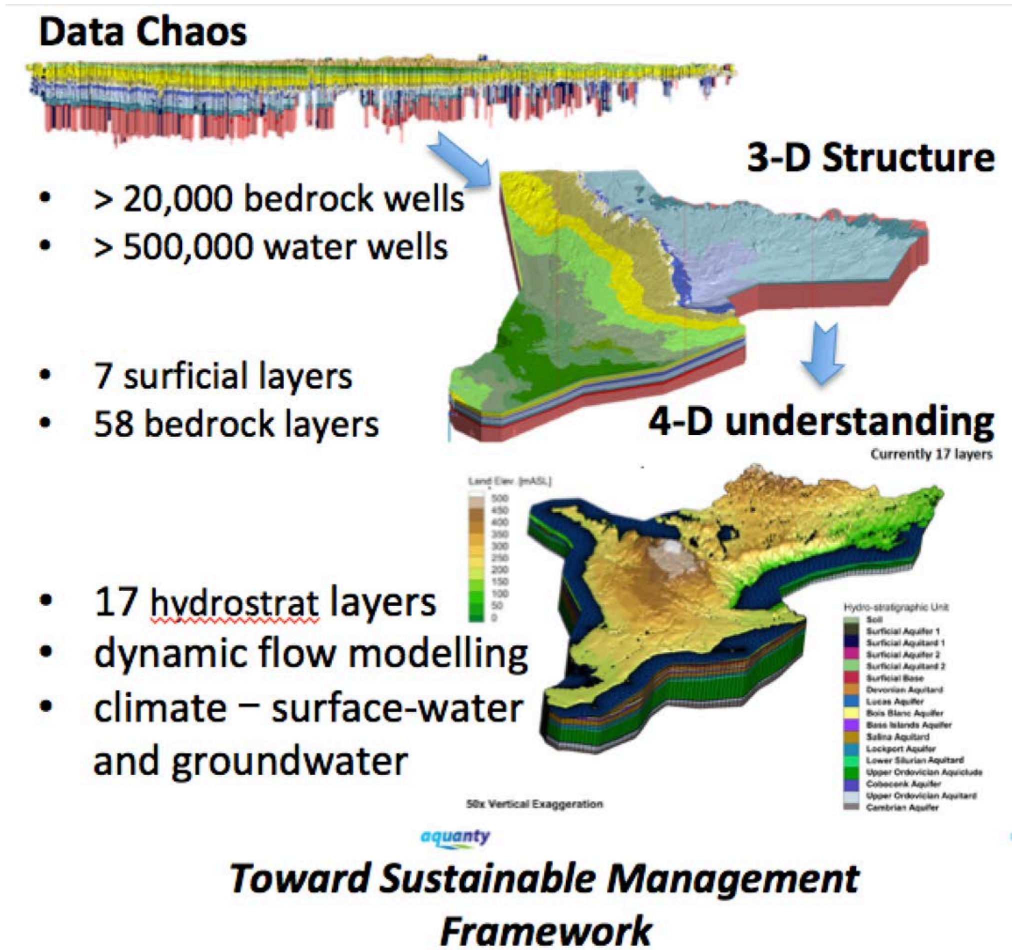


Figure 2. Transition in data framework from 2-dimensional point data (boreholes) to regional interpolated surfaces (geological model) to numeric groundwater model and groundwater knowledge framework.

2006) and 3-D semi-regional models within the Greater Golden Horseshoe region (e.g., Bajc et al. 2014). These data are supported by the archival water well records (WWIS) of the Ministry of Environment and Climate Change (MOECC).

Chemostratigraphic framework

A regional geochemical data set exists for surface sediments of southern Ontario (e.g., Sharpe et al. 2016); however, subsurface geochemical characterization of the Quaternary sequence is very limited. To alleviate this lack of knowledge, subsurface samples have been analyzed for geochemistry from more than 40 boreholes distributed along 2 transects, which are: 1) an approximately 300 km east-to-west transect from Rice Lake (near Peterborough) to London and 2) an approximately 200 km north-to-south transect from the Oro Moraine (north of Barrie) to Niagara (Russell et al. 2017). Analyses have been completed on 4,500 samples using portable X-ray fluorescence for 70% and ICP-MS analysis for the remainder. The results provide a data set to support the interpretation of regional ambient water chemistry sampling of Hamilton (2015) and assist with stratigraphic unit characterization.

Physical attribute capture

To support the transition from formation-scale geological models to more hydrostratigraphic models, physical attribute information is being captured where and when possible for integration into future versions of the modelling initiatives. To date, bedrock attribute data from drill core from 445 bedrock wells and 27,429 core plug analyses have been integrated into a database format for 55 of the 58 formations. The distribution of measurements per formation range from 1 to 8,956, with the Guelph Formation accounting for 33% of the measurements. Half of the 55 formations have <100 measurements. The core plug attributes include permeability, porosity, bulk density, and grain density, with reporting per attribute ranging from 47 to 84%. Groundwater in the Paleozoic units has a down-dip transition from fresh water at the surface in the surficial sediment and bedrock, to brackish, to saline sulphur water at intermediate depths, to dense brines in the deepest bedrock (e.g., Carter et al. 2014; Sharpe et al. 2014). The base of the fresh-water regime, the depth at which the water is no longer potable, and the base of the sulphur water of the intermediate groundwater regime are being mapped.

For the shallower potable water zone, particularly within surficial sediments, municipal supply well information has been compiled for >900 municipal wells culled from more than 500 reports. Municipal wells are linked with the WWIS and PTTW databases, which makes it possible to assemble information on well construction details, stratigraphy, water takings and local well management. Information was assembled for more than 30 attributes in 7 general groupings (Russell et al. 2017) that capture well information (i.e., administrative information, location, well construction details, and PTTW data) and aquifer information (i.e., description and physical properties). Additionally, based on the reports reviewed, 163 named aquifers have been tabulated.

Ambient groundwater chemistry

To provide a baseline regional characterization of the ambient groundwater, Hamilton (2015) has sampled domestic water wells on a regular 10 × 10 km grid. Subject to local availability, samples from 1 surficial sediment and 1 bedrock well were collected in each grid node. This ongoing survey provides the first regional data on groundwater chemistry collected within a narrow time frame and with a single protocol that accounts for well use, age, and sensitivity of various analyses to sample deterioration, etc. Each sample record contains 134 fields, including 27 station attributes, describing features such as the well, plumbing, wellhead security, and sampling point; and 107 sample attributes, including physical description of the water, field-measured parameters, water chemistry, isotopic chemistry, and the concentration of various dissolved gases. This survey protocol is currently being implemented by Conservation Authorities to improve the data density and identify local variability.

Hydrogeological model development

Ontario Drinking Water Source Protection has completed numerous hydrogeological modelling initiatives focused on watershed-scale and municipal wellhead protection areas. To date, no regional hydrogeological model exists for the entire southern Ontario Phanerozoic region even though numerous issues such as climate change scenarios and cumulative impacts from industry, municipalities, and agriculture require information at this scale (e.g., Frey et al. 2016). Furthermore, to account for regional-scale influences, watershed-scale hydrogeological models require peripheral boundary condition information. Hence, the overarching consistency of watershed models can be improved if a regional modelling framework exists as a homogeneous source of boundary condition information. The southern Ontario hydrogeological framework is being adapted to a HydroGeoSphere (HGS) groundwater–surface water simulation platform as a regional proof-of-concept modelling exercise. Because HGS is a 3D fully integrated groundwater–surface water (GW-SW) flow and transport simulator, the surface water system and the spatially and temporally varying groundwater–surface water interactions will be resolved in the hydrologic model. The hydrostratigraphic component of the HGS model is being developed from surface down to the base of sulphur water, with the possibility of 18 layers across bedrock, surficial geology, and soils. Additional data support for the HGS model includes detailed soils, land cover, and hydrology data, as well as data from the Province's network of surface water and groundwater hydrometric monitoring stations. The hydrostratigraphic data will support an unprecedented level of detail within such a large, regional-scale integrated model (Figure 2).

Summary

By the end of the collaborative OGS–GSC project in March 2019, a first fit-for-purpose framework will be completed. This framework will allow all data with x, y, and z coordinates to be positioned within a definitive geological, hydrostratigraphic and flow system context. This is the initial step towards development of a more robust multiagency hydrogeological decision support system for sustainable groundwater understanding and management in southern Ontario. This initiative aligns with perspectives voiced by a national review of groundwater needs for sustainable groundwater management regionally and nationally (CCA 2009).

Acknowledgements

An internal GSC review by Charles Logan is much appreciated. The work was completed under the Geological Survey of Canada Aquifer Assessments and Support to Mapping Project of the Groundwater Geoscience Programme. This work is a contribution of the GSC–OGS southern Ontario project on groundwater 2014–2019.

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DETAILED 3D GEOLOGICAL MAPPING INTENDED FOR ASSESSMENTS OF CLIMATE CHANGE IMPACT AND CONTAMINANT TRANSPORT IN GROUNDWATER

P.B.E. Sandersen[1], A.J. Kallesøe[1], and J.F. Christensen[2]

[1]Geological Survey of Denmark and Greenland, C.F. Møllers Allé 8, 8000 Aarhus, Denmark, [2]Region of Southern Denmark, Sorsigvej 35, 6760 Ribe, Denmark

psa@geus.dk

Abstract

Geological models can be made at different scales and with different degrees of detail. Typically, high accuracy is needed when outlining groundwater protection zones; therefore highly detailed geological models are essential. If risk assessments of contaminant transport are necessary, even higher levels of detail may be required. Traditionally, digital borehole data are combined with available geophysical data to make 3D geological models and based on that, 3D hydrostratigraphic models are constructed. Afterward, hydrological modelling including groundwater abstraction and contaminant transport scenarios can be made. However, to get the required model detail, it is sometimes necessary to take a step further than the traditional geological modelling approach by adding new types of data and combining with more in-depth analyses of the existing data sets. Whether this type of approach is needed in a given area depends on the actual case, and most likely, a balanced evaluation of expenses versus need for accuracy will precede the decision.

The present case is an example of a partnership project from the City of Odense in the central part of Denmark. Here, a detailed 3D geological model was needed as a basis for optimising the long-term use and administration of a groundwater resource challenged by potential contamination from human surface activities as well as climate change impacts. The mapping and modelling were performed in a partnership collaboration between the regional authority (the Region of Southern Denmark), the municipality (City of Odense), the waterworks (VCS Denmark), and the Geological Survey of Denmark and Greenland (GEUS).

Overview and approach

As a part of the National Groundwater Mapping Project in Denmark, spatially dense hydrogeological mapping surveys, including collection of geophysical data, borehole data, water samples, etc., have been performed since the late 1990s (Thomsen et al. 2004). The mapped areas, amounting to around 40% of Denmark, cover particularly valuable groundwater abstraction areas, and the overall purpose of the mapping has been to establish site-specific groundwater protection zones, and within these regulate land use to prevent groundwater contamination, mainly from agricultural activities. The National Groundwater Mapping Project generally focuses on areas outside the cities because this is where the major part of the groundwater abstraction takes place. However, groundwater abstraction in areas fringing the cities also will be challenged by potential contamination from point sources in and around the urban areas. Even when National Groundwater Mapping covers areas close to the urbanized areas, the data coverage in these areas will often be less dense. This is particularly the case for geophysical surveys because the subsurface infrastructure often hinders collection of high-quality data. Thus, gaining a sufficient amount of high-quality data for detailed 3D geological modelling can be challenging in these areas—especially when the geological setting is very complex.

In the case presented here, the study area (Figure 1) has been covered by surveys related to both the National Groundwater Mapping Project and supplementary data collection campaigns performed by the waterworks. However, to be able to create a 3D geological model with a higher level of detail than previously achieved, the solution was not additional data collection using the same types of geophysical methods previously used, but rather to look for new ways of gaining the required geological detail (Sandersen and Kallesøe, 2017). As an alternative approach, it was decided to pinpoint the uncertain parts of the existing geological understanding of the subsurface and try to find new types of data sets that could add the needed detail. The approach was based on the idea that if the geological history of the area could be better described and understood by adding just a limited amount of new data, the interpretation of the existing data could be taken further than before. Therefore, in this case, it was decided not to add more data of the same kind to gain more detail, but rather to add just the right amount of new data to get a better geological understanding. The area has a complex succession of Quaternary sediments, and to get a better geological understanding of the geology, it was important to establish a geological event chronology for the area. To this end, fine-gravel analyses of tills and coarse-grained meltwater deposits from boreholes were used in combination with detailed topographic analyses.

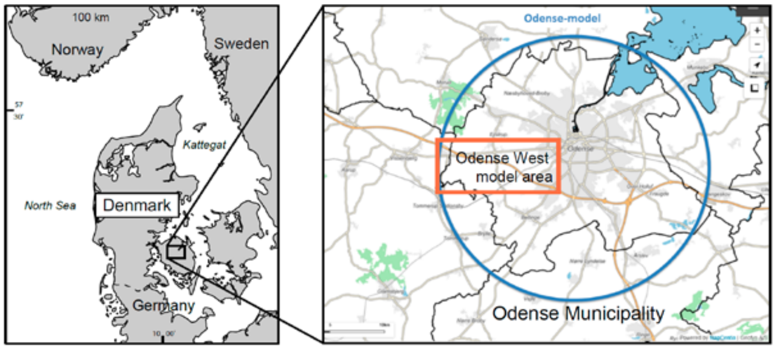

Figure 1. Study area.

Conceptual geological understanding and focus of the mapping

The study area is situated in an area with a sedimentary succession consisting of Danian Limestone followed by layers of Palaeogene clays and marls in the lower parts, and alternating Quaternary clays (meltwater clays and glacial tills) and layers of meltwater sand and gravel in the upper parts (Figure 2). A couple of deep tunnel valleys have been eroded into both the Quaternary and the pre-Quaternary successions and this—in combination with glacial deformations of parts of the Quaternary succession—adds to the geological complexity.

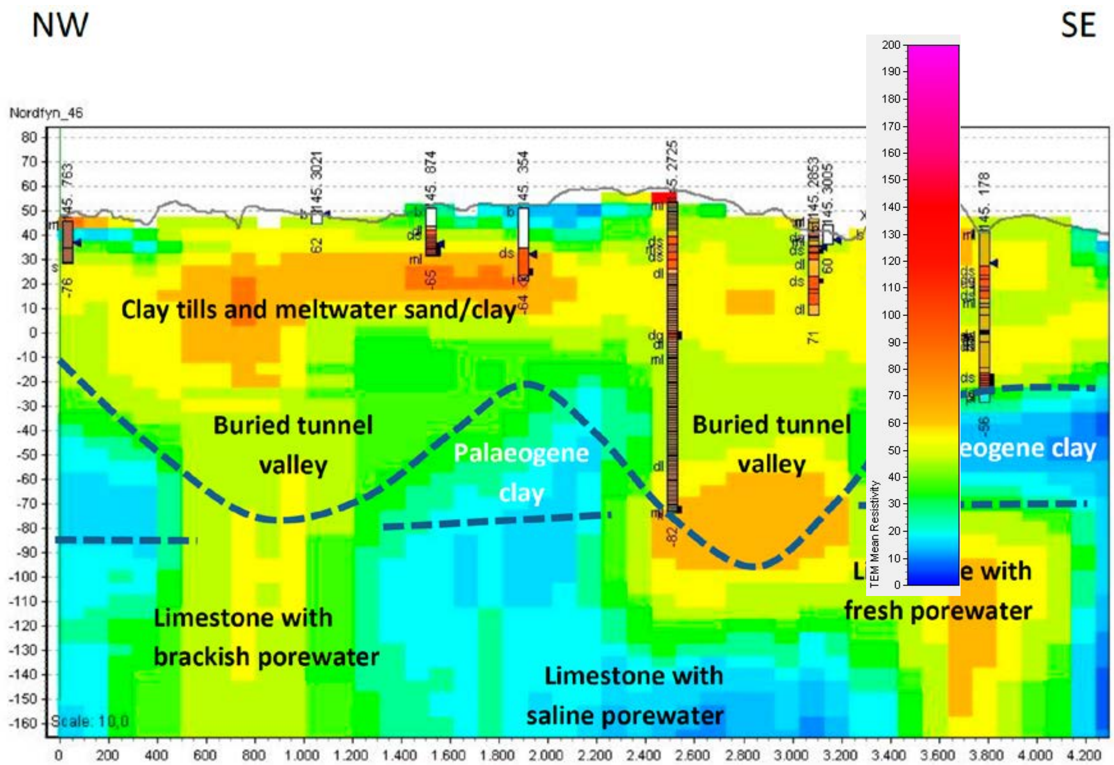

Figure 2. Conceptual cross-section through the study area. The coloured background is a 3D grid of resistivities from TEM data (transient electromagnetic data; resistivity scale to the right). Vertical rods are boreholes from the national borehole database Jupiter (red colours represent sand/gravel; brown is till; orange is meltwater clay; blue is Palaeogene clays). Vertical scale to the left is in meters above sea level and vertical exaggeration is 10 times.

As shown in Figure 2, the variations in the pore water salinity in the deep parts of the succession are related to the presence of the buried valley structures because the coarser valley infill can facilitate movement of fresh groundwater to deeper levels (Sandersen and Kallesøe, 2017). Because buried tunnel valleys in general have a high influence on groundwater flow, mapping of these structures is very important (Sandersen and Jørgensen, 2016). Previous geological modelling projects in the area (i.e., Mielby and Sandersen, 2017) were not able to map the maximum elevation of the buried valleys from the available data. The valleys could easily be seen in the lower part of the succession, but not in the upper parts (see Figure 2). If the valleys were young, the flanks would probably come close to the terrain surface and probably have a greater influence on the groundwater flow pattern if they instead were old and deep-seated. It was therefore important to find the relative age of the buried valleys and their infill and compare them with the surrounding and covering sediments. In other words, the geological chronology of the sediments and the geological events that created them were the focus of the mapping.

Two new boreholes—one outside the buried valleys (borehole no. DGU 145.3487) and one inside (borehole no. DGU 145.3488)—were drilled to around 80 and 120 meters depth, respectively (Figure 4, centre). Fine-gravel counts were made on selected sediment samples and compared with previously collected samples from other boreholes in the region (Andersen and Sørensen, 2016). The fine-gravel analyses focuses on the petrographic signature of the individual glacial layers (i.e., Ehlers, 1979), which opens up for a horizontal layer correlation that is not otherwise possible. After establishing the chronology, the existing geophysical and geological data were reinterpreted and related to the event chronology and the lithostratigraphy based on the fine-gravel analyses. In addition to this, the LiDAR-based digital elevation model of the area was investigated to add details about the latest geological events.

Results and discussion

The focus area of the Odense West project (red rectangle in Figure 3) is lying in a hilly, glacial landscape with an overall WNW-ESE orientation. The topography is irregular, with signs of stagnant ice in the highest parts (A0), and the A3 landforms are sediments deposited in former ice-dammed lakes. To the northeast and east, the glacial landscape slopes downward but retains a WNW-ESE orientation, now in the form of drumlinoid shapes and erosional channels rather than hills. Situated at a significantly lower elevation, the central parts of Odense are dominated by late- and postglacial erosion and sedimentation (upper right in Figure 3).

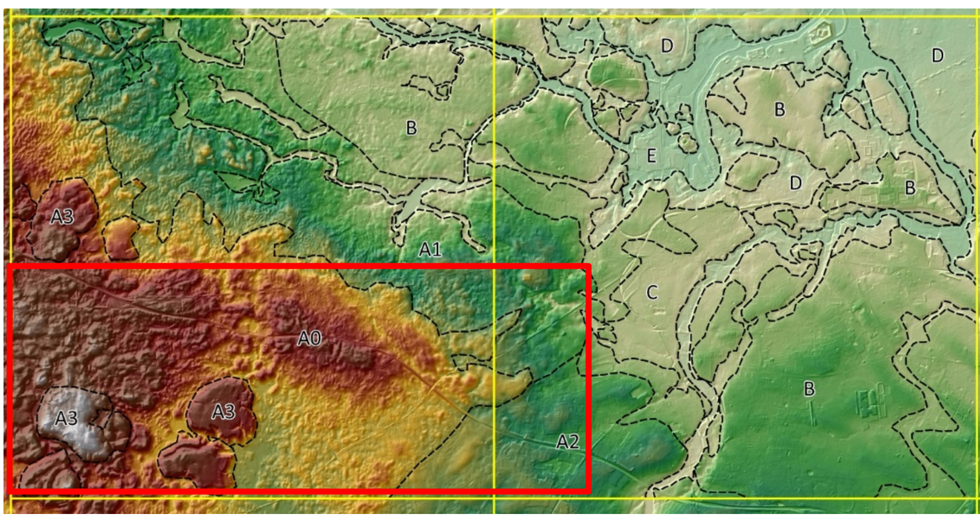

Figure 3. Digital terrain model (LiDAR data). Red rectangle shows the Odense West focus area. Altitudes range from around 120 m a.s.l. in the hills (brown/white; lower left) to 0–5 m a.s.l. in Odense City centre (bluish green; upper right). Areas with similar topography are outlined by hatched black lines: A: high glacial terrain; B: low-lying glacial terrain; C: late glacial outwash plain—Phase 1; D: late glacial outwash plains—Phase 2; E: postglacial freshwater streambeds. The yellow squares are 9 × 9 km. From Sandersen and Kallesøe (2017).

The topography shows a pronounced difference between the hilly parts to the southwest and the lower-lying areas to the north and northeast. The signs of stagnant ice and the pronounced orientation of the glaciated terrain (A0, A3) are in contrast to the smooth terrain of the lower-lying parts. This gives valuable information about the youngest events in the area.

The results of the fine-gravel analyses and the geological interpretations and correlations can be seen in Figure 4. The boreholes shown on the panel combine fine-gravel results from 7 boreholes inside and outside the focus area. The two new boreholes are seen in the centre of the panel. The fine-gravel analyses show that the infill of the two buried tunnel valleys does not have the same petrographic signature and therefore must be separated in time. The sediments of the clay-dominated valley to the left on the panel appear to be older than the valley to the right because the clay layers appear to be eroded by the valley (D). Because the petrographic signature of the valley fill has a greater resemblance to the layers above the valley, it further accentuates that the valley to the right is the youngest. The layers right above the valleys can be correlated based on the petrography and lithology

(D-layers), and with the greater lateral extent, it is clear that the buried tunnel valleys cannot be detected in the succession at levels above 10 m b.s.l. The meltwater clay and a large part of the meltwater sand (D-layers) can be found over both of the valleys, meaning that the influence of the valleys on the sedimentation patterns have come to an end with the formation of the meltwater clay and sand (uppermost D-layers). The glacial tills and meltwater sands and gravels of the A-B-C succession in the uppermost parts of the subsurface have a comparable petrographic signature and can therefore most likely be attributed to the same series of events. The results of the topographical analysis combined with the fine-gravel analysis adds an understanding of the A-B-C layers, suggesting that this part of the succession is the result of an oscillating WNW-ESE-oriented ice margin.

The results of the investigations have enabled the establishment of a new chronology of geological events for the Odense area. Based on this chronology, a 3D geological model with a higher degree of detail was made because correlation of existing data became easier and important questions, such as the relative age of the buried tunnel valleys, could be answered.

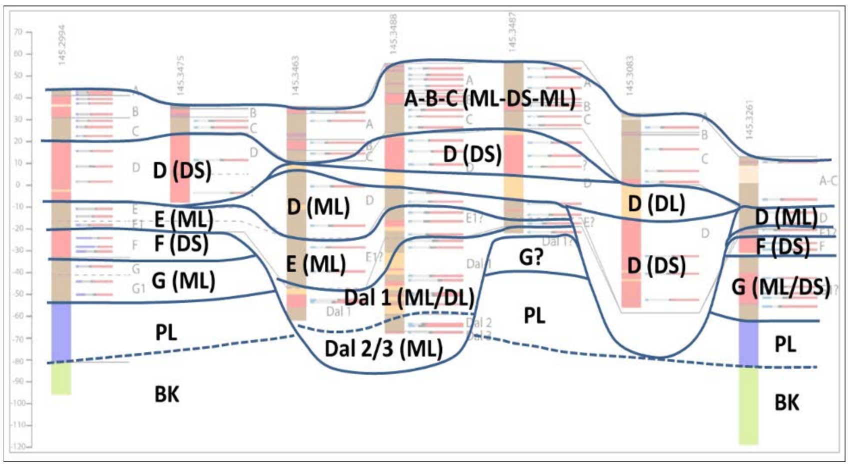

Figure 4. Geological interpretations based on fine-gravel analyses. ML: Clay till; DS: Meltwater sand; DL: Meltwater clay; PL: Palaeogene clay; BK: Danian Limestone. Figure from Sandersen and Kallesøe (2017). Fine-gravel analyses shown as background for the geological interpretations are from Andersen and Sørensen (2016).

Conclusions

The investigations have added a significant amount of new detail to the previous geological understanding of the area and therefore made it possible to take the geological interpretations and correlations a step further. The chosen approach has resulted in a far better geological knowledge of the study area and a more detailed 3D geologic/hydrostratigraphic model. The demand for more model detail in this example was not met by using more of the same data types, but instead by adding new and specialised data and thereby gaining a better geological understanding.

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DEVELOPING A THREE-DIMENSIONAL GEOLOGIC FRAMEWORK OF THE UNITED STATES

David R. Soller

National Geologic Map Database, National Cooperative Geologic Mapping Program, U.S. Geological Survey, 12201 Sunrise Valley Dr., Reston, VA

drsoller@usgs.gov

With the increasing volume and availability of three-dimensional (3D) geologic data, the U.S. geoscience community and stakeholders would significantly benefit from a national "seamless" 3D geologic map database. In response to this, the USGS National Cooperative Geologic Mapping Program (NCGMP) has developed a new Strategic Plan in cooperation with its partner agencies, the State Geological Surveys (represented by the Association of American State Geologists [AASG]). In that Plan, the NCGMP's vision is stated as follows: "to create an integrated, 3-D, digital geologic map of the United States and its territories to address the changing needs of the Nation by the year 2030."

The details of how to achieve this vision are currently under discussion. The Strategic Plan offers this preliminary guidance: "The USGS' National Geologic Map Database (NGMDB, Figure 1, https://ngmdb.usgs.gov/) has been since 1992 the Congressionally mandated element of the NCGMP that archives and delivers geological maps, merges published geological maps into a single database, and develops standards and guidelines for map and database content. The cooperative effort that has existed for many years between the USGS and State Geological Surveys has demonstrated the success of this concept of a multi-state/national distributed geologic map database as presently exists as the NGMDB.

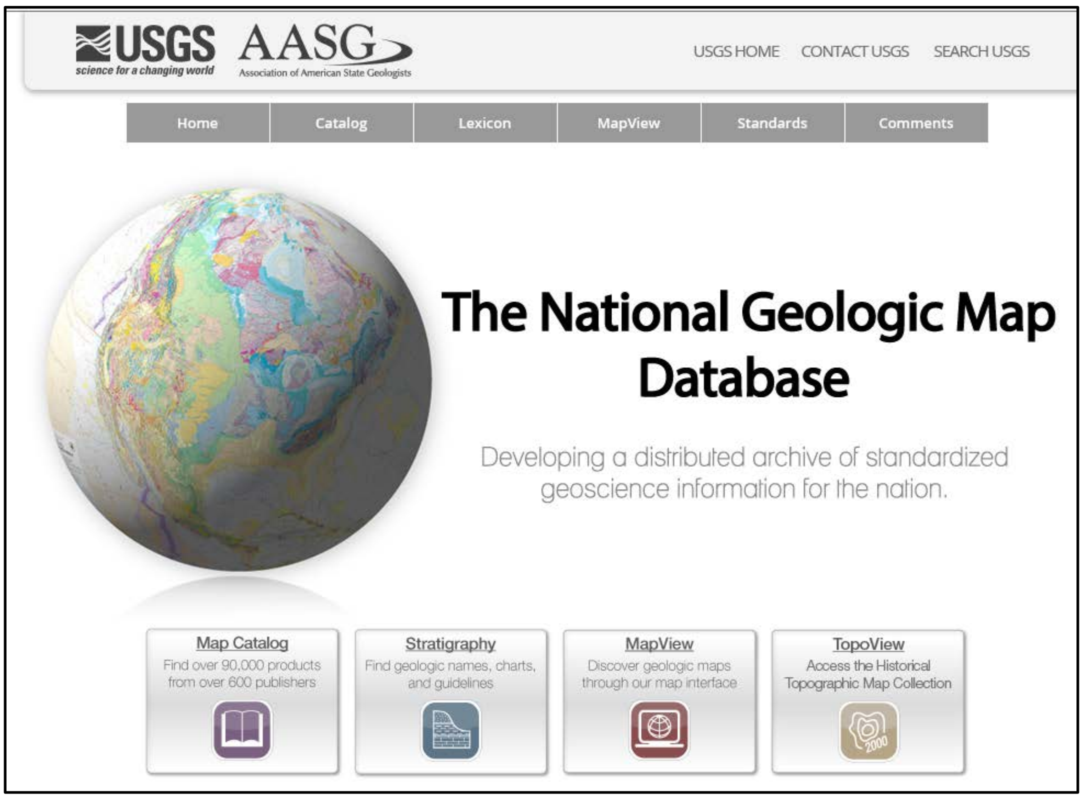


Figure 1. The National Geologic Map Database website (https://ngmdb.usgs.gov/).

However, now this geologic map database, in addition to being a foundational source of basic metadata, must be expanded to an Enterprise system containing national, regional, and detailed geologic framework model coverages managed according to content and format specifications. It also must comprise all data that supports geological mapping and 3D geologic modeling, including:

1) Topographic data of the Earth's surface (and particularly LiDAR-enhanced topography),
2) Structure contours (surfaces), thicknesses, and boundaries of surface and subsurface deposits (e.g., see Figure 2),
3) Topography of the basement (Precambrian or as defined regionally; e.g., see Figure 3) and characterization of basement properties and selected structures where needed, and
4) The physical and chemical properties that characterize the materials from the land surface to basement."

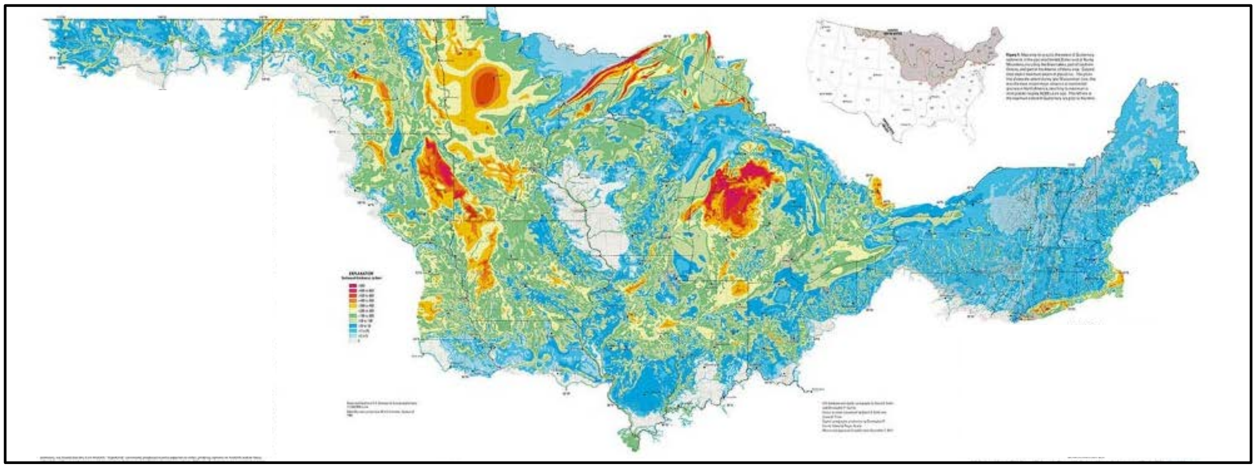
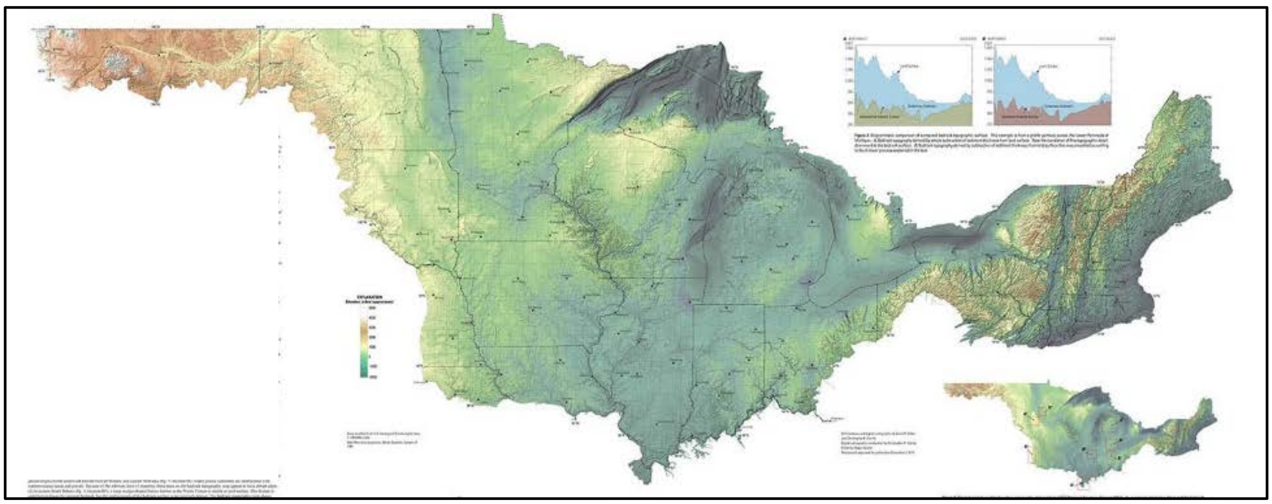


Figure 2. Sediment thickness map (above) (Soller and Garrity, 2018).
Figure 3. Bedrock topography map (below) (Soller and Garrity, 2018).
Both figures are example data to be included in the national 3D geologic framework database of the glaciated U.S., and have been modeled at a scale of 1:1,000,000 (reduced to 1:5,000,000 for publication, https://ngmdb.usgs.gov/Prodesc/proddesc_106843.htm).



What are the principal challenges to building this national database of geologic framework? Obviously, funding and technology will have some influence on development of the plan and its execution. But, emphatically, technology must not drive the vision and design. Rather, the challenge is scientific—for example, which source publications should be used as part of the compilation of this geologic framework? Which subsurface horizons should be modeled regionally or (if feasible) nationally? These horizons enclose the bodies of rock and sediment for which critically important physical and chemical properties must be available in the literature and then compiled into the framework database. A significant challenge will be to identify high-quality information on rock and sediment properties that is consistent in terms of content and format; without consistency, 3D modeling and query will be restricted significantly.

Initial compilation of the nation's geologic framework could be guided by major surfaces such as land surface, the sediment–rock interface, and top of basement rock (and, if desired, the Moho). But even this simple subdivision brings scientific challenges to the fore—for example, how should the sediment–rock interface be defined in the Coastal Plain? There, the degree of consolidation of sedimentary units generally increases gradually with depth, thereby arguing for an arbitrarily placed interface. Should it be based on engineering properties or geologic time (for example, the base of the Pleistocene, or the Miocene)?

As the level of detail in this geologic framework model increases, reliance on stratigraphy becomes important. Since the beginnings of geological surveys in the United States in the 1800s, stratigraphic studies and geologic mapping have been conducted and published. This knowledge is compiled in the Lexicon of Geologic Names of the U.S. (Geolex, Figure 4, https://ngmdb.usgs.gov/Geolex/), a resource managed within the NGMDB. Geolex will be a critically important standard reference for geologists charged with compiling this framework model, especially for reconciliation of stratigraphic interpretation differences between adjacent source maps. It is supported by the NGMDB's direct access to >21,000 publications containing stratigraphic columns and cross sections. Developing a 3D geologic model as large as the United States, with numerous geologic mapping agencies, will be a daunting task. The USGS and AASG welcome guidance and collegial interaction with other national and regional Geological Surveys as they embark on this effort.

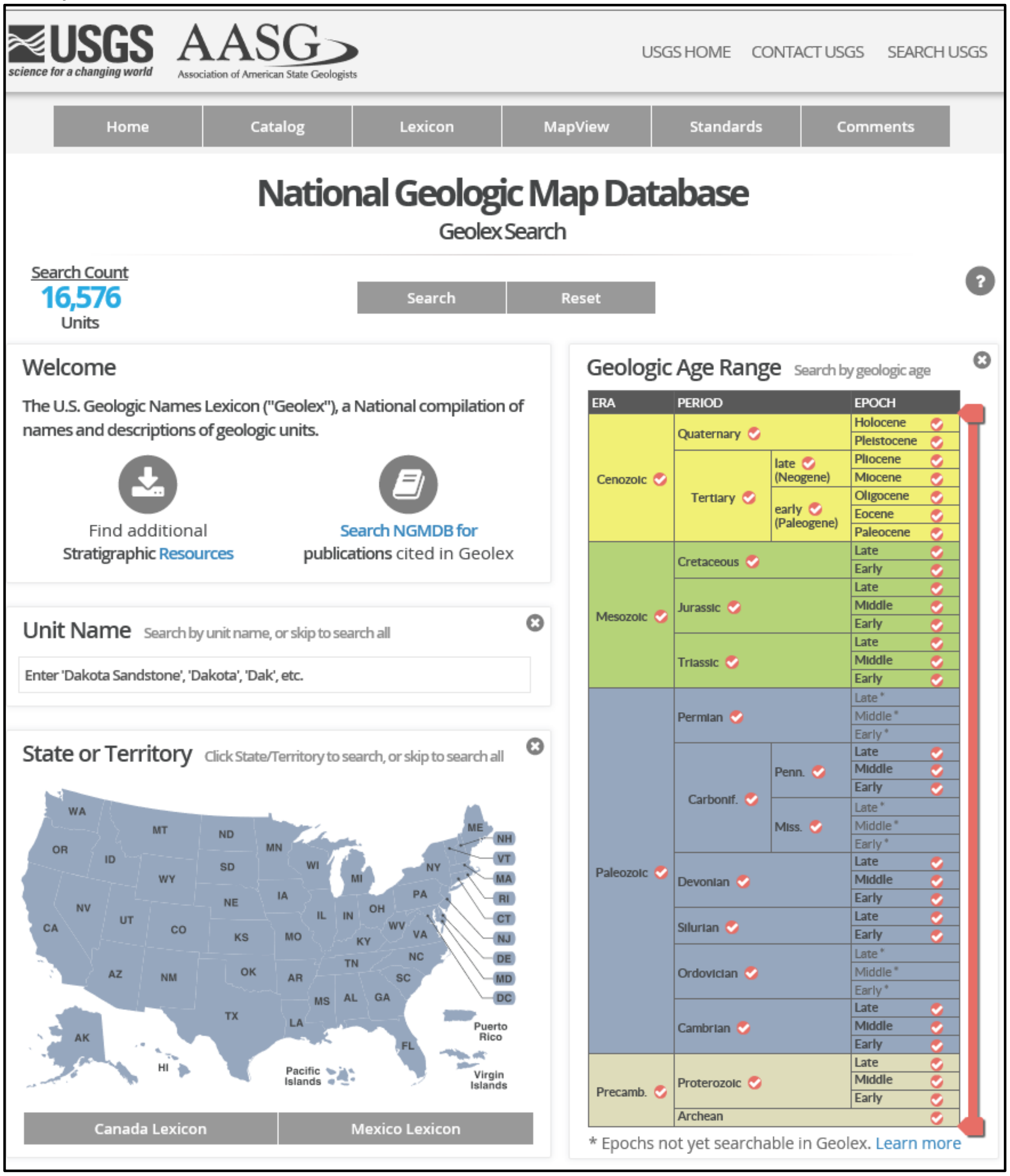


Figure 4. Geolex website (https://ngmdb.usgs.gov/Geolex/).

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AN INTEGRATED MODELLING APPROACH AT TNO–GEOLOGICAL SURVEY OF THE NETHERLANDS

Jan Stafleu, Denise Maljers, Jan Hummelman, Freek S. Busschers, Jeroen Schokker, and Michiel J. van der Meulen

TNO–Geological Survey of the Netherlands, P.O. Box 80015, 3508 TA Utrecht, the Netherlands

jan.stafleu@tno.nl

Abstract

TNO–Geological Survey of the Netherlands (TNO–GSN) defines digital geological models as estimates of both geometry and properties of the subsurface. In contrast to singular observations in boreholes and the projected information of traditional maps, models provide continuous representations of the subsurface built with all the geological expertise available. The models are quantitative and user oriented, i.e., they are applicable for non-geologists in their own area of expertise. They are also stochastic in nature, which implies that model uncertainty can be quantified.

TNO–GSN systematically produces 3D models of the Netherlands. To date, we have built and maintain 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 and hydrogeological units, and (2) voxel models in which the subsurface is subdivided into a regular grid of voxels to which a number of geological properties are attributed. Layer-based models of the shallow subsurface include the national geological framework model DGM (Gunnink et al. 2013) and the geohydrological model REGIS II (Vernes and Van Doorn 2005). A third layer-based model is DGM-deep with Carboniferous to Neogene seismostratigraphical units up to a depth of 7 km. The two main voxel models are the aggregate resources model (Maljers et al. 2015) and the multipurpose GeoTOP model (Stafleu et al. 2011).

Our models are disseminated free of charge via the DINO-web portal (www.dinoloket.nl/en/subsurface-models) in a number of ways, including an online map viewer with the option to create virtual boreholes and cross sections through the models, and as a series of downloadable GIS products. A freely downloadable Subsurface-Viewer® was added to the portal, allowing users to download and visualize the layer-based models as well as GeoTOP on their desktop computers.

This extended abstract explores the three main models of the shallow subsurface, with an emphasis on the GeoTOP voxel model, discusses how we are currently integrating the layer-based models of DGM and GeoTOP, and gives some examples of applications.

Layer-based models: DGM and REGIS II

Modern digital mapping of the Dutch subsurface started in 1999 with the development of the so-called Digital Geological Model (DGM; Gunnink et al. 2013). DGM, constructed using a set of ca. 26,500 consistently interpreted boreholes, is a 3D stacked-layer lithostratigraphical model of the entire onshore part of the Netherlands up to a depth of ~500 m (with a maximum of 1,200 m in the Roer Valley Graben). It consists of a series of raster layers, where each lithostratigraphical unit is represented by rasters for the top, base, and thickness of the unit (cell size 100 × 100 m). Raster layers are stored in the raster format of ESRI (ArcGIS). The lithostratigraphic units are at the formation level; the complex fluvio-deltaic Holocene deposits are represented by one layer only.

A second important step in digital mapping was the development of the Regional Geohydrological Information System (REGIS II; Vernes and Van Doorn 2005). The model uses the same data set of ca. 26,500 boreholes as used in DGM. REGIS II further subdivides the lithostratigraphic units of DGM into aquifers and aquitards. In addition, representative values of hydrological parameters (e.g., hydraulic conductivity and effective porosity) are calculated and assigned to the model, making it suitable for groundwater flow modelling on a regional scale. Like DGM, REGIS II models the complex Holocene deposits as a single confining layer. Both DGM and REGIS II are widely used by regional authorities and water supply companies in groundwater flow modelling studies.

Voxel models: GeoTOP

GeoTOP is the latest generation of Dutch subsurface models at TNO–GSN. GeoTOP schematizes the shallow subsurface into millions of voxels of 100 × 100 × 0.5 m up to a depth of 50 m below MSL, which is the main zone of current Dutch subsurface activity (Stafleu et al. 2011; Maljers et al. 2015). The model provides probability estimates of lithostratigraphy and lithological classes (including grain-size classes for sand) per voxel, based on the average of 100 equiprobable model realizations. We are currently adding physical and chemical parameters, such as hydraulic conductivity, seismic velocity, and chemical element concentrations. At present, GeoTOP covers 23,325 km^2 (57%) of the surface area of the Netherlands. We are currently extending the model towards the southeastern part of the country and expect to reach a coverage of 28,605 km^2 (70%) by the end of 2018.

GeoTOP workflow

The GeoTOP workflow consists of four main modelling steps (Figure 1). In the first two steps, a layer-based model is constructed (Figure 1A,B). This layer-based model is more refined than DGM because it features all Holocene formations that DGM combines into one unit, as well as certain Holocene and upper Pleistocene members and beds, and it uses, in principle, all available coded digital borehole descriptions rather than a subset (Van der Meulen et al. 2013). Given the large number of boreholes—tens of thousands per model region and ca. 500,000 in total—we developed automated stratigraphical interpretation routines. A region-specific lithostratigraphical concept, featuring superposition, extent, diagnostic properties, and approximate depth ranges, is used to identify and label the units in each borehole. This procedure delivers a uniform, consistent, and reproducible set of interpreted boreholes (Figure 1A).

Next, 2D interpolation techniques are used to construct surfaces bounding the bases of the stratigraphical units (Figure 1B). The interpolation algorithm allows for calculation of a mean depth estimate of each surface and its standard deviation. Subsequently, all surfaces are stacked according to their stratigraphical position, resulting in a consistent layer-based model with estimates of the top and base of each stratigraphical unit (Figure 1B). Top surfaces are derived from the bases of the overlying units. The surfaces are then used to place each voxel in the model within the correct lithostratigraphical unit.

In the third step, the boreholes are revisited and classified in six different lithological classes (peat, clay, sandy clay, fine sand, medium sand, and coarse sand and gravel; Figure 1C). In the last modelling step, a 3D interpolation is performed for each stratigraphical unit separately. The interpolation results in 100 equiprobable realizations of lithological and grain-size class for each voxel. Postprocessing of the realizations results in probabilities of occurrence as well as a “most likely” estimate of lithological and grain-size class (Figure 1D).

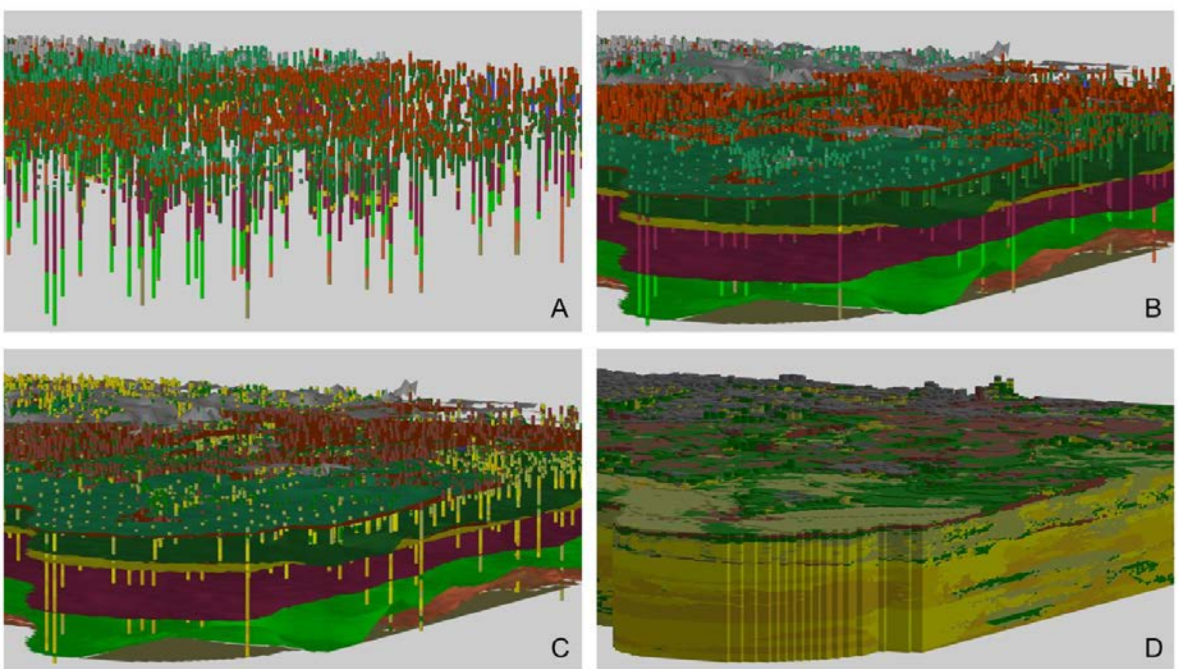

Figure 1. The four main modelling steps in the construction of layer-based and voxel models from borehole data: A) automated stratigraphical interpretation of borehole descriptions; B) 2D interpolation of stratigraphical surfaces; C) subdivision of boreholes into lithological and grain-size classes; D) 3D interpolation of lithological class for each stratigraphical unit separately. In C, yellow colours indicate sand in three different grain-size classes, green colours are clays, and brown is peat.

Model integration: DGM and GeoTOP

A new model directive (DGM+) was initiated in 2015 to integrate the national framework model DGM with GeoTOP on a national scale. DGM+ will incorporate the GeoTOP workflow of a more refined layer-based model including all Holocene formations that DGM nowadays models as one unit, as well as additional Holocene and Pleistocene members and beds (Figure 2). Furthermore, the original regional GeoTOP models will dissolve into a single national layer-based model that displays a great amount of detail in the upper tens of meters, but at the same time reaches, albeit with less detail, depths of several hundreds of meters. In doing so, we eliminate differences between models of the same geological units for the subsurface reaching down to ~500 m depth. In addition, the work efficiency and reproducibility will increase by using a single national framework model.

The integration of the shallow framework models appears to be a relatively straightforward step, mainly because they are constructed using comparable data sets (mainly boreholes) and the same modelling software (Isatis®), but it is nevertheless time-consuming. The new integrated model will serve as the future carrier of the GeoTOP voxel models with detailed lithological information as well as our hydrogeological REGIS II model with aquifers and aquitards.

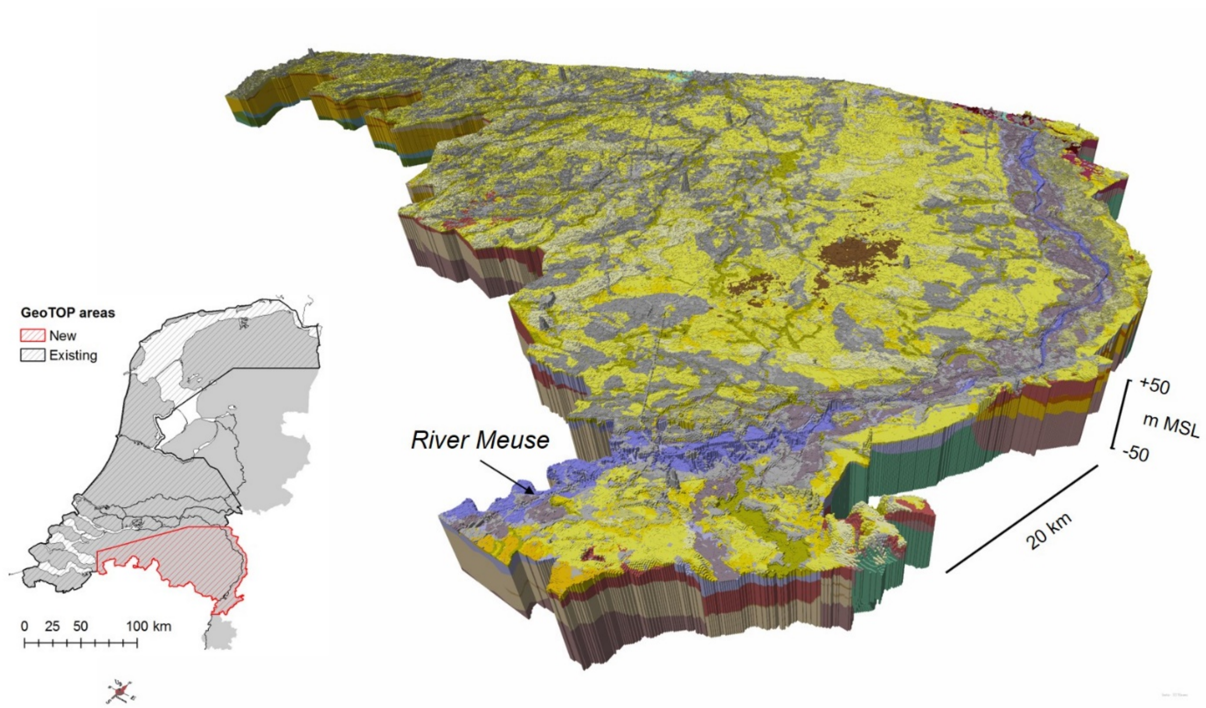

Figure 2. 3D view of the latest GeoTOP model area in the southeastern part of the Netherlands. The voxels are color-coded with stratigraphy. This part of the model was derived by voxelizing the upper part of the new, integrated national framework model that reaches down to ~500 m and has detailed stratigraphy (including many Holocene and upper Pleistocene formations, members, and beds) in the upper ~50 m.

Applications in and outside the Netherlands

The addition of physical properties to voxels enables these models to be deployed for a wide range of applications, such as groundwater management, risk assessments, the planning of infrastructural works, and aggregate resource assessments. The underlying assumption is that the spatial variation of many subsurface properties, such as hydraulic conductivity and seismic shear-wave velocity, strongly depends on the two main geological properties in the model: stratigraphy and lithology. A recent application of the GeoTOP model is the hazard and risk assessment of damage caused by induced seismicity in the Groningen gas field (Kruiver et al. 2017; Figure 3).

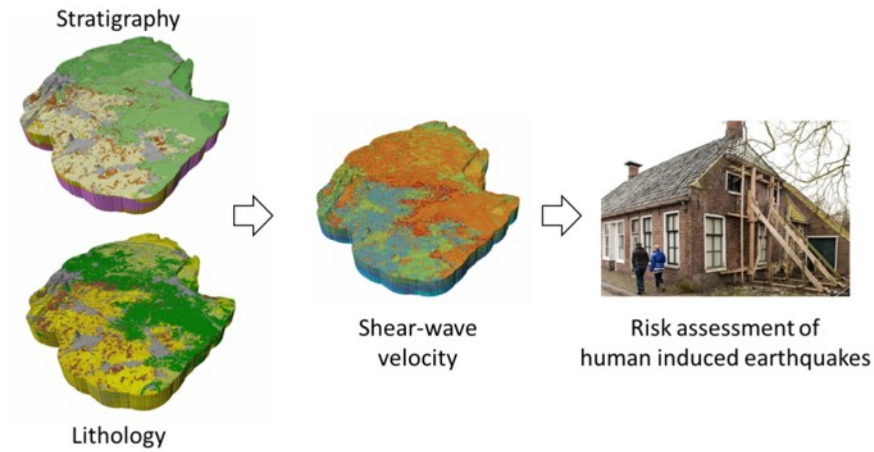

Figure 3. Putting the GeoTOP voxel model to work by adding properties related to the application at hand.

Another GeoTOP application is the long-term prediction of land subsidence attributable to the oxidation and compression of peat layers. Earlier applications included the use of GeoTOP as an add-on to REGIS II in groundwater flow models; the construction of risk maps in the deepening of a waterway, based on the architecture and sediment composition of channel belts; risk assessment in the construction of a new subway tunnel in the city of Rotterdam, with an additional local voxel model based on additional borehole descriptions and cone penetration test data; and the study of saltwater penetration problems in the coastal areas.

Examples of successful application of the GeoTOP modelling approach outside the Netherlands include a detailed model of the subsurface of Tokyo Lowland, Japan, which was used to study the relation between the accumulated thickness of soft Holocene mud and the amount of damage caused by natural earthquakes, and a voxel model of the Belgian Continental Shelf aimed at estimating resource volumes for the construction industry and for the reinforcement of the Belgian coast.

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GEOLOGICAL MODELS FOR INFRASTRUCTURE DESIGN: REDUCING GEOTECHNICAL RISK AND SUPPORTING SUSTAINABILITY

Alan Keith Turner

Colorado School of Mines/British Geological Survey

kturner@mines.edu

Abstract

For more than 30 years, several national geological surveys have implemented sophisticated subsurface geological modeling methods. The advent of accessible modeling software has enabled a step-change in the way in which geological data are used by the environmental and infrastructure sectors. A landmark modeling application occurred during the design and construction of Farringdon Station on the new Crossrail underground railway in London. In 2009, the British Geological Survey developed a 3-D geological site model. Subsequently, the model was transferred to the construction consortium and integrated into the site supervision workflow. The geological model materially reduced the geotechnical risk, allowed for efficient construction, and resulted in a four-month reduction in the planned construction time. The success of the Farringdon Station project prompted several other infrastructure design applications to use geological models. Encouraged by UK government policies, geological models have become an integral part of the geotechnical design and construction process and form the basis for ensuring sustainable groundwater supplies.

Introduction

Sophisticated subsurface geological modeling methods have become the primary method used by several national geological surveys to transmit geological information. Subsurface modeling has evolved in three phases over the past three decades. Between 1985 and 1995, the primary emphasis was on the question *"Can we do it?"* In this period, small academic research groups tackled fundamental research topics. Initially constrained by existing computer software and hardware limitations, these efforts were advanced by the advent of the first modern computer workstations. The first commercial 3-D geological modeling software products, when released in the period 1995–2005, encouraged further experimentation by some geological surveys. As increasingly mature and stable software platforms became available, the topic became *"How do we do it?"* After 2005, the primary emphasis became *"Why are we doing it?"* As subsurface geological models became accepted as a valuable resource-management and planning tool, geological surveys became active participants in satisfying the expectations of diverse user communities active in environmental sustainability and infrastructure development.

Modeling for Farringdon Station

Scheduled to open in December 2018, Crossrail is a new underground railway system that will provide a direct East–West connection through the center of London. The central portion of Crossrail includes 21 km (13 miles) of twin-bore tunnels and eight new stations. The existing underground infrastructure at Farringdon Station required the platform tunnels to be about 30 m (100 ft) below the surface. This placed them in the Lambeth Group, which underlies the London Clay and includes "hard grounds," water-bearing channel sands, and local gravel beds. These characteristics have caused previous tunneling projects to experience difficulties and delays.

During the initial ground investigation at Farringdon, geological correlation of 30 boreholes revealed the expected complex lithology in the Lambeth Group but did not establish a coherent ground model. Identified geotechnical hazards included potential "randomly located" water-bearing sand layers and inferred fault zones. Surface deformation resulting from the excavation was also a concern as sensitive buildings and surface railway tracks above had to be protected. In 2009, these concerns led Crossrail to commission the British Geological Survey (BGS) to produce a 3-D geological model of an area 850 × 500 m (2800 × 1650 ft) containing the Farringdon Station site (Aldiss et al. 2009, 2012). By modeling an area much larger than the footprint of the proposed station, the model incorporated nearby geological observations and more accurately identified the positions and characteristics of faults.

BGS built this initial 3-D model using an explicit, cross-section-based modeling methodology (Kessler et al. 2009) and incorporated experience from a completed regional 3-D London model (Mathers et al. 2014). The resulting Farringdon model (Figure 1) defined a faulted multilayered subsurface with 18 identifiable geological units and seven faults (Aldiss et al. 2009, 2012). These faults were not represented on published geological maps; limited observations constrained the model-predicted location of each fault to an envelope about 20 m (65 ft) wide at the level of the tunnels. The model also identified sheet-like and short channel-like sand bodies in the Lambeth Group.

In April 2013, the BGS model was handed over to the contractor and its specialized tunneling consultant. It became an integral part of the site-supervision workflow (Figure 2). Between 2009 and 2013, the model was updated with data from shaft excavations and additional boreholes. When tunneling to create the Farringdon Station started in May 2013, the 3-D model became an integral part of the site supervision workflow. Daily updates permitted progressive refinement of the model as the station excavation advanced.

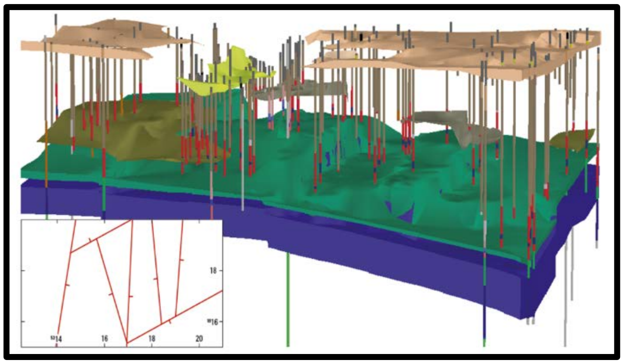

Figure 1. Sand and gravel (water-bearing) units in the BGS Farringdon 3-D geological model, with borehole "sticks" (Aldiss et al. 2012).

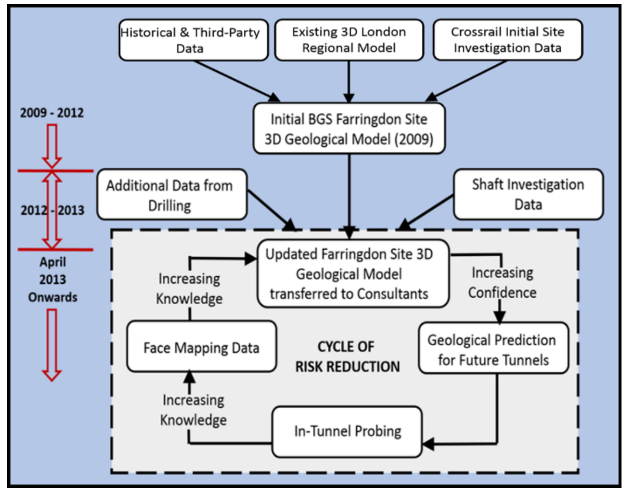

Figure 2. Cycle of risk reduction through the implementation of geotechnical risk management tools. (Modified from Cabrero and Gakis 2014.)

Predicted fault locations in the initial 3-D model proved remarkably accurate when tunnel excavations revealed the real conditions. The model assumed faults had a dip of 70°, but a typical dip angle of 60° was encountered during the tunneling. Thus, observed fault locations were displaced in the direction of dip from their interpreted positions. Sand lenses were accurately predicted in the northwest portion of the station, overestimated at the east end, and partially underestimated in the central and west parts of the station. Any sand lenses encountered as excavation progressed were carefully observed and their modeled geometry and continuity updated.

Geotechnical risk analysis used five risk grades, ranging from I (low risk) to V (high risk). Comparisons of geotechnical risk posed by water-bearing sand units to the tunnel lining during the design and construction phases showed a reduction in effective overall geotechnical risk from Grade III during design to Grade II during construction (Gakis et al. 2014). Application of the 3-D model was responsible for much of this risk reduction.

The successful design and construction of Farringdon station between 2013 and 2015 was materially helped by using the 3-D geological model to integrate the most recently acquired geological data. A sophisticated nonlinear 3-D finite-element model accurately simulated the sequential excavation steps and the geometry of the tunnels; this ensured the stability and adequacy of the primary tunnel lining. Predicted in-tunnel deformations and surface settlements induced by station construction closely matched the actual monitoring results (Cabrero and Gakis 2014). Gakis et al. (2016) defined several additional benefits to the project resulting from use of the 3-D model. Perhaps the most significant were a 70% reduction of planned in-tunnel probing and the reduction in geotechnical risk, which allowed for efficient construction and resulted in project completion four months ahead of schedule.

Modeling for infrastructure improvement

The success of the Farringdon Station project prompted several other infrastructure design applications to use geological models. When the UK government mandated the use of Building Information Modeling (BIM) techniques on all government-funded construction, integration of geological modeling with BIM data management and visualization offered expanded support for the entire design and construction process.

In 2015, the BGS produced a detailed 3-D conceptual ground model (CGM) for 28 km (17.5 miles) of railway between Leeds and York in Northern England that was being electrified. The CGM evaluated bedrock and superficial geology conditions that might affect electric mast foundations and other infrastructure improvements (Burke et al. 2015). The digital CGM was constructed using 1:10,000 scale digital geological map data and 102 borehole logs from the BGS national archive. The CGM contains 57 geological units, including 11 coal seams, and 29 mapped geological faults, defined as planes with a generic 70° dip. The railway route was modeled in three sections to allow rapid model construction; the entire CGM was completed and delivered in one month. The model is only 80 m wide and extends to 30 m depth. It consists of a series of short "rung" sections, which cross the track, and three parallel sections, located along the centerline and each side of the route (Figure 3). The BGS delivered the digital CGM to the design client as CAD files, allowing for the integration of geological subsurface information with infrastructure design elements developed by BIM workflow design documents (Figure 4). The modeling procedure yielded several benefits, including less on-site investigation expense and more economical designs. The process has since been adopted on other projects.

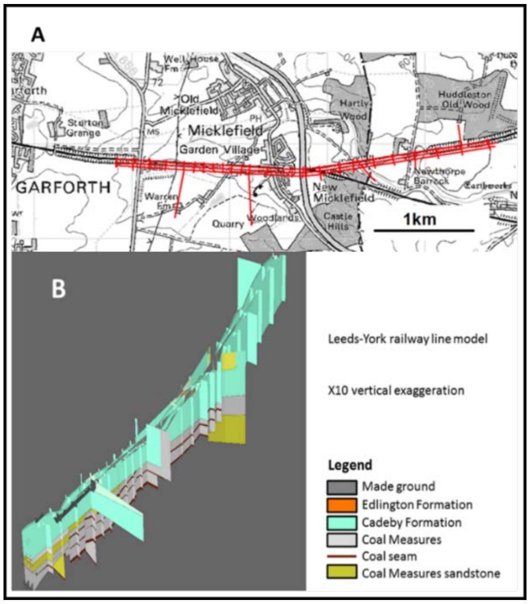

Figure 3. A 4 km section of the central portion of the Leeds-York route. A is map view; B is isometric view of the 3-D model. (Source: BGS and OS Data © Crown Copyright 2015)

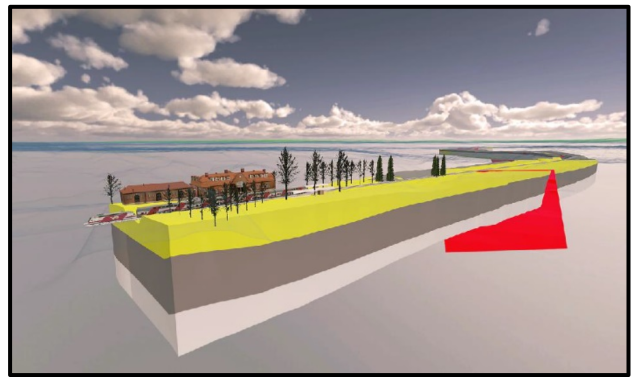

Figure 4. Example of BIM infrastructure design elements integrated with geological subsurface information, including faults. (BGS)

Modeling sustainable groundwater sources

The BGS has supplied several regional geological models to support the Environment Agency's regulatory role of ensuring sustainable abstraction schemes for major groundwater resources. Based on extensive geological mapping and modeling by the BGS, a recent model of the Vale of York in northern England (Figure 5) supported regional evaluations of the Triassic Sherwood Sandstone Group aquifer, which underlies heterogeneous glacial deposits in the area. Higher-resolution site-specific models, based on this regional model, are being prepared for use by water-supply companies to understand potential pathways of nitrate pollution.

The national BGS model (Waters et al. 2015) is also being applied to the study of sustainability issues. A study of the Chalk aquifer of southeast England (Figures 6 and 7) addresses the sustainability of this important groundwater resource and the geohazard it presents from groundwater flooding.

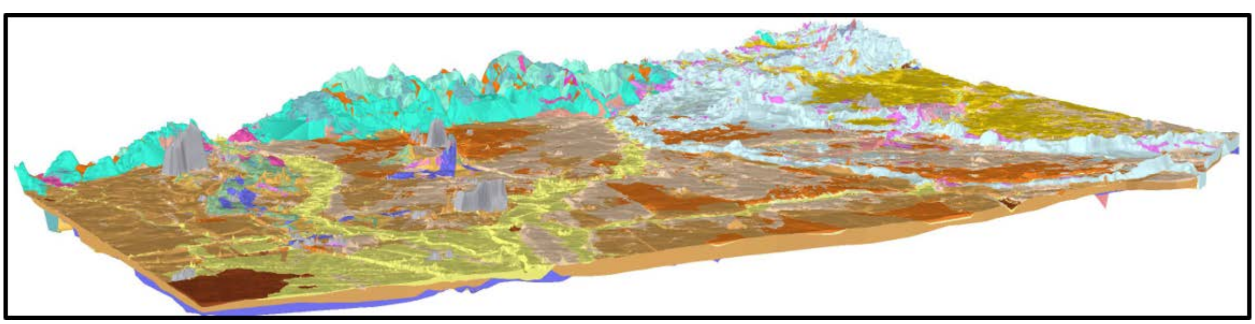

Figure 5. Regional geological model of the Vale of York looking northwest, with the Pennines in the background and showing the complex glacial and Holocene deposits in the foreground. (From Burke et al. 2017, supported by the Environment Agency.)

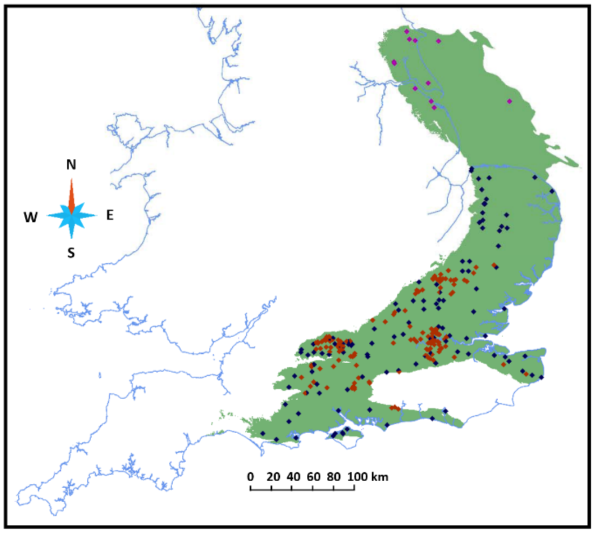

Figure 6. National 3-D model attributed to show Chalk aquifer classification (Mathers et al. 2014).

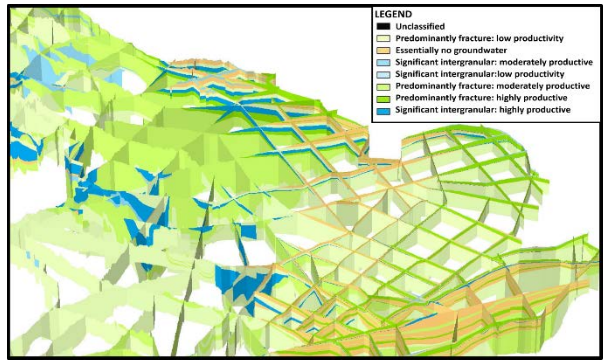

Figure 7. Extent of the Chalk aquifer model in southeast England. Dots show borehole control points (Woods et al. 2015).

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SYSTEMATIC SUBSURFACE MAPPING IN THE NETHERLANDS: ITS FUTURE SECURED BY A NEW LAW, AND ITS FUNDING BECAUSE OF A POSITIVE BUSINESS CASE

Michiel Jan van der Meulen

TNO–Geological Survey of the Netherlands, P.O. Box 80015, 3508 TA Utrecht, the Netherland

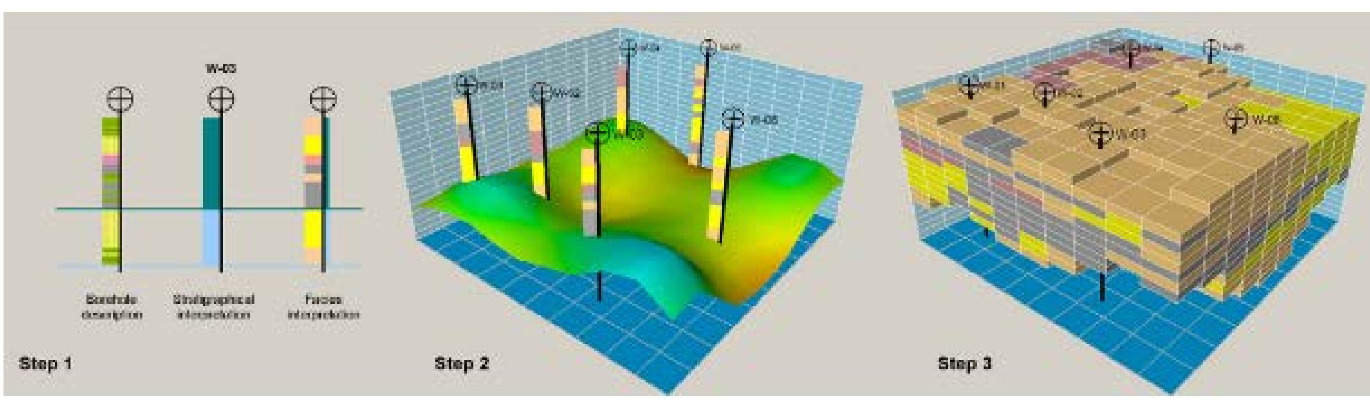
michiel.vandermeulen@tno.nl

The Geological Survey of the Netherlands runs four subsurface mapping programs that serve three main application domains. Down to a depth of about 5 km, the DGM-deep program maps 13 Carboniferous to Neogene seismostratigraphic horizons, using exploration data that energy and mining companies have to submit to the Survey under the Mining Law. The model is made publicly available to attract investments in exploration, up until now primarily for hydrocarbons, but gradually shifting to geothermal energy and other new uses of the deep subsurface.

Down to about 500 m, the country is covered by the lithostratigraphic model DGM, which maps the geometries of Neogene to Quaternary lithostratigraphic units. While DGM is used in its own right for any application requiring geological information, its primary purpose is to serve as the basis for REGIS II, the Dutch national hydrogeological model, which subdivides DGM units into hydraulically parameterized hydrostratigraphic units. REGIS II is a de facto standard used in hydrological studies or assessments for Dutch water and environmental authorities.

While DGM-deep, DGM and REGIS II are basically modern ways to fulfil traditional needs for geological information. Our most recent program, GeoTOP, is opening new perspectives for geological surveying. GeoTOP is a voxel raster having lithostratigraphic and lithologic attributes, covering the upper tens of meters of the subsurface. The program was originally designed to supplement REGIS II with the higher level of detail needed for surface water–groundwater interaction modeling. However, it has also been taken up by the geotechnical community. In fact, a positive business case for its application in the planning and development of national infrastructure and hydraulic engineering works has been instrumental in passing a new law on subsurface information and getting the implementation funded, thereby securing the continuity, role, and data position of the Geological Survey of the Netherlands.

This abstract has also been submitted to the conference sessions for RFG2018.



TIME-SERIES FACIES MODELS OF SEDIMENTARY DEPOSITION IN THE LAST 20,000 YEARS TO IDENTIFY PREHISTORIC DEVELOPMENT OF HYDRAULIC PROPERTIES OF A COASTAL AQUIFER SYSTEM, WAIRAU PLAIN, NEW ZEALAND

P.A. White[1,3], R. Davidson[1], C. Tschritter[1], and P. Davidson[2]

[1]GNS Science, Private Bag 2000, Taupo, New Zealand, [2]Marlborough District Council, 15 Seymour St., Blenheim, New Zealand

p.white@gns.cri.nz

Abstract

Three-dimensional models of geomorphic units have been created for Wairau Plain, Marlborough District, New Zealand. These models describe the key features of the development of Late Pleistocene and Holocene geomorphic units associated with the coastal aquifer and show the evolution of these features in an animation covering the last 20,000 years at a 1,000-year time step.

This evolution was categorised by three key periods: 1) 20,000 years before present (B.P.) to 8,000 years B.P., where sea level rose to a position inland of the current coast and Holocene gravels were deposited above a Pleistocene gravel fan; 2) 8,000 years B.P. to 5,000 years B.P., when a gravel riser was formed landward of the current coast and an estuary formed behind the Boulder Bank; this period was significant for the formation of the present-day Wairau Plain groundwater system because the drowning of the Pleistocene Wairau River channel and the formation of the estuary probably led to development of artesian conditions, and springs, in the area west of the gravel riser; and 3) the period 5,000 years B.P. to the current day, where in-filling of the estuary continued, the Wairau River channel shifted to its present position behind the Boulder Bank, and Rarangi gravels were deposited in northern Cloudy Bay.

Demonstrations of the 3D model animation, together with a 3D printed hard-copy of the model, at numerous outreach activities has received uniformly positive feedback from audiences; one fascinating response to the printed model was from blind people who appreciated being able to explore topographic and geological features with their hands.

Introduction

Groundwater is an important source of water in the Wairau Plain, Marlborough District (Figure 1). Agricultural users are almost totally reliant on groundwater, principally for vineyard irrigation, and groundwater is the sole supply for the urban population in the main towns of Blenheim and Renwick. The Wairau Plain coastal aquifer system supplies water to spring-fed streams, which are popular amenities that are widely used for recreation and are navigable in part.

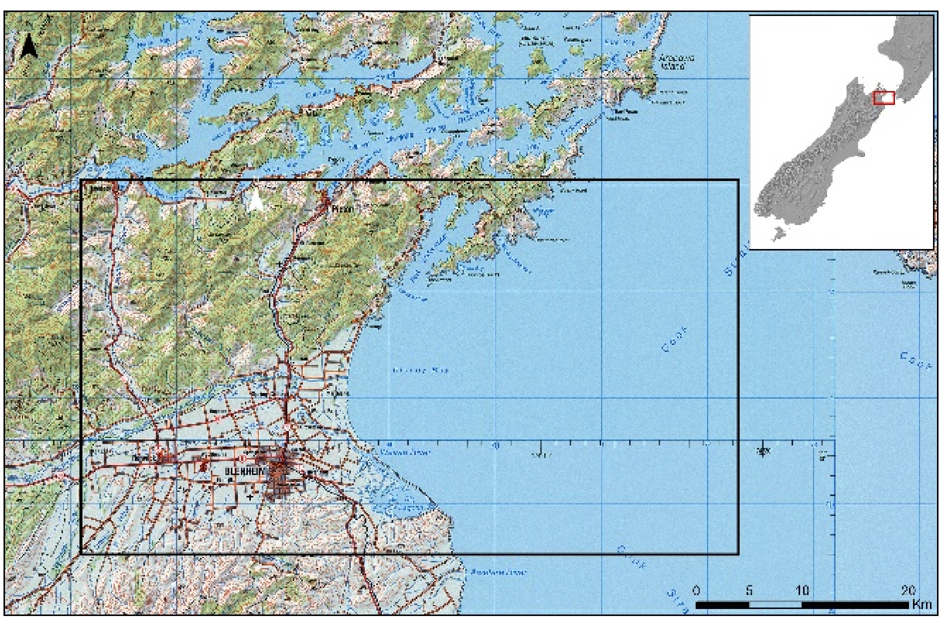


Figure 1. The Wairau Plain showing the extent of the geomorphic model and the 3D print of the model with locations of the Wairau River, Blenheim, Renwick, and Cloudy Bay.

Traditional 3D geological modelling, which typically represents chronostratigraphic units and layer properties, offers many opportunities in understanding groundwater systems (White et al. 2013). In addition, geomorphic models can describe the key features of a basin relevant to groundwater systems and the evolution of these features over geological time scales to assist in the understanding of present, and prehistoric, groundwater flow.

This paper presents the development of models of Late Pleistocene and Holocene geomorphic units of the Wairau Plain. The models describe the formation of these units (e.g., estuary, Boulder Bank, and Rarangi gravels), including their geographic distribution over the last 20,000 years at a 1,000-year time step, and maps prehistoric locations of coastlines, estuaries, rivers, and associated deposits. The paper also describes the evolution of the estuary between 8,000 years before present (B.P.) and 5,000 B.P. following Holocene sea level rise and examines the implications of the formation of this feature on prehistoric groundwater flow and locations of aquifers, aquicludes, and springs in the Wairau Plain.

New techniques in 3D printing offer opportunities for outreach and for increasing the community's understanding of geology and groundwater flow. This paper outlines the method that was used to print the 3D model of eight current-day geomorphic units, with rivers and the ocean, and summarises some outreach activities with the model.

Method

Geomorphic models were derived at 1,000-year time steps using relevant published information (e.g., White et al. 2016) to identify the drivers of sedimentation, including:

- sea level, which rose significantly between 20,000 years B.P. and 8.000 years B.P.;
- channels of rivers and streams that have moved in response to sea level rise and estuary formation;
- the development of the Boulder Bank, which played a significant role in the creation of the estuary;
- estuary formation, which coincided with the deposition of relatively large thicknesses of sands and silts that are aquicludes.

Firstly, the model used the geological modelling software EarthVision to represent two-dimensional surfaces through time. Then 3D data sets were used to assign the property of depositional age to Late Pleistocene and Holocene sediments in the Wairau Plain (e.g., White et al. 2016). The formation of geomorphic units in the period was represented as a cartooned set of 3D model images.

The evolution of the estuary between 8,000 years B.P. and 5,000 years B.P. was identified by reconstructing the movement of the coastline with Holocene sea level rise and the resulting formation of geomorphic units. Aquifers were identified with a 3D model of gravel distribution, as derived from well logs. The position and properties of the estuary were identified with a 3D model of the distribution of markers for prehistoric shorelines (i.e., identification of gravel with shells in well logs) and the 3D distribution of sands and fine sediments. The prehistoric distribution of the piezometric gradient was then estimated using a model of the current-day groundwater pressure distribution, perturbed for estuary position and properties.

3D printing of the current-day geomorphic model, with rivers and the ocean, required reprocessing of layer grids, i.e.,

- revising model layers so that wall thicknesses were greater than 1 mm in the final plot.
- the model elevation range was approximately 1,000 m above mean sea level to 500 m below mean sea level. Therefore, differential scaling of layers enhanced the units of prime interest to groundwater flow (i.e., layers within $\pm$10 m of sea level) in the 3D print.
- final scaling of 0.0065 to horizontal and vertical coordinates (i.e., the ratio of printer coordinates to revised model layer spatial coordinates).
- exporting printer coordinates as 3D-printer-ready stl files.

The 3D printer model was an Ultimaker 3 Extended with a print layer height of 0.2 mm and software, including Ultimaker Cura and Autodesk Netfabb. The print material was polylactic acid with multiple colours. The final model, printed in four blocks, has a size of approximately 40 $\times$ 23 $\times$ 14 cm. Print time was approximately 200 hours for all layers.

Results

The history of the development of key units for groundwater flow in the Wairau Plain was described in three key periods: 1) Between 20,000 years B.P. and 8,000 years B.P., sea level rose from approximately 120 m below current sea level to approximately current sea level. Holocene gravels were deposited above a Pleistocene gravel fan. 2) The period 8,000 years B.P. to 5,000 years B.P. saw development of a gravel riser that was formed from coarse beach-deposited gravels in the area landward of the current coastline between approximately Blenheim and Spring Creek.

The estuary formed behind the Boulder Bank, which developed in southern Cloudy Bay. This period also saw the development of spring-fed streams at Spring Creek and in the Blenheim area. 3) The period 5,000 years B.P. to the current day, where infilling of the estuary continued, the Wairau River channel shifted to its present position behind the Boulder Bank and Rarangi gravels (a coarse beach-deposited gravel) were deposited in northern Cloudy Bay at a linear rate of approximately 1 km per 1,000 years.

Mapped in 3D, the geomorphic units provided evidence for the development of aquifers and aquicludes in the Lower Wairau Plain. For example, the gravel riser generally marks the eastern boundary of relatively thick Holocene gravels deposited by the Wairau River. The location of the Boulder Bank was a significant control on the progressive infilling of the estuary and on the location of gravel deposits associated with the Wairau and Opawa Rivers. Groundwater pressures probably changed significantly in the period from 8,000 years B.P. to 5,000 years B.P because of a rise in Holocene sea level with estuary formation, progressively from the south. Firstly, the drowning of the Pleistocene Wairau River channel (located below modern-day Marshlands) early in this period probably led to formation of springs in the Spring Creek area. Then development of the estuary, which formed an aquiclude and a hydraulic barrier to surface flow, probably led to infill of now-buried valleys west of the gravel riser and the onset of artesian conditions, and commencement of spring flow, in the area west of the gravel riser.

The 3D printed model (Figure 2) has been demonstrated with the 3D model animation at a scientific conference, a meeting with Marlborough District councillors, a Rotorua Maori group, and a group of local citizens. The response to the model was uniformly positive. For example, one district councillor said after the presentation, “I learnt more in that 10-minute talk than in my whole first year of studying geology at university!” A presentation of the model to citizens was attended by blind people, who highlighted how much they appreciated being able to explore topographic and geological features with their hands.

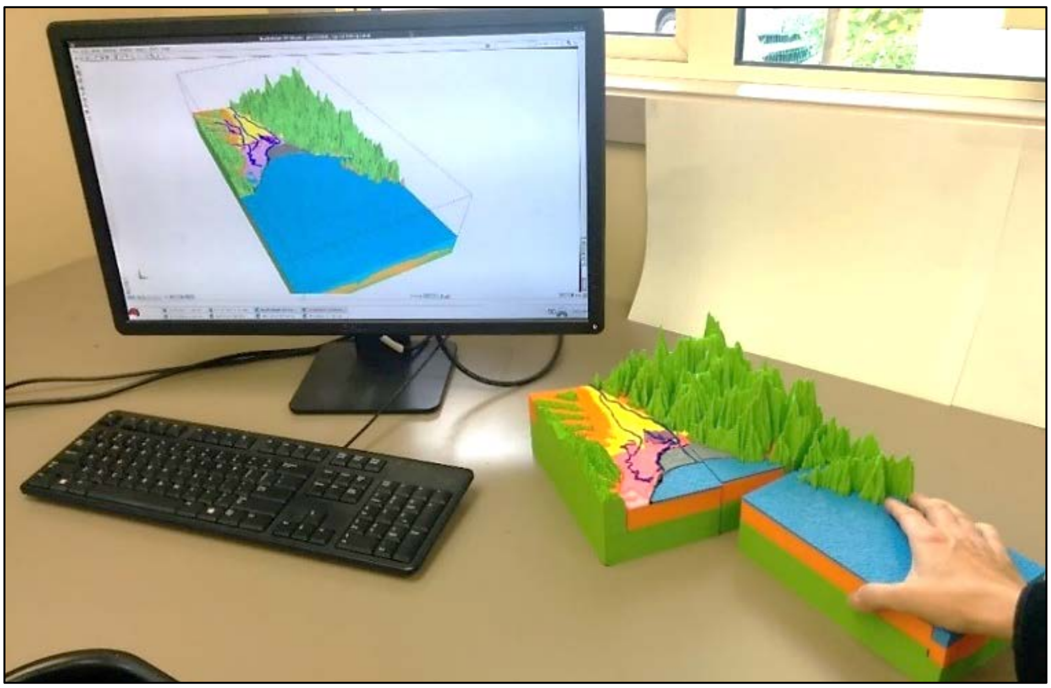


Figure 2. 3D geological models of the Wairau Plain, Marlborough District. The left-hand side of the image shows the 3D computer model. The right-hand side of the image shows the 3D print of this model. Note that unit colours in the printed model were chosen to match colours in the computer model.

References

White, P.A., C. Tschritter, and P. Davidson, 2013, Development of 3D models of sedimentary lithologies and piezometric levels to understand groundwater and surface water flows, lower Wairau Plain, Marlborough, New Zealand: Geological Society of America workshop on three-dimensional geological mapping, Denver, Colorado, October 26.

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