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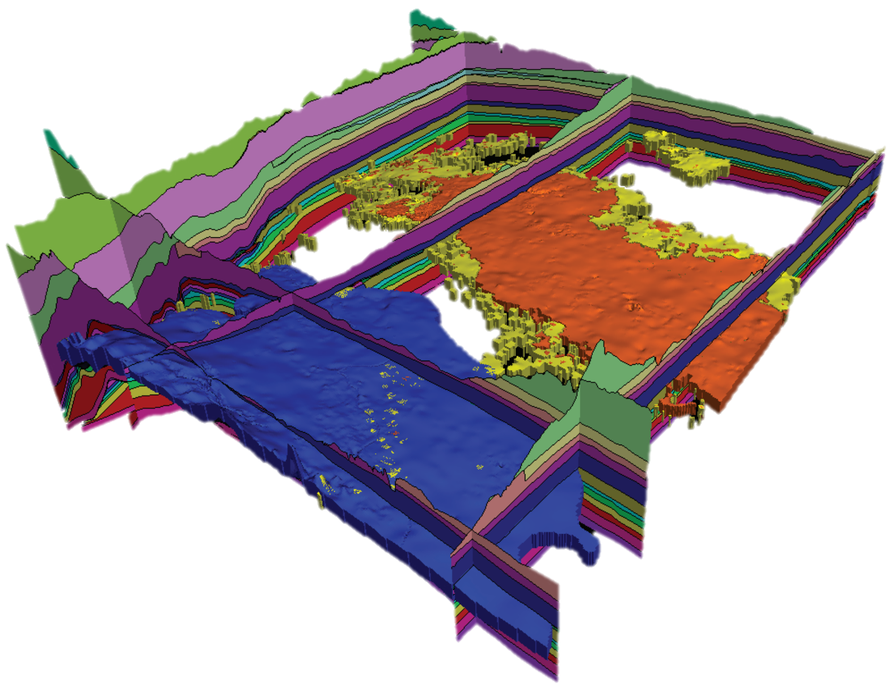
Three-Dimensional Geological Mapping



Workshop Extended Abstracts
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Kelsey MacCormack, Harvey Thorleifson,
Richard Berg, and Hazen Russell

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AER/AGS Special Report 101

Three-Dimensional Geological Mapping: Workshop Extended Abstracts

K.E. MacCormack[1], L.H. Thorleifson[2], R.C. Berg[3], and H.A.J. Russell[4]

[1] Alberta Energy Regulator
Alberta Geological Survey
[2] Minnesota Geological Survey
[3] Illinois State Geological Survey
[4] Geological Survey of Canada

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Alberta Energy Regulator
Alberta Geological Survey
4th Floor, Twin Atria Building
4999 – 98th Avenue
Edmonton, AB T6B 2X3
Canada

Tel: 780.638.4491
Fax: 780.422.1459
E-mail: AGS-Info@aer.ca
Website: ags.aer.ca

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Introduction

K.E. Maccormack[1], L.H.Thorleifson[2], R.C. Berg[3], and H.A.J. Russell[4]

[1] Alberta Geological Survey
[2] Minnesota Geological Survey
[3] Illinois State Geological Survey
[4] Geological Survey of Canada

Abstract

The objective of this year's 3D workshop is to bring experiences and knowledgeable people from all over the world to share advances in their 3D mapping and modelling programs, and discuss future strategies.

This is the 9th 3D Geological Mapping Workshop as part of a series that began in 2001. These workshops continue to provide opportunities for geologists and geoscience organizations from around the world to congregate and share information on methods for constructing, visualizing, and delivering jurisdictional scale 3D models to meet the needs of a variety of stakeholders. This event also provides an excellent opportunity to engage international experts in the field to strategize on the future of 3D mapping initiatives.

This year the GSA is honouring the bicentennial of William Smith's revolutionary map, we will also take a look back at the past, present, and speculate on the future of 3-D mapping.

Past – where have we been?

Looking back to the geological maps produced by William Smith 200 years ago, the cross-section views on his map to give users an appreciation of the third dimension. Early 3D mapping workshops hosted speakers focussing on necessity for developing stratigraphic framework models at a variety of scales, and the benefits of using these models to support hydrostratigraphic modelling efforts. As such, it was common for geoscience organizations to develop numerous models for a particular region, each for a separate purpose or objective function in mind.

Present - where are we now?

It has been 14 years since the first 3D mapping workshop (hosted in 2001), and we have seen the talks evolve from how to generate surfaces and access data suitable for building models, to talks on sophisticated, systematic modelling workflows capable of accounting for data quality, optimizing model output, and providing estimates of model uncertainty.

Models are typically constructed much earlier in the project lifecycle to assist with communication between interdisciplinary teams, and as a means to integrate and catalogue vast amounts of data and information. Speakers increasingly refer to their models as multi-purpose, as they are able to integrate more and more data into their models, turning them into 3D data repositories. This has resulted in an overall reduction in the number of jurisdictional scale models that are being built, with a much greater emphasis on data and information integration. Now that many organizations are focused on maintaining fewer models, they can focus their efforts on updating select models with new information to improve model accuracy and/or add additional resolution and detail to reflect the current subsurface understanding. This increased focus and efficiency of model updates has allowed static geological models to appear dynamic as they evolve, reflecting developments in our subsurface understanding over time.

Technological advances in modelling hardware and software have allowed current models to ingest vast amounts of data, and in turn, the models themselves are generating numerous realizations, scenarios, and information that must all be catalogued and stored. Although data management has always been important, society now expects to be able to access, view, manipulate, query, and download huge amounts of data at the touch of a button. Many of the talks in this workshop discuss the challenges of dealing with exceptionally large datasets, and the need for improved information dissemination mechanisms.

Future – Where are we going?

The demand for 3D models has been steadily increasing, and this trend will likely continue for quite some time. Many jurisdictions are requiring 3D models to assist with decision making and for policy development. Three-dimensional models are increasingly being used to facilitate stakeholder engagement and improve access to open data in a timely manner. In support of these initiatives, jurisdictions are transitioning from building separate models for specific uses, to building a single multi-disciplinary model that can be used for multiple uses. This will promote continual development of primary, multi-disciplinary models that will be designed to adapt and evolve over time. These developments will likely have cost and staff resourcing implications for geoscience organizations needing to find ways to integrate increasing amounts of data, and build models more efficiently. As a result, we will likely see more organizations push towards the development of systematic and semi-automated workflows allowing models to be updated with new data and information, and disseminated to stakeholders in a timelier manner. We will also likely see an increasing trend towards more interactive data dissemination methods, providing users with the ability to choose the information they are interested in visualizing, and view it within an interactive 3D geological context. Rather than provide users with maps or images of the information we think they would like to see, dissemination tools will continue to develop allowing users to interact and access a wide variety of information in a timely manner. This will allow geoscience organizations to more readily adapt to changing requirements, and meet user needs.

Summary

At this year's 3D workshop, the focus will be on how various geoscience organizations and their partners are characterizing subsurface strata in 3D space at a variety of scales for multi-disciplinary analysis, and developing dissemination mechanisms to communicate data and information to a variety of stakeholders.

Extended abstracts and presentations from all workshops are available on the Illinois State Geological Survey web site.

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Rationale and Methods for Regional 3D Geological Mapping Programs

L. H. Thorleifson

Minnesota Geological Survey, St. Paul, Minnesota, USA, thorleif@umn.edu

Abstract

Regional three-dimensional (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, to support applications such as groundwater management, engineering, and sedimentary basin assessments. 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. 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).

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 thus is 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 material, process, 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, due to increased data availability, improved technology, intensified land use, and escalating societal expectations.

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), wellhead protection (EPA, 1998), hydrogeological conceptual modeling (Anderson and Woessner, 1992; Bredehoeft, 2005; Kresic, 2007; LeGrand and Rosen, 2000; Royse et al., 2010), hydrogeological property attribution, quantitative groundwater modeling, engineering (Fookes, 1997), sedimentary basin assessments, mineral resources assessment, hazards, and fundamental research.

Geological mapping is guided by well-established stratigraphic principles. Facies models and basin analysis (Miall, 2000; 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; Seaber, 1988; Weiss and Williamson, 1985).

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, whose 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).

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, to digitize, to georeference, and to categorize by lithology (Thorleifson and Pyne, 2004).

Data acquisition – What field work is needed?

Some new field work will be required to benchmark the 3D mapping. Geophysical surveys (Everett, 2013; Pellerin et al., 2009; Styles, 2012) may include EM (Abraham et al., 2012; Jorgensen et al., 2013; Oldenborger et al., 2013), seismic (Pugin et al., 2009; Chandler and Lively, 2014), radar, borehole geophysical surveys, and marine geophysics (Todd et al., 1998). New drilling will be required in many programs to provide stratigraphic benchmarks that the models are anchored to.

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 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; Jones et al., 2009; Patel and McCechan, 2003; Kaufmann and Martin, 2008; 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 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 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), 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).

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).

Research on heterogeneity includes, for example, recognition of structure-imitating approaches, process-imitating models, and descriptive methods (Kolterman and Gorelick, 1996). 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). 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).

Examples – What have other people done?

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

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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Building Information Modelling (BIM) – A Route for Geological Models to Have Real World Impact

Holger Kessler[1], Ben Wood, Gary Morin[2], Angelos Gakis[3], Gerard McArdle[4], Oliver Dabson[5], Ross Fitzgerald[5], Rachel Dearden[1]

[1] British Geological Survey, Nicker Kill, Keyworth, Notts, NG125GG, UK
[2] Keynetix, Systems House, Redditch, Worcester, B98 9PA, UK
[3] Dr. Sauer & Partners Ltd, 11 Langley Avenue, Surbiton, Surrey, KT6 6QH, UK
[4] Tata Steel Projects, Meridian House, The Crescent, York, YO24 1AW, UK
[5] CH2M, Elms House, 43 Brook Green, London, W6 7EF, UK

Abstract

The rapid rise of Building Information Modelling (BIM) represents a major opportunity for Geological Survey Organisations (GSO) to make their data and in particular three-dimensional geological models accessible to the civil engineering and construction industry. The paper presents how GSOs and the private sector are preparing themselves for a possible paradigm shift with the vision of a 'live' ground model becoming a possibility, leading to real efficiency gains and risk reduction during construction and throughout the life time of an asset.

Introduction

Three-dimensional geological models are now routinely used in within geological surveys and to some extent in the development of groundwater models (Royse et al 2010, Berg et al 2011). Uptake in the construction and civil engineering sectors however has lagged behind (Kessler et al 2008). This situation might be about to change rapidly with the uptake of the concept of Building Information Modelling (BIM) within the geotechnical industry. BIM is a process involving the generation and management of digital representations of physical and functional characteristics of a building or places. The BIM process will facilitate the sharing of data and models such that isolated teams can work together in a much more integrated and collaborative manner. This will enable much better decision-making about the design, construction, management and the eventual decommissioning of the building or structure as depicted in Figure 1.

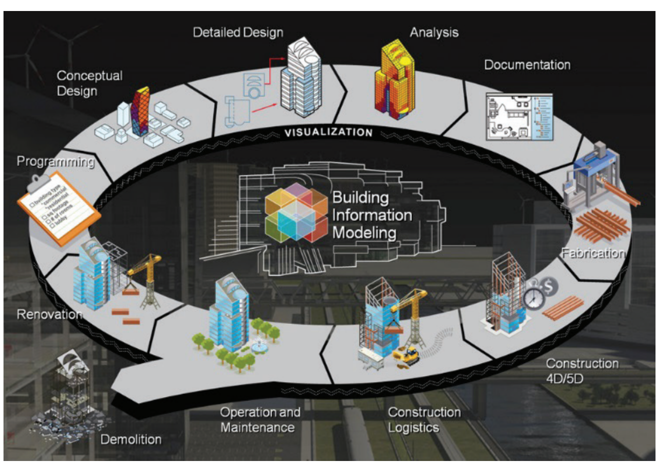

Figure 1. BIM lifecycle (image courtesy of Autodesk)

BIM is becoming increasingly important in the UK; the UK government has stipulated, for example, that all public sector funded work must be carried out to BIM level 2 by 2016. Given that the global construction sector is forecast to grow by 70% by 2025 (HM Government 2015) interest in BIM is likely to increase. In the UK, projects such as Crossrail, High Speed 2, new nuclear builds, electrification of railways and major upgrades to the road network and flood defences will all require major ground investigations and are all to be delivered BIM compliant. Since most construction happens to be placed on or in the ground, the implications for Geological Survey Organisations (GSO) and their data and models are huge.

Implications and opportunities for Geological Survey Organisations

The main themes of BIM are collaborative working, data sharing and full life cycle of data management – all of which are core principles of any GSO. Consequently GSOs have been on a very similar journey over the past few decades, Figure 2 illustrates how the stages of BIM maturity closely match the stages of the evolution of a GSO (Kessler and Mathers 2006).

The transition for GSOs from mapping geology in two to three dimensions, required a fundamental reconsideration of acquisition methodologies, data management and dissemination mechanisms. In times of reduced resourcing, geological surveys need to be more open to keep pace with the continuously evolving understanding of the subsurface, which is driven by the acquisition of new data by external parties in particular the construction sector as mentioned above. As a national survey it needs to be able to create and maintain authoritative models nationally and convey uncertainty, particularly where data is sparse, clustered or of varying quality, and it needs to be sufficiently flexible to allow the generation of outputs at a wide range of resolutions. To resolve these challenges, the British Geological Survey, as well as many other leading GSOs, are developing infrastructure that allows geologists to make interpretations and models that can easily be incrementally updated as more data becomes available. It is therefore paramount that data and models are as accessible as possible to the user community and integrate seamlessly with the methodologies and software tools used in the construction sector.

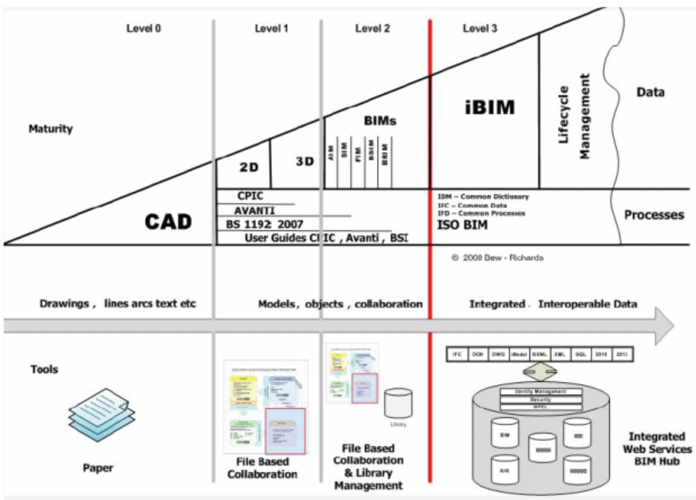

Figure 2. BIM levels and associated methodologies and technologies (BIM Working Party 2011)

Involving the end user community – BIM for the Subsurface

Geology is still absent from most BIM models but technology together with data transfer standards such as the AGS format (Association of Geotechnical and Geoenvironmental Specialist http://ags.org.uk/data-format/) are already available to allow the fast access and visualisation of factual geotechnical data in standard software tools used by engineers. These standards currently allow project based factual geotechnical data to be managed and visualised, generating high-quality output of geotechnical logs, sections and 3D visualisation. However this needs to be taken to the next level to allow engineers to fully collaborate and utilise the wealth of existing knowledge and share both factual and interpreted data throughout all construction projects; this is the intention of the BIM for the Subsurface project (http://www.keynetix.com/bimforthesubsurface/). This two year project is funded by Innovate UK under its Digitising the Construction Industry initiative and is due to be completed in April 2017; the project partners include Keynetix, BGS, Atkins and Autodesk. (Grice and Kessler 2015)

The aim of the project is to significantly advance current technology, HoleBASE SI and the extension for AutoCAD Civil 3D, and deliver a geotechnical BIM solution through the development of a cloud based repository that will allow the storing, sharing and re-use of subsurface data, including interpretative data and access to the wealth of BGS historic data, throughout the supply chain. The project will integrate the BGS proven 3D geological modelling methodologies within the AutoCAD Civil 3D extension (a prototype is shown in Figure 3), with the aim of generating detailed 3D site models from local geotechnical data together with data from the BGS National Geological Model (Mathers et al 2014). The ultimate aim is for geotechnical engineers to use and create more detailed site models and for these to be shared, where possible, to enhance the national knowledgebase.

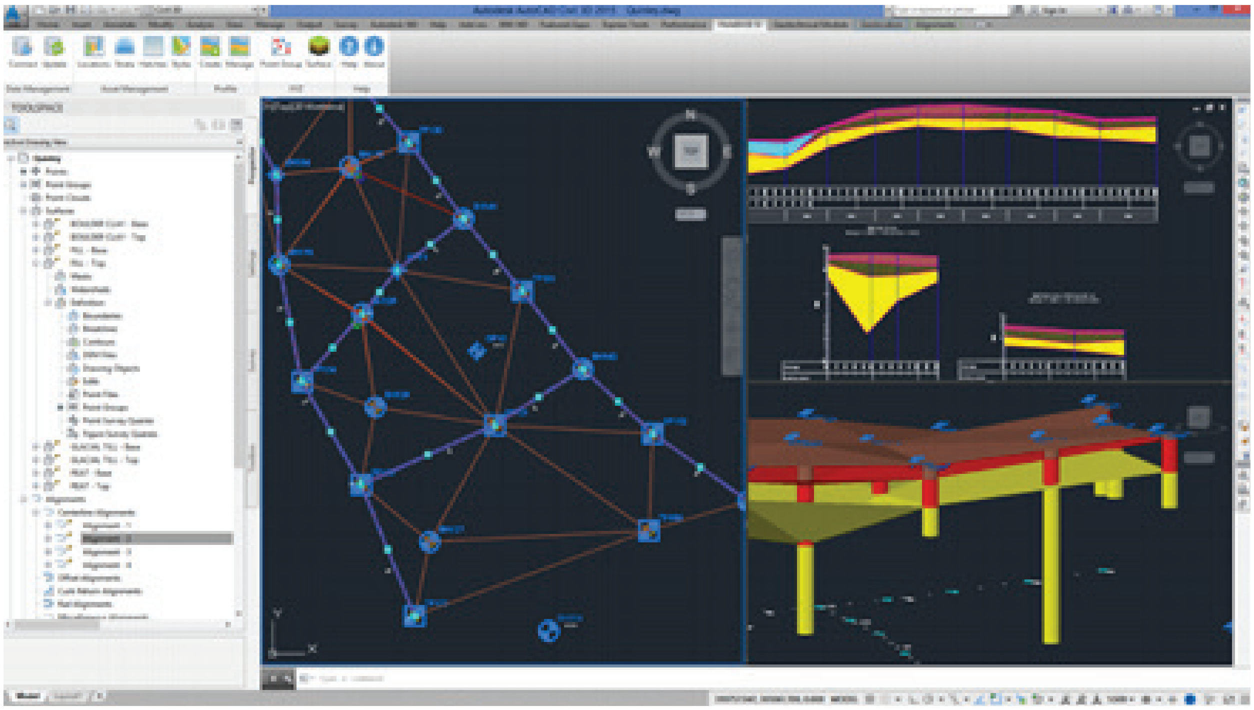

Figure 3. BIM software showing 3D geological objects (courtesy of Autodesk)

An emerging BIM strategy at CH2M

As mentioned the process of fulfilling BIM objectives in industry has certainly been more straightforward in some markets than others. Strong focus has been placed on the construction, operation and maintenance of new structures, and consequently the teams rooted in the design of these already have a suite of BIM-complicit software products at their disposal. In the geotechnical sector, where relatively traditional, 2D methodologies are still commonplace, the production of an integrated 3D information hub has been noticeably more difficult. Achieving this is crucial in major infrastructure schemes where effective and integrated management of 'Big Data' significantly enhances project efficiency.

CH2M have recently undertaken a research and development project to explore the feasibility of 3D subsurface modelling as a technical solution to this challenge. It was identified at an early stage that 3D modelling provides a fully digital interface to store, visualise and interrogate ground conditions. In a manner that is coherent with BIM ideologies, this information 'hub' can house all subsurface data and interpretation across the project site (see Figure 4). This may be used to identify areas of uncertainty or risk at an early stage to focus subsequent ground investigation to these locations, which at a commercial level maximises the investment into GI while reducing down-the-line costs associated with 'unexpected' geotechnical issues during construction.

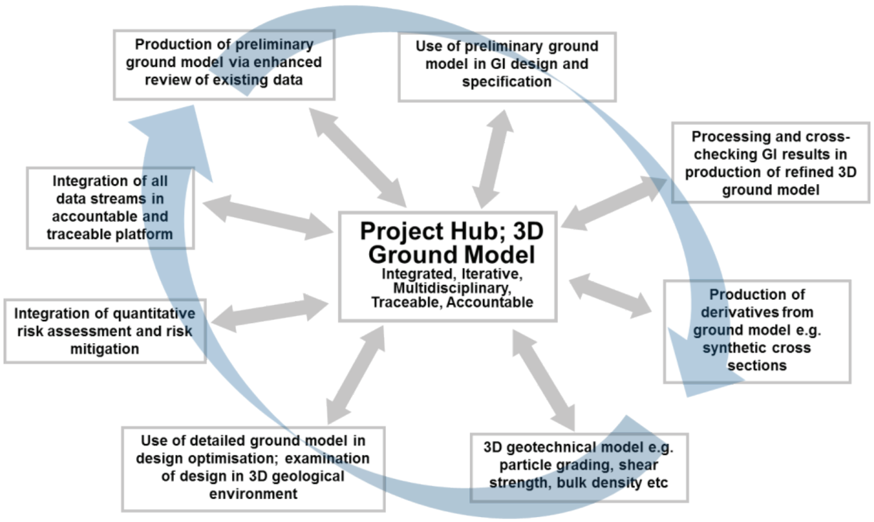

Figure 4. 3D model as the nucleus of a typical interactive project workflow as per BIM philosophy (from Fitzgerald and Dabson 2015)

The use of 3D geological models in real world engineering projects

Farringdon station project – benefits of a ground model in reducing construction risk

Crossrail is currently Europe's biggest construction project creating a 42 km long east-west rail connection beneath London. Most of the tunnelling was carried out in London Clay which is a perfect tunnelling medium and, with thicknesses reaching above 40m, is widespread beneath London. However, at Farringdon, the ground conditions are more complex as the station was excavated below the London Clay in the Lambeth Group. Additionally, Farringdon Station is the first application of sprayed concrete lining (SCL) to a tunnel excavated almost entirely in the Lambeth Group. Due to these geological and construction complexities an early decision was made to exploit the existing BGS 3D geological model (Aldiss et al, 2012) and integrate it into in the site supervision workflow. The main geotechnical risks arose from the presence of randomly distributed, water bearing sand lenses, interbedded within the clays of the Lambeth Group and the presence of multiple geological faults. The 3D model was progressively developed by being fed geological data recorded following each step of tunnel excavation. As a result ground conditions could more reliably be predicted ahead of subsequent tunnel excavation.

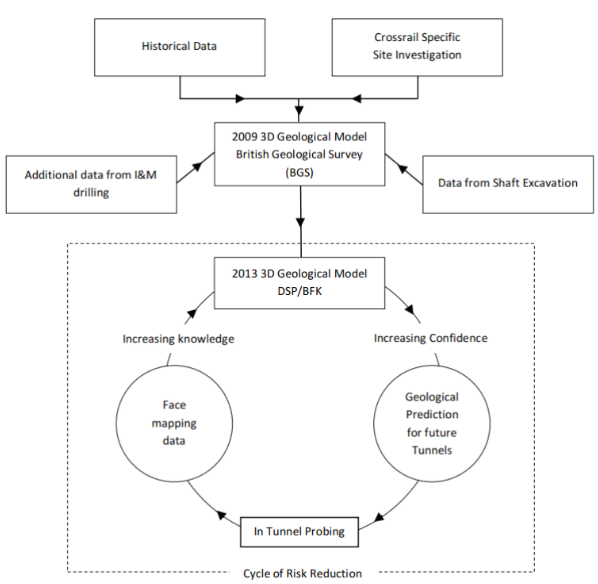

Figure 5. The cycle of risk reduction (from Gakis et al 2014)

Using this method the 3D geological model forms the hub of a cycle of risk reduction (see Fig 5). It uses data from in-tunnel probing and face mapping to progressively increase knowledge of ground conditions, enhance the accuracy of and confidence in predictions and ultimately reduce geotechnical risk to the project. As per the BIM principle of life-time asset management all the geotechnical data from the excavations have been stored in the 3D model's database and will be handed over to the BGS to be used by Crossrail and others for future purposes.

A 3D geological model for Railway Electrification between Leeds and York

Recently the BGS undertook a 3D modelling project along 28 km of railway line between Leeds and York on behalf of Tata Steel Projects (Burke et al 2015). The model was constructed using 1:10,000 scale digital geological map data and 102 borehole logs. The final conceptual ground model (CGM) indicated the top and base elevations of the geological units and weathered rockhead and major faults were defined as separate surfaces. The purpose of the work was to identify areas where targeted ground investigation could be undertaken in the early assessments of the design of deep or shallow mast foundations for the electrification of the route. After overcoming substantial challenges with projection systems, the model was delivered as CAD files and the client was able to integrate the CGM within their in house BIM workflow as shown in Figure 6.

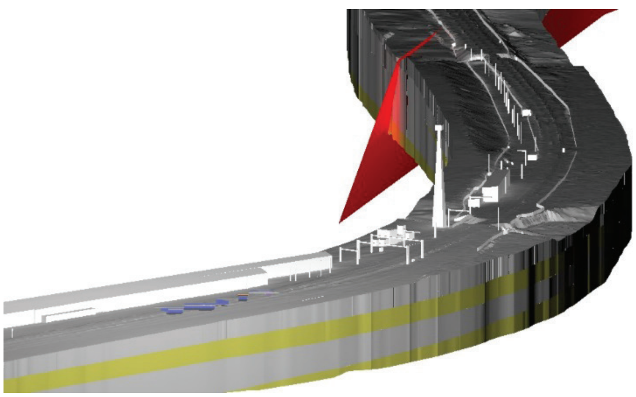

Figure 6. BGS Conceptual Ground Model (sandstones and mudstones in grey and yellow plus a fault in red) of a site near Leeds (UK) with existing and proposed overhead line electrification and building infrastructure

Conclusions

Current and future growth and investment in national infrastructure in the UK is providing a perfect storm of new data and opportunities for collaboration and technical advancement. Furthermore, government commitment to the application of BIM strategies to publically funded projects is providing a driver for digitization of the construction sector, and will enable the sharing of construction models. Unforeseen ground conditions continue to be a major source of project delay, and ambitious schemes and testbeds are underway to explore ways of incorporating geology into real projects via geotechnical BIM workflows to minimize cost and risk. GSO's are key players in this arena and need to step up to the challenge of delivering their data and models seamlessly into BIM workflows. In the future, provision of BIM-compliant data services and software will be routine. The ability to seamlessly incorporate and share subsurface data within construction projects will ultimately lead to the realization of 'live' ground models, where pertinent data is available on-demand in suitable formats and can be easily shared throughout the project lifecycle.

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National-Scale 3D Mapping – What Approach Might Be Feasible For The United States?

SOLLER, David R. and STAMM, Nancy R.

U.S. Geological Survey, 926-A National Center, Reston, VA 20192, drsoller@usgs.gov

Since the beginnings of geological surveys in the United States in the 1800s, stratigraphic studies and geologic mapping have been conducted and published. The result is a substantial body of readily available knowledge regarding the regional geologic framework; that is, the Nation's geology in three dimensions. It is widely recognized that national, regional, and local 3D mapping is urgently needed in order to address societal issues, as well as to provide a general understanding and visualization of the upper portion of Earth's crust.

In order to contribute to improved understanding of the Nation's geologic framework, the USGS and the Association of American State Geologists (AASG) are mandated by Congress to provide a National Geologic Map Database (NGMDB, http://ngmdb.usgs.gov/) of standardized, spatial geoscience information, for use by the public and by scientists alike. The NGMDB provides access to >21,000 publications containing stratigraphic columns and cross sections, a subset of which could be used as source information to compile a generalized depiction of the Nation's 3D geology. The challenge is scientific, not technological – for example, which source publications should be used, how many subsurface horizons should be modeled regionally or (if feasible) nationally, and so forth. Discussion of the feasibility of this work has begun; this presentation will focus on various possible approaches to this work at a generalized, national scale.

A Perspective on a Three Dimensional Framework for Canadian Geology

H.A.J. Russell[1], B. Brodaric[1], G.R. Keller[2], K.E. MacCormack[3], D.B. Snyder[1], and M.R. St-Onge[1]

[1] Geological Survey of Canada, 601 Booth St. Ottawa, ON., K1A 0E8, Canada
[2] Manitoba Geological Survey, Winnipeg, MB., Canada
[3] Alberta Geological Survey, Alberta Energy Regulator, Edmonton, AB., Canada

Introduction

The intensification of economic development over the past 200 years and the increasing impact and conflict in land use requires an adaptation in how we investigate, analyze, report, store, and disseminate geological knowledge. In the 19th century William Smith mapped much of Great Britain in two dimensions. Smith's mapping was spurred on by the emergence of the industrial revolution and enormous changes required to support mineral exploration, and transportation of raw and manufactured goods. In developed countries, particularly in Europe, there is an increasing realization and acknowledgement of the need for three-dimensional (3D) geological mapping programs to address the complexity of conflicting land use practices in the 21st century. Two hundred years after Smith's seminal map, the 21st century requires a move from 2D to 3D geological mapping, particularly at the national scale (e.g., Thorleifson et al., 2010). This transition is less dramatic than it might seem. Even in the early maps of Smith, geology was presented with an appreciation for the third dimension, through the use of cross-sections and subsequently structural symbols. A wealth of subsurface information has been accumulated from drilling and geophysical studies supporting surface mapping. With access to surface and subsurface data, Geological Survey Organizations (GSOs) in a number of jurisdictions have made significant progress in the development and implementation of 3D mapping programs (e.g., Howard et al., 2009; Berg et al., 2011; Meulen et al., 2013; Mather et al., 2014). Such programs commonly have much broader objectives than just 3D visualization of a jurisdiction's geology. These programs are focused on a full continuum of data management, storage, analysis and classification for 3D realization (e.g., Howard et al., 2009). The recent proliferation in jurisdictional wide 3D mapping is the outcome of the maturity of a digital transformation in geological data collection and management that started over 25 years ago and includes computer hardware and software developments of the past half century.

Canada is a large country at 9 million km2, and dwarfs most countries with developing 3D mapping programs by up to several orders of magnitude (Table 1). Furthermore, whereas some of these countries have relatively simple geological successions of undeformed sedimentary strata (e.g., Netherlands, Denmark), the geology of Canada is diverse, locally complex (e.g., orogenic belts) and with extensive submarine extensions of its terrestrial geology into the marine environment of archipelagos and continental shelves. An exception to this statement is Australia, which is only 20 % smaller than Canada, has diverse, complex geology, yet has made progress modelling nearly one-third of the country. A parallel initiative called DigitalCrust (Fan et al., 2014) has an objective of developing a 4D geological framework of the upper crust of the continental USA. In a number of countries physical based modelling appears to precede national geological modelling by a considerable period. Denmark had a national hydrological model over ten years before consideration of a national geological model (Henriksen et al., 2003). Similarly in North America significant progress has been made in modelling the groundwater regime of both the USA and Canada with simplified geology (Maxwell et al., 2015; Chen, 2015).

The objective of this paper is to review the extent of current 3-D mapping, address the question of data support for 3D geological mapping, consider how the geological landscape may be parsed into distinct entities to facilitate 3D geological mapping, and illustrate a progressive approach to advance discussion on to how to achieve the ambitious goal of a 3D framework for the geology of Canada.

Status of regional 3D mapping in Canada

The term 3D geological mapping evolved in the 1990's as digital geological mapping techniques started to emerge as a complementary term to differentiate the digital mapping - modelling approach from traditional subsurface studies. For decades subsurface studies had been completed, and subsurface data (borehole data, geophysics) have been analyzed and archived through the construction of cross-sections, and development of structural and isopach surfaces of geological formations. Progress has systematically advanced from more conceptual models to progressively more data driven realizations. This is true across the Canadian landscape from definition of the lower crust (e.g., Perry et al., 2002), complex bedrock structure (e.g., de Kemp et al., 2015) to sedimentary basins (e.g., McCrossan and Glaister, 1964) and the Quaternary succession (e.g., Matile et al., 2011). In the Phanerozoic bedrock basins of Canada the crowning achievement in this regard is the latest version of the Western Canadian Sedimentary Basin Atlas by Mossop and Shetsen (1994). This landmark publication heralds the transition from conventional compilation and publications as it managed and produced the 2-D structural maps using computer technology. More modest were the many maps of larger scale produced by geological surveys across Canada of bedrock surfaces, commonly at 1:50,000 scale to support a range of activities, but particularly groundwater studies. In the marine environment the wealth of data being collected by seismic surveys has also been interpreted and archived in 2D format (e.g., Syvitski and Praeg, 1990; Campbell et al., 2015). In the 1990's as GSOs transitioned from traditional cartography to digital map production there was an increase in the use of GIS systems to manage and visualize subsurface geology. Much of this 2.5D model construction forms the basis for existing regional 3D mapping coverage developed to support environmental applications (e.g., Russell et al., 2010). At the Canadian provincial scale the three Prairie Provinces have the most advanced 3D mapping programs (e.g., McCormick and Banks, 2013; Card et al., 2010; Matile et al., 2011), with Ontario advancing both bedrock and surficial modelling initiatives. The Alberta framework model covers an area of 661,848 km using primary borehole stratigraphic logs (McCormick and Banks, 2013). Conversely, working with legacy structural interpretations from the Western Canada Sedimentary Basin Atlas Matile et al. (2011) generated a 1,425,000 km^2 model (Fig. 1). Using primary stratigraphic well picks from > 9000 borehole logs they also constructed a 494,000 km^2 model of the Williston Basin (Table 2). In Quebec groundwater funding has supported regional scale 3D mapping of the surficial geology (e.g., Cloutier et al., 2014) and to a lesser extent bedrock stratigraphy in the St Lawrence Lowlands. Saskatchewan has been particularly active in 3D modelling of uranium rich Athabasca Basin (Card et al., 2010) and the GSC has completed 3D modelling of mineral deposit camps (e.g., de Kemp et al., 2015). Less visible are the variety of 3D geological models being developed by industry for resource extraction, environmental monitoring and project planning and development. One example in Southern Ontario is the 35,000 km2, 37 layer model of the Phanerozoic by the Nuclear Waste Management Organization (Itasca and AECOM, 2011).

Table 1. Size and characteristics of some jurisdiction wide geological and groundwater modelling initiatives. [1]Meulen et al. (2013), [2]Jørgensen et al. (2013) [3]Henriksen et al. (2003), [4]GeoMol Team (2015), [5]Mathers et al. (2014), [6]Matile et al. (2011), [7]MacCormack and Banks (2013), [8]Australia. (2015), [9]Maxwell et al. (2015),[10]Chen (2015).

	Jurisdiction	Model type	Size km²	Characteristic	Model extent
1	Holland	Geological	5000	sedimentary	complete
2	Denmark	Geological	42,000	sedimentary	partial
3	Denmark	Hydrogeological	42,000	sedimentary	complete
4	Bavaria	Geological	55,000	Orogenic, foreland	partial
5	Great Britain	Geological	229,848	Sedimentary, crystalline, orogenic	partial
6	Manitoba	Geological	647,797	Sedimentary, crystalline	partial, sedimentary region
7	Alberta	Geological	661,848	Sedimentary, crystalline, orogenic	partial, sedimentary, undeformed region
8	Australia	Geological	7,692,024	Sedimentary, crystalline, orogenic	partial, 1/3 country
9	USA	Hydrogeological	~8,000,000	Numeric flow model, continental US	complete, continental
10	Canada	Hydrogeological	9,984,670	Numeric flow model, continental Canada	complete, continental

Table 2. Examples of public domain regional bedrock modelling in Canada. References 1de Kemp et al. (2015), 2Itasca and AECOM (2011), 3Card et al. (2010), 4,6Matile et al. (2013), 5MacCormack and Banks (2013).

	Jurisdiction – region	Size km²	Geology	layers	Data support
1	Purcell Basin	7,000	volcanic	15 km	Boreholes, outcrop, geophysics
2	OPG Repository, ON.	35,000	sedimentary	37	borehole stratigraphy
3	Athabasca basin	35,000	sedimentary	6?	borehole stratigraphy
4	Williston Basin	494,000	sedimentary	42	borehole stratigraphy
5	Alberta	661,848	sedimentary	23 – 52	borehole stratigraphy
6	WCSB	1,425,000	sedimentary	11	legacy

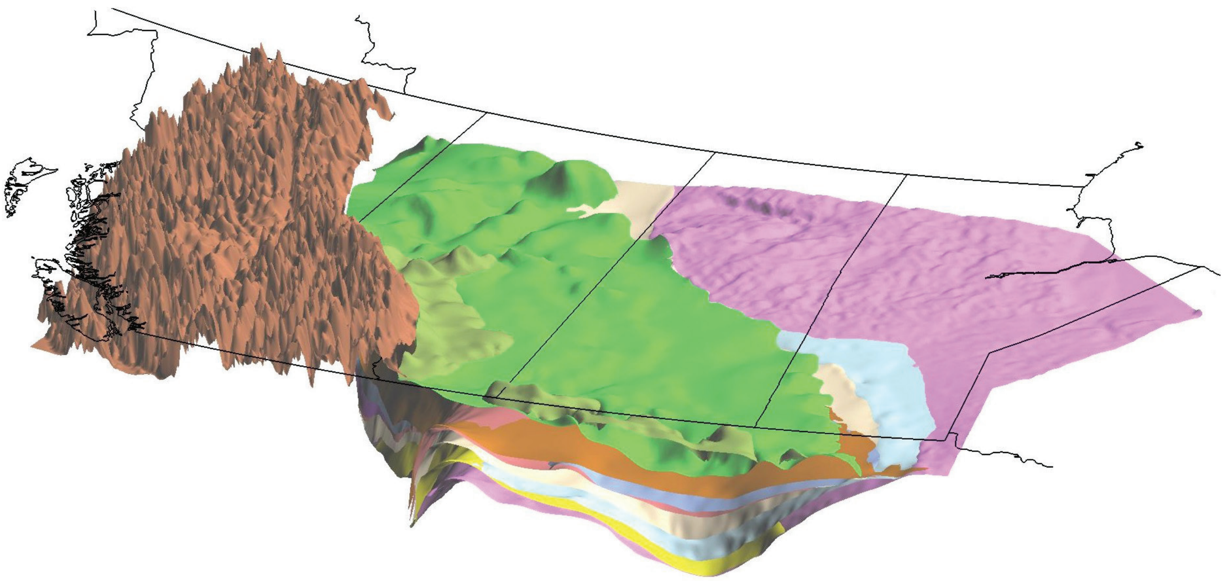


Figure 1. Three dimensional geological model of 1,425,000 km^2 area of the Western Canadian Sedimentary Basin (WCSB). Model consist of 11 layers developed from structural and isopach data of the WCSB Atlas (Mossop and Shetsen, 1994). Reported in Matile et al. (2013).

Collaboration and Data support

Data support for a national 3D initiative is diverse and reliant not only on public domain data but also accessibility to additional data that may be held by public agencies under a user-pay-system or proprietary private sector data. Data support is also dependent upon collaboration between provincial geological surveys and the federal GSC. Much of the geological data and the expertise necessary for respective regions of the country are divided between provincial and federal agencies. Given diminishing human and financial resources along with jurisdictional responsibilities collaboration is essential and has implications for the nature of the data management framework (see section 4). Unlike some other national geoscience organizations (e.g., Australia, Riganti et al., 2015), the GSC lacks a coherent data management system that could provide a turn-key operation to support 3D mapping. Rather much of the legacy data available to support 3D mapping is in paper or analogue format and is thus costly and time consuming to access and re-interpret. Where formally published this material is being systematically digitized and made available online, unfortunately as individual PDF or raster format digital files of respective publications (e.g., Geoscan). Fortunately, for the petroleum provinces of Canada, legislated data reporting has resulted in extensive and well managed stratigraphic databases (e.g., Carter and Castillo, 2006). This accounts, however, for less than one-fifth of the Canadian landmass. Private sector datasets, particularly geophysical data are extensive but difficult to access, assess, and integrate into public initiatives. On a positive note the progressive move by governments to Open Data initiatives (e.g., http://open.canada.ca/en) backed in some cases by well-organized digital databases greatly facilitates the ability to synthesize and deliver data for a Canada 3D initiative. For example a number of provinces maintain databases of water well records and for 8 of 10 provinces this data is available via the Groundwater Information Network (GIN; Brodaric et al., 2014). Similarly for petroleum provinces respective provincial jurisdictions maintain pay-for-access data repositories (e.g., Carter and Castillo, 2006). Such regional to national coverage are also available for deeper depths, for example geophysical datasets exist for the crust and Moho (e.g., Perry et al., 2002).

Table 3. Examples of public domain regional surficial modelling in Canada. [1]Cloutier et al. (2014), [2]Logan et al. (2006); [3]Gao et al. (2006); [5]Smith and Lesk-Winfield (2010); [6,7]Matille et al. (2011).

	Jurisdiction	Size km^2	Layers	Data support
1	Abitibi, Quebec	9,200	11	water wells
2	Oak Ridges Moraine	12,000	6	water wells, core, seismic
3	S Ontario	72,000	2	water wells
4	Mackenzie valley	~1,600,000	2	seismic shot holes
5	Manitoba, SE	45,000	17	water wells
6	Alberta	131,000	4 - 8	water wells
7	Manitoba, SW	176,225	35,	water wells, seismic

Data Management

Advancement of the geological knowledge component of the 3D mapping is only possible with a solid data management framework. Given the diversity of data and end objective of a national 3D model the optimal option is a hierarchical system of distributed databases with a central database that manages model inputs and outputs, and metadata links to its source databases. The central database enables an evergreen approach, by which the model can be updated upon new model inputs, and it also enables thematic search and visualization of outputs and inputs. As much of the mapping data is currently in legacy holdings of geological agencies as either unpublished material, knowledge publications, published data releases, and databases a means of maintaining access to the data being interpreted and coded is necessary. Many datasets have been scanned and are only available as raster or PDF publication products. There is a need for the conversion and often reattribution of this data for integration into a control dataset. The challenge of capture, storage organization, and maintenance of data during this intermediary step is likely subject or discipline specific. For example the capture, interpretation and extraction of geological interpretations of geophysical data (e.g., de Kemp., 2015). Fortunately a number of initiatives have established working components for this process. A geological database of geological unit descriptions, i.e. a lexicon of geological units, has been established and implemented through the Geological mapping for Energy and Minerals (GEM) initiative and the Tri-Territorial Bedrock compilation project (Brodaric, et al., 2015). This database provides information about a specific bedrock unit, compiled from many sources of literature, enabling sophisticated querying of the units. The communication, standardization and client delivery of data has been implemented at a national scale by the Groundwater Information Network (GIN) which is serving disparate data from 8 provincial water well databases along with time series monitoring data from a number additional provincial and international data sources including the USGS (Brodaric, et al., 2014). Through the work of various participants there is also a strong integration with international geological standards for delivery of geological information via web protocols (Sen & Duffy, 2005).

Parsing geological complexity

The geology of Canada is diverse, the data support ranges from surface mapping to extensive subsurface datasets, and the knowledge framework has similar diversity in understanding. The 3D mapping of Canada needs to address these differences by integrating support across the provincial and federal levels. Consequently it is unlikely that one approach will work for the entire country. It is also, equally unlikely, that progress will be advanced for all geological layers, domains, and jurisdictions with equal timing. It is thus necessary to consider how to parse the geological complexities into manageable and as geologically homogeneous entities as possible, both vertically and horizontally. The extensive physiographic, and geological mapping along with subsurface studies completed to-date provides insight into this issue. The

9 volume Geology of Canada (e.g., Wheeler and Palmer, 1993) provides a guideline on how to approach the problem with its division of Canada into shield, orogenic belts, cover rocks, and Quaternary (Fig. 2). Both the shield and orogenic belts are structurally complex with extensive folding and faulting resulting in stratigraphic reversals and abrupt lateral and vertical changes in rock units. These two elements are thus the most complicated domains in which to complete 3D mapping. Each is nevertheless composed of large structural domains that have some elements that can be conceptualized in consistent manners and likely delimited by available data support. Sedimentary cover rocks whether on the shield (Athabasca Basin) or one of the numerous Phanerozoic basins generally have limited structural complexity with predominantly subhorizontal and only modest normal and reverse fault offsets of strata (e.g., Southern Ontario, Fig. 3). For large parts of the country where petroleum resources are exploited there is extensive data support for regional 3D mapping (e.g., Carter and Castillo, 2006; Mossop and Shetsen, 1994). The Quaternary cover of Canada is an element on its own but the distribution, thickness and character of glacial sediment is also closely correlated with the bedrock domains. Consequently across areas of extensive cover rock surficial

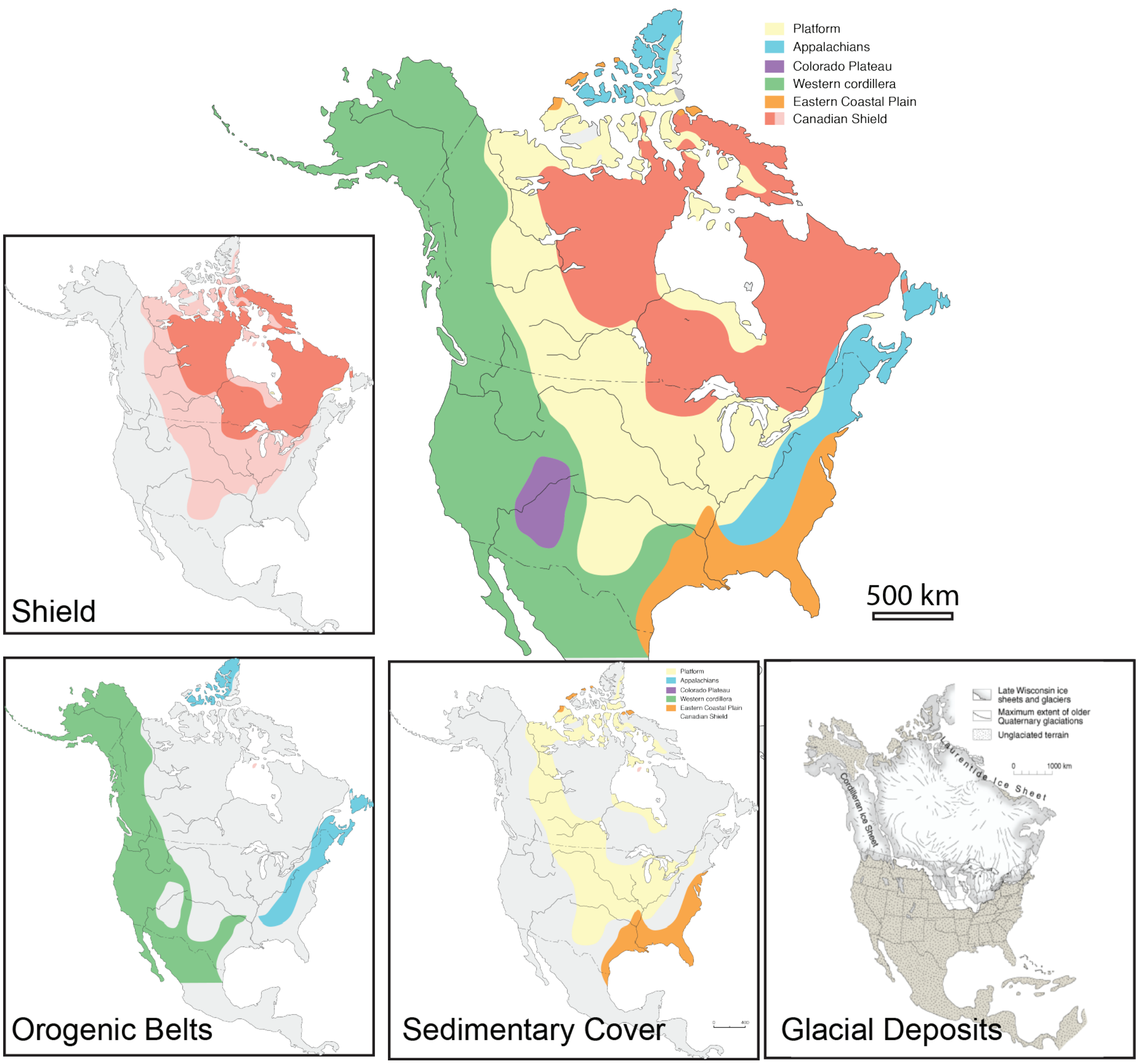
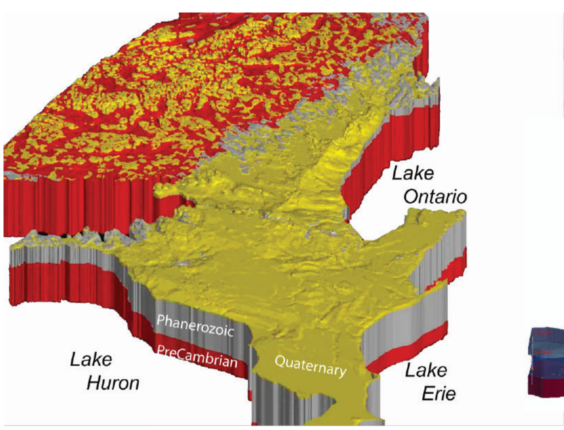


Figure 2. Principal geological domains pertinent to parsing of the geological landscape of North America for national 3D modelling. Modified from Reed et al. (2005).

sediment is commonly thick (e.g., Gao et al., 2006), whereas for much of the Shield and orogenic belts of the Appalachians and western Cordillera, particular in areas of high relief, sediment is thin and restricted to intra montane and alluvial valleys.

Large infrastructure tasks require systematic workflow models that allow for the realization of progress at smaller scales while advancing toward a long-term objective. This is the case for a Canada wide 3D mapping initiative. Individual geological mapping and basin studies will continue to advance our knowledge and contribute datasets with legacy data being integrated into a suitable framework.

When envisioning a model for > 9, 000,000 km^2 it is easy to succumb to the thought that the model will be nothing more than a cartoon realization of the geological complexity of the country. As data support and geological complexity is highly variable, and to minimize computational issues of a large model, it is likely to both vary in resolution and contain higher resolution embedded models of local interest. To ensure scientific rigour of 3D mapping an initial step is ensuring the accessibility and integration of high quality geological information that will be available for interrogation within a model framework. To access the broadest datasets possible for model generation, and to meet the challenges of a large model domain considerable generalization will be required. For example, modelling of the Quaternary commonly relies on water well records that lack information to support stratigraphic assignments other than by lithostratigraphy. Locally, however, the Quaternary stratigraphy may be defined by one or more of a number of stratigraphic approaches (e.g., lithostratigraphy, seismic stratigraphy, chemostratigraphy, biostratigraphy, radiometric dating). Integration of the index benchmark stratigraphic data ensures a connection between the science and the generalization of large scale regional modelling. In the sedimentary basins there is commonly a subset of stratigraphic boreholes that are considered as benchmark reference data (Fig. 3). Furthermore, data input cannot be limited to a black box approach where the backward accessibility to input data is lost. In this regard a seamless national compilation of the bedrock and surficial geology is critical, one that consists of not only lithological or chronostratigraphically coded polygons but a full wealth of structural measurements that can inform subsurface data projection (e.g., de Kempt et al., 2015). Given the scarcity of subsurface data for country beyond the petroleum provinces, modelling will require methods to exploit geophysical data and interpolate structural and lithological trends from surface to subsurface.



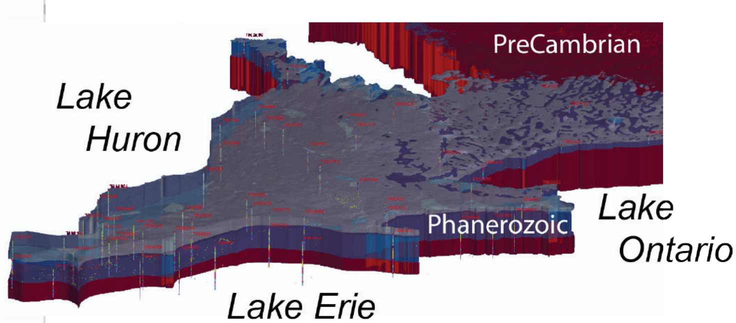


Figure 3. Perspective views of proof of concept model for approximately 150,000 km^2 of Southern Ontario straddling Shield - Phanerozoic region of Southern Ontario. A) Perspective view to the northeast of three layer model of Quaternary (yellow), Phanerozoic (grey) and Precambrian (red). B) Perspective view from south of Phanerozoic model volume populated with 66 stratigraphic control boreholes.

To facilitate data interrogation - mapping refinement requires visualization and access to the primary data and a simple means of regionalizing data limited to geographic point and line format. One possible model for this realization is the Macrostrat model (Peters et al., 2015) that uses Delaney Polygons to parse the country into neighborhoods for individual data points. Such an approach assumes the default status that the geology of a region is represented by the centroid of the polygon such that synthetic regional stratigraphic columns form the underpinning of the model; for Canada a similar approach could be adopted or it could be populated with real data both in terms of the surface areas chosen (e.g., unit boundaries) and subsurface columns (e.g., from sections or derived from geologic relations stored in databases). It is efficient as no interpolation is required and there are no issues of whether the correct stratigraphic - structural geometries have been maintained during model interpolation.

Another approach is a national four layer model of principal geological domains from the surface to Moho comprising surficial sediment, Phanerozoic cover rock, orogenic belts, Precambrian and crystalline rocks, and lower crust. In this approach the geology of respective bounding surfaces simplify to the most general geological scenario possible, issues of inverted or disrupted stratigraphy are eliminated. The simplified mega block model also affords an opportunity for the nesting of visualization approaches and models. Within the respective mega-block volumes data can be presented in point and line form as drill hole data and cross-sections (e.g., Hammer et al., 2011). An approach similar to that adopted by the National Lithoframe model of Great Britain (e.g., Mathers et al., 2014). This permits visualization of geological variability without the challenge of dealing with issues of stratigraphic interpolation.

Summary

To-date limited work has been completed in development of a national 3D model of Canada. The GSC is exploring the feasibility, has held internal workshops, and developed working groups for such a project (Snyder et al., unpublished) and is communicating with provinces. In some provinces 3D modelling programs are already well advanced and construction of regional scale models of 10,000 to 100,000s kms scales is in progress. Development of a 3D framework for the geology of Canada is also a necessary initiative to ensure the preservation and access to a wealth of subsurface data collected by geological survey organizations in Canada during the past 50 years. In the 21st century a national 3D model should be viewed as an underpinning infrastructure element, similar to other national infrastructure frameworks. It is also a potential natural successor to delivering the knowledge framework and successor to benchmark publications such as the 9 volume Geology of Canada contribution to the The Geology of North America (e.g., Wheeler and Palmer, 1993). Furthermore, a continental scale 3D model of Canada could support investigations into a host of science orientated (e.g., Fan et al., 2014) and economic development issues.

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From wallflower to eye-catcher: 3D geological modelling in Switzerland – more than XYZ, less than a Swiss Army knife

Baumberger Roland, Allenbach Robin, Volken Stefan

Swiss Geological Survey, Seftigenstrasse 264, CH-3084 Wabern, roland.baumberger@swisstopo.ch

Abstract

Today, 80% of political and economic decisions are related to – mostly 2d – spatial data, with the visualization and characterization of the subsurface in three dimensions playing an only minor role. In Switzerland, the usage of the underground for energy production, waste disposal, assessment and mining of mineral resources and infrastructural planning has turned a wallflower topic into an eye-catcher discipline over the course of the last few years. It's becoming evident that with these upcoming challenges the usage of the subsurface will increase and needs to be planned accordingly. Consequently, the subsurface and its competing claims, in line with related conflicts (3d property, 3d spatial planning), denote one of the main societal conflict areas in the future. This change does not only impact our understanding of the subsurface and its potentials, but it also forces the geoscientists to supply their highly complex and extensive three-dimensional products to non-specific target groups. Thus, the main challenge is not only to construct correct and highly informative 3d geological models, but preferably to make them accessible to a wide range of potential end-users. Here, we particularly focus on the advances of the Swiss Geological Survey in the field of 3d geological modelling and data management and its future plans in this domain.

Introduction

In general, 3d spatial planning plays a key role in future use of the subsurface, which requires reliable data to meet advances in technology (e.g. unmanned goods traffic) and the consequences of population growth (e.g. deep cities). Today, public interest in Switzerland is focusing on subsurface potentials (e.g. hydrocarbons, raw materials), the unsolved contemporary energy supply problems (e.g. radioactive waste disposal), the challenges of the energy transition (e.g. geothermal energy production) and the climate change (CCS). In this context, geological data and information have become increasingly important to decision makers, planning authorities and even the public – with the geosciences being in charge to supply concrete solutions and coherent explanations.

Despite being a small country in Western Europe, Switzerland is a federal directional republic consisting of 26 cantons, each of them having the sovereignty of the subsurface at their own disposal. Whereas geology does not stop at boundaries, the Swiss Geological Survey (SGS) faces a cluster of narrow legal situations, where relevant regulations change within short distance. Since 2008, the Federal Act on Geoinformation and the corresponding ordinances clearly define the fields of activity of Swiss federal institutions operating in the subsurface. According to this, the SGS has the task to produce and supply geological products, data and information of national interest and to coordinate the competing interest of federal and state authorities.

In order to fulfill its task, the SGS relies on three concepts: 1) The production of harmonized and integrated geological data and information, 2) the simple and easy access to these product as well as data and information and 3) the usage of the standardized Federal Geoinformation Data Infrastructure (FGDI) for the storage and the distribution of geological data.

The tripartition in data management as shown in Figure 1 enables the SGS to concentrate on data production as its core competence, while the other pillars are covered by specialists within the federal

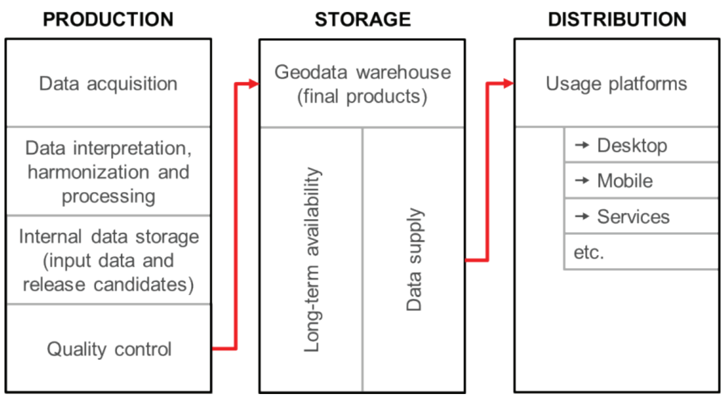

Figure 1. Data management concept of the FGDI with three interdependent pillars: Production, storage and distribution. Production covers the SGS internal data production, storage comprises the standardized filing of geodata for the entire Swiss Federal Administration and distribution handles the standardized distribution of geodata to the public.

authority. To enforce this situation, SGS initiated the Geological Information and Production System (GIPS), a mid-term program aiming at initiating standardized data production workflows for 2d and 3d data along with centralized, standardized and harmonized and daily updated input data storage across production units within SGS.

Production of 3d geological models at SGS

At SGS, 3d geological models are considered to be 3d knowledge bases with varying purposes, extents and scales. In production, three aspects are key: 1) input data, 2) the three-dimensional model management and 3) the modelling environment.

To 1): In general, the SGS uses the common input data types for the production of its 3d geological models: Wells, boreholes, seismic data, cross sections and surface geology. This data suite is complemented by additional geophysical data (e.g. gravimetry) and a sound knowledge of the corresponding methodologies and geological concepts. According to the GIPS concept presented above, all input data, which is necessary for the manufacturing of any kind of product at the SGS, is stored on centralized systems and continuously updated by specialized teams and by results obtained out of the production process. Regarding 3d modelling, selected interpreted input data is retrieved from these central data stores, transferred to the 3d modelling environment and processed therein (Figure 2). In order to keep the master data sets up-to-date, modelers are obliged to push any re-processed or newly gained input data back to the original storage systems. This basic understanding of input data management ensures that 3d geological models are up-to-date and built from harmonized and standardized input data.

To 2): From a technical point of view, the SGS skips file-based model storage and introduces database based 3d model management until the end of 2015. This means that the relevant geometries (e.g. points, lines, surfaces, tetrahedrons; 3d grids in the near future) are seamlessly stored at one single location instead of having the models stored at varying locations. This transition helps the SGS to overcome common difficulties of the traditional approach (huge amount of files, geometrical boundary effects between two files etc.). Besides the seamless model storage, state-of-the-art database management functionality (concurrent user access, lock-modify-unlock of features, versioning of data, traceability of manipulations, etc.) is natively provided by the database software. In consequence, the modelling staff can access all available 3d models at one single location by using one single software tool, relying on a direct and bi-directional link between the modelling software and the 3d database. This kind of 3d model management improves the model quality and provides the foundation for their publication to the target groups.

To 3): GIPS (input data) and the 3d database (3d model management) not only denote the end members of the modelling workflow, but they also thoroughly impact the production of 3d geological models at the SGS (Figure 2). The modelling workflow (modelling environment) at the SGS is likely to be the same or at least similar as at most other Geological Survey Organizations (GSO).

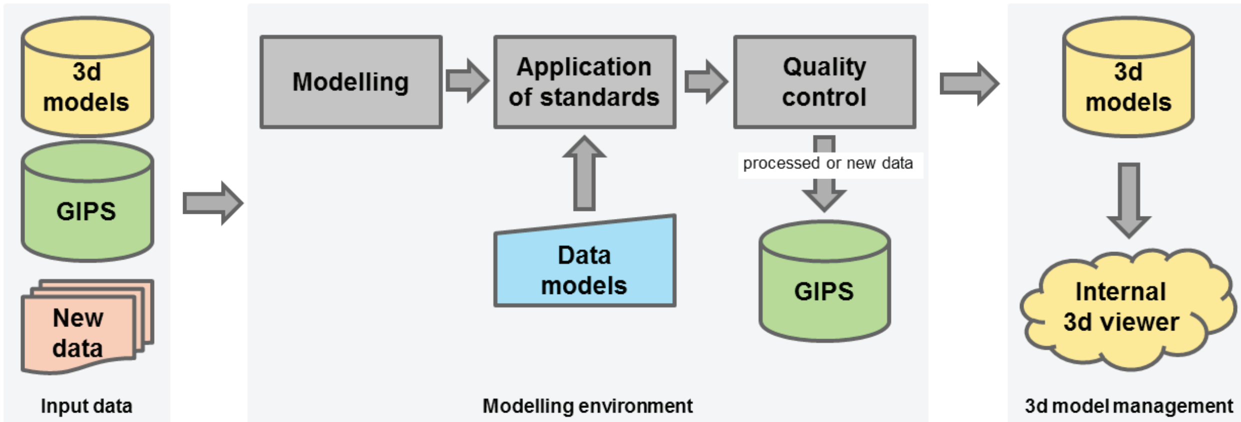

Figure 2. Basic modelling process at the SGS: Input data comprises the most common data sets, 3d models or newly acquired data. They are processed to build 3d geological models in the modelling environment and finally pushed to the 3d data store.

However, the SGS distinguishes between modelling of unconsolidated and consolidated sediments.

Unconsolidated sediments: This model type comprises the Quaternary rocks. Due to their specific deposition processes and numerous interplays of glacial advances and retreats, the internal structure of the Quaternary is very heterogeneous and complex. The utilization of these models for a wide range of applications (construction activity, drinking water, heat pumps, mineral raw materials, etc.) is key for a broad spectrum of end users. The amount of input data (e.g. drill holes, cross sections, geophysical data and surface mappings) regarding the Quaternary is enormous, reflecting the varying utilizations in this domain. Therefore, special attention must be paid not only to the detailed production of the models, but also to their meaningful characterization and interpretation.

Consolidated sediments: Modelling focuses on Tertiary and Mesozoic horizons including the base of the Mesozoic deposits. Compared to the Jura Mountains and the Central Alps in Switzerland, geological complexity in the Swiss Midlands is low. In contrast to the former model type, the number of possible utilizations is considerably lower. However, the role of these models will be key to face future challenges as mentioned above. Due to the lower density of input data (seismics, ca. 40 deep wells, ca. 200 deep drill holes and gravity measurements), it is not possible to achieve the same high input data density as is the case for the models treating the unconsolidated sediments.

During last three years, the SGS has developed two layer cake national framework models for the consolidated sediments. They exist in resolutions of 200 m and 100 m grid sizes, which resemble scales of 1:200000 (published) and 1:50000 (as of mid-2016), respectively. Modelling of the unconsolidated sediments is currently under development. Thus, the modelling workflow as presented in Figure 2 has been applied to the modelling of the consolidated sediments only.

Regarding the modelling workflow, the fully bi-directional link between the Move™ modelling software and the GST 3d database allows the modelers to retrieve data directly from the database (Figure 3), to manipulate the features within Move™ and to finally push the edited data back to the storage facility. In order to guarantee data consistency and attribute completeness, data storage is constrained by the underlying data model (see below).

It is not only possible to retrieve, edit and push back already existing models. Also new and previously unprocessed data can be directly integrated into the modelling process. However, while pushing new data to the database, data model constraints are applied to ensure data consistency. Even though the

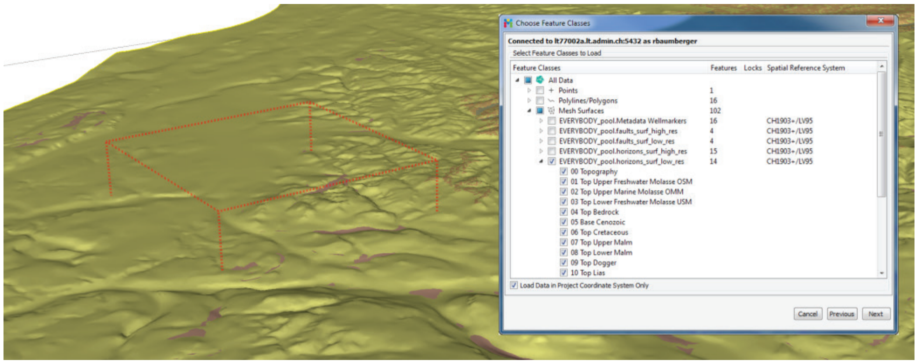

Figure 3. The nation-wide 3d model of the Swiss Midlands. The user defined query box is visible as a dashed red line. Within this area, features are locked for editing by the database, preventing concurrent access and manipulation by other users. Inset shows database content, which can directly retrieved from the software.

time and effort needed for modelling increase, the overall gain in consistency as well as the improved usability across data sets legitimates the additional work. The application of these kinds of standards to 3d geological modelling ensures that 3d models do not remain simple geometrical objects, but denote a first and important step for serving as future 3d knowledge bases.

Characterization of data

The SGS is commissioned to produce more than simple 3d geological models and the application of standards (e.g. data models) denotes a fundamental step to achieving this goal. However, consistent data alone is by far not enough to build up significant 3d knowledge bases. Additionally the parametrization of models with rock properties is the most obvious way to increase the value and application of 3d data. Finally, special effort must be paid to the inherent uncertainty of 3d data. Therefore, the characterization of data at the SGS comprises three domains: 1) semantic description, 2) rock properties and 3) uncertainty.

1) The most important property of any data set produced by the SGS is their internal semantic consistency among each other. In order to achieve this goal, SGS developed a comprehensive set of interdependent minimal data models (2d geology, 3d geology, boreholes, raster data, portrayal and the suite is growing). These internationally compatible standards introduce a standardized semantic description of the products, data and information and ease the data exchange between any institutions within the geological community in Switzerland.

2) The second important domain covers the attribution of the models with rock parameters such as lithology, density, permeability, porosity, heat flow, rock classifications, etc. Depending on the model type and its application, the amount of input data is very different, ranging from more than half a million drill holes and heat pumps which are used for modelling the unconsolidated and consolidated sediments, to less than 40 deep wells providing information for models of consolidated sediments. General data availability is narrowed by the general clustered political and legal situation in Switzerland mentioned earlier. In addition, an extensively interpreted copyright law allows geologists to claim subsurface data processed by themselves, as intellectual property. This, in consequence, may hinder data exchange needed for a national and comprehensive 3d geological data set.

3) The uncertainty of different characteristics (e.g. data density, data quality, and lithology) is going to be a mandatory component of any 3d model developed at the SGS. Consequently, the increasing demand for

quantifying the reliability of subsurface models can be satisfied. Firstly, indications of the density of the input data will be added in order to supply some sort of a model reliability index. Secondly, the model quality will be assessed, concentrating on the investigation precision, the quality of the documentation and the age of the input data. Thirdly, an uncertainty estimation regarding the lithology at a certain location will be integrated. Up to now, focus has been laid on the completion of the first 3d geological models of the Swiss Midlands. Therefore, the uncertainty topic has been given only minor attention, although tests in pilot regions delivered promising results.

Transfer of data to target groups

Fully attributed 3d data sets as outlined above denote the basics for the development of new products, applications and services. Although the visualization of the third dimension offers fascinating perspectives to earth sciences, the limitations of 3d models have to be kept in mind. Even geoscientists, relying on their professional attitude, have difficulties grasping and technically understanding such visuals. On the other hand, simplified models enable non-professionals to recognize geological correlations to support e.g. decision making processes. This will become increasingly important in the future, when upcoming challenges related to the subsurface need to be transferred from geoscientists to laymen. Therefore, the SGS offers various approaches for the distribution of 3d models and the corresponding data transfer. For the experts, the SGS provides full access to the existing 3d models (based on the 3d database mentioned above) via a web based 3d viewer (https://viewer.geomol.ch/). Users are allowed to query the models in 3d view (rotating, slicing, WMS overlay, attributes histogram) and virtual boreholes and cross sections (vertical, horizontal) can be constructed live. These can then be downloaded as images and in the near future, a download option will allow downloading the data directly from the web.

Figure 4. The geodata portal of the Swiss Confederation (http://map.geo.admin.ch) currently offers more than 80 data sets related to earth sciences. The access to the website is free of charge and the responsive design allows querying the content from different mobile devices.

For all user groups (with focus on non-experts), the federal geoportal (http://map.geo.admin.ch; Figure 4) offers a variety of 2d data sets related to geology. From there, the 3d models can be queried live with the same possibilities regarding the construction of virtual boreholes and cross sections. Many of these 2d data sets can be downloaded for free or can be purchased in the SGS internet shop. Furthermore, the SwissMap mobile app for mobile devices also covers some 2.5d functionality, such as draping geological maps on to digital elevation models and loading pre-existing cross sections.

Two main challenges remain: The easy and comprehensible procurement of 3d geological models as well as the improvement of the access to geological data. Firstly, the dispersion of geological data must be kept as simple as possible. This is a core business of any GSO and an everyday challenge for every geoscientist. Secondly, the SGS plans to participate to the Open Governmental Data (OGD) movement as of 2017. It is expected that this change of paradigm will ease the access to geological data and will additionally increase the overall economic benefit.

Outlook and long-term plan

Geological data, which is 3d data by definition, should be stored and supplied accordingly. At the moment, several projects (modelling of unconsolidated and consolidated sediments) result in 3d products, each relying on different basics. A consolidation is urgently needed in order to have only one central input data storage, one modelling environment, one 3d model management platform and one central 3d access in operation. To achieve this goal, the SGS is going to

- strengthen its current national framework models to serve as a starting point for the deviation of new products (e.g. block models, depth serialized maps, etc.), online applications (e.g. 3d resource knowledge bases → geothermal energy, unconsolidated sediments) and services (e.g. WMS, WMTS).
- build up 3d geological models from the nationwide geological surface mapping at a 1:25000 scale and to analyze the trans-dimensional relations between 2d data and 3d data (quality control, data transformation, data consistency, etc.) as well as the workflow to integrate observed 2d data (maps, vector data) and mostly inferred 3d data (models).
- clarify the requirements in order to consolidate the 3d modelling environments of the modelling domains of unconsolidated and consolidated sediments into one modelling environment and model management platform.
- subsume all geological data (e.g. models, 2d vector data, drill holes, seismic data, cross sections, maps, etc.) and information (meta data, rock parameters, reports, etc.) under the Swiss Geological Subsurface Model (SGSM). The SGSM denotes not a model s.s., but rather a central 3d access for visualizing available data, while providing full overview in 3d space, preventing redundant data storage and accounting for already existing IT components.

Starting with 3d geological modelling in 2010, the SGS follows adapted schedules to achieve the above-mentioned goals: First deviated products will already be released by the end of 2015, a prototype 1:25000 model will be available by mid-2017, the consolidation between the modelling approaches will be achieved by the end of 2018, and the SGSM will be introduced by 2020. Within ten years' time, the initially dismissed wallflower will have turned into an influencing and strategically important eye-catcher for the SGS.

Geological 3D Modeling Of Large Plains In Italy: Basin Analysis, Active Faults, And Characterization Of Uncertainties

Chiara D'Ambrogi* & Francesco E. Maesano

Servizio Geologico d'Italia – ISPRA. Rome. Italy chiara.dambrogi@isprambiente.it;

Introduction

Geological 3D modeling of buried structures, especially in large plains, is a strategic goal for the Servizio Geologico d'Italia (SGI). Despite the common perception that plains are geologically stable, the societal and industrial activities in such areas have often to face with various geological hazards.

The Po Plain, one of the biggest plain areas in the European continent, does not escape this general rule. On the ground surface, it hosts nearly a third of the Italian population, along with important historical centers, many industrial facilities, critical infrastructures, hydrocarbon plays and gas storage sites, while underground it is characterized by active blind thrusts, among which also those responsible for the May-June 2012 seismic sequence (MW max 6.1). After this seismic event and following a strong public concern, a scientific and political debate started (ICHESE 2014, Cartlidge 2014) to address and investigate the possible interactions between the impact of human activities in the subsurface (e. g. oil and gas production) and the seismicity, as already experienced in recorded cases of induced and/or triggered seismicity all around the world (e. g. Evans et al. 2012, National Research Council 2013). This case pointed out the basic need of a publicly available 3D geological infrastructure (models and tools) to analyze geological bodies and faults, to quantify and parameterize their behavior, to assess resources, supporting decision-makers, and facilitating the public acceptance of subsurface uses.

The Po Plain, with its active and seismogenic blind thrusts and related folds, has been identified as a case study to implement and test a comprehensive workflow based on 3D modeling, restoration and characterization of geological structures, including basin analysis.

Workflow & Tools

The SGI has, as its main institutional commitment, the collection, harmonization, analysis, storage, and dissemination of geoscience data and observations (ISPRA, http://sgi.isprambiente.it/geoportal/catalog/main/home.page).

Since 2000, it has expanded its institutional activities by using 3D modeling techniques to interpret and display surface and subsurface data available in the national geological databases. Starting from these data, 3D models at crustal to subcrustal-scale and from local to nation-wide coverage (D'Ambrogi et al., 2010), have been built to describe various geological domains, from fold-and-thrust mountain belts (De Donatis et al., 2002) to plain areas (GeoMol Team, 2015).

These experiences led to design and implement a workflow (Fig. 1) that can be widely applied in all the various Italian geological contexts, which integrates data characterized by different domains of the vertical axis: time (e.g. seismic lines, velocity data, time-depth or time velocity curves of wells) or depth (e.g. field data, published geological maps, cross sections, isobath and isopach maps).

The workflow was tested and refined in the framework of the EU-funded GeoMol Project (www.geomol.eu), applied for the 3D model construction of the central portion of the Po Plain, a 5,700 km^2 wide area, that extends from the Southern Alps piedmont, to the north, to the Northern Apennines buried thrust front, to the south; the latter including the blind thrusts which generated the May-June 2012 seismic sequence.

The model was based on the integration of a dense and consistent dataset (130 well logs, 12,000 km of seismic lines), with the support of a high-pass filtered Bouguer anomaly map; it was realized following a complex workflow of interpretation, harmonization, 3D velocity model elaboration, time-depth conversion, conditioning and refinement of geological surfaces (Fig. 1A).

The result is a 3D model that includes 15 horizons, from the top of Permian-Triassic to Pleistocene, and more than 150 faults. This complete 3D imagery of the central Po Plain has become the core for a multiplicity of further applications.

Parallel to the workflow for 3D model production, the SGI tested methods for:

- analysis of sedimentary basins (Maesano & D'Ambrogi, 2015; Chiarini et al., 2014),
- fault restoration and sediment decompaction for calculating long term slip rates and characterize active faults (Maesano et al., 2015),
- estimation and representation of the uncertainties to support the model validation (Maesano & D'Ambrogi, 2015).

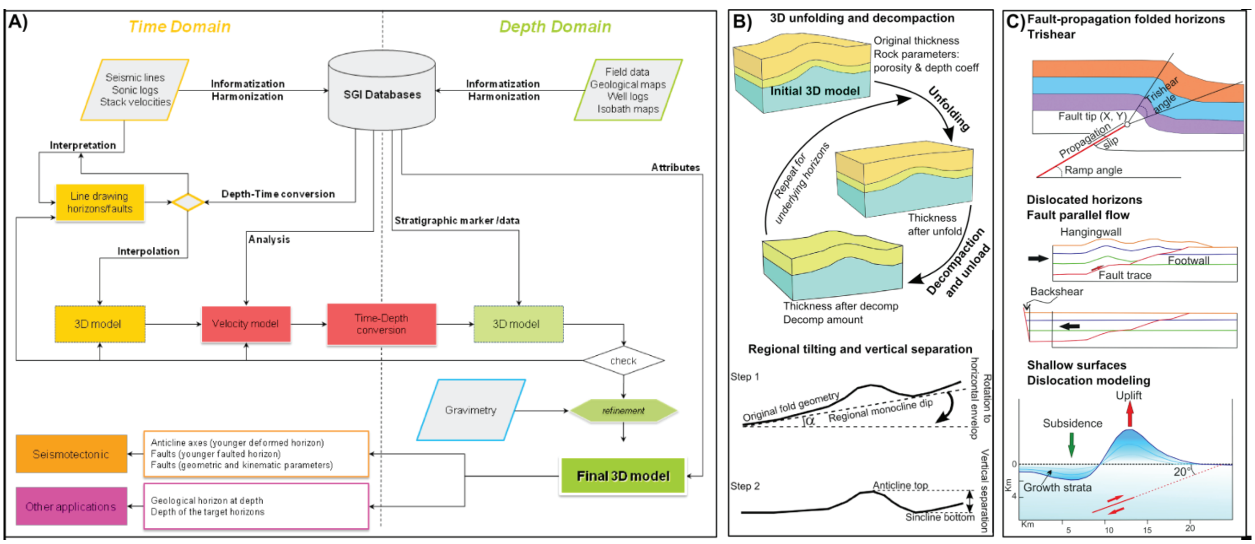

Figure 1. A) Workflow for 3D model construction; B) restoration workflows for basin analysis (Maesano & D'Ambrogi, 2015) and C) characterization of folds and faults (Maesano et al., 2015).

Basin Analysis

A basin-wide detailed 3D model, derived from the interpretation of a very dense network of seismic lines (12,000 km, provided confidentially by ENI S.p.A.), correlated with 130 well stratigraphies and with the existing literature data that provided stratigraphic and magnetostratigraphic constraints, is the core of a workflow of decompaction and sequential restoration in 3D aimed to quantify the Quaternary sedimentation and uplift rates in the central part of the Po Plain (northern Italy).

The interactions of these processes and the analysis of the resulting effects (syn-tectonic deposits and growth strata) are strategic to describe the basin evolution and tectonic control, especially in subsiding basins where the signals of active tectonics can be disguised by the sedimentary processes. As a matter of fact, where the sedimentation rate is higher than the tectonic-related uplift rate, a generally flat topographic surface can result, without clear evidence of deformation, despite the presence of active, and possibly seismogenic, faults in the subsurface.

The Pleistocene portion of a detailed 3D model was the starting point of a sequential 3D restoration workflow that included the unfolding and decompaction of six, chronologically constrained, sedimentary units ranging from 1.5 to 0.45 Myr. The aim of this methodology was to obtain a 3D picture of each horizon unaffected by sediment compaction and the local and regional tectonic deformation recorded in the uppermost horizons and to assess the residual vertical separation that can be attributed to the folding process only.

The restoration workflow (Maesano & D'Ambrogi, 2015) (Fig. 1B) consisted of the following steps of unfolding and decompaction of the unconformity-bounded units:

- unfolding;
- decompaction and unload;
- removal of regional monocline dip and measure of the residual vertical separation along antiformal structures.

After the first two steps, the resulting 3D surfaces (Fig. 2) represent the basin configuration and the changes and migration of regional depocenters, controlled by thrust activity until the Pleistocene. The workflow enabled the analysis of the interaction between the basin infill and the evolution of weak elusive syn-sedimentary anticlines in the central portion of the basin, considered less affected by the main structures (e.g. Emilia and Ferrara-Romagna arcs). In the analysis of these anticlines the subtraction of the foreland tilting from the topography, resulting after unfolding and decompaction, was crucial to obtain the residual signal related to the growing anticlines, and the uplift rate of the structures during Pleistocene.

Active Faults

The identification and characterization of potentially active tectonic structures, are two of the goals achieved from the 3D model of the Po Plain; the model provided a display of fault planes that is more accurate and geometrically consistent than those classically obtained through regional 2D cross sections. Particularly, the evidence of folding and growth strata that are often elusive (e.g. mild folding with low amplitude and long wavelength) can be more easily identified in a 3D model rather than in a single seismic profile.

A great deal of accuracy is needed during data acquisition and interpretation in order to obtain the best constraints for the subsequent structural analysis. The position of the fault tips and the evidence of dislocation or folding of horizons younger than 1.6 Myr have to be carefully highlighted.

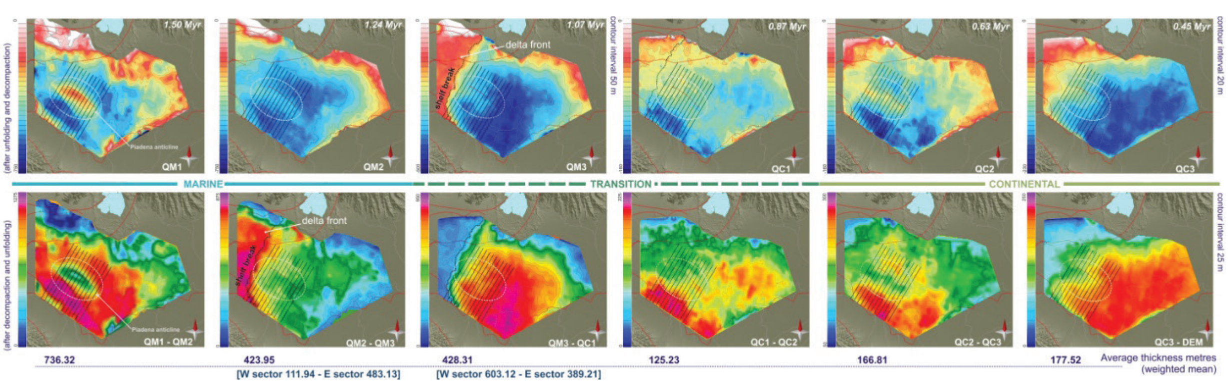

Figure 2. 3D surfaces describing the evolution of the basin topography, step by step, and the evolution of the basin infilling (thickness analysis) (Maesano & D'Ambrogi, 2015).

From the 3D model of the Po Plain, the following characteristics were attributed to the faults (or folds): i) orientation compatible/not compatible for being reactivated in the present-day stress field; ii) age of the younger faulted/folded horizon; iii) position in relation to the stratigraphic succession (e.g. position of the detachment level and mechanical properties of the intersected units).

The faults with an orientation compatible for a reactivation in the present-day stress field that can be also associated with deformation (dislocation or folding) in horizons younger than 1.6 Myr were defined as active faults. These faults were further analyzed following the designed restoration and analysis workflow (Fig. 1B and C) that can be summarized in the following steps:

- decompaction on the target horizons;
- restoration with appropriate algorithm (trishear, fault-parallel flow, simple shear) based on the type of observed deformation;
- slip rates calculation and uncertainty estimation.

The characterization of active faults, the slip rate values and their lateral variability are key parameters for a better definition of the fault kinematics, and support the identification of seismogenic sources which, in turn, provide a fundamental input to build more detailed models for seismic hazard assessment.

Characterization Of Uncertainties

The 3D modeling techniques, as opposed to the classic 2D modeling, allow one to consider the full spatial variability of input parameters both in the reconstruction and restoration of geological structures (e.g. strike and dip of faults, fold geometry) and in the geomechanical characterization of the geological bodies (e.g. velocity in the depth conversion, porosity in the decompaction). At the same time they need the quantitative evaluation of uncertainties, which are strongly requested in many aspects of the geological investigations and by the stakeholders of geological products.

Considering the velocity model used for the time-depth conversion, one of the most important factor controlling the accuracy of the final 3D geological model, the SGI tested a method to estimate and represent the uncertainty related to the geo-statistical interpolation of velocity data in the 3D model of the Po Plain, in order to obtain an independent control of the final results.

In the available datasets, often there are only few well logs provided with time-depth or velocity curves. This lack of information is particularly problematic when the 3D model covers a wide and heterogeneous area.

The depth conversion of the 3D model was performed by testing different strategies for the use and the interpolation of velocity data, such as i) well logs; and ii) pseudo-wells from stack velocities. Firstly, the final depth model was obtained using a 4-layer cake 3D instantaneous velocity model that considers both the initial velocity ($v0$) in every reference horizon and the gradient of velocity variation with depth (k), derived from the well logs. Secondly, a set of pseudo-wells obtained from the stack velocities available inside the area, geostatistically interpolated, was used to obtain a depth conversion for the same 4 reference layers of the final model. Thirdly, the surfaces obtained from the two methods were compared using as control points the marker constraints derived from the well logs not included in the velocity model (Fig. 3).

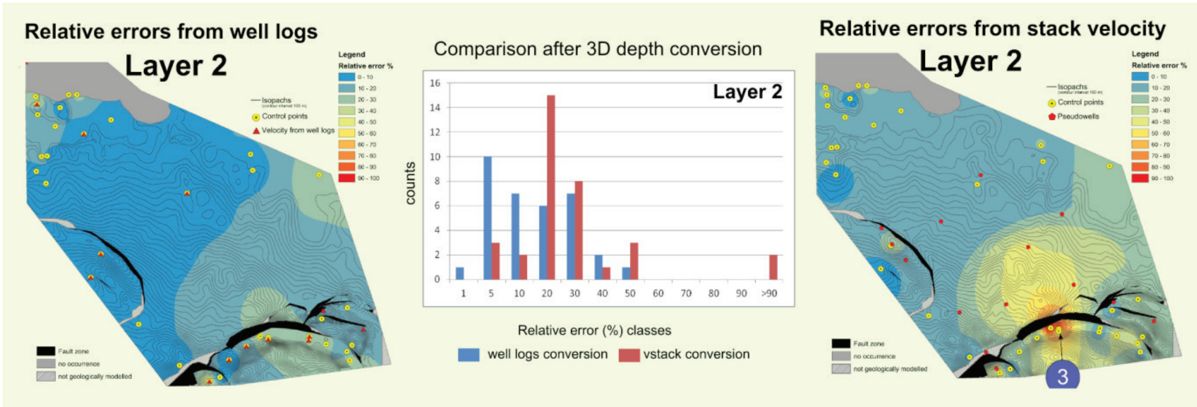

Figure 3. Comparison of the results after time-depth conversion with the control points: velocity model based on velocity from well logs (left), velocity model from stack velocity (right).

Conclusions

The 3D modeling techniques are commonly recognized as the best synthesis to understand, characterize, and describe the geological structures, thanks to the integration of various types of data. Collectively, this information provides the foundation in analyzing and monitoring the geological structures, both for their possible geopotential usage and for the hazards they can generate.

The SGI tested a complete workflow for 3D model construction and analysis, able to support the increasing demand of consistent geological and seismotectonic knowledge, from the Italian public, national and local, authorities with responsibilities on authorization procedures for exploiting subsurface resources (e. g. geothermal, oil and gas, gas storage, CCS).

The SGI makes the 3D-model-derived thematic maps discoverable and accessible through standard metadata and web services (WMS) in compliance with the INSPIRE Directive from its web portal (http://sgi.isprambiente.it/geoportal/catalog/main/home.page).

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Modelling The Geological Structure Of Poland – Approach, Recent Results And Roadmap

Zbigniew Małolepszy, Marcin Dąbrowski, Adam Mydłowski, Tomasz Żuk, Ewa Szynkaruk, Marta Tomaszczyk, Marta Adamuszek, Jacek Chełmiński, Tomasz Gogołek, Łukasz Jasiński, Wiesław Kozdrój, Łukasz Nowacki, Piotr Olkiewicz, Marcin Słodkowski, Paweł Sydor, Urszula Stępień, Urszula Wyrwalska;

Polish Geological Institute – National Research Institute, GeoModelling Laboratory, Rakowiecka 4, 00-975 Warsaw, Poland; Marta.Tomaszczyk@pgi.gov.pl

Introduction

Modelling of the geological structure of Poland started ca. 10 years ago at the Polish Geological Institute – National Research Institute (Polish Geological Survey, PGI-NRI). The first model was a low-resolution, nationwide model showing the stratigraphic framework based on published horizontal-section maps and deep boreholes. Since then, several regional and local models have been produced, both structural and parametric, aimed at specific applications such as CCS, geothermal energy (both deep and shallow), urban geology, geological storage or resources. More recently, a systematic program has been launched to model all sedimentary basins of Poland one by one, in a way that would support decision-making at a regional scale. The first model in this series – the model of the Lublin basin – is sufficiently advanced to produce results that will be discussed below. This serial modelling program is a game-changer that is currently driving the development of a systematic workflow for developing models, and probably more importantly a new geological database approach. It is focused on storing geological data in 3D space and area-based data retrieval. Moreover, a model delivery system is being developed within this project, both for easy internal access to data by geomodelers and for external access promoting re-use of available models.

Several other modelling projects are currently being carried out, or have recently been completed, and below we have highlighted the recent activities of the GeoModelling Laboratory at PGI-NRI, including geothermal modelling, imaging sedimentary architecture to construct training images for facies modelling and recently rapidly expanding the activities of the Computational Geology Laboratory, where flow and geomechanical models are being developed.

Lublin basin

The first part of the 3D sedimentary basins modeling program carried on at the Polish Geological Institute is the multiscale static model of the regional structure of the Lublin Basin. It has been built in accordance with the principles of integrated 3D geological modelling, and is based on a large dataset of geospatial data available from all Polish digital databases as well as analogue archives including 420 deep boreholes and several thousands of kilometers of 2D seismic interpretation. The regional structure mapped covers an area of 260 x 80 km located between Warsaw and the Polish-Ukrainian border, along the NW–SE-trending margin of the East European Craton. Within the basin, the Paleozoic beds with the coal-bearing Carboniferous strata underlain by older hydrocarbon reservoir formations and unconventional prospects are unconformable covered by Permo-Mesozoic and younger rocks. The regional model stretches from the ground surface to a depth of 6000 m, reaching the Proterozoic crystalline basement. The project focuses on the internal consistency of models at different scales – from the basin scale (small scale; 1:500000) to the field scale (large scale; 1:10000). The models, nested in a common structural framework, are built using regional geological knowledge, ensuring a smooth transition between the 3D models of different resolution and degree of geological detail.

The model consists of all chronostratigraphic systems from the Ediacaran to the Quaternary, each of them including detailed stratigraphic and lithological information. The distribution of lithofacies and depositional systems has been reconstructed over the entire study area. The lithofacies models for each stratigraphic unit have been created in separate grids generated from of the common structural framework. The property modeling was carried out for selected formations in order to assess both shallow and deep regional groundwater systems. The large collection of core samples and wireline data allowed the reconstruction of reservoir properties for groundwater resources.

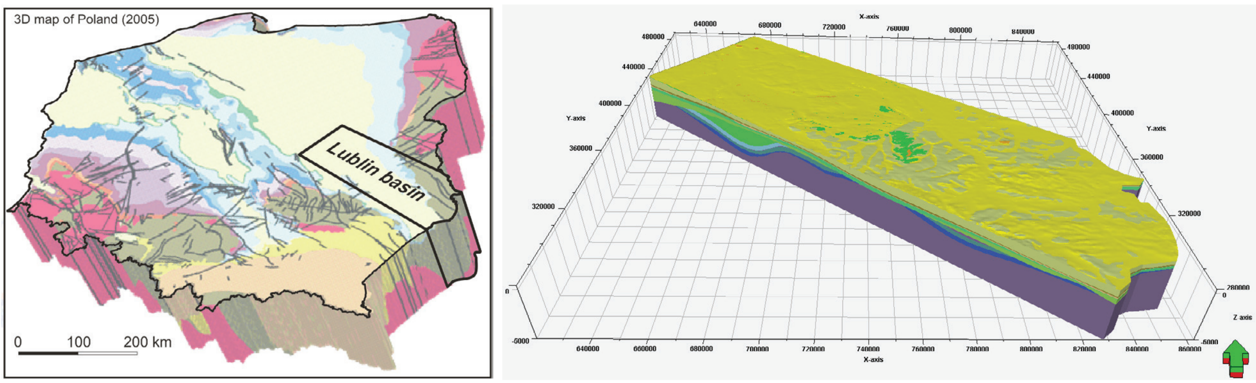

Figure 1. 3D geological model of the Lublin Basin, Poland.

The model is delivered to the end user through a standalone 3D viewer which is freely distributed as well as a 3D web viewer, which will be launched at the end of 2015.

Uncertainties of the Lublin Model

The major challenge of the multiscale approach to subsurface modelling in the Lublin Basin is the assessment and consistent quantification of various types of geological uncertainties tied to the submodels at different scales. The decreasing amount of available information with depth, with very limited data collected below exploration targets in particular, and the accuracy and quality of data have the most critical impact on the model. At deeper levels of the Lublin Basin, seismic interpretation of 2D surveys is sparsely tied to well data. Therefore, time-to-depth conversion is the major uncertainty when modeling the subsurface, especially below a depth of 3000 m. Furthermore, as all models at different scales are based on the same dataset, we must deal with different levels of generalization of geological structures. The same degree of generalization shall be applied to uncertainties. However, the approach to the uncertainty assessment and quantification may vary depending on the scale of the model. In the small-scale regional and sub-regional models, deterministic modelling methods are used, while stochastic algorithms can be applied for uncertainty modelling at the large-scale multi-prospects and field models. It can be assumed that the 3D multiscale modelling which describes geological architecture with quantified structure uncertainties, presented on standard deviation maps and grids, will allow us to outline exploration opportunities as well as to refine the existing and build new conceptual models. As the tectonic setting of the area is a subject of long-term dispute, the model depicting both structures and gaps in geological knowledge at different resolutions will allow the confirmation of some concepts related to the geological history of the Lublin Basin and the rejection or modification of other hypotheses.

TransGeoTherm

This cross-border, Polish-Saxon project was developed as a tool to support the development of shallow geothermal energy resources, and to make the results of geothermal modelling and mapping available to the public. The secondary goal is to increase and to popularize the use of low-temperature geothermal energy as one of the sources of renewable energy, thus addressing the need to reduce the emission of CO2 as well as the „smog-causing" gases and dusts from using fossil fuels. The success of the project is based on an innovative and advanced technology of analysis and interpretation of geological, geothermal and

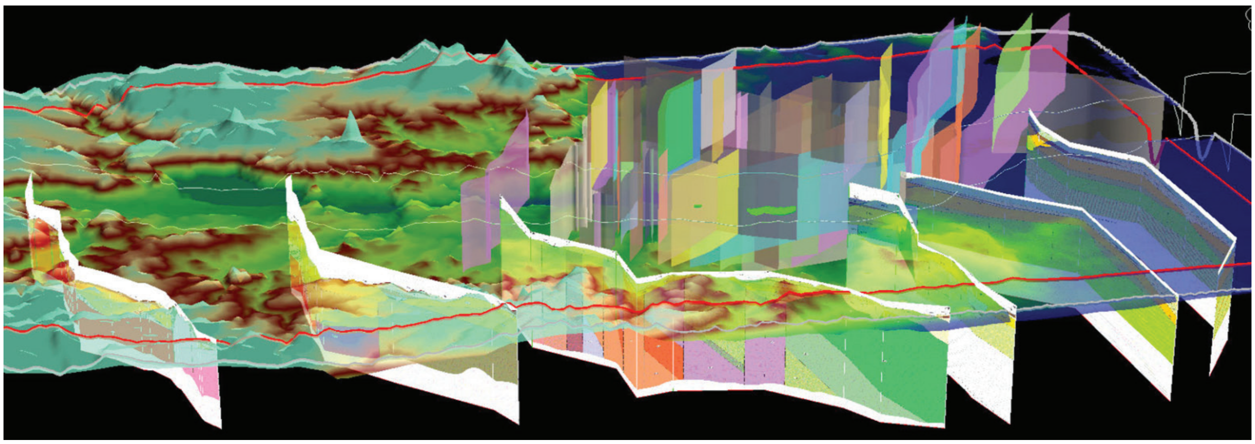

Figure 2. TransGeoTherm model showing the topographic surface, cross-sections from the Detailed Geologic Map of Poland used to delineate bases of geologic units and color-coded faults that often form boundaries between geobodies with contrasting geothermal properties shown on (lower depth) geothermal-potential maps. View towards the west.

hydrogeological data as well as on the preparation of a 3D numerical model of the subsurface. The core of the database consists of 5146 selected borehole logs and 5168 virtual boreholes, with rock formations / layers grouped into 75 hydrogeological–geothermal (HGE) units. The boreholes (codified using HGE units) and geological cross-sections are used as a leading reference to construct a 3D numerical model processed using the GOCAD software, down to a depth of 200 m below the ground level (locally down to 340 m) – Figure 2 (http://gst.pgi.gov.pl/gstweb/GSTws/gui2.php).

The GOCAD modelling procedure uses raster datasets consisting of the top and bottom surfaces of every HGE unit as well as its thickness calculated from the model using cells with dimensions of 25 × 25 meters. Based on the geothermal properties of rocks and their groundwater content, a specific value of geothermal conductivity (λ, [W/m*K]) is allocated to each rock type (layer) in every borehole. A depth-weighted mean λ value is calculated for every section of a borehole, belonging to a certain HGE unit of the 3D geological model. The results are presented in the following ways (http://www.transgeotherm.eu/mapy_geoter.html):

- 8 maps of mean geothermal extraction rate [W/m]
- 4 depth-intervals x 2 annual operation hours
- 4 maps of mean thermal conductivity [W/m•K]
- Lambda-distribution for 4 depth-intervals (Figure 3)

The project results are available free of charge, and can be used by all interested parties. The results serve as a decision-making tool for local and regional planning and development, and thus are of special interest

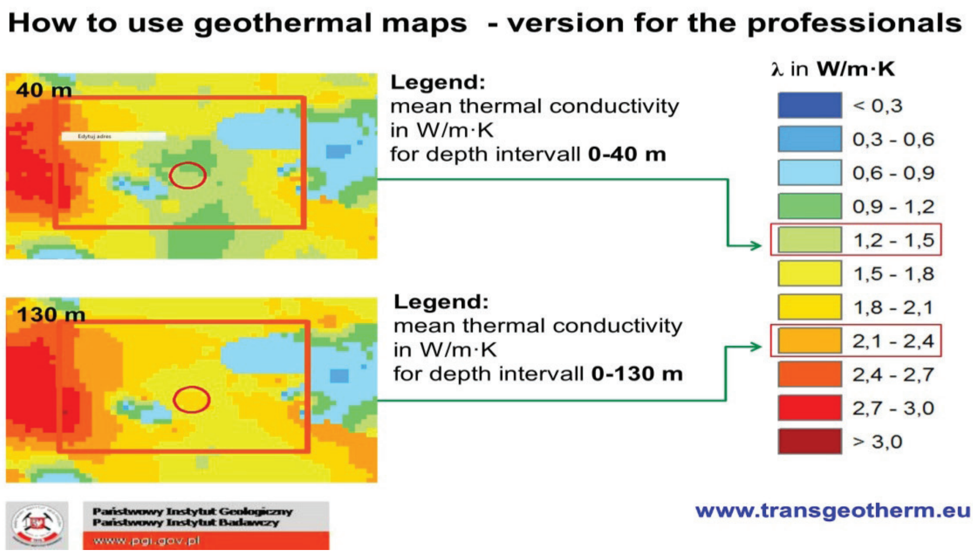

Figure 3. Illustration showing how to use geothermal maps – version for professionals.

to the local authorities, planners and the general public as well as to the business sector (for example producers and installers of heat pumps). The geothermal maps can also be used for renewable energy auditing at the local and regional scale.

Sedimentary architecture of coastal dunes

Although modelling software is designed for geographically extensive projects which use seismic and deep well data, it is also well suited for modelling based on high-resolution datasets such as ground penetrating radar (GPR), vibrocoring, or trenches. We use GOCAD for display and interpretation of shallow geophysical and borehole data in sedimentological projects which aim to reconstruct the evolution of Holocene landscapes and investigate the sedimentary architecture of depositional systems. Figure 4 shows an example of 3D GPR data from a larger dataset (6 3D grids and several km of 2D lines) collected across the Mrzeżyno dunefield, southern Baltic Sea coast, NW Poland. Geophysical data was calibrated using vibrocores and trenches, while the topography of dunes was reconstructed using LIDAR data. The datasets showed the internal organization of individual dunes to depths exceeding 20–30 m with reflections representing various-scale erosional surfaces ranging from sand-flow cross-strata to interdune surfaces and lithological boundaries. Horizontal slices showed the paleotransport directions which were quantified and compared between the GPR datasets, current dunefield morphology and the wind regime. Quantitative conclusions about the heterogeneity of aeolian deposits across the dunefield can be used to generate training images for facies modeling in similar situations in ancient rock records.

Geological Processes Modelling

The Computational Geology Laboratory, a section within the GeoModelling Labroratory, has been established to complement the modelling of the geological structure beneath Poland with numerical models of geological and industrial processes. The core activities of the group include the development of geomechanical models for shales and geothermal systems, the studies of flow and transport in porous media, and the modeling of salt tectonics, shear zone dynamics, and fold-and-thrust belts.

In the presented example, fluid flow in either a rough or a propped fracture is studied using our unstructured mesh finite element code MILAMIN (Dabrowski et al., 2008). In both cases, the fluid flow

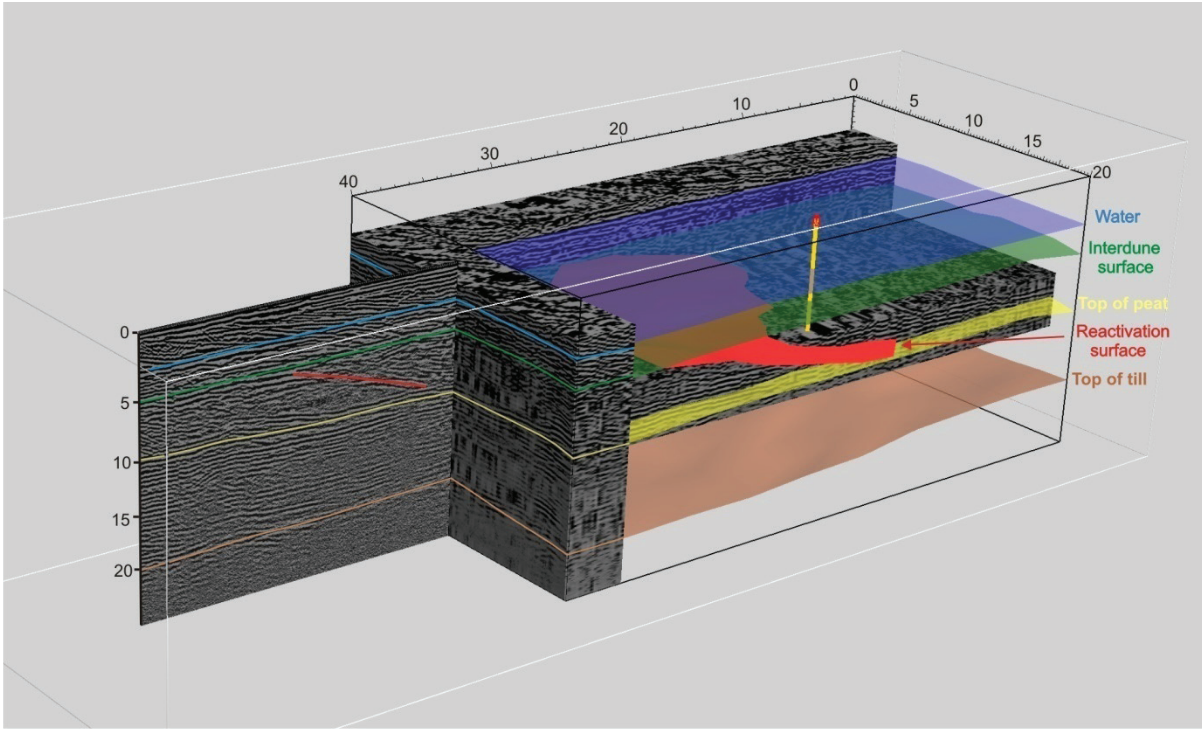

Figure 4. One of the high-resolution models from the Mrzeżyno dunefield produced using GOCAD based on 3D GPR data (collected with 250 MHz shielded antenna), vibrocores and trenches. The blue surface is the groundwater table at 2.5 m; green indicates an erosional surface separating cross-stratified sets (interdune surfaces); red shows erosional surfaces created due to changes in wind direction and velocity, i.e. reactivation surfaces; yellow represents the bottom of the aeolian sequence (supersurface) underlain by organic deposits; the brown horizon is the top of the glacial till associated with strong signal attenuation and diffraction hyperbolas. All dimensions shown are in meters.

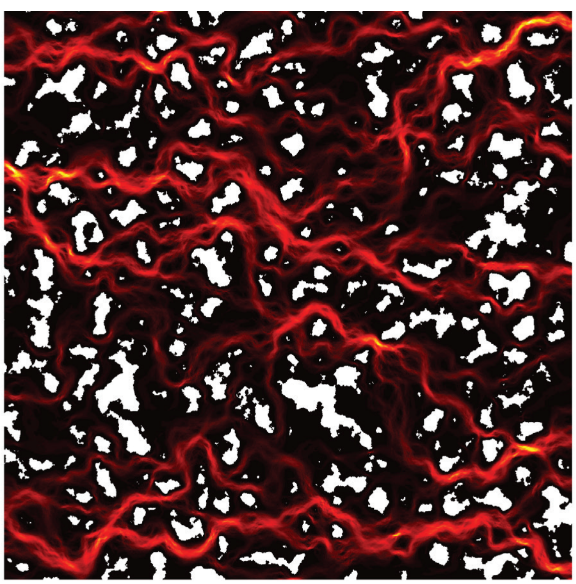

Figure 5. The magnitude of the fluid flow velocity in a pressure driven flow through a fracture with roughness.

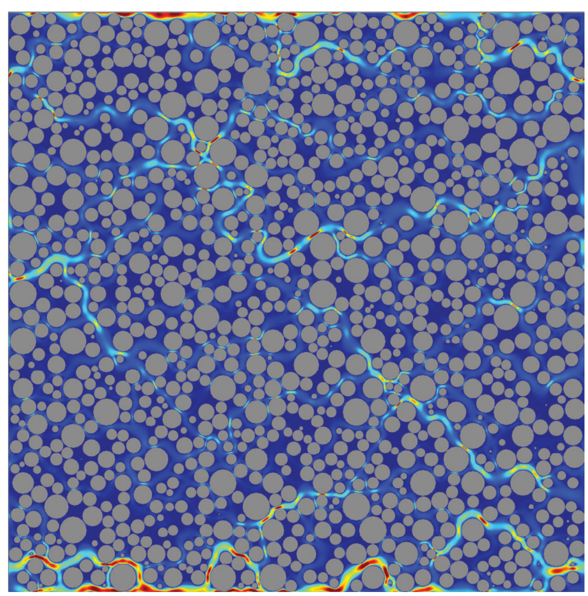

Figure 6. The magnitude of the fluid flow velocity in a pressure driven flow through a propped fracture.

exhibits a non-trivial channel-like pattern, which shows that mass transport is strongly heterogeneous in such systems. The obtained results can be directly used to measure the impact of the roughness or the proppants on the effective fracture transmissivity. Our direct numerical simulations of the fracture flow allow us to study transport characteristics such as mechanical dispersion, residence times, and the evolving morphology of incoming fronts. Local wall stresses, which can have an effect on mass exchange between the surrounding porous medium and the fluid in the fracture, can be easily inspected. The numerical model is currently under development towards a direct FEM-based multi-phase flow solver.

Roadmap

In the long term the, Polish Geological Institute is planning to produce a complete 3D map of every regional-scale sedimentary basin in Poland. We are seeking to develop a modelling workflow that will be systematic, but sufficiently flexible to include site-specific requirements related to the scope and detail of representation of each sedimentary basin in question. To accompany this flagship program, we will deliver several, usually smaller-scale projects targeting specific scientific and applied issues, such as salt mobility modelling, coastal zone modelling, resources modelling, geothermal energy and others.

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A modelling strategy to develop a regional Quaternary geological model across rural and urban areas and administrative borders using existing geological information

M. Ross[1], M. Parent[2], A. Taylor[1]

[1] Dept. of Earth and Environmental Sciences, University of Waterloo, 200 University Ave W, Waterloo, Ontario, Canada, N2L 3G1

[2] Geological Survey of Canada. 490 rue de la Couronne, Québec, QC, CANADA G1K 9A9, maross@uwaterloo.ca

Introduction

Geology is best represented in three dimensions. Yet, in a large country like Canada, most of the near-surface landmass is still described in two dimensions. Bedrock topography maps and 'overburden' thickness maps, for example, are common digital products available for download from geological surveys' websites. However, such products vary greatly in format, resolution, and coverage from one province to the next and seamless maps extending across provincial boundaries are not yet available. Furthermore, three-dimensional geological models are generally project-specific, such as those developed to improve understanding of groundwater systems and resources at watershed or regional municipality scales (e.g. Ross et al. 2005; Bajc et al. 2007; Tremblay et al. 2010). This has led to a patchy mosaic of maps and models at different scales and resolution with major gaps in-between. Meanwhile, the need for 3D Quaternary geology has rapidly increased due to urbanization, aging infrastructures, population growth, geohazards, and climate change. When a 3D model is not available for a specific study area, users make their own map to meet the needs of a specific modelling project. Users, unlike geological surveys, tend to focus more on physical properties (e.g. specific recharge or shear-wave velocity) averaged over a certain thickness/depth than on the geology itself. A common approach is thus to measure or estimate the property of interest at a limited number of sites where the stratigraphy is known (e.g. borehole sites), and interpolate the values across the map area. This approach has been used, for instance, for seismic hazard studies where shear-wave velocities and seismic site classes have been contoured using geophysical and borehole data (e.g. Motazedian et al. 2011; Rosset et al. 2014). In many cases, the geological model is not published and thus cannot be reviewed or used for a different application. The only common data may be the borehole database, but users may interpret and classify borehole descriptions differently. The interpreted "3D" geology becomes the 'hidden' layer.

In this paper we present a strategy that is in development to build a "super-regional" 3D model of the bedrock topography and overlying Quaternary stratigraphy for a large area of interest extending across eastern Ontario and parts of Quebec and including urban, semi-urban, and rural areas (Fig. 1). The modelling effort is part of a regional seismic risk assessment, but the strategy is to build a model that could be useful for many other regional-scale applications.

The modelling challenge and strategy

Because the study area is large (Fig. 1) there is a wealth of geological information to build a model, but it is also very heterogeneous. Geological information includes several surficial maps, a mosaic of 3D models of various complexities and resolutions, multiple borehole databases, and stratigraphic frameworks from the scientific literature. This is a typical case where the data and knowledge needed to develop the 3D geology model have been acquired over several decades by various organizations including geological surveys, municipalities, consulting or engineering firms, and universities, and with no common infrastructure (cf. Karrow and White 1998, for a good historical perspective on these

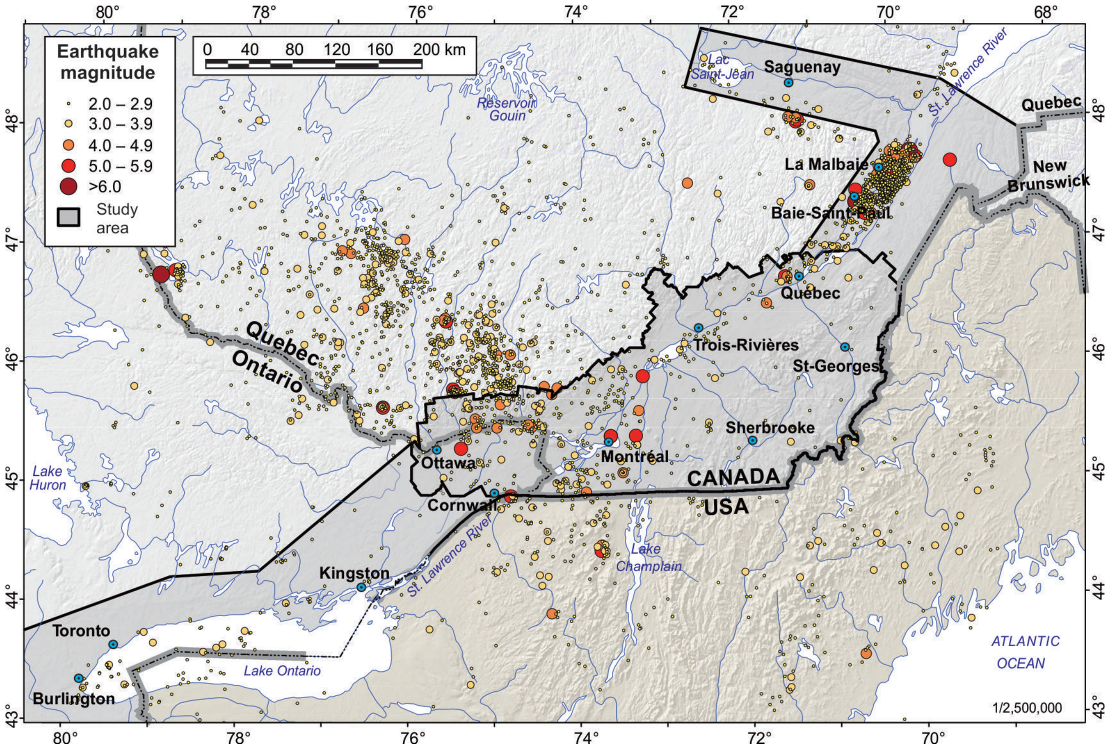

Figure 1. General outline of the study area where all the available geological information is to be integrated to develop a regional 3D model of the Quaternary stratigraphy and bedrock topography. The model is being developed for a seismic risk study, but its structure, format, and resolution are intended for multiple applications.

issues across Canada). Parts of the study area have been modelled at a resolution that is higher than what is needed at regional scale, whereas other parts have geological map information that is several decades-old and with patchy subsurface information of variable quality. The challenge is to produce a seamless regional model that integrates all that heterogeneous information while minimizing issues due to resolution changes (upscaling and downscaling of available models and maps), geological map inconsistencies across overlapping regions or across administrative borders (Fig. 2).

Another important challenge is to find ways to test the model without extensive resources to acquire new geological information. This challenge, common to most projects, is exacerbated in large urban areas because of the many organizations involved in collecting data as well as the difficulties in studying subsurface geology and obtaining an accurate digital terrain model in an urban environment. The general approach is to 1) Build an elevation model from a mosaic of DEMs and DTMs in order to get the best elevation data (i.e. some models are better for rural areas while others are more suitable for urban areas); 2) Compile all the surficial maps and create a seamless map covering the study area; 3) Compile all available 3D models, bedrock elevation maps, and drift thickness maps and then upscale them to generate a simplified stratigraphic model consisting of no more than 3 geological units in addition to the bedrock topography; 4) Check overlapping areas and correct problems; 5) Fill gaps using available public borehole databases and any other data (e.g. geophysical data); 6) Produce a regional stratigraphic grid at a resolution of 0.25 km^2 (0.5 km × 0.5 km cell); 7) Make the models and grid in their original format available to the research and users community.

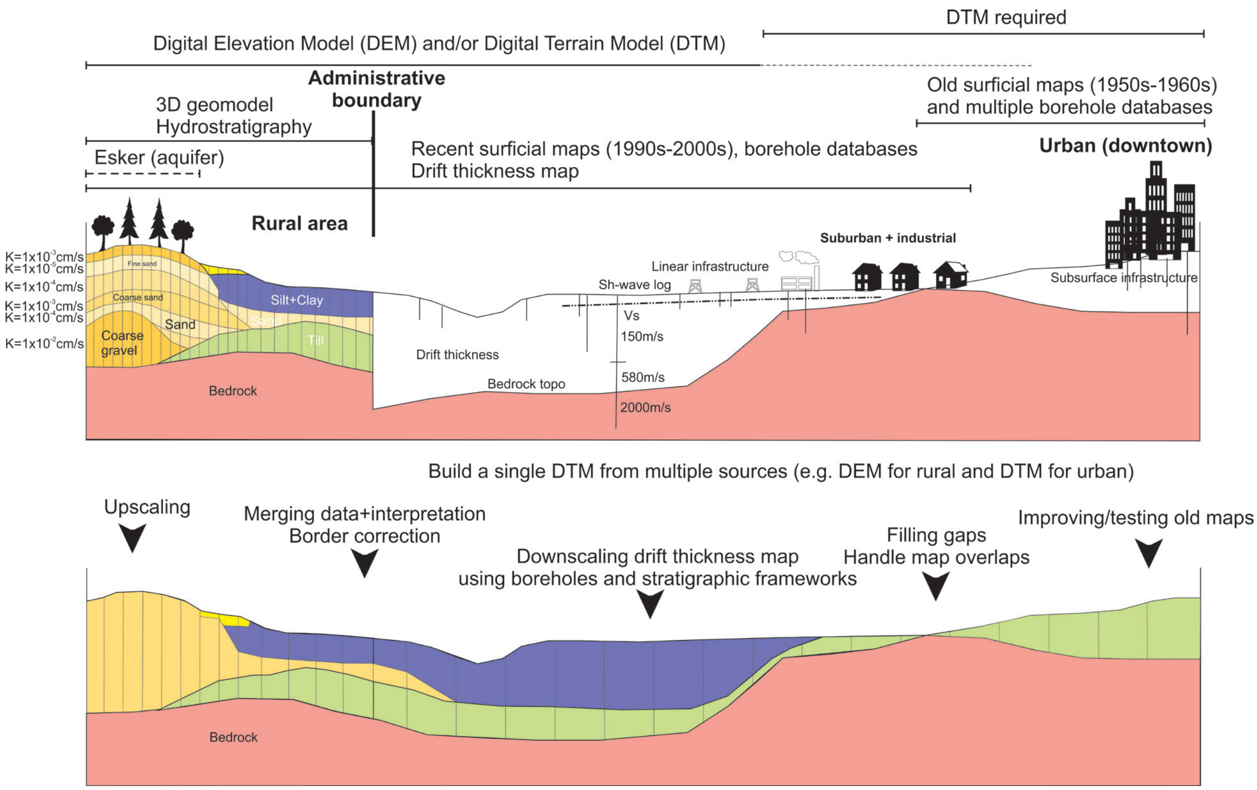

Figure 2. General approach to develop a regional three-dimensional model from existing geological information at various scales and resolution.

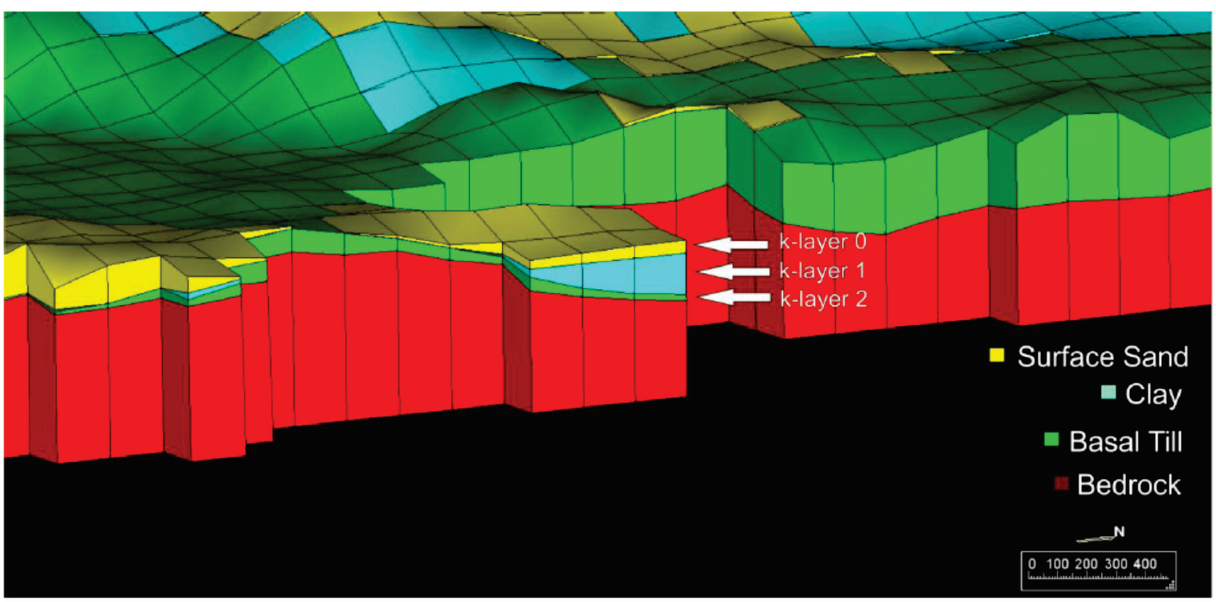

Figure 3. Example of a stratigraphic grid (SGrid) developed in Gocad® that is used to populate models with physical properties for various applications (e.g. geophysical or geotechnical property, hydrogeological parameter). The regional model consists of interlocked triangulated surfaces that provide the bounding surfaces of the grid. The original model can be scaled-up (a coarser grid is produced) for a specific modelling task.

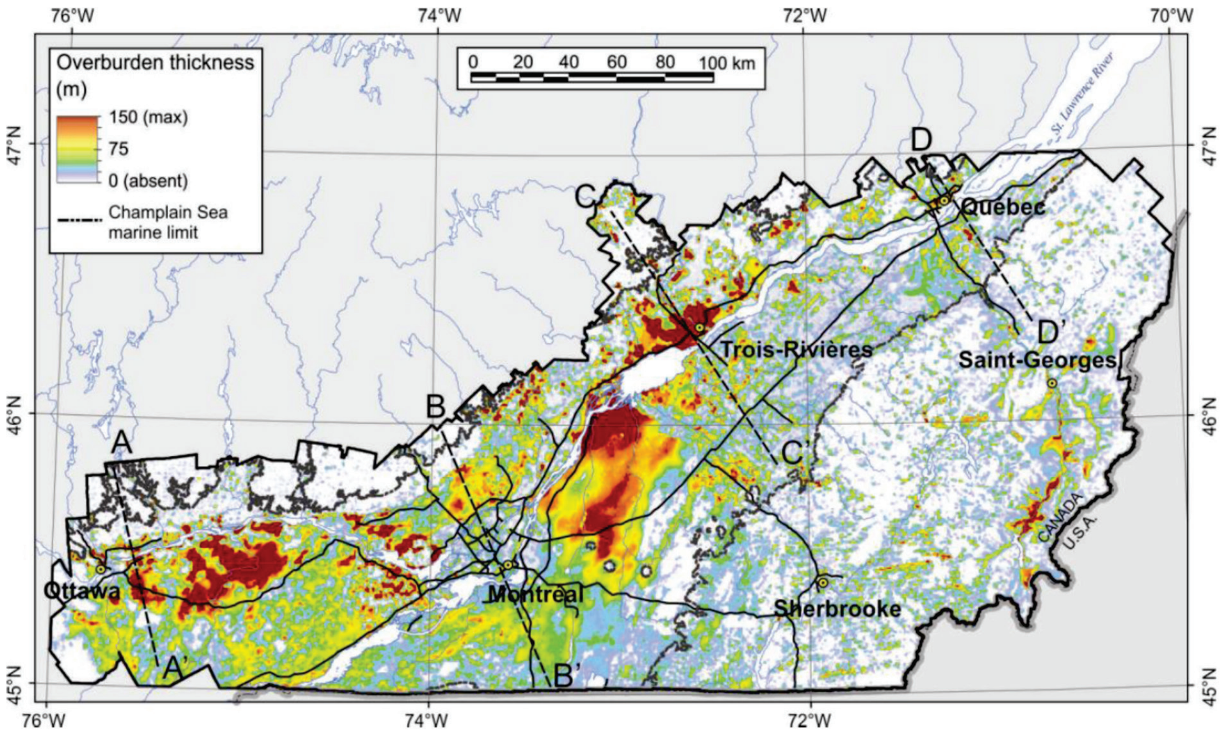

Figure 4. Overburden thickness map produced from the project (Phase 1) regional geology model (modified from Howlett, 2012). A new model (Phase 2) is being developed for the new study area (cf. Fig. 1).

Conclusion

Three-dimensional models are not yet available for most of Canada, even across populated regions where many pressing issues require 3D geological information for appropriate management of land and resources. While some geological surveys in the country have active 3D mapping programs, it will take many years to cover all the populated areas. In the meantime, rapid solutions are needed to generate regional models from the existing heterogeneous mosaic of geological information to produce models for immediate to short-term needs. An approach from a seismic hazard case study is summarized herein which involves compilation of surficial maps, drift thickness maps, existing detailed 3D models, and other datasets (e.g. boreholes), as well as a series of upscaling or downscaling steps of available information, correction of inconsistencies and handling of overlapping maps, and filling of gaps. New approaches are also being considered to help improve maps and models and to test the new 3D model in heavily urbanized areas, such as crowd-sourcing strategies to collect geotagged photos of large excavations. The goal is to have a robust, yet simplified regional geological model in a one- to two-year timeframe.

Acknowledgments

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Attributing Groundwater Withdrawals To Aquifers Using 3-D Geological Maps In Delaware, USA

Peter P. McLaughlin, Jaime L. Tomlinson, and Amanda K. Lawson

Delaware Geological Survey, University of Delaware, Newark, DE 19716-7501 (ppmclau@udel.edu)

Introduction

Groundwater is an essential natural resource in Delaware. The geology of the state's Coastal Plain is characterized by a broad complex of surficial and near-surface Quaternary deposits with internal cut-and-fill that is underlain by a succession of southeast-dipping Cretaceous to Cenozoic sediments. In Kent and Sussex Counties, which make up the southern two-thirds of the state, sedimentary aquifers are the source of all drinking water and most of the water used for crop irrigation, poultry, and industry. This study provides the first comprehensive analysis of groundwater use in Delaware from the perspectives type of water use, geography, and source aquifer. This presentation will be focused on the methodology used in the study to understand groundwater withdrawals in the context of a three-dimensional geologic framework.

Three-Dimensional Aquifer Mapping

Three-dimensional geologic maps of aquifer sands are essential to the assessment of groundwater withdrawals by aquifer in the study area. Twelve confined aquifers and one unconfined aquifer were mapped in three dimensions in Kent and Sussex Counties. A database of depths for tops and bottoms of aquifers was compiled using borehole data from more than 6,600 sites with carefully evaluated locations, yielding approximately 14,000 stratigraphic pick records. To create three-dimensional geologic maps, elevation data were exported from the stratigraphic database for every aquifer pick by subtracting the pick depth from borehole elevation. Maps of aquifer surface elevation (top and/or bottom surfaces of aquifer) were constructed by gridding the pick elevations using ArcMap Geostatistical Analyst with the Radial Basis Function method at 100 m grid resolution. To minimize edge effects, gridding included borehole data from just outside of the study area. The aquifer grids were checked and, where necessary, corrected to ensure they did not violate three-dimensional geographic constraints, specifically that two discrete masses do not occupy the same space, and to ensure that the three-dimensional framework conforms to stratigraphic rules such as the Principle of Superposition (Dugan et al. 2008). This check was done by comparing each aquifer grid to a) the digital elevation model of the land surface, b) the immediately adjacent confined aquifer grids (first grids above and below) and c) the unconfined aquifer grid.

The unconfined aquifer map and the confined aquifer maps were created using slightly different approaches. The unconfined aquifer has a relatively variable thickness because it is made up of sands from numerous formations, and these formations have significant erosion at their bases. Therefore, data volume was emphasized for mapping of the unconfined aquifer. Geophysical logs, geologist logs, and numerous less detailed driller logs from nearly 1900 boreholes were used to grid the base of the unconfined aquifer in Kent County. An existing grid (Andres and Klingbeil 2006) made from a similarly dense dataset was used to delineate the base of the unconfined aquifer for Sussex County and merged with the Kent County grid at the county line. A map of the thickness of the unconfined aquifer was created by subtracting the grid of the elevation of the base of the unconfined aquifer from the digital elevation model of the land surface. In contrast to variable unconfined aquifer, the confined aquifers have simpler and less varying stratigraphic geometries. Because of this, the data used to create the confined aquifer grids could be less dense geographically so allowed a focus on higher quality data, mostly from sites with geophysical logs. Maps the elevation of the top and base of each confined aquifer were subtracted to calculate confined aquifer thickness. By locating the intersections of each confined aquifer grid with the base of the unconfined aquifer, “windows” between the unconfined and confined aquifer were identified and used to define likely aquifer recharge areas. Aquifer maps produced by these procedures are available as grids for use in GIS applications and as illustrations that were edited in Adobe Illustrator and finalized as PDF format maps.

The confined aquifers mapped include one Cretaceous, two Paleogene, and nine Neogene sand units. These aquifers are typically tens of feet thick and occur at progressively greater depths southeastward from their northern recharge areas. The Mount Laurel aquifer is Late Cretaceous in age and composed of glauconitic quartz sands deposited in a marine shelf environment. It occurs in northernmost Kent County, where it is commonly about 100-ft thick, and passes southeastward into fine grained non-aquifer lithologies in central Kent County. The Rancocas aquifer is Paleocene to Eocene and occurs in glauconite- and shell-rich quartz sand. It is used for groundwater in northern Kent County, where it is as much as 200-ft thick; it becomes thinner and finer-grained southeastward across a narrow zone in north-central Kent County, passing into completely non-aquifer muddy lithologies in central Kent County and southward. The Piney Point aquifer is middle Eocene and occurs in shelly, glauconitic, quartz sand. It is an important aquifer in central and southern Kent County but becomes progressively thinner and disappears northwestward as it is truncated updip under a basal Miocene erosional surface. The overlying lower to middle Miocene section is composed of alternating sands and muds, with confined aquifers developed in seven sand units. The aquifers are typically shelly quartz sand, several tens of feet thick, and developed in the shallowest-marine lithofacies at the top of coarsening-upward cycles. The lower four of these seven sands occur in the Calvert Formation and are designated, in upward order, the lower Calvert, Cheswold, Federalsburg, and Frederica aquifers; these are most important in Kent County. The upper three of these sands occur in the Choptank Formation and are here referred to as the Milford, middle Choptank, and upper Choptank aquifers; they are more important in southern Kent County and northern Sussex County. The southeastward dip of these units gives a subcrop pattern in which each successively younger confined aquifer subcrops further southeast under the more horizontal surficial formations, resulting in recharge areas for each younger aquifer occurring successively further to the southeast. Two upper Miocene confined aquifers are important groundwater sources in Sussex County. The lower one, the Manokin aquifer, is the sandy upper part of a coarsening-upward succession of shallow-marine to estuarine deposits in the Cat Hill Formation. The Manokin subcrops under sandy surficial formations across a wide belt of northern Sussex County and thickens southeastward to more than 100-ft thick. The upper one, the Pocomoke aquifer, is developed in the thicker sands occurring in the mosaic of coastal facies that comprise the Bethany Formation. The Pocomoke subcrops in southeastern Sussex County and has a net thickness of more than 100 ft in some coastal areas.

The unconfined aquifer occurs in Pliocene (?) and Pleistocene formations in most of the study area. The unconfined aquifer is generally less than 100-ft thick in Kent County but varies from a few feet thick to more than 200- ft thick in Sussex County. In eastern Kent County, the unconfined aquifer occurs in Pleistocene sediments of the Delaware Bay Group; in western Kent County and much of Sussex County it is predominantly Pliocene (?) Beaverdam Formation sand; and in parts of the Nanticoke watershed, the Inland Bays watershed, and the Delaware Bay coast, it typically occurs in sandy zones in the stratigraphically equivalent Pleistocene formations of these areas (Nanticoke River, Assawoman Bay, and the Delaware Bay Groups, respectively). The confining layers between the Manokin, Pocomoke, and unconfined aquifers are commonly poorly developed or absent, so these aquifers may be hydrologically connected in many parts of Sussex County.

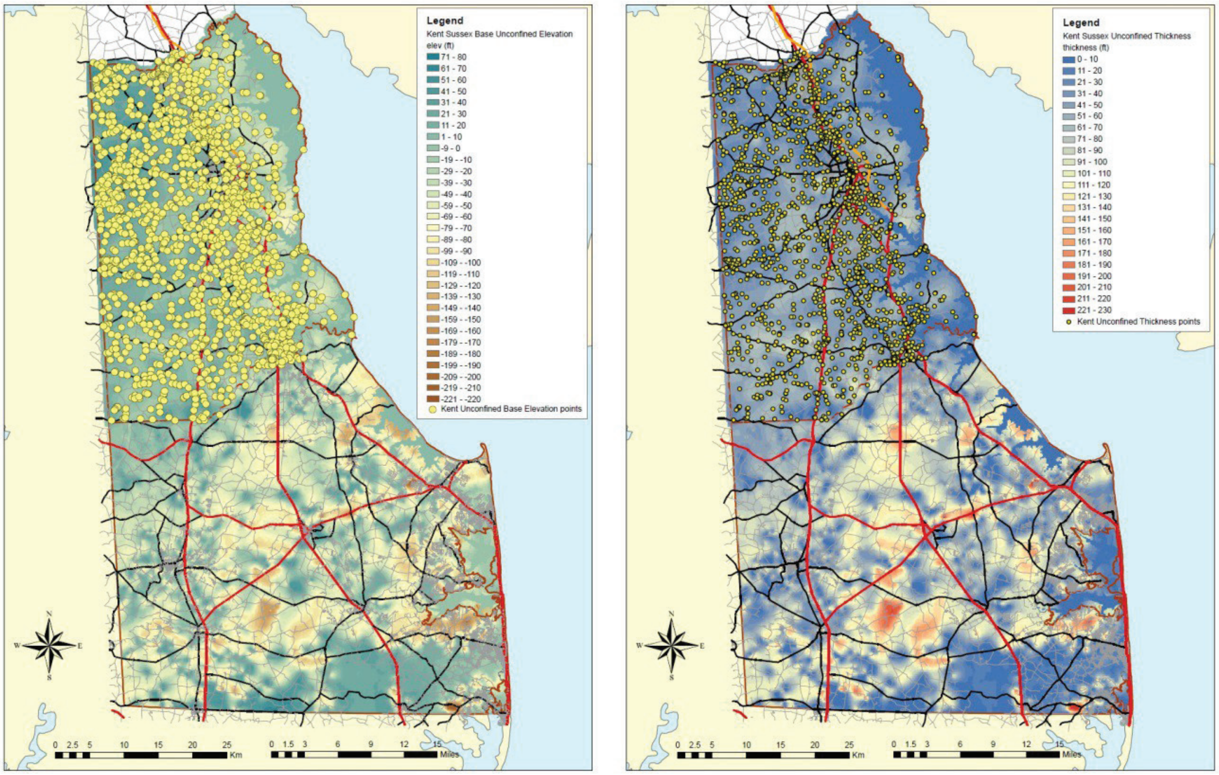

Figure 1. Elevation of the base (left) and thickness (right) of the unconfined aquifer.

Geospatial Analysis of Groundwater Withdrawals

Geospatial analysis of groundwater withdrawals by water use category, geography, and source aquifer was done using ArcMap. Nine well categories were considered: public community systems, public non-transient non- community systems, public transient non-community systems, industrial self-supplied, domestic self-supplied, agricultural irrigation, golf course irrigation, self-supplied lawn irrigation, and non-irrigation agricultural. Reported withdrawal data were compiled where available for wells associated with larger public water systems and industrial water supply wells. Water use was estimated for the other categories (smaller public supply systems, domestic self- supplied, agricultural irrigation, golf course irrigation, self-supplied lawn irrigation, and livestock) to determine likely groundwater withdrawals. The geographic locations of these withdrawals were tallied on a well-by-well basis for categories where well locations are precisely known (wells for large and small public water systems, industrial wells, golf course wells); for categories where all individual well locations could not be accurately compiled (irrigation, domestic self-supplied, and non-irrigation agricultural), withdrawals were spatially estimated on the basis of demographics of unit areas (in this project, census blocks). To assign water use to aquifers, withdrawals were assigned using one of two general approaches: well specific or spatially estimated. For water use categories where withdrawals could be attributed to specific wells (public, industrial, and golf-course wells), aquifer assignments were made by comparing well screen elevations to aquifer elevation maps at the same location. For categories where estimated water use could not be linked to specific, individual wells (irrigation, domestic self-supplied, and livestock), spatial estimates were made for each census block in which the proportion of wells in each aquifer was used to estimate the proportion of groundwater withdrawals from each aquifer.

Examining data for years 2004 to 2008, the total of reported and estimated groundwater withdrawals for all uses was calculated to be between 89 and 144 million gallons per day (Mgal/d) annually, which is comparable in scale to recent USGS estimates (Wheeler 2003, Kenny et al. 2009). Examined by water use, irrigation (1) was the largest use, followed by (2) reported public community water systems, (3) domestic self-supplied, (4) industrial, (5) livestock, (6) golf course irrigation, (7) smaller public community and non-community systems, and (8) lawn irrigation. Groundwater withdrawals for irrigation (1) were estimated to be as much as 91 Mgal/d for a dry year and as little as 50 Mgal/d in a year with abundant, well-timed rainfall. Irrigation well withdrawals were estimated for each area of irrigated farmland identified on aerial photographs by using a daily-crop-demand model (KanSched2, Rogers and Alam 2008) that incorporated daily rainfall and evapotranspiration data, as well as crop type and soil type at each site. The unconfined aquifer provides an estimated two-thirds of irrigation withdrawals, with most of the rest from shallow confined aquifers. Reported pumping data for public wells with groundwater allocations (2) totaled between 22.8 and 26.2 Mgal/d annually; the areas served by these public water systems have a total resident population of just over 200,000 and numerous non-household users. The unconfined aquifer provides approximately one-fourth of these reported public well withdrawals; a key deeper confined aquifer with limited recharge, the Piney Point aquifer, provides approximately 15 percent; and five other confined aquifers provide between 7 and 15 percent.

Domestic self-supplied well withdrawals (3) are estimated to total 11.6 Mgal/d annually during this period. Usage was estimated on a census block basis for areas outside of public water system service areas using a per capita water-demand model that was based on five census parameters -- household size, housing unit density, population density, median year of construction, and median value of owner-

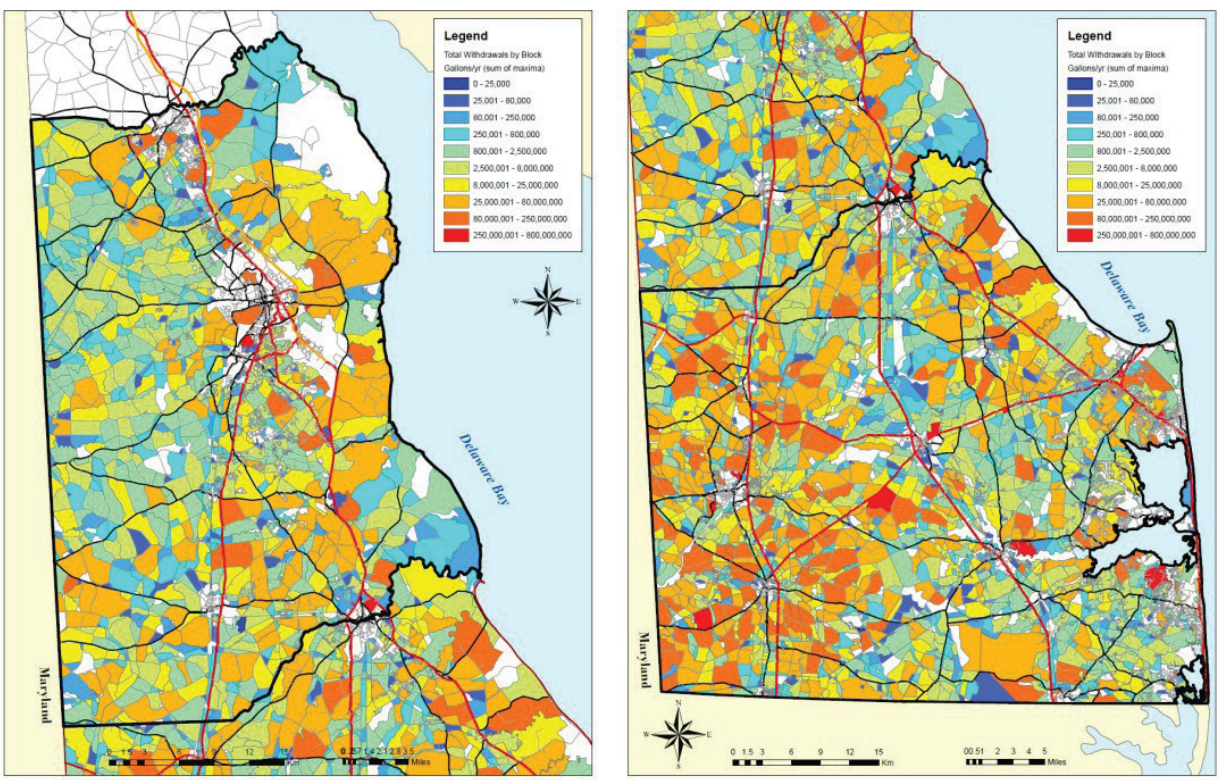

Figure 2. Total groundwater withdrawals by census block, as the sum of the maximum estimated values for each type of water use (from annual values 2004-2008) in each block in Kent (left) and Sussex (right) Counties (gallons per year, gal/yr).

occupied single family homes – similar to the approach used by Horn et al. (2008). The population of census blocks (and partial blocks) totals 159,000, so per capita consumption is calculated as 72.9 gallons per day. Most domestic wells are shallow; the unconfined aquifer accounts for nearly two-thirds of associated withdrawals. Industrial well withdrawals (4) were compiled from the same database of annual pumping data as the public water supply systems and ranged between 6.66 Mgal/d and 7.66 Mgal/d annually from 2004 through 2008. The unconfined aquifer yielded more than half of industrial well withdrawals; several shallow confined aquifers providing the other half. Livestock (5), specifically poultry houses, represent nearly all of the non-irrigation agricultural well withdrawals and are estimated to be more than 4 Mgal/d. This category was estimated on a census block basis using the locations of active chicken houses identified on aerial photography and accepted water demand rates for chicken drinking water (Czarick 2011) and for evaporative cooling systems in the houses (Campbell and Donald 2012). More than half of poultry well withdrawals were from the unconfined aquifer and approximately one-fourth from the confined Columbia aquifer. Golf course well withdrawals (6) were estimated to be 2 Mgal/d from reported pumping data and from estimates based on pumping allocations for wells with no reported pumping data. Nearly half of the groundwater applied to golf courses is from the unconfined aquifer and the remainder from several shallow confined aquifers. Withdrawals for smaller public water systems (7) – including community, transient non-community, and non-transient non-community systems – were estimated to be 1.8 Mgal/d. Estimation techniques were used because of the lack of requirement for smaller users to report pumping; smaller community system withdrawals were estimated on the basis of the same census factors as self-supplied domestic users whereas non-community system withdrawals were estimated on the basis of typical water demands for each specific facility type and size. The unconfined aquifer and confined Columbia aquifer were the largest sources for the smaller public system category. Self-supplied lawn irrigation well (8) withdrawals are minor and were estimated to be 0.03 Mgal/d using a multiplier of domestic household water use multiplied by the number of wells in the class in each census block. Lawn irrigation water is almost entirely withdrawn from the unconfined aquifer.

Final Thoughts

The findings presented here allow groundwater use in the two southern counties of Delaware to be viewed through the lenses of type of water use, geographic location, or source aquifer. In particular, the subtotals by aquifer highlight the value of integrating analysis of groundwater withdrawals with a high-quality subsurface geologic framework. The results of this study indicate unconfined aquifer accounts for more than half of all groundwater withdrawals in Kent and Sussex Counties. The confined Columbia and Pocomoke are estimated to each represent around 11% of withdrawals, the Manokin 8%, the Cheswold, Frederica, and Piney Point each 3 to 5%, and other confined aquifers less than 2% each. Beyond the findings presented here, the data compiled provide a starting point for future, more detailed analyses of site- or problem-specific questions, including aquifer models at several scales.

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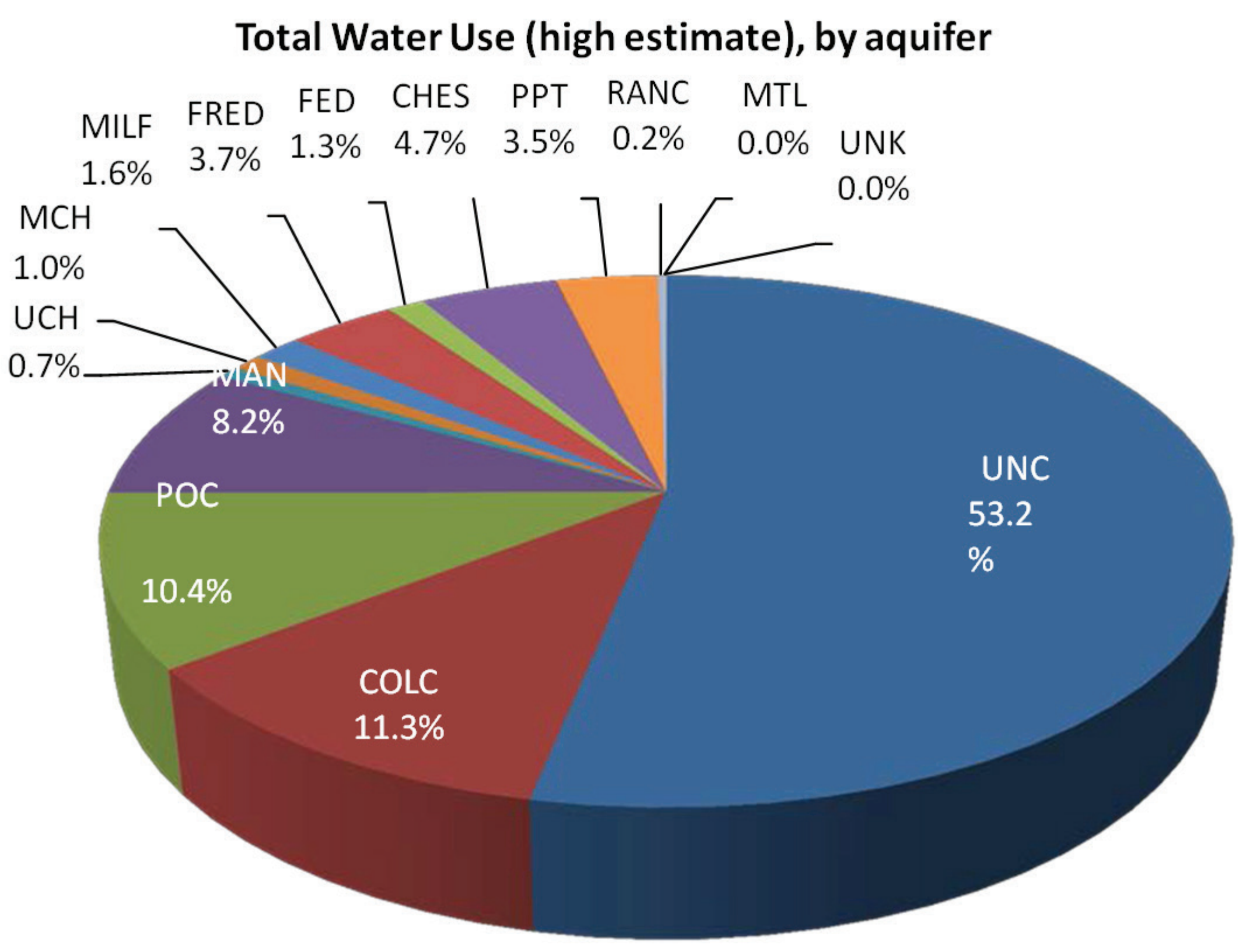

Figure 3. Proportion of estimated total groundwater withdrawals, by aquifer, on the basis of the high-end sum of values from a compilation of high-use and low-use years in Kent and Sussex Counties. Percentages may not add to 100% due to rounding to one decimal place.

3DT – Constructing A Subsurface Geologic Model Of Texas

Sean C. Murphy, David L. Carr, Aaron Averett, John Andrews, Dallas Dunlap, Cari Breton, and Allan R. Standen (independent consultant)

Bureau of Economic Geology, University of Texas at Austin, University Station, Box X, Austin, TX 78713-8924, sean.murphy@beg.utexas.edu

Introduction

The Bureau of Economic Geology (BEG) at the University of Texas at Austin hosts a physical archive reflecting the history of subsurface exploration and production over the last century. BEG is the curator for 1.5M boxes of core and bags of cuttings representing more than 200,000 unique wells from Texas as well as other states and nations. These are carefully stored in three large facilities located in Austin, Houston and Midland. BEG has also collected more than 1.5 million paper logs kept in the Geophysical Log Facility (GLF), a repository for the geophysical records received from the Railroad Commission of Texas (which regulates oil and gas activities within the state), private donations, and BEG research projects. In addition, historical information such as geologists' "picks" of tops and bottoms of formations and detailed geologic descriptions are often found in the 2.5 million-well scout tickets, the 330,000+ driller's logs and the 280,000 scout reports. Other records of the subsurface are captured in 100,000 geochemical analyses, 75,000 thin sections, 14,000 strip logs, and over 1000 mudlogs. Finally, historic cable-tool driller's reports, generated at a time when operators could not anticipate formations using measurement-while-drilling technologies, are used in counties where these are the only deep-well records.

During the last decade, software applications customized for the oil and gas industry have matured into sophisticated, multi-user desktop platforms supported by large data and service providers; (examples include Schlumberger's Petrel, Halliburton's Decisionspace©, and IHS' Petra® suites). These software platforms have been optimized to model basin-scale subsurface vertical and horizontal stratigraphic relationships and complex structures (faults, salt structures, etc.) using both seismic and geophysical well logs, as well as other data. Over time these software platforms have grown in sophistication and complexity to enable exploration teams to visualize plays in three dimensions, optimize drilling programs, estimate reserves, model uncertainty, and develop stimulation schemes. Research scientists at the Bureau of Economic Geology have been fortunate to have had access to many of these tools because of the generosity of oil-industry software and data providers.

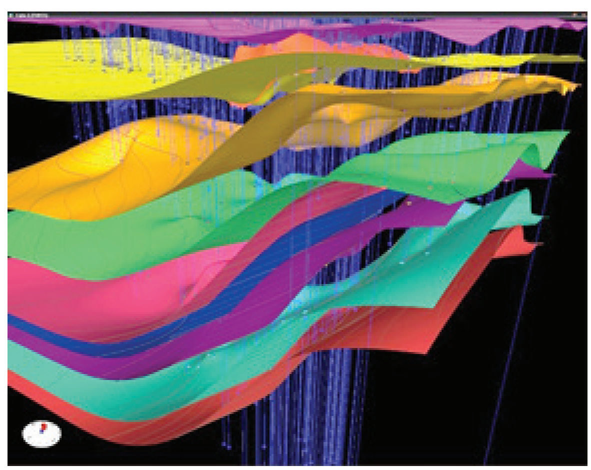

Figure 1. Ward County prototype 3-D model showing major stratigraphic units and well traces (as rendered in Halliburton's DecisionSpaceDesktop©).

Building upon the Bureau's ready access to subsurface data and sophisticated software, the spirited goal of this project is to construct a three-dimensional subsurface model that encompasses the entire state of Texas. In any location across the state, the model would display a number of (relatively) easily identifiable top or bottom geologic reference surfaces that would graphically convey the stratigraphic depth of the well core and cuttings intervals that are stored in the BEG core warehouses. Once established, the framework of this model could then be used to display the locations of any subsurface information, as long as the geospatial locations are known. Delivering archived physical subsurface data (paper and rock) using tabular or graphical formats so that it is accessible to customers (industry professionals, the research community and decision makers) through a web browser would be a profound and transformational achievement.

Building The Statewide Model

Proof of Concept Pilot Model, Ward County

A county-scale, proof-of-concept pilot subsurface model (Figure 1) was constructed using Ward County (area 836 sq. miles), which is situated in west Texas on the eastern flank of the Delaware Basin along the transition to the Central Basin Platform. This county was selected because it is structurally and stratigraphically complex and contains some of the more productive oil and gas fields in the Permian region. Formation tops for 14 geologic formations were selected using geophysical logs, cable tool reports, scout tickets, Texas Water Development Board (TWDB) driller's reports, and previously published BEG and TWDB reports (Meyer et. al. , 2012; Standen and Finch, 2009). Data from more than 1000 wells were loaded into Halliburton's DecisionSpaceDesktop© modeling application, and simplified surfaces were generated reflecting conformable and unconformable relationships, but ignoring faults. Surface geology using the Geologic Atlas of Texas (GAT) Pecos Sheet, (Barnes, 1976) was integrated with the subsurface formation tops. The resulting surfaces were gridded and exported from DecisionSpace© and integrated into a proprietary standalone software platform so that the model could be viewed from any perspective and projected in 3-D using two projectors. The final version was shared with participants at the West Texas Geological Society Fall Symposium (Andrews et al., 2013; Murphy et al., 2013).

Statewide Model, Base Surface, Ordovician Ellenburger Formation

IHS' Petra® application software was used for scale-up because of its facility for well-based subsurface geologic modeling and, given BEG's institutional experience base, a large number of archived projects could be mined for well data and stratigraphic surface picks. While the Ward County effort demonstrated the ability to take a bottom-up approach over a relatively small area (0.3% of Texas), it was decided that that a top-down approach would be preferable in initiating a state-wide effort. This entailed identifying two large, relatively non-complex, boundary layers (top and bottom) to which all other data points could be referenced with a high level of confidence. The logical upper boundary was the surface, as both geology and elevation are generally well established. Precambrian rocks might be the obvious choice for the lower surface; however, the paucity of wells across the state drilled to basement has confounded previous efforts to define this surface and most models resort to assumptions about the thickness of overlying formations (Ruppel et al. 2005). In contrast, the laterally extensive, typically deep-lying, Lower Ordovician Ellenburger Group has been a production target for decades, both as a petroleum reservoir and as a saline aquifer. This has resulted in a significant amount of state-wide data collected for the upper surface of this unit. Because very few wells with cored intervals extend below this carbonate sequence, the top of the Ellenburger Group was selected as the model's lower boundary.

The top of the Ellenburger Group covers most of the state from West Texas, north to the Palo Duro Basin, and south and east where it disappears into the highly sheared rocks representing the Ouchita structural belt. The lithology of the Ellenburger Group has been extensively described and studied (Loucks, 2003; Kerans, 1990) and is characterized as primarily shallow-water, platform carbonates, which are devoid of fauna and pervasively dolomitized over much of its extent. Evidence of subaerial exposure and ubiquitous karst development prior to deposition of the overlying middle Ordovician (Simpson Group) transgressive sequence has been documented by many (Kerans, 1990; Loucks, 1999); this aids in the recognition of

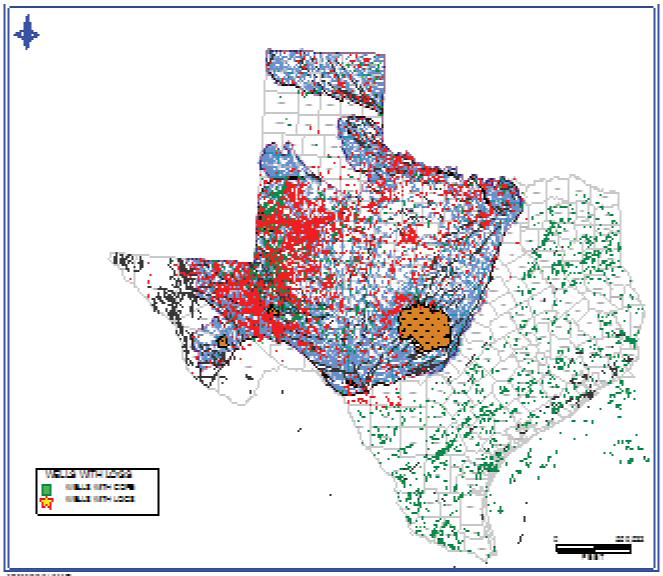

Figure 2. Working Petra® structural map of Ellenburger, with contours (blue), reference wells (red), BEG core repository (green), faults (black) and Precambrian outcrops (no ELBG subcrops) noted

the unconformable top surface in many logs due to its distinctive gamma and resistivity signatures.

Another advantage of using the top of the Ellenburger Group as the reference basement is that it has been included in previous studies looking at regional aquifer resources (Core Laboratories, Inc., 1972) and oil and gas resources (Ruppel, 1985; Ruppel and John, 2009). All contour and fault trace data from these structural interpretations were used to produce spatially registered GIS shape files that were then imported into the Petra® project as separate layers. These published maps guided our structural mapping, and GIS shape files representing Texas basement faults were also imported (Ewing, 1991; Ewing, pers. Comm., 2014). A working map is presented in Figure 2.

Initially the project was populated with data from approximately 50,000 wells gathered for other BEG projects across the state of Texas, regardless of whether or not they penetrated the Ellenburger formation at depth. Raster and digital logs are linked to some of these wells, but quality varies and many are not depth registered. The priority for adding wells to the database are those that match BEG's core holdings, or wells in close proximity to those with core. Since operators typically generate core only in regions and at depths where there is potential economic value, most of the BEG collection is derived from producing basins and oil fields across the state.

Verifying the Ellenburger picks that were used to construct published structure maps and filling in gaps where wells did not penetrate the lower Ordovician was the most time consuming and resource intensive stage in the project. This was because the wells identified with Ellenburger top picks in these reports were not listed with their American Petroleum Institute (API) standard unique well identification numbers. Matching well descriptions from the reports to their correct unique API identification required laborious, manual well-by-well comparisons to national databases (e.g., IHS, DrillingInfo) rather than very rapid uploading of data available for wells having known API numbers.

Although we were not able to find the API numbers for all wells with Ellenburger tops from published sources, we nonetheless found them for 859 key wells: 421 wells from the TWDB Aquifer report (Core Laboratories, Inc., 1972), 184 wells from the Permian basin report (Ruppel and John, 2009), 155 wells from the Llano Uplift Aquifer report (Standen, 2007), and 99 wells from Palo Duro Basin report (Ruppel, 1985). Other sources of relevant wells were regional cross sections that were reported in research studies (Kerans, 1990), or basin-related studies published by regional geological societies of Texas (examples include Gardiner, 1990; Groves, 1968; and others).

Additional wells were added to the Petra® database in counties outside basins or away from plays, but only where there were not enough wells to validate the contour traces, or to extend the Ellenburger top surface beyond the previous studies. These were initially identified by searching for wells in the IHS database by location (typically county) that intersected the Ellenburger formation, and then matching to wells in the Drilling Info database that included relevant geophysical log rasters. Information and rasters from this subset of wells was loaded into the Petra® project and then Ellenburger tops were selected.

At the time of this report, the total number of wells loaded into the Petra® database for this project is 60,302, but these blanket the state of Texas. Examining only those wells that specifically overlap with the mapped aerial extent of the Ellenburger Group (determined to be 119,890 sq. mi.) reduces that number to roughly half (29,897); geophysical raster logs are attached to 4902 of these wells and digital Log ASCII Standard (LAS) logs to 1928. Validated Ellenburger tops were picked for 4421 wells, 1436 by the author and the rest recorded by trusted sources (other BEG researchers or contractors to BEG). A sample area is shown in Figure 3.

Petra® enables the user to easily adjust and move structural surface contour traces while viewing well picks; the contours from previous reports were validated or moved by comparing to the validated well picks and added in regions where the Ellenburger had not been mapped previously (examples include the Val Verde Basin and Devil's River Uplift). Even though Petra® was used to integrate all the well, log, and published data sets, it was not used to grid the final surface. Through trial-and-error, the authors determined that ESRI's ArcMap 'spline barrier' gridding function produced the fastest and most accurate surface, given the total area and structural complexity of the model. To accomplish this, all wells with Ellenburger picks, faults (which define the 'barriers' in the method), and structural contours (our own and modified from publications) were exported from Petra® as ESRI shape files. Using ArcMAP and applying its 'spline barrier' gridding functionality we were able to produce continuous geologic surfaces within discrete fault blocks. The resulting Ellenburger 'basement', DEM 'surface' and BEG core intervals could be integrated using ArcScene's 3-D visualization capability.

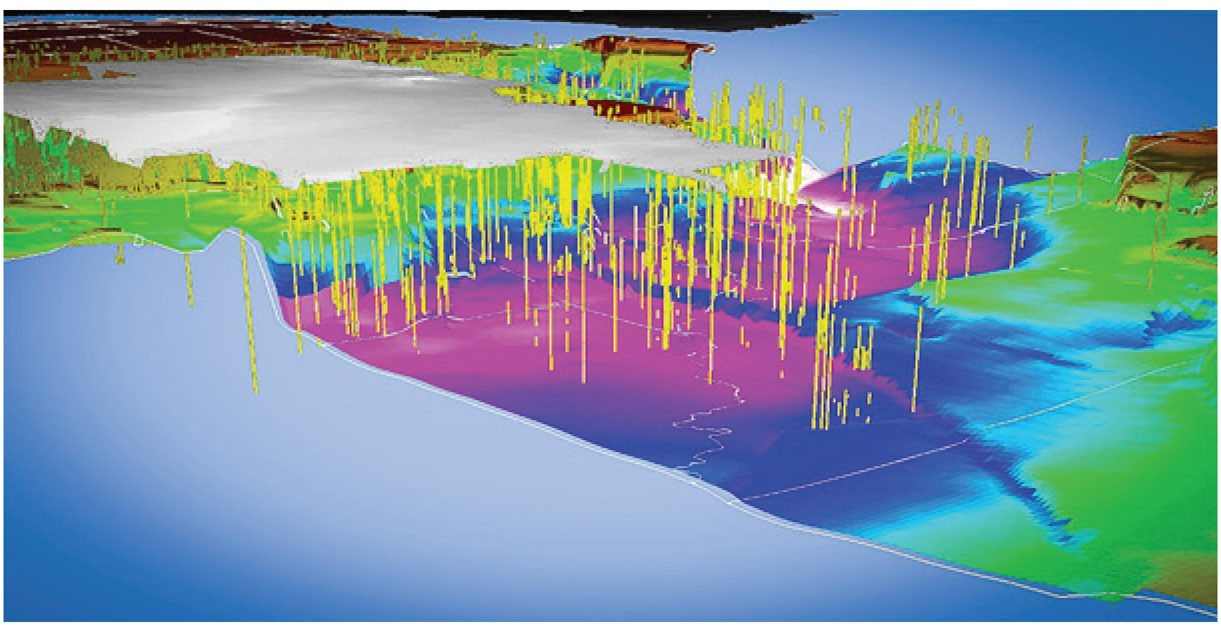

Figure 3. 3-D rendering of BEG's Well Core Holdings, with actual intervals plotted against reference top DEM (grey) and bottom Lower Ordovician Ellenburger (contoured) surface, looking through the Delaware Basin with Central Basin Platform on left, perspective view from Loving County towards the southeast (ESRI ArcScene). This represents just a small window into the entire 120K sq. mile area of Texas underlain by the Ellenburger.

Delivering The Model To The Public

Data representing well locations, core samples, and geophysical logs are stored in a Microsoft SQL Server database, and served to the client using the ESRI ArcGIS Server REST API. REST API services are available to a variety of clients including desktop applications such as ArcGIS for Desktop, Google Earth, or custom web applications.

The primary client is a custom web site making use of Leaflet and Angular JavaScript frameworks to deliver two dimensional map and feature data to the user. This application enables the user to query the base data for well records based on their location or other attributes including depth relative to a particular surface. The results of queries are presented as 2D maps or in a tabular format, and can be exported as a spreadsheet for more convenient use.

Open source libraries using the THREE.JS JavaScript framework available today from the Cesium consortium make it possible to create compelling 2D and 2.5D dynamic data visualizations in web browsers without a plugin. The dozens of demos on the Cesium website (www.cesiumjs.org/demos.html), created by Cesium founders, Analytical Graphics, Inc. (AGI) and others from around the world (such as NICTA based in Australia) convey the potential for quickly creating compelling web-based scientific and educational services starting from a global vantage point. Additional code would need to be written to convey subsurface features realistically in 3D space viewable from any perspective, in a manner mimicking a physical globe. Principles at AGI assess the necessary code generation as challenging but achievable, requiring no more than 6 months and a couple of programmers.

Short And Long Term Plans

Generating additional lithological reference surfaces for this project will not proceed without additional outside funding. With funding, adding stratigraphically younger formations above the basement (Ellenburger Group) will provide geologic context and generate reference planes for the BEG core archives. Unfortunately, none of the younger stratigraphic units in Texas have the extensive aerial coverage of the Ellenburger Group, so the focus will become more region- and location-specific. Realistically, this subsurface model could provide a framework to support the delivery of any surface or subsurface geo-referenced well data to the public through a user-friendly, map-based web interface (data such as geophysical logs, geothermal well profiles, core geochemical analysis results, digitized well-based reports, etc.)

Funding programmers to code the additional JavaScript libraries for the open-source Cesium community necessary to implement subsurface graphics would create new and compelling visualization tools for conveying geo-referenced data and geo-information to the public directly on mobile devices (the Cesium framework runs today on all of the common web browsers, without a plugin). Acquiring this code through open source libraries, any public entity (university, geologic survey) or private enterprise with some level of JavaScript programming knowledge could create and deliver their own customized implementation.

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A National 3D Geological Model Of Denmark: Condensing More Than 125 Years Of Geological Mapping

Peter B.E. Sandersen, Thomas Vangkilde-Pedersen, Flemming Jørgensen, Richard Thomsen, Jørgen Tulstrup and Johnny Fredericia

GEUS - Geological Survey of Denmark and Greenland, Lyseng Allé 1, DK-8270 Højbjerg, Denmark, psa@geus.dk

Introduction

Two years ago the Geological Survey of Denmark and Greenland (GEUS) celebrated its 125 year anniversary (Fredericia & Gravesen 2014) and an event like that was a good opportunity to look back at a long and eventful period of geological mapping. But it was also an opportunity to visualize the future contours of geological mapping in Denmark – a field that is now undergoing major changes. The tendency both nationally and internationally is that along with the ever-increasing computer powers and the improved capabilities of software packages, there is a growing demand for geological models and 3D maps that meet these new technical standards. In addition to this, modelers and end-users expect to be able to solve more and more complicated and sophisticated problems related to the subsurface. Accordingly, we are transforming our ways of mapping and modelling geology from 2D to 3D – in the future probably even 4D. Our ways of interpreting depositional environments, lithology, structures and so on may be more or less unchanged, but we are forced to look at our data and interpretations from new angles when working in three dimensions. In this process we inevitably gain new insights when combining data in new ways – insights that could lead to updates of former geological interpretations, but also to realizing that changing from 2D to 3D poses new challenges of both technical and organizational character.

It is a part of GEUS' strategy for the coming years to build a national, digital 3D geological model for the Danish area that can act as a publicly accessible database representing the current interpretation of the subsurface geology. A national model like that should constantly be in development – focusing on meeting current demands rather than focusing on delivering a static product for the shelf.

So how can 125 years of geological mapping activities be condensed into a single digital 3D geological model that is capable of merging decades of research and collected data, and still convey a coherent and contemporary interpretation of the geology on a national scale? What should be the focus of the model and should the model be capable of operating at different scales? And do we have enough data to map the detail we want?

This paper will reflect on some of the considerations and discussions we have had in GEUS on how to make and maintain a national geological model, and the paper will add to the early sketches presented at the Workshop in Denver two years ago (Jørgensen et al. 2013). We have now reached a point in the work leading to a national model where we are able to give a status of the strategy and the planned framework for the activities in the coming years.

Model Considerations

Before initiating the construction of the national 3D model there are a number of issues that have been discussed and given a great deal of consideration. A few of these are:

Model area

GEUS is surveying the geology of both Denmark and Greenland. The area of Denmark (43,000 km^2) is very small compared to the area of Greenland (2,180,000 km^2) and even if only accounting for the ice free areas, Greenland is still 9 times as large as Denmark (not including the offshore parts). Geographically Greenland and Denmark are separated, so obviously two separate models will be needed. But because of the large size of Greenland it may be necessary to split the Greenland model up into several smaller models. In terms of geology the setting of Denmark and Greenland is very different and a common legend cannot be constructed, but it is imperative that the construc-tion of the models follows the same set of principles and procedures. Up till now we have worked mostly on the model for the Danish area so this paper will focus on the work related to this area.

Depth range

One of the important questions is which parts of the subsurface should be included in the model and how do we cope with the general problem of varying data coverage and/or data resolution? In the deep parts of the subsurface (>300-400 m) we primarily have borehole data and seismic data collected by the oil industry, with data having an uneven coverage dictated by the focus of the oil and gas exploration surveys. In the more shallow parts of the subsurface (<300-400 m) the data are primarily borehole data, seismic data, electric and electromagnetic data combined with information from outcrops. Data have been collected mainly in connection with groundwater investigations, raw materials/minerals exploration, soil contamination investigations and geotechnical projects. The data density is generally much higher in the upper parts of the subsurface.

A large part of the sediments of the shallow subsurface in the Danish area is affected by the glaciations during the Quaternary both in terms of varying lithologies and deformations. This makes the upper part of the succession very complex and generally requiring a much larger amount of data in order to be mapped. Can this heterogeneity of the geology and the data be incorporated in one model? Or is it necessary to split the subsurface into an upper and a lower part and therefore deal with two separate models? Some GSO's have chosen to have different national models with varying resolution (e.g. the Netherlands: van der Meulen et al. 2013) or focus on having one model that can handle varying resolution (e.g. Great Britain: Mathers & Ford 2013).

Building on existing data and knowledge

GEUS has a long tradition for making national 2D maps of specific sub-surface layer boundaries and surface geology maps. 3D geological mapping and modelling has been performed regionally and locally for some years primarily by governmental agencies (including GEUS), regions and municipalities, oil companies, mining industry and consulting companies. The models are typically targeted towards evaluations related to oil/gas, groundwater/drinking water, geothermal, raw materials/minerals or soil/groundwater contamination issues and apart from models made by/for the oil and minerals industries, many of these models are publicly available. Especially the intensive groundwater mapping campaign during the last 15 years has produced a large number of publicly available models (Thomsen et al. 2013).

The large number of individual mapping projects has created a patch-work of models, but as the models are made in different ways with varying quality and for different purposes, they are very difficult to merge. When building a new national geological model it is, however, necessary to collect and evaluate existing data and models (2D or 3D) and create a new and coherent model that is built upon the results of earlier mapping projects.

In Denmark we have a range of public databases hosted by GEUS that contain both raw data and model interpretations, and these databases are planned to represent the backbone of the national model. Therefore it is very important to keep these databases updated and ensure that everybody uses this vast amount of data.

Defining the end-users

Early in the planning phase it is important to have an idea of who could be potentially interested in a national model and what could be their needs? The reality is that there is a wide range of end-users with different and very specific purposes for their use of a national model. This means that purpose-specific models like we normally produce, do not apply for a national model. But if we construct a model that is not purpose-specific there is a risk that we will end up with a model which is either too sketchy or too heterogeneous to be attractive to a majority of the end-users. As a national model has a long time perspective (and a large budget) it will need to have continued support from the end-user community.

Model detail/scale

Can we map the detail we want with the data we have - or do we need more data? A complex geology requires a large amount of data, and most often our data is geographically clustered. This leaves us with the dilemma that detailed models can only be made within the data cluster, and outside the clusters data can only support a large-scale model with less detail. So can we, in terms of a national model, use only one single scale or shall we try to make a model that can manage multiple scales? In modern 3D modelling software there are no zoom limitations meaning that, if not otherwise stated, your data and model can be viewed and evaluated at any scale. It is very important to convey the scale-limitations of the model to the end-user.

Model update

If the model is not regularly updated the end-users will lose interest in the model and go elsewhere to get subsurface information. The model should be dynamic and therefore it is important that the model is regularly updated and applied with a strict version annotation so that every model version can be clearly identified. Generally, a “static” model approach should be a thing of the past.

The Components Of The National Model

As a result of our internal discussions and considerations the contours of the Danish national 3D geological model can now be described:

The national model will be constructed as a 3D framework model, where the surfaces will represent for instance tops and bottoms of defined geological formations, stratigraphic complexes or other types of spatially recognizable units. In addition to this, the surfaces will represent for instance erosion surfaces, stratigraphic markers and transgressional surfaces. The surfaces will represent units defined in the legend of the Danish subsurface constructed in connection with the national 3D model project (Figure 1). The surfaces will be defined and controlled by interpretation points, lines, polygons etc. together with an interpolated grid or triangulation. This framework model will along the way continually grow with the addition of new surfaces.

The layered framework model will be supplemented by volumetric cells containing detailed geological information between the mapped surfaces. To these cells attributes describing e.g. lithology and lithofacies or related parameters such as porosity can be added. It is important to emphasize that the

Figure 4. Legend of the Danish Pre-Quaternary succession

national 3D model for Denmark is a geological model focusing on geology – not hydrostratigraphy or physical/chemical properties.

The model will start out with selected key surfaces but more detail will be added continuously. The plan is that it shall be possible to include a varying level of detail within the national model, and that the model can be handled at different scales. Users will be able to extract the elements they want. Of course this will create a demand for guidance to at which scale the specific model element can be used.

The model elements will be built according to standards and procedures which have to be defined early in the process. The same applies for quality assurance, quality assessment and model updates/versioning.

The national model is planned to be platform-independent meaning that construction of individual model elements can be made in a variety of modelling software, but with a required standardized export format.

The model will in the first stages only include the Danish onshore, with the Danish offshore areas and Greenland being added later, but built with a similar general setup.

As of now, 13 surfaces encompassing the deep succession from top of Pre-Zechstein (Permian) to the top of the Chalk Group (Danian; Paleocene) exist in a preliminary version and await import to the national model. Above this part of the succession the construction of two major tertiary surfaces and the top of the Pre-Quaternary surface is planned. The complex geology of the Quaternary will be built locally and regionally using layer-boundaries and volumetric cells that are not necessarily bound tightly to a Quaternary legend. This is due to general difficulties of correlating over long distances.

An important part of the national model is the databases. The model database is currently in the pre-construction phase with focus on constructing an architecture that can contain all desired model elements and at the same time possess a flexibility that makes future amendments possible. Different visualization tools are being evaluated but no decisions have been made at this point.

Challenges

Modelling complex heterogeneous and geology

One of the main challenges when constructing a national geological model is how to model complex geology and heterogeneous successions. Especially the Quaternary succession is often highly complex and typically we only have a limited amount of detailed data and the data is often clustered. This leaves us with a patchwork of small areas with high resolution and large areas outside with low resolution. If the area is very geologically complex we may understand the general architecture, but we will not have enough data to model it in high detail. This challenge can be met by constructing a model that can handle different scales with different degrees of detail, but not necessarily has a full geographical coverage with interpretations. We believe that a model like this will convey the actual status of the mapping and give a good visualization of where our knowledge is good and where it is poor.

Keeping the model up-to-date

Another challenge is that whenever we make a model, chances are that the model will be outdated even before it is finished. On one hand there is the fast and on-going development in computational capabilities, modelling software and also constant improvements of modelling and mapping methods, and on the other hand the continuous emergence of new data. This means that we will constantly be confronted with the need to keep our methods and procedures up front and to having included the newest data. Therefore, there will be a need for strict versioning procedures including options for visualization of the hard data on which the new interpretations are based.

Handling uncertainty

The issue of model uncertainty has been heavily discussed for many years, but when changing from 2D to 3D there is a growing demand from end-users that we can present an uncertainty assessment along with the model. This issue is highly complex and the challenges are numerous. One thing is how to assess the uncertainties of each dataset, but another is the challenge of assessing the uncertainties related to a combined dataset. Added to this is the challenge of handling both the quantitative and the qualitative aspects. It will be necessary to make an uncertainty assessment concept tailored especially for the national model and apply this to all model elements.

Meeting the end-user needs

As described earlier it is important that the national model is attractive to a broad end-user community and this means that the national model should be able to provide the users with the model-output they are looking for. As the users are very different and as the model-download probably will be used for very different purposes, there may be specific user needs that standard model-outputs cannot meet. A way of handling this could be to distinguish between standardized off-the-shelf products and individually tailored products, but with all products being made from the same framework model. A standard product from the "3D Model Department Store" could for instance be a suite of nation-wide surfaces (in 1:200,000) to be used in a project dealing with regional or national assessments, whereas a tailored product from the "3D Custom Shop" could be a number of specific surfaces in a small urban area (in 1:25,000) supplied with lithology in volumetric cells in that specific area. In this way the 3D model construction procedures can be kept stringent while the model output can be more flexible in order to meet the end-user needs.

Organizing the work

A large undertaking as the construction of a national 3D geological model will require an organization that is capable of supporting a project of this size and complexity for a prolonged period of time. GEUS is an institution with many highly specialized researchers and the organization will need to provide the project with the required man-power and ensure that they have the required skills. But at the same time it is important that the project has a high level of research potential in order to be attractive to the researchers. Added to this is a need for a high level of collaboration between different departments.

A national model of a certain complexity that shall be disseminated to a variety of end users needs a transparent construction process and needs to be well documented. Therefore we are in the process of describing workflows and procedures. These will in time also include guidelines for QA/QC. The documentation and descriptions of procedures and guidelines will be led by an editorial function in order to keep up a high degree of consistency.

Funding

A prerequisite for making a national model is that stable funding is secured for a long period of time. This matter is still not fully resolved and different scenarios including user-financing are being discussed. A classic problem in this connection is that a national model might be difficult to sell before is has been made – especially when the construction process will span several years.

Perspectives And Strategy

At this stage the contours of a unique nation-wide 3D geological model emerges. We have a large amount of data and numerous existing geological models that can serve as a platform for the model building.

The short-term strategy is that we within the next 4 years will have:

- Established an organization around the national model
- Established at least 15 key surfaces of the model
- Initiated the work on regional and local elements in the upper parts of the model
- Established and launched the database for the national model
- Established a beta-version of the web interface
- Described standards and procedures in a number of guidelines
- Established a dialogue with end-users
- Established a long-term financing plan

The long-term strategy is that we in 10 years will have:

- Finished modelling the major mapped areas with local/regional surfaces
- Included the Danish offshore areas in the model

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Analyzing Lithological And Grain-Size Trends Using A 3D Voxel Model: A Case Study From The Holocene Rhine-Meuse Delta

Jan Stafleu and Freek S. Busschers

TNO – Geological Survey of the Netherlands, P.O. Box 80115, 3508 TA Utrecht, the Netherlands, jan.stafleu@tno.nl

Abstract

TNO Geological Survey of the Netherlands systematically produces 3D voxel models for answering subsurface related questions. One of these models (GeoTOP) schematizes the shallow subsurface of the Netherlands in millions of voxels each measuring 100 by 100 by 0.5 m up to a depth of 50 m below sea level.

The GeoTOP model was used to perform a quantitative 3D spatial trend analysis on channel belt lithology, sand grain-size and architectural characteristics in the Holocene Rhine-Meuse delta. An analysis of the coarse-sand and fine-sand fractions shows clear spatial trends that relate to downstream changes in gradient, reworking of older sediments and tidal influence. Channel deposit proportions show an almost linear downstream decrease with an average value of about 0.5% per km. The analysis results can be used as input parameters for groundwater flow modeling studies in areas or at depths where this type of information is not available.

Introduction

TNO Geological Survey of the Netherlands systematically produces 3D voxel models for answering subsurface related questions. The unique combination of vast amounts of borehole data and the voxel-based approach of capturing geological heterogeneity makes the models valuable new sources for exploring the Quaternary fluvial record. The latest generation of 3D voxel models (GeoTOP) schematizes the shallow subsurface of the Netherlands in millions of voxels each measuring 100 by 100 by 0.5 m (x, y, z) up to a depth of 50 m below sea level (Stafleu et al., 2011). Each voxel in the model contains information on lithostratigraphy, lithological class (including grain-size classes for sand) and the probability of occurrence for each of the lithological classes. The GeoTOP model of the Rhine-Meuse delta in the central Netherlands is characterized by a complex of fluvial channel belt systems (Stafleu et al., 2009) (Figure 1).

A preliminary 3D analysis of a single channel belt in the western part of the Rhine-Meuse delta (Figure 2) showed a clear downstream increase in percentages of fine-grained sand and a decrease in percentages of the coarser fractions. This observation, illustrating the potential of the GeoTOP model to identify grain-size trends in sandy lowland rivers, was the trigger for performing a full scale 3D analysis of the entire delta.

3D Modeling Of The Rhine-Meuse Channel Belts

Modeling of the channel belts was carried out as part of the 3D modeling program GeoTOP that also models the flood plain sediments adjacent to the channel belts as well as the Pleistocene substratum. However, in the modeling procedure described below we will focus on the channel belts.

Data extraction and lithological classification - The GeoTOP model of the channel belts was constructed using some 82,000 borehole descriptions from the DINO and Utrecht University databases. The outline of the channel belts was derived from maps published by the Geological Survey and Utrecht University

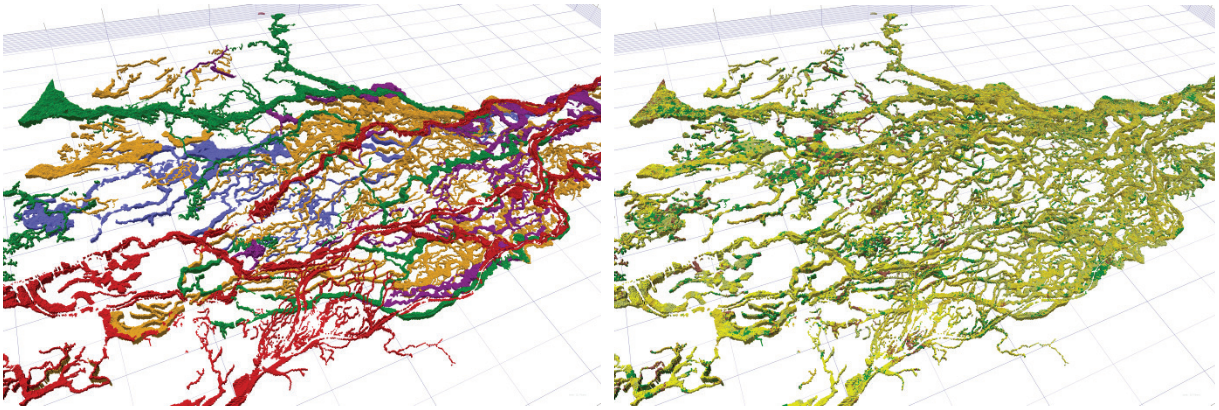

Figure 1. 3D visualization of channel belts in the Holocene Rhine-Meuse delta (the Netherlands). A: Channel belt units. Colors represent different generations (relative ages). B: Channel belt lithology and grain-size variation. Colors represent lithological classes: sand (yellow), clay (green) and peat (brown). Inset shows position of Figure 2.

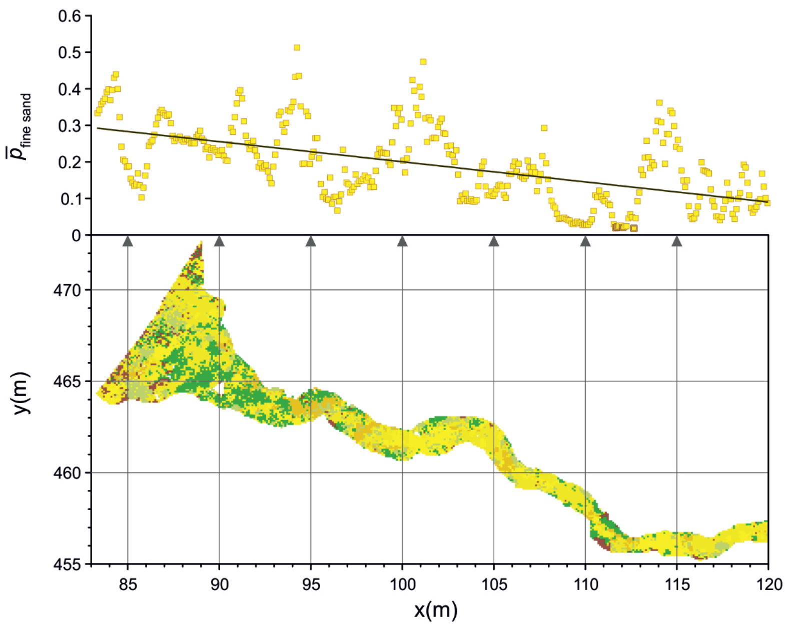

Figure 2. Channel belt lithology and grain-size variation along the Roman age "Oude Rijn" channel belt (western Rhine-Meuse delta) (Van der Meulen et al., 2013). The upper panel shows the average probability of the occurrence of fine sand in north-south sections through the belt. The probability increases downstream (from right to left). The lower panel shows the lithology of the uppermost voxel of the belt. The number of clay voxels (in green) increases downstream. Voxels with sand are shown in yellow.

(Berendsen and Stouthamer, 2001). The channel belts were classified into five generations (relative ages) each positioned at successively deeper burial depths. All borehole descriptions in the DINO and Utrecht University databases that were located in the channel belts were extracted to the modeling environment. After applying basic quality criteria, 85% remained available for the modeling. Each borehole interval was assigned a lithological class and each sandy interval was assigned a grain-size class.

Interpretation of channel belt sands in boreholes - We developed automated procedures to determine the depth of the top and base of the channel belt sands in each of the borehole descriptions. The top of a channel belt was defined as a succession of at least 1.5 m of sand, with a maximum of 0.5 m thick intercalations of other sediments positioned at least 1.5 m above the regional, westward dipping Pleistocene surface. Criteria to find the base of the channel belt sands were (1) a sharp transition from sand to clay, (2) a sharp transition from coarse to fine sand (indication of a channel lag), (3) a transition from clay-rich sands (characteristic for Holocene channel belts) to sands without clay admixture (characteristic for Pleistocene deposits).

Modeling tops and bases of the channel belt units - Channel belt tops and bases found in the boreholes were interpolated to regular grids with a cellsize of by 100 by 100 m (x, y) using Sequential Gaussian Simulation (SGS) (Goovaerts, 1997; Chilès & Delfiner, 2012). The simulations were carried out using the Isatis® modeling software package of Geovariances and resulted in 100 different realizations of statistically equally probable surfaces of top and base of the channel belt units. From these realizations, mean surfaces were calculated and subsequently used to place each voxel in the model within the correct channel belt unit (Figure 1A).

3D interpolation of channel belt lithological class and sand grain size - The lithological classes in the boreholes were used as input for a 3D stochastic simulation procedure of lithological class within each channel belt unit. For this, we used the Sequential Indicator Simulation technique (SIS) (Goovaerts, 1997; Chilès & Delfiner, 2012) using the Isatis® modeling software package. SIS estimates lithological classes for each voxel within a particular channel belt unit based on the lithological class of the surrounding borehole intervals from the same channel belt unit.

The SIS procedure resulted in 100, statistically equally probable distributions (called realizations) of lithological class. From these 100 realizations probabilities of occurrence for each lithological class were calculated. In addition, the probabilities were used to compute a 'most likely lithological class' for each voxel, using the averaging method for indicator datasets as described by Soares (1992) (Figure 1B). The individual realizations remain available for future use in e.g. groundwater flow modeling, but are not used in the case study presented in this paper.

3D Channel Belt Lithology And Grain-Size Trends

The 'most likely lithological class' model was used to perform a 3D spatial trend analysis of both lithology and sand grain-size in the Rhine-Meuse delta. We analyzed the model in 115 slices, each 1 km wide and oriented north-south, i.e. perpendicular to the delta axis. Several types of analyses were carried out of which we present two examples.

An analysis of the sand grain-size in the combined fluvial and marine-estuarine channel belts shows a clear nearly linear decrease in the percentage of coarse sand from 35-45% in the east to about 10% in the west (~0.3% decrease per km) (Figure 3). The amount of fine sand remains constant in the eastern part of the delta (~5%) but shows a rapid increase to values of 15-30% west of x-coordinate 120,000 m (indicated by an asterisk in Figure 3). Values for medium sand (not plotted) remain constant. The changes in sand grain-size reflect a combination of a westward decrease in gradient, a decrease in reworking of older Pleistocene sediments and an increase in the influence of tidal processes.

Analysis of the channel deposit proportion (CDP) revealed an almost linear downstream decrease in CDP from 0.6-0.7 in the east to 0.1-0.2 in the west (~0.005 decrease per km) (Figure 4). These CDP values correspond well with published transect-based estimates of CDP in the eastern part of the delta (Gouw, 2008). More analysis results, including downstream changes in channel belt connectivity will be presented at the workshop.

The GeoTOP voxel-model allows for quantitative analyses of an entire delta in 3D. The analysis results (i.e. trends in lithology, grain-size, CDP) may serve as input parameters for groundwater flow modeling studies in areas or at depths where this type of information is not available.

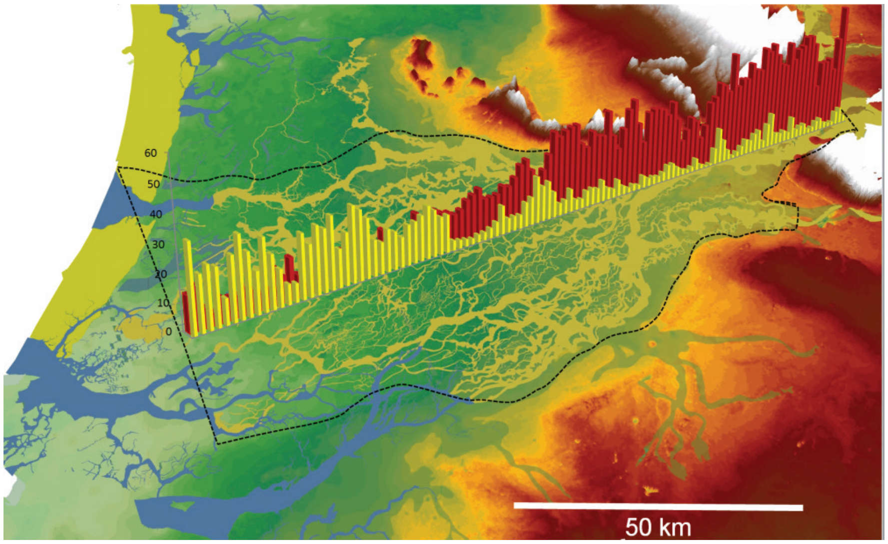

Figure 3. Downstream changes in percentages of fine-sand (yellow bars) and coarse-sand (red bars) in the channel belts of the Holocene Rhine-Meuse delta. Fluvial (yellow) channel belts and estuarine-marine (blue) channel belts are depicted within the context of flood basin and tidal flat sediments (green), coastal barrier sediments (yellow) and (elevated) Pleistocene surface. In order to minimize edge effects the analysis was restricted to the area indicate by the dotted line.

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Systematic Geomodeling: What Does It Actually Imply?

Michiel J. van der Meulen, Patrick Kiden, Denise Maljers, Jan Stafleu, Ronald W. Vernes, Jan L. Gunnink, Wim E. Westerhoff and Tirza M. van Daalen

TNO – Geological Survey of the Netherlands, P.O. Box 80115, 3508 TA Utrecht, the Netherlands, michiel.vandermeulen@tno.nl

Abstract

The Geological Survey of the Netherlands maps its country systematically in 3D, putting out four models that each correspond with a particular application domain. Rather than the models themselves, we discuss the implication and implementation of working systematically, focusing on quality assurance and model versioning and maintenance. Our aims for quality assurance are to put a system in place that arranges for independent and documented checks of all model output, according to well-defined quality standards, finding a balance between rigorousness on the one hand, and user demands for faster information delivery on the other. Regarding model versioning and maintenance, we aim to significantly shorten our release cycles, publishing models after making specific improvements rather than full updates. These two aspects of working systematically are particularly important to establish our accountability in terms of the value and quality of our modeling work, which in its turn is vital to the continuity of our Survey.

Introduction

All publications on 3D modeling by the Geological Survey of the Netherlands have introductory statements saying that we work systematically (e.g. Stafleu & Busschers, this volume). While each such publication then typically proceeds with specific modelling outcomes, the present contribution focusses entirely on the meaning and implications of the word 'systematically' (for a full account of our activities we refer to Van der Meulen et al., 2013). We focus on versioning and quality control, as well as on the strategy and organization behind these, addressing the general question: how do we put out reliable, up-to-date, national-scale subsurface information for the management of Dutch natural resources and hazards?

Key Concepts

The very subject of this paper requires us to be specific on a number of key concepts. We define, for a start, **geomodelling** (also referred to as 3D mapping or subsurface modelling) as predicting the structure and properties of the subsurface down to economically relevant depths. '**Properties**', in the case of the models of our Survey, include stratigraphic unit, lithological class, and a selection of hydraulic parameters. '**Structure**' refers to the fact that we account for geological features and architectural elements such as basins, fault units, sedimentary systems and facies units. Our current 3D portfolio includes three layer / framework models and a voxel model:

- **GeoTOP:** a 100 × 100 × 0.5 m voxel grid with lithological and stratigraphic attributes, maximum depth 50 m
- **REGIS-II:** 133 parameterized hydrostratigraphic units, maximum depth ~1000 m
- **DGM:** 34 Neogene and Quaternary lithostratigraphic units, maximum depth ~1500 m
- **DGM-deep:** 13 Carboniferous to Neogene seismostratigraphic units, maximum depth ~7000 m

'**Systematic geomodeling**' indicates an ongoing activity, which we have organized as a process of information production. A very important trend is moving towards working primarily with third-party data; legal mechanisms for compulsory subsurface data delivery to the Survey are either in place or in development. As a result, we are starting to tap into a body of data that is many times larger than what we could ever hope to acquire on our own resources. The rate and costs of geological mapping in the previous century were determined largely by the actual field surveying and data acquisition. Working with pre-existing and third-party data, digitization and automated data handling made mapping a much more efficient process, time and cost-wise, but it is still by no means a push-button operation. National-scale geological information delivery can still only be the result of a sustained, systematic effort: it is delivered by a process, not a project.

We aim for **consistency** in space, as we work nationwide and cover large areas, and we aim for consistency in time, because we release our models in (regional) parts and versions. Consistency implies that our subsurface models need to be well-defined, not only in terms of their characteristics and properties (scale, resolution, parameters), but also in the sense that their quality needs to be quantified and controlled.

In manufacturing, **quality** is defined as a "measure of excellence, or a state of being free from defects, deficiencies and significant variations". ISO, the international Organization for Standardization, connects quality with a standard: "the totality of features and characteristics of a product or service that bears its ability to satisfy stated or implied needs" (ISO 8402:1986), reformulated as "degree to which a set of inherent characteristics fulfils requirement" (ISO 9000:2000). All such definitions are as bold as they are difficult to apply to geomodeling. What, in fact, makes a good model? What about requirements of a product made in anticipation of, rather than responding to a specific application or request, or one that is used for other purposes than it was conceived for altogether?

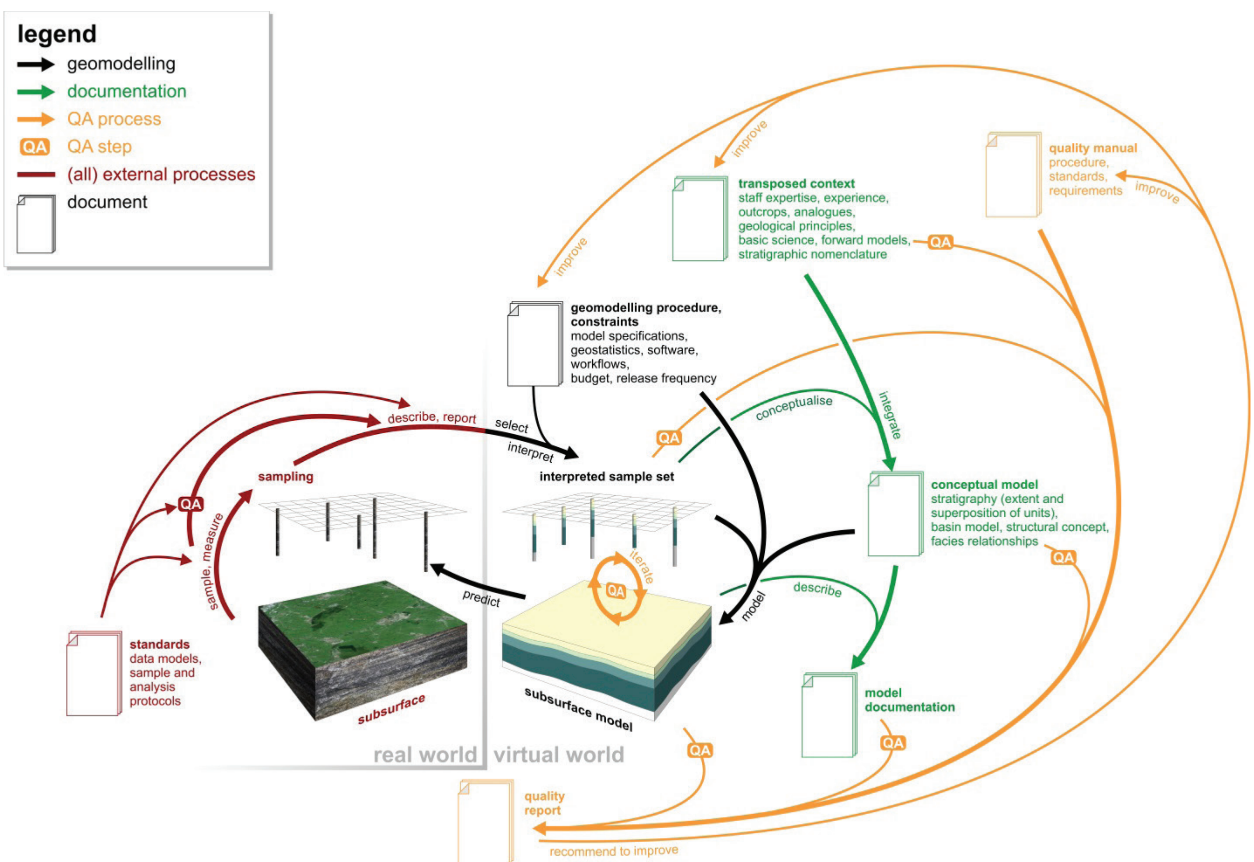

Figure 1. Outlines of a quality system for geomodeling at the Geological Survey of the Netherlands, showing flows of data and information, processes, documents and products.

Probably for that reason, geomodel quality appears not to be very well constrained: if assessed it is often reduced to inverse uncertainty (high quality = low uncertainty and vice versa), and in other cases it seems to be implicitly taken as closeness to geological perfection – which is not actually helpful. We are currently defining model quality as we go along devising a quality system, starting from the following basic definition: **model quality is a measure for the predictive value of a model**. 'Measure' bears to quality preferably being quantifiable and objective, and 'predictive value' connects model result with model specifications as well as with new (field) observations.

Quality Assurance

Challenge. 3D modelling differs from 2D mapping in the fact that it uses and produces more information than one can wholly oversee by visual inspection or traditional reviewing. In addition, whilst a geological map can relatively easily be corrected if a feature is disputed, a misconceived model may set you back to the start of the whole exercise. As our direct investments in systematic modeling add up to about 3 M€/yr, we consider such risk significant. Quality assurance of 3D model needs to address the information overload aspect, find ways to capture errors as early as possible in the production chain, and make use of clever visualization techniques for a full appreciation of the product under scrutiny.

Status quo. Our former 1:50,000 geological maps and explanatory notes were subjected to a rigorous, scientific-type editorial review procedure, which addressed the consistency and geological plausibility of the interpretation, with particular attention for cartographic representation (Van der Meulen et al., 2013). This procedure and the responsible board were dismantled when 2D mapping was discontinued in the late 1990s, so a quality system for geomodeling has to be designed and implemented basically from scratch. We currently have a system in development, which arranges for independent checks, and documents (perceived) errors, preparing for a triage that precedes the final model release (as well as certain intermediate modeling stages): (1) residual small errors will be corrected, (2) 'medium' errors will be published in the model documentation and fixed in the next release, (3) large errors will block a release. Furthermore, we produce uncertainty information for all geomodels, but not yet for not for all of their attributes. Finally, we research novel ways for quality assessors to process large amounts of information efficiently (e.g. Van Maanen et al., 2015).

Desired situation. We aim for a quality checking process that performs independent and documented checks of all our model output. Quality standards need to be distilled from developing practices and published. A sensible balance between production and quality control needs to be established, being rigorous while satisfying users (and legal requirements) to deliver information faster. The system as currently envisaged is shown in Figure 1.

Model Versioning And Maintenance

Challenge. An upcoming law on subsurface information will declare our models officially authentic and attaches obligations to their use by government. The same law will arrange for a faster influx of data to our Survey. Among the many responsibilities and obligations this law will bring, shortening the release cycles of models is particularly important to geomodeling: it will be expected that our modeling will keep up with the influx as much as reasonably possible.

Status quo. Our 20th century geological maps were publishedwith the perspective of a life of many decades (Figure 2). Current production cycles of 3D subsurface models, the successor products of these maps, are expressed in years rather than decades. DGM and Regis have had multiple releases in the 15 to 20 years that their respective programs have been running. GeoTOP will achieve national coverage in about 20 years, but individual model blocks are already updated according to the insights gained while proceeding with new areas.

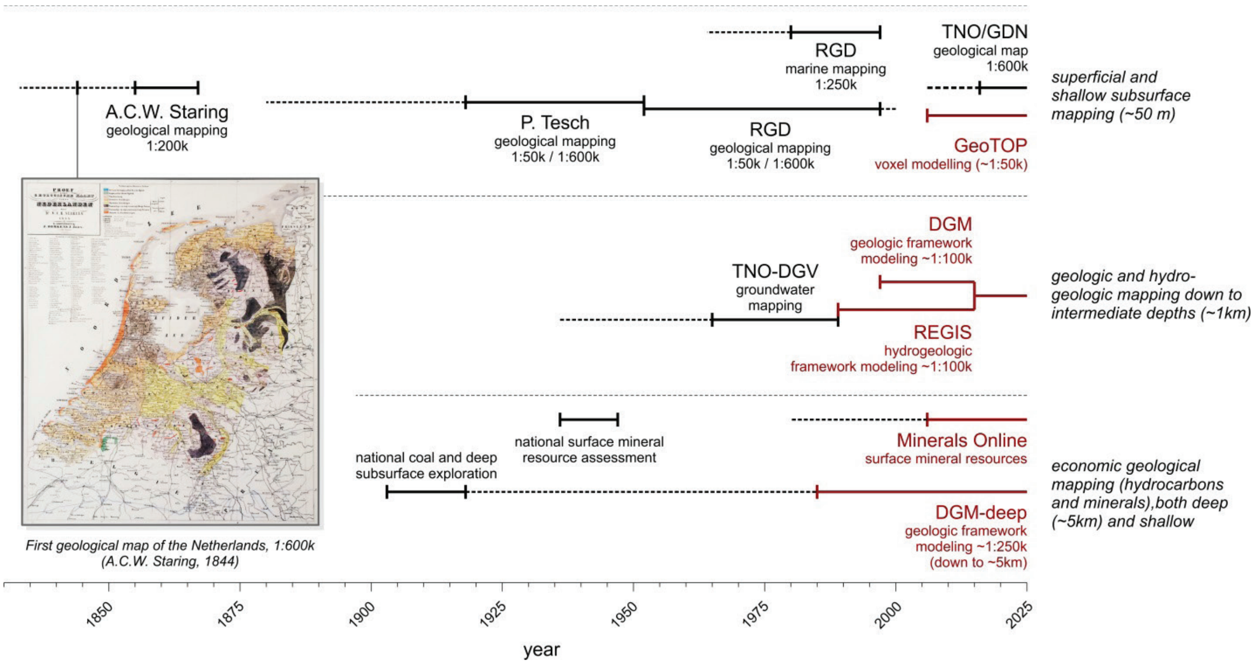

Figure 2. The evolution of geological mapping in the Netherlands from its birth in the mid-1800s to present and beyond. Thick black lines indicate the duration of the various programs, and are named after the leading person or organization, or their actual name or acronym. Dotted lines indicate their preludes. 3D mapping programs and derived products are indicated in red. Organizations referred to are predecessors of the current Geological Survey of the Netherlands, which resides under applied research organization TNO: RGD is the former State Geological Survey, DGV is the former Groundwater Survey.

Desired situation. Even without considering the abovementioned legal context to geomodeling, withholding improvements from users while we are striving for an unreachable state of perfection will arguably become less and less acceptable to our modern information users. We envisage model maintenance resulting in frequent releases of model versions, e.g. annual or biennial, with fixes of issues that were either identified in our own quality assurance process, or are reported by users. In this way, maintenance and versioning are closely related to the quality system described above. Just as with common software, it is up to the users whether or not they will adopt a particular version, but we want the models we release online to be as up-to-date as reasonably achievable.

Vision And Outlook

We addressed two aspects of systematic geomodeling that we consider important to achieving our vision of a 21st century geological survey organization. The focus is shifting towards data management and information production, and away from surveying and data acquisition that underpinned mapping in the past. Existing and pending legal arrangements will make for an excellent data position, the associated challenge is be to be able to manage and interpret a rapidly growing body of data. Working systematically and improving ourselves in this respect are key.

- The primary processes serving these purpose, and by which we have organized ourselves and our work, are, data ingestion, data management, information production (geomodeling), and the delivery of data and information. Our main secondary processes include quality management, the development and maintenance standards, and research, by which we underpin and advance our activities and products.

- We consider our core assets to be our data, information (models), standards and staff (for its knowledge and skill base). As their joint value is and can only be contextual, equally important assets are our communities of users and stakeholders, our credibility and reputation, and our independence.
- Our core capacities include, geosciences, data and information analysis, data management, IT, stakeholder management and – given the long planning horizons that apply to geological surveying – strategizing.

The license to operate of a geological survey is ultimately determined by the value it adds, referring its expanding collection of data, and particularly to the value-adding processes of producing geomodels using this collection. Quality assurance helps determining how much value is added at which costs; versioning determines in what portions value is returned to the taxpayers. We consider our awareness of this, and being open about it vital to the continuity of our business to be the provider of subsurface information for the Netherlands.

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3-D Geological Modelling at the OGS – Products and Applications

Abigail Burt (abigail.burt@ontario.ca), Andy Bajc, Desmond Rainsford, John Dodge and Riley Mulligan

Ontario Geological Survey, 933 Ramsey Lake Road, Sudbury, ON P3E 6B5

Introduction

It was Prince Otto von Bismarck who coined the phrase 'politics is the art of the possible' and noted that 'politics is not an exact science'. Substitute 'geology' for 'politics' and we have succinct descriptions of the challenges facing researchers developing and delivering 3-D geological models which genuinely provide public benefit. The challenges are rooted in the geology; often complex and consisting of Quaternary sequences from multiple glaciations. They continue with the fact that we must use legacy data of diverse origin and quality. Designing a field and analytical program (mapping, geophysics, drilling, sampling, and monitoring well installation) that delivers optimum results for multiple clients within a restricted budget and timeframe is difficult at best. Neither is asking a geoscientist to be a consummate 3-D modeller. But the hardest challenge is conveying what the esoteric 3-D geological outcomes of this work mean for the public – our internal and external clients. Internal clients are geoscientists within the OGS and other Ontario ministries who are using various products to aid in their own work while external clients range from groundwater flow modellers, researchers and educators to engineers and policy makers. All use our products and each has different levels of geological knowledge (and interest) and different needs.

This presentation will explore the life-cycle of Ontario Geological Survey (OGS) 3-D mapping projects, focusing on the different products that are being released along the way. We will look at who uses the products, how they are being used and what our clients have suggested we could do to improve them.

What is the OGS 3-D mapping team doing?

3-D mapping project areas are identified based on client needs (gap analysis and client requests) and prioritized during the OGS project planning process. Seven 3-D sediment mapping projects (1500 to 5000 km^2 in area) have either been completed or are underway in southern Ontario. They focus primarily on areas reliant on groundwater obtained from thick glacial deposits overlying bedrock. The goal of each project is to build an interactive 3-D model of Quaternary deposits that form both regional and local aquifers and aquitards. Key objectives are 1) reconstruction of the regional Quaternary history, 2) development of a 3-D model of Quaternary sediments and 3) characterization of the properties of the modelled sediment packages. The models are based on the interpretation of natural and man-made exposures, legacy datasets (e.g., water wells, geotechnical records) and new drilling and geophysical data. Each 3-D mapping project typically takes 4-5 years from conception to release of the final products. Given the length of time it takes to complete each project, it is important to release interim products to assist those clients with immediate needs for subsurface information as well as to appease government auditors that require well defined, timely outputs as justification for tax dollars spent (Table 1).

Reconnaissance and surficial map assessment

3-D mapping projects are initiated with an abbreviated reconnaissance field season to improve understanding of late-glacial history, verify existing surficial mapping (which may involve the identification of areas that require updating) and to log natural and man-made exposures. This information is invaluable for the development of a conceptual geologic framework, especially for the shallow subsurface. A Summary of Fieldwork article, which is part of a published annual report outlining all OGS activities, is completed following this first field season and may include field descriptions and basic interpretations of the various landform-sediment assemblages, a compilation of existing mapping, photos and summary logs. The traditional view taken of Summary of Fieldwork reports is that they have limited distribution and are often viewed by just a select few. In spite of this, feedback from numerous consultants indicated that these articles are indeed accessed and read. There are numerous large and small hydrogeological consulting companies working in southern Ontario, and their geologists routinely download the summary reports to see where OGS geologists are working (and where they can expect to find high quality, detailed reports and data in the future), what progress has been made on multi-year projects and to gain early access to continuously-cored borehole information. Our observations and preliminary interpretations are used to refine conceptualizations of regional stratigraphy, particularly in areas where there has been limited detailed work to date.

Geophysics

In recent years, ground-based gravity surveys have been conducted during the first year of each project to identify the locations buried bedrock valleys. These are of considerable interest as they not only have the potential to host large and productive aquifers but may also move groundwater across watershed boundaries. The gravity surveys are designed around the needs of our 3D mapping projects. We use them to select drilling targets in areas known, or suspected, to have buried bedrock valley systems. There aren't sufficient resources to drill every potential target on every survey line, but we are able to drill enough to confirm the results of the survey. Results of the geophysical surveys are released in map form and as a geophysical dataset that includes both raw and processed gravity and elevation data, grids of the gravity and elevation products, residual Bouguer gravity contours, profiles of elevation, Bouguer gravity, regional gradient, and residual Bouguer gravity in portable document format, and survey report and documentation (see Table 1 for file formats). The geophysical datasets and maps have also been used by external clients, for example municipal engineers, to answer questions about the bedrock surface.

Other geophysical methods, have been (and are being) used to assist with 3-D modelling. These include an airborne electromagnetic (EM) test survey, high resolution seismic reflection surveys and borehole geophysical logging. The latter two activities have been carried out in collaboration with the Geological Survey of Canada (GSC). Airborne EM methods offer the possibility of covering large areas quickly, but suffer from cultural "noise" (e.g. powerlines) and require strong electrical conductivity contrasts to distinguish subsurface units. Seismic reflection surveys, carried out using the GSC's Minivibe landstreamer system, have yielded high resolution images of Quaternary sediments and underlying bedrock surface. Access to this technology is, however, limited and only a few strategically placed profiles can be obtained in any project area. The borehole physical property data, which have been acquired both by commercial contractors and the GSC, are instrumental in understanding the results of the ground and airborne geophysics as well as in the processing of the seismic data. The results of this work are published as standalone geophysical data sets, Summaries of Fieldwork articles and GSC open file reports.

Drilling

Subsequent field seasons (two or three depending on the project area and sediment thicknesses) are devoted to drilling, typically mud rotary, continuously-cored holes. Drilling targets are selected within distinct physiographic regions to define/refine sediment stratigraphy, establish landform-sediment associations and determine the nature of buried bedrock valley fills. In the field, the core is logged, photographed and sampled for grain size, carbonate and heavy mineral content. In some project areas, additional samples are taken for other analytical determinations (eg. thin section analysis, magnetic susceptibility and moisture content) as part of collaborative efforts with universities and other government agencies. In an effort to meet client needs, pocket penetrometer readings have also been

Table 1. 3-D project products and release formats.

Product	Description	Format
Summary of Fieldwork reports 1-4	• Observations, conceptual geological framework, summary logs of boreholes, and preliminary interpretations	• Text and graphics (.pdf)
Geophysical maps	• Contour of residual bouguer gravity (ground) • Contoured residual magnetic field, EM decay constant and apparent conductance (airborne)	• Text and graphics (.pdf)
Geophysical datasets	• Database of ground gravity and elevation data • Grids of residual bouguer gravity and DEM • Colour image and contours of residual bouguer gravity • Gravity station locations • Gravity survey logistics and processing report • Database of airborne EM and magnetic data • Grids of residual magnetic field, EM decay constant and apparent conductance • Colour images and contours of residual magnetic field, EM decay constant and apparent conductance • Flight line locations • Sections of inverted electrical conductance • Airborne survey logistics and processing report	• ASCII (.xyz) and Geosoft® (.gdb) • ASCII (.gxf) and Geosoft® (.grd) • Raster (geoTIFF), Vector (.dxf) • Vector (.dxf) • Text and graphics (.pdf) • ASCII (.xyz) and Geosoft® (.gdb) • ASCII (.gxf) and Geosoft® (.grd) • Raster (geoTIFF) and Vector (.dxf) • Vector (.dxf) • Text and graphics (.pdf) • Text and graphics (.pdf)
Borehole data	• Interactive graphic borehole logs, detailed descriptions, analytical data, core photos and geophysical logs.	• Text and graphics (.pdf), database (.mdb), spreadsheet (.xls), photos (.jpg)
New interactive map	• Interactive maps of borehole logs and interpreted hydrostratigraphic units, GIS project, printable maps.	• Text and graphics (.pdf), database (.mdb), spreadsheet (.xls), GIS project (.mxd)
Groundwater Resources Study	• Report: Data sources and translations, modelling process, Quaternary reconstruction, discussion of modelled surfaces and aquifer vulnerability	• Text and graphics (.pdf)
	• Analytical Data: Coded according to hydrostratigraphic unit and depositional environment.	• Database (.mdb), spreadsheet (.xls)
	• GIS Grids: Structural contour and isopach grids of modelled units. Hillshade (25 m cell size) of the bedrock surface.	• GIS raster datasets

Product	Description	Format
	• Google Earth: Isopach and structural contour maps of hydrostratigraphic units, subsurface database and excerpts from seamless geology maps viewable using Google EarthTM mapping service.	• Google EarthTM (.kml, .kmz) and portable network graphic (.png)
	• Graphic borehole logs.	• Graphics (.jpg)
	• Modelled Surfaces: Isopach and structural contour data on a 100 m grid for each hydrostratigraphic unit.	• Comma-delimited data files (.csv)
	• Movies showing the use of the cross-section viewer and the Google Earth™ mapping service.	• Movies (.avi)
	• High-resolution plates: Cross-sections (hydrostratigraphic units and aquifer / aquitard class legends) and isopach, structural contour and aquifer vulnerability maps.	• Graphics (.pdf)
	• Section Viewer: Displays cross-sections of the block model along user-defined lines. Cross-sections can be saved then viewed in Google EarthTM.	• Microsoft® Virtual Earth™ executable SectionViewer.exe
	• Subsurface Data: Abbreviated version of the dataset used to construct the 3-D block model including location, formation and picks tables.	• Database (.mdb),
Scientific contributions	• Fieldtrip guidebooks, journal papers, workshop proceedings and conference proceedings	• Various formats

added to the routine core logging in clay-rich areas. Monitoring wells are installed in some boreholes for municipalities and conservation authorities to allow for long-term groundwater monitoring of both shallow and deep groundwater.

Summary of Fieldwork reports are released containing preliminary graphic logs, example photos and preliminary interpretations of key sediment packages. The OGS works on the principal that 'no one gets it until everyone gets it'. What this means is that, as a publicly funded organization, we have a mandate to publish as much information as possible. The only stipulation is that all clients must have the opportunity to obtain the information at the same time. Publishing preliminary summary logs, often while drilling is still in progress, means that we can engage in meaningful discussions with clients before the final products are released. The price for speed is that there aren't any analytical results and stratigraphic interpretations may change as key datasets come in and new boreholes are acquired.

Once all drilling activities have been completed, and the results of grain size, carbonate and heavy mineral analyses obtained, more formal products are released. The first product is a borehole release consisting of detailed written logs, graphic logs, interpreted depositional environments, analytical data (pebble counts, grain size, carbonate, heavy mineral and borehole geophysical data) and core photos as well as a visual representation of the information in a hyperlinked portable document format (.pdf) file. This release is designed for consultants working within specific project areas as a supplement to their own drilling and publicly available legacy datasets. In return, consultants often share information with us and even provide samples so that we can compare analytical results. The release is also useful for academics and other geoscientists by providing insights on glacial history and climate change, an improved understanding of groundwater flow and information on the characteristics of key stratigraphic units that can be used to support ongoing studies. Over the years, it has become apparent that an excessive level of detail can overwhelm some clients. Follow-up meetings have prompted the addition of simplified geological interpretations including a basic aquifer – aquitard classification. Most recently, there has been a request to add a graphic log and database table to reflect oxidized vs reduced conditions in the sediment logs.

Recently, a new digital interactive product was designed to make hydrostratigraphic information available to clients prior to completion of the 3-D block model and detailed report. The product consists of new graphic logs (including aquifer class, hydrostratigraphic units, summary geology and interpreted environments) presented on interactive and printable maps. There are links to a slideshow of drilling operations, the conceptual geologic model, descriptions of the hydrostratigraphic units, and a fully functioning GIS project containing files used to build the hydrostratigraphic map. The product grew out of a simple map depicting surficial geology and detailed borehole geology that was being used internally to aid with the 3-D modelling process. It is now being used by conservation authority clients to determine which aquifer their monitoring wells are screened in. The final 3-D model would be better, but this is useful in the interim.

3-D model and final products

Following completion of fieldwork and construction of interim products, the geologist is tasked with building a 3-D model of the project area using the hydrostratigraphic units defined in the conceptual geologic framework. The model is created from borehole location, standardized geologic formation and screen / static water level data using Datamine Studio ® software. 3-D points (referred to as picks), identifying the upper surface of a given hydrostratigraphic unit, are manually digitized onto the borehole traces with additional picks digitized off trace in order to refine the geometry of the modelled surfaces. Wireframe surfaces representing the elevations of each hydrostratigraphic unit are interpolated on a 100 m grid using all picks within user-defined search radii. The final 3-D block model is generated by filling in the spaces between the wireframe surfaces using 100 X 100 m blocks of variable thickness. The blocks are used to calculate the volume of each hydrostratigraphic unit and produce a series of output files.

The final model outputs are released digitally as a Groundwater Resources Study (GRS) comprising both data and interpretative material (see Table 1). Comma-delimited (.csv) files, depicting the elevation of each hydrostratigraphic unit as x, y, and z coordinates on a 100 m grid generated from the block model, are the primary outputs. Printable structural contour maps depicting the surface topography, isopach maps indicating the thickness of each hydrostratigraphic unit, maps of the digitized picks, colour-coded by quality, that were used to generate the surfaces and a series of west-east and north-south cross-sections are designed as reference guides. A cross-section viewer was developed that allows flexibility to cut sections of any length and orientation using the legend of choice. The cross-sections can be saved then imported into Google Earth™ resulting in customized output. The structural contour maps, isopach maps and standardized subsurface database are also viewable using Google Earth™. Many of the data files have been designed so that they may be used as inputs to other software packages; for example for hydrogeological modelling, or visualisation.

What do our users think of the final products? A client recently told me that the GRS's are like having a present within a present within a present. An OGS colleague said it best – people are only just starting to discover the many uses for our products as we start working in their geographical areas of interest. The cross-section viewer is one of the most popular products with a wide range of clients. For example, one conservation authority is using it to determine the hydrostratigraphy around their monitoring wells and categorize their datasets by specific aquifer unit. Geoscientists within the OGS are using the viewer for similar purposes when we aren't available to input specific well data into our modelling software. The 'picks' table used to create wireframe surfaces generates most interest within the database. Other feedback is that the models we generate are great for the regional picture but when you zoom in to site specific projects, there is room for improvement. Much of this is a reflection of us not having access to confidential information adjacent to areas of hydrogeological concern such as waste disposal sites, brownfields or municipal well fields.

Getting the message out!

One of the greatest challenges we face is getting our products into the hands of those that need it to do their job. Cost is not the issue, as everything can be downloaded free of charge from our website. The problem is that people still don't know what we are doing. 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? Is there value in tracking downloads to see where and to whom we need to focus our attention? How can we improve our products and are there new directions that we should be exploring?

In an attempt to assist clients with searching OGS products, the organization has developed a platform called OGSEarth www.ontario.ca/ogsearth that enables the user to view a large number of Ontario's geological, mining and index datasets in Google Earth. OGSEarth provides metadata for all OGS publications and allows one to quickly download maps, reports and digital datasets held within the online warehouse known as GeologyOntario www.ontario.ca/geology This tool has had a lot of positive feedback from clients. Geology Ontario http://www.geologyontario.mndm.gov.on.ca/, a text based search engine on the ministry website, also allows publications to be downloaded using more traditional search criteria (author, date, key word, etc.).

Characterizing Alberta's subsurface in 3D – exploring innovative solutions to enhance communication of geoscience information to stakeholders and provide decision support

Kelsey E. MacCormack

Alberta Geological Survey, Alberta Energy Regulator, Alberta, Canada, kelsey.maccormack@aer.ca

Introduction

The Alberta Geological Survey (AGS) is developing a 3-dimensional (3D) geological framework for the province of Alberta (661,848 km^2). Our goal is to develop 'The Framework' as a sophisticated platform, capable of integrating a variety of data types from multiple sources enabling the development of multi-scale, interdisciplinary models with built-in feedback mechanisms, allowing the individual components of the model to adapt and evolve over time as our knowledge and understanding of the subsurface develops. The Framework will be delivered as a multi-scale geocellular model based on the properties of each stratigraphic unit within the regional modelling domain (Figure 1). The success of this model is contingent on well documented and transparent processes to generate reproducible and scientifically credible predictions that can be used to communicate complex geology and subsurface geoscience information to users with various levels of background knowledge.

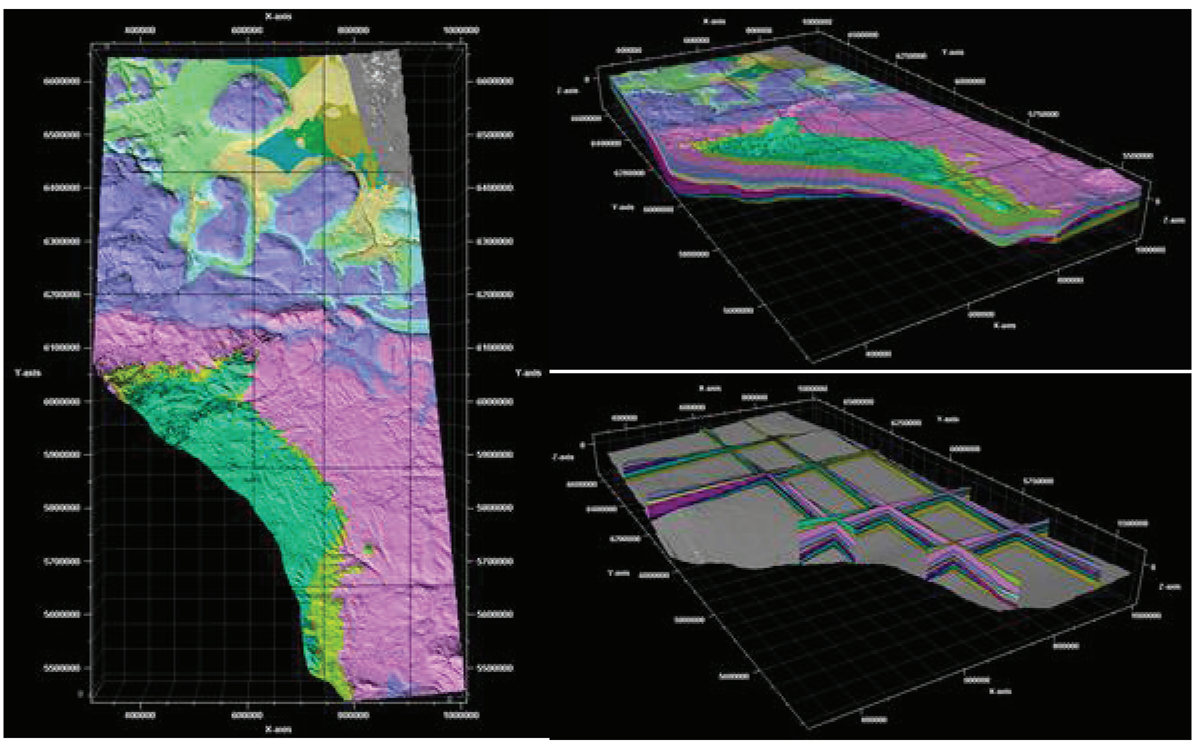

Figure 1. A) Birds eye view of the Geological Framework of Alberta. B) Oblique angle view of the Geological Framework. C) Cross-sections through the provincial scale model.

Geological Framework Objectives

The Geological Framework of Alberta will provide the 3D geospatial context within which all geospatially referenced information either on the ground surface or within the subsurface can be integrated (Figure 2). Thus the Geological Framework will provide a mechanism to support data integration, and will also be used as a data repository to identify and visualize subsurface data. The Geological Framework has been used to support subsurface investigations by integrating a variety of subsurface data to more accurately and efficiently evaluate the relationship of subsurface properties and interactions, ultimately allowing for improved geologic risk characterization. The Geological Framework has been effectively used to provide a consistent and reliable subsurface geological context, ensuring efficient communication between subject matter experts, decision makers, stakeholders, and the general public. Ensuring that we can provide open access to our geoscience information in a way that all stakeholders can easily understand is a key component of regulatory excellence.

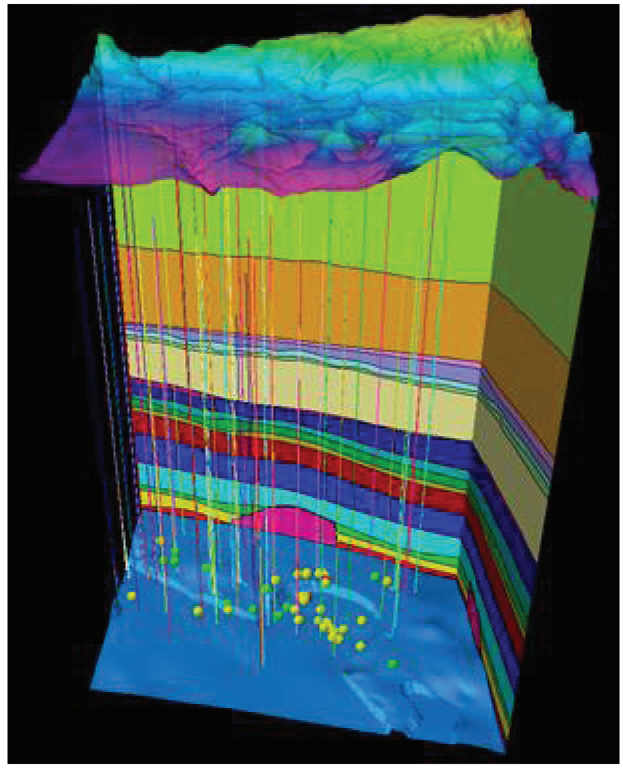

Figure 2. Subsurface model with integrated well and event data.

The Geological Framework has been built to;

1) The AGS has access to vast amounts of subsurface data (+ 465,865 wells), however not all of this information is considered to be high quality. Therefore, our modelling workflows must be able to ***account for data quality*** to ensure that the model results are more heavily influenced by the high quality data, while the impact of lower quality data is constrained to areas of spares data coverage.
2) Have ***well documented workflows to ensure transparency and credibility*** in our modelling results.
3) Integrate models provided at a various scales throughout the province. The Geological Framework is designed to be ***multi-scalar*** ensuring that any modelling work done within the province, regardless of the level of detail required, can be incorporated back into the Geological Framework. This allows us to optimize and incorporate all modelling efforts within the province and preserve the highest level of resolution, detail, and accuracy possible.
4) Able to ***characterize geological complexity*** such as faults and unconformities, where present. These features can have a significant impact on subsurface investigations and should be accounted for when estimating subsurface complexity and uncertainty.
5) Be able to ***integrate multi-disciplinary datasets***. The Geological Framework needed to be adaptable, in order to integrate all subsurface information with geospatial coordinates (X,Y,Z). Information without accurate Z coordinates can still be integrated into the Geological Framework by assigning the data to the most representative surface. This allows the Geological Framework to be used as both an individual and integrated resource management tool (Figure 3). Provide graphical ***representations of geological uncertainty*** to facilitate communication with stakeholders. The concepts of uncertainty can be difficult to communicate, especially in geographic areas where they vary significantly. The

Geological Framework provides geospatial estimates of uncertainty to provide stakeholders and decision makers with additional information about the models.

6) Support semi-automated systematic workflows to allow for ***timely and efficient model updates*** when new information becomes available. This allows us to produce multi-scalar models where necessary to address specific questions and ensure that this higher resolution information is integrated back into the Geological Framework. The system is also triggered to identify areas requiring further investigation or update when information integrated into the Geological Framework conflicts with current predictions. This feedback mechanism ensures that our models remain as accurate as possible.

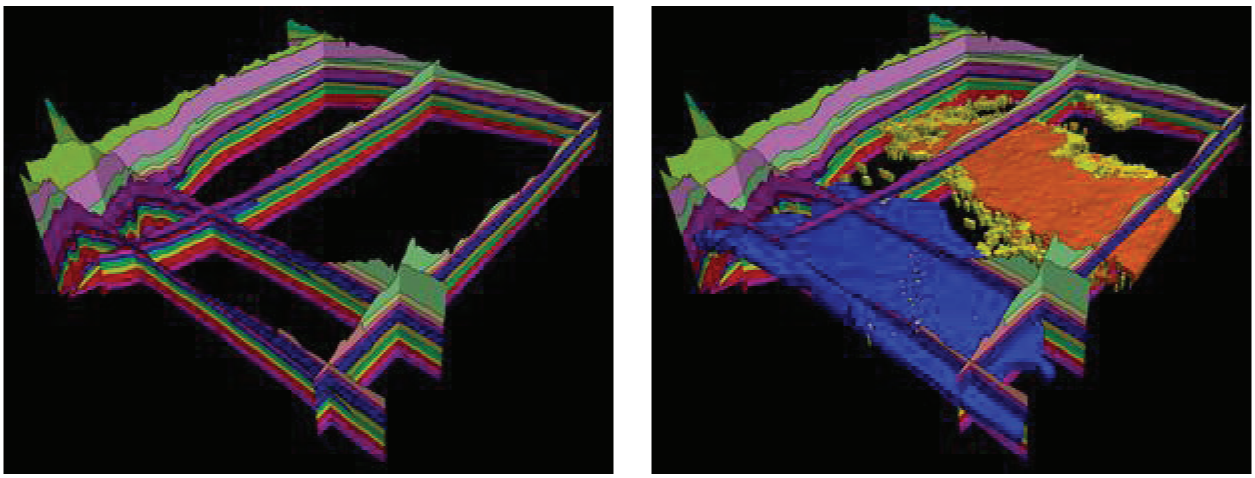

Figure 3. A) Cross-section through a 88,786 km^2 model in southern Alberta. B) Integration of groundwater and hydrocarbon resources within the model.

Current Development

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

Another positive attribute of the Framework is that the workflow has an adaptable design, which allows individual surfaces, or specific areas to be updated. The need to update and remodel these surfaces can be initiated by either internal or external triggers such as; 1) a significant amount of new data becomes available for a particular stratigraphic unit, 2) the results of an external project conflict with a current surface, or 3) a unit has not been updated for a long period of time and requires reassessment (Figure 4). This allows us to develop the Framework on an 'as needed' basis, by integrating units of varying quality and refinement, thereby allowing modelling tasks to be triaged and focused on those units that have the greatest strategic priority, or in specific regions identified as areas of high risk or concern.

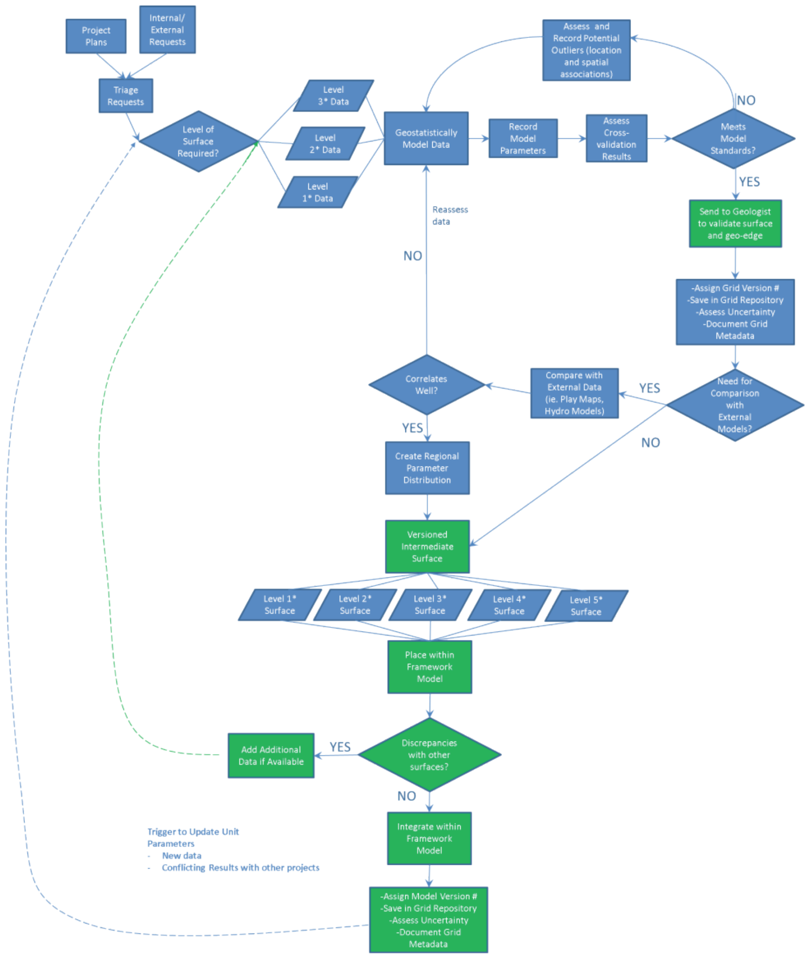

Figure 4. Modelling workflow highlighting multiple feedback loops

Future Development

We are working to enhance the Geological Framework capabilities in a few key areas; 1) easy, open, and interactive access to our subsurface information, 2) Improve efficiencies in model building and updating, 3) enhanced predictive modelling capabilities.

It is important that we are providing open access to our subsurface information in a manner that is accessible and comprehensible to both industry, and the public. We are constantly looking for innovative ways to communicate and disseminate our 3D Geological Framework models, allowing users to interactively navigate our 3D subsurface geological models and geospatially referenced subsurface data. We need to put our our subsurface geoscience information in the hands of our stakeholders and then let them explore. This will likely require multiple solutions to fully engage with our diverse stakeholder groups. For example, offering our subsurface geology in Minecraft format (#1 downloaded game with over 100 million downloads, as of February 2014) can be targetted at people between the ages of 5 and +100, and would allow generalized exploration of Albertas subsuface geology and resouces.

Ensuring reproducibility of our modelling results is a key component of scientific credibility. However, in areas of high geological complexity, there are often many modelling steps that are taken in order to achieve the final model surface. Therefore we are in the process of developing semi-automated model construction workflows to ensure model updates are more efficient and less susceptible to user error, and also serve as a method for documenting modelling procedures.

We are also working to enhance the predictive capabilities of our subsurface models by evaluating subsurface properties and interactions to characterize geologic risks. Once subsurface characteristics in known high-risk areas have been identified, we will query the Geological Framework to predict additional locations of potential risk based on similarities in subsurface characteristics.

Summary

The Alberta Geological Survey has made significant progress on the Geological Framework this year. Development has been focused in producing strategically located high-resolution sub-models, containing multi-disciplinary datasets to enhance communication of geoscience information to stakeholders and provide decision support. We are well underway to achieving our goal of developing the Geolgical Framework as a sophisticated platform capable of integrating multi-disciplinary data within a strategically devleoped, multi-scalar, geological context. The development of semi-automated workflows with built-in feedback mechanisms, will allow individual components of the model to adapt and evolve over time as our knowledge and understanding of the subsurface develops. The success of this model is contingent on well documented and transparent processes to generate reproducible and scientifically credible predictions that can be used to communicate complex geology and subsurface geoscience information to users with various levels of background knowledge.

Take Home Message

Our goal is to produce a 3-dimensional, multi-scalar, geostatistically optimized, probabilistically parameterized, geocellular model of Alberta to effectively communicate and disseminate geological information meeting the needs of a diverse stakeholder group to ultimately develop a tool for integrating information and communicating geoscience information with anyone