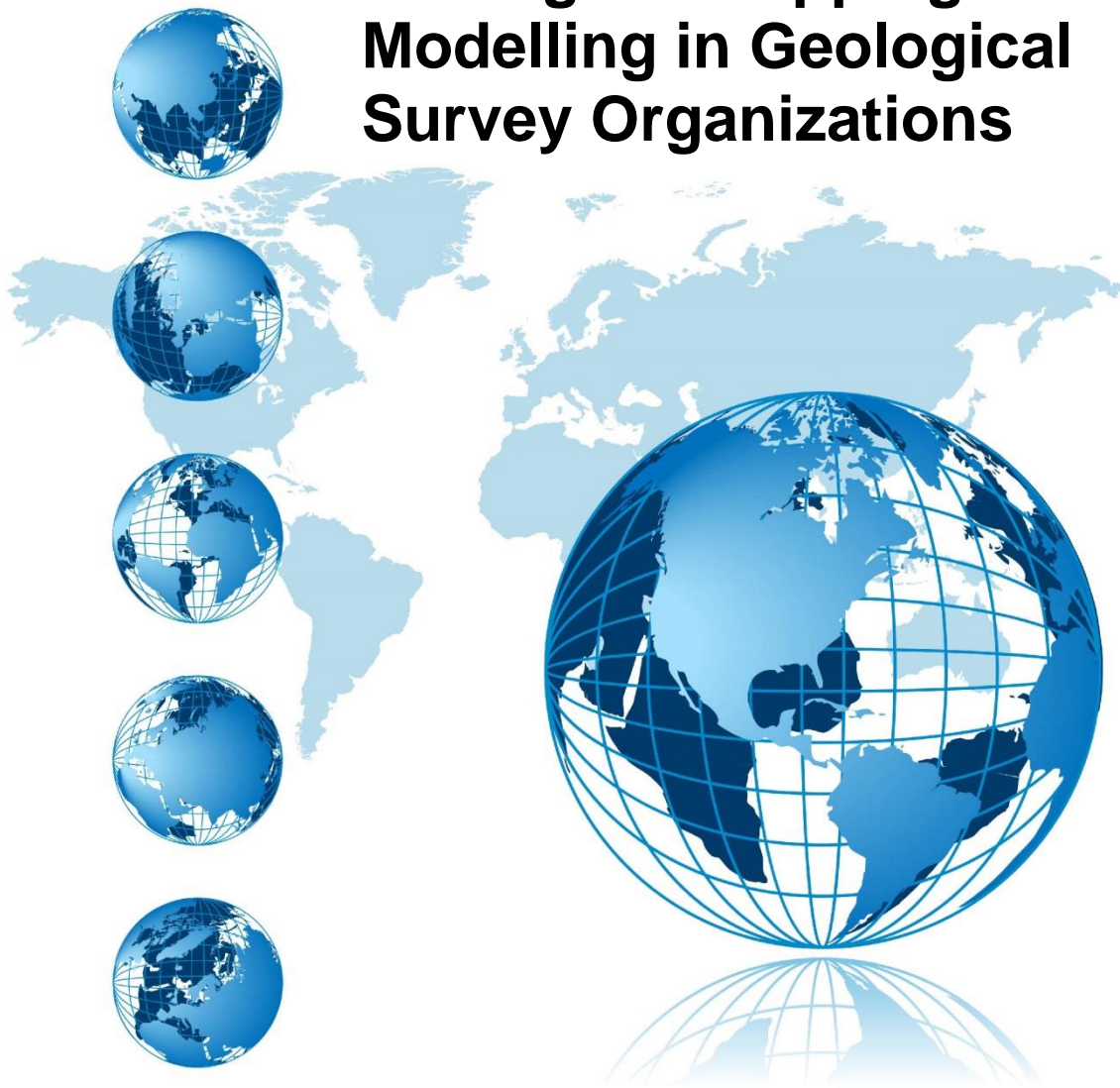


# 2019 Synopsis of Current Three-Dimensional Geological Mapping and Modelling in Geological Survey Organizations



# 2019 Synopsis of Current Three-Dimensional Geological Mapping and Modelling in Geological Survey Organizations

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# Chapter 1: Overview

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An increasing number of societal decisions are based on spatial data in general, and geoscience in particular. Fulfillment of several sustainable development goals regarding health, wealth, safety and heritage will require optimized geological information. Around the world, geology therefore is increasingly being used to facilitate societal objectives regarding energy, minerals, water, hazards, and infrastructure design.

This information is being built and provided by the entire geoscience community, including the geological survey organizations (GSOs) that play long-term roles in documenting the geology of entire jurisdictions, through their ongoing research, mapping, monitoring, synthesis, and dissemination. As data accumulate, as technology advances, and as societal expectations escalate, all fields of endeavour are moving from established practices to new approaches that deliver benefits more efficiently and effectively.

In the world of GSO activity, therefore, systematic documentation of geology is undergoing a transition from static, 2D, paper publications to digital 3D reconstructions that can be integrated with temporal monitoring and thus directly support the modelling and management that facilitate

societal objectives. GSOs thus are responding to issues, and supporting unanticipated needs, by beginning to produce what is meant to eventually be jurisdiction-wide, multiple-resolution 3D geology that will be a queryable replica of their landmass.

GSO geological mapping by necessity is often conducted on the basis of sparse data, relative to industry practice, where 3D is the norm. At least for this reason, geological mapping by GSOs has tended to be limited to 2D cartographic products. This began to change in the 1980s, as data and technology permitted initiation of an evolution from 2D geological mapping toward production of 3D machine-readable depictions in which thickness, properties, heterogeneity, and uncertainty are specified.

The purpose of the current volume is to document and synthesize examples of this transition by GSOs to 3D geology. The volume is an update of an earlier version (Berg et al., 2011) that emerged from a series of workshops initiated in 2001. As with the earlier version, the volume includes three parts. Part One provides background, Part Two provides jurisdictional summaries, and Part Three provides synthesis. Part Two in the current volume includes 22 chapters, from provincial, state, and national GSOs in Europe

(13), North America (7), and Australasia (2). The volume represents a broad sampling of GSOs involved in 3D work; however, there are many additional GSOs who are active in 3D that are not included. Contributors were asked to follow a template to structure their chapters, thus allowing the reader to more clearly compare 3D program objectives, approaches and strategies amongst various GSOs.

An update to the 2011 volume seemed warranted due to the growth in GSO 3D activity, emerging methods, new regional and global initiatives, and increasing interest by client groups. Additionally, pressures on resources, subsurface space, and the environment add urgency to ongoing documentation of geology, such that more realistic and machine-readable reconstructions are needed. There also are parallel developments in the sophistication, scale, and diversity of modelling initiatives taking place.

GSOs are now supporting not only framework lithostratigraphic modelling, but also associated property models such as texture, physical properties, and other derivative applications such as for groundwater and heat flow. From the prototype national models that were presented in 2011, work documented in the current

volume highlights the advancement in jurisdictional modelling resolution and approaches.

GSOs thus are demonstrating that they have embraced the transition to 21st Century community information protocols such as big data, machine processing, and digital twins. This volume indicates that through a balance of explicit and implicit modeling, and development of interoperability for data integration and exchange, GSOs will be well positioned to continue advancement of 3D geology.

The contributions demonstrate the value of 3D geology, and highlight the heightened need for improved transboundary reconciliation of the

mapping, with concurrent application support. National and international collaborations such as OneGeology and EuroGeoSurveys also highlight the need for such collaboration.

In a world with increasing environmental stresses and pressure on natural resources, enhanced geoscience products therefore are much needed as a fundamental underpinning of the infrastructure of modern societies. It is clear, however, that a commitment to a 3D geology GSO paradigm requires thinking that is long-term, institutional, and jurisdiction-wide in scope, such that needed data compilation and acquisition, followed by required iterative mapping, can be

achieved in a complete and consistent manner over several years to decades.

This provides the rationale for the current volume, so that we can learn from each other, allowing us to make progress in fulfilment of our obligations to society with a maximum of efficiency and effectiveness.

## Reference

Berg, R. C., S. J. Mathers, H. Kessler, D. A. Keefer (eds.). 2011. Synopsis of Current Three-dimensional Geological Mapping and Modeling in Geological Survey Organizations, Illinois State Geological Survey Circular 578, Champaign, Illinois, 92 p.



# Chapter 2: Background and Purpose

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## Introduction

The understanding of earth materials, processes, and history that geological investigations provide informs much of what we need to know about energy, minerals, water, hazards, and infrastructure design. In all fields, research produces conceptual advances, monitoring indicates variation over time, and mapping provides a comprehensive spatial accounting. In geology, therefore, research and monitoring, along with resultant management and benefits for society, are underpinned by geological mapping, which provides a spatial depiction of solid earth materials along with their included liquids and gases.

In industry, large expenditures are applied to characterizing the geology of a site or a lease, for purposes such as energy, mineral, or groundwater production, or to support engineering. In this activity, specification of vertical position, thickness, geometry, and properties of sediments and rocks is essential for acceptable fulfilment of the activity, so 3D geological mapping has been de rigueur in industry.

In the public sector, in contrast, academic research focuses on answering specific conceptual questions, and efficiency demands that activity be limited to what is needed to do so.

Government geology, however, occupies a distinct niche that is centered on comprehensive geological mapping that to a large degree is meant to support unanticipated needs, and that at least goes beyond the scope of landholding, and in some manner is meant to be jurisdiction-wide.

Since 1815, this activity has followed the model of William Smith's geological map of England and Wales. This regional geological mapping, customarily conducted by geological survey organizations (GSOs), by necessity is often conducted on the basis of sparse data, relative to industry practice. At least for this reason, geological mapping by GSOs has been limited to 2D depictions meant to be consumed by a geologist's eyes, for the purpose of informing his or her thinking.

This paradigm began to change in the 1980s, however, due to accelerating computing power and data availability, along with concurrent escalation of societal expectations. GSOs therefore are evolving from a focus on 2D geological maps as illustrations, to 3D machine-readable models, with specified thickness, properties, heterogeneity, and uncertainty, and that directly can support time-varying (4D) modeling through inference of a 3D matrix of estimated material properties.

## Geological Survey Organizations (GSOs)

Most nations, as well as provinces, states, or territories in federal systems, have a geological survey. Many of these organizations were established as projects in the 1800s, to support government efforts to make consequential decisions on topics such as where to place canals and railways, and where to plan for agricultural development. These survey projects of the 1800s that could be completed and delivered, became permanent institutions in the 1900s, as it was recognized that societal needs would change, science and technology would advance, and data would accumulate.

GSOs thus are an essential branch of government that need to exist so that government, industry, and society can function in an informed manner. In Canada, for example, all GSOs are government-based, whereas in the US, one-third of the state geological surveys are government-mandated services based in universities. In many jurisdictions, the GSO has been placed in a government department, thus causing a tendency to focus on the needs of that department, despite the broader need for geological information.

GSOs map the geology of their jurisdiction at multiple levels of resolution, along with maintenance of the informational resources that are needed to complete the mapping, including geophysical and geochemical surveys, geochronology, and databases holding observations and metadata for collections. GSOs also advise government, conduct fundamental research that is needed to optimize their spatial roles, and disseminate geological knowledge widely to their populace.

## History of 3D Geological Mapping

Government 2D geological mapping had reached a high level of maturity when 3D methods began to emerge in this field in the 1980s. Geological mapping had, of course, been 3D since its inception, at least in the form of structure symbols, cross-sections, structure contours, and isopachs. In addition, the earliest manifestations of comprehensive 3D in this sector were the stack-unit maps that conveyed information on multiple strata through intricate map legends (Rijks Geologische Dienst, 1925; Berg et al., 1984). In the 1980s, however, more comprehensive 3D began to emerge, for example as regularly spaced, orthogonal cross-sections (Mathers and Zalasiewicz, 1985). Concurrently, fundamental development of 3D GIS was outlined by Vinken (1988), Turner (1989), Raper (1989), and Vinken (1992). Subsequently, Soller et al. (1998) worked out a method for regional 3D geological mapping based on 2D geological maps, stratigraphic control points, and large public drillhole databases, that was demonstrated by work in Illinois (Soller et al., 1999), and that outlined an approach that remains typical in this field (Thorleifson et al., 2010).

## Applications

The role of GSOs is to stimulate societal benefits related to resources, safety, public health, and natural heri-

tage (Culshaw, 2005). Accumulation of data, new methods, intensified land use, and pressing societal issues are spurring GSOs worldwide to respond to urgent 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. Societal needs of escalating importance now benefiting from this 3D geological mapping include:

- In the field of **energy**, fossil fuel assessment and related topics such as produced water disposal relies on sedimentary basin models, while geothermal potential is rapidly emerging as another energy discipline that benefits from 3D geology.
- **Mineral** resource assessment in most cases focuses on hard rock geology in which 3D work emphasizes structures rather than strata, although enhanced 3D information such as depth to bedrock and depth to basement supports assessments, and mapping of stratified rocks is fundamental in the field of industrial minerals, as well as in all site planning for mines.
- In the field of **water** resources, groundwater capacity and vulnerability remains a topic of increasing importance that relies heavily on 3D geological mapping, to depict aquifers and their properties, and enclosing strata that govern recharge and protection.
- In the broad field of **hazards**, modelling of earthquake propagation is one example of an activity that requires comprehensive 3D geological mapping.
- All civil **engineering** takes into account the geological substrate, and linear developments such as transportation and communication infrastructure particularly benefit from comprehensive and consistent geological mapping of ground conditions.
- Geological mapping also facilitates all **research** that builds fun-

damental understanding of earth materials, processes, and history.

- Communication of this knowledge in the field of **education** greatly benefits from 3D mapping, as the visualizations that can be produced are more accessible to the general public than conventional geological information products.

## 3D Workshops

Workshops meant to facilitate the sharing of ideas in the development of regional 3D geological mapping by GSOs emerged spontaneously in the early 2000s. In North America, ten workshops have been held since 2001, in North America in conjunction with the Geological Society of America (GSA), Geological Association of Canada (GAC), and Resources for Future Generations (RFG) meetings conducted in the states of Oregon, Utah, Colorado, Minnesota, Illinois, and Maryland, as well as in the Canadian provinces of British Columbia and Ontario. Similar workshops have been held in Europe, in Scotland, Holland, Germany, France, and Spain.

The workshops (e.g., Berg et al., 2018) have provided GSOs and partners a forum to share their thinking, and to discuss the current state of activities, approaches, and methodological developments. Whereas the earliest workshops focused on data compilation and pilots, and subsequent meetings included a focus on concepts such as heterogeneity and uncertainty, more recent workshops have indicated that surveys now see themselves as being in the business of building jurisdiction-wide 3D geological information products to support pressing applications, in some cases at more than one level of resolution.

The October 2009 GSA workshop in Portland, Oregon, featured an unprecedented representation from the world's leading GSOs in 3D geology. Workshop presentations indicated that although these GSOs shared the same

vision for characterizing 3D geology, their methods, strategies, and business models were highly varied. It therefore was decided by workshop participants to produce a volume summarizing these various approaches, which appeared in 2011 as the first 'Synopsis of Current Three-dimensional Geological Mapping and Modeling in Geological Survey Organizations' (Berg et al., 2011).

It was evident at the 2018 workshops in Europe and North America that significant progress had been made in the field of 3D geology. Thus, it was decided to produce an update of the synopsis. Compilation of the current volume benefited from contributions from many GSOs located around the world.

## State of the Activity

It has been recognized that initiation of a 3D geological program is a daunting, demanding, and expensive activity whose costs are justified by the compelling societal benefits that emerge. Equally, it has been recognized that all GSOs are in the 3D business, and that long-term planning will lead to an optimal 3D program at any GSO.

Much work by GSOs over the past two centuries has been done on a project basis. Project planning has been followed by funding, field work, analyses, compilation, and paper publications. This model works well for geological mapping of exposed rocks. This project paradigm tends to be incompatible with 3D geological mapping, however, as it customarily is not possible to compile required data within the timespan of a project. The alternative to a project and publication paradigm at a GSO is an institutional database paradigm, in which observations are permanently maintained on a jurisdiction-wide basis, and each new geological map is an incremental step toward consistent, complete mapping at multiple levels of resolution.

One of the most important components in developing a viable 3D program is a long-term commitment to establishing jurisdiction-wide databases that are meant to compile all public-domain drillhole records. This will include multiple data types, from hydrocarbon or mineral resource drilling to geotechnical boreholes and water wells. This often-abundant data of varying quality can be coupled with stratigraphic borings and geophysical profiles to at least define top of bedrock, and in some cases aquifer versus non-aquifer materials, if not a more fully resolved stratigraphic model. Development of drillhole databases must include long-term plans for digitizing, optimal specification of location, and either categorization of lithological reports or stratigraphic correlation of intersections, such that trends can confidently be seen in abundant data. This activity is mature in many jurisdictions, whereas elsewhere, the required databases have not yet been initiated. Comprehensive thinking therefore is required among GSO managers, so that a long-term plan can be developed.

Ideally, 3D efforts build on 2D. Each polygon on a 2D map represents either a layer or basement. A layer is a polygon whose thickness can everywhere be adequately mapped. Layers should be removable from future geological maps, initially as stacked polygons with unspecified thickness, followed by mapping of thickness, properties, heterogeneity, and uncertainty; under the layers is basement.

Having committed to a decadal strategy for jurisdiction-wide 3D geological mapping, a careful assessment of data adequacy is needed, in relation to its extent and depth. In some regions, a few cores and geophysical tests, combined with abundant water well data, might give a satisfactory depiction of the geology. In other regions, new drillhole compilations, geophysical surveys, and drilling will be required to adequately bring regional geology into focus.

A topic in which there is much diversity amongst GSOs is modelling approaches. Explicit methods such as geologists' interpretations that are hand-drawn from cores through drillhole and geophysical data is a desirable approach that captures the expertise of field geologists, but it cannot easily be updated. In contrast, implicit methods involving geostatistical procedures may produce depictions of the subsurface that are easily updated, although they may not as readily depict geologists' knowledge and judgment, unless hybrid approaches are applied.

Usage of the terms mapping and modelling varies, and the title of this volume respects that diversity of perspective. In the past, a map was a sheet of paper, and subsurface mapping was cited as structure contour and isopach maps. In current usage, however, a 3D geological reconstruction often is referred to as a model or geomodel. Nevertheless, research is conceptual, mapping is spatial, and monitoring is temporal, with all three being needed to produce 4D models. Research, mapping, monitoring, modelling, and management yield societal benefits. In the context of 3D geology, there seems to be a tendency, however, for the word mapping to be preferred by persons who wish to promote unity among geologists doing 2D and 3D. The word modelling seems to be favoured by those who see a distinction between 2D and 3D methods, for example in relation to expectations for professional qualifications. It is hoped that the reader of this volume will be able to tolerate varying terminology, and that the intent of the author will be indicated by context.

In summary, a commitment to a 3D program requires long-term, institutional, and jurisdiction-wide planning, such that needed data compilation and acquisition, followed by iterative mapping using methods suited to the geology, data, and context, can be achieved in a complete and consistent

manner over years to decades. Therefore, it is crucial that GSO staff share their thinking so we all can make progress and enhance fulfilment of our mandates with efficiency and effectiveness.

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# Chapter 3: Overview of Geological Survey Organizations Contributions on Modelling Approaches

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## Introduction

This chapter provides an overview of content presented on modelling approaches and methods from the 22 contributions by geological survey organizations (GSOs) in Part 2 of this synopsis volume (MacCormack et al., 2019). To that end information is reviewed that is presented primarily in sections on i) modelling activities, ii) modelling resources, and iii) modelling approaches. Content has also been resourced from outside of those sections when appropriate. Comprehensive referencing to contributions in Part 2 is not provided, but an attempt has been made to reference illustrative examples by jurisdiction (e.g., Catalonia).

The chapter first reviews the approach to data management, followed by approaches to model development and assessment. In sequence, the review addresses framework models both explicit and implicit, machine learning, expert systems, stochastic modelling, uncertainty, and collaboration and open source exchange.

A noteworthy difference from the 2011 volume (Berg et al., 2011) is the greatly increased scope in this volume on implicit modelling and property modelling (i.e., physical rock properties: density, magnetic susceptibility, sedimentary facies, and flow parameters: porosity and permeability etc.) of geological volumes created by frame-

work modelling approaches. Hence characterization of heterogeneity within model volumes is discussed more as is the application of models within physical process-based software for fluid and heat flow modelling, and geophysical inversions.

## Data Management

### Overview

The relationship between GSOs and data support for geological 3D modelling is diverse and much less controlled by the GSO in many jurisdictions than would be imagined. Commonly, data support for modelling is divided between topographic, natural resources, environment, and hydrographic organizations. This can complicate acquisition, preparation, and updating of data for modelling. Data may be derived from public sector activity (e.g., geological mapping, topographic information) and private sector activities that have varying degrees of data permitting, reporting standards, management, and accessibility. Approaches vary enormously across jurisdictions and datasets. In a number of jurisdictions, the importance and value for managing subsurface data is being increasingly recognized, and efforts have been initiated to improve the collection and management of data across organizations and themes. However, in some GSOs data is managed on a project by project and data type basis, with no institutional data-

base management structure. A number of strong emerging exemplars using contrasting approaches are discussed in Part 2 that can provide guidance and encouragement (e.g., Denmark, Netherlands, UK). Nevertheless, lessons learned may be hard to implement in many jurisdictions due to differences in governance structures and complications arising from legislative issues, organizational mandates, scale, and funding (e.g., Canada, USA).

The following examples highlight differences in jurisdictional approaches working toward national and international mapping and modelling coordination, data synthesis, and collaboration.

- UK: The British Geological Survey (BGS) Accessing Subsurface Knowledge (ASK) Network is a knowledge-exchange consortium linking the BGS with a range of data contributors in industry and academia. It supports dialogue regarding the use and applications of geological models and helps with digital data sharing and standards for onshore borehole data. The ASK project is also focused on enhancing geoscience data sharing, application, and integration for urban areas with European initiatives such as Sub-Urban (see below).
- Denmark: The Danish geological survey (GEUS) has developed a number of databases that serve as a repository for data used in 3D

modelling. Three national databases manage the disparate data required for 3D geomodelling: JUPITER contains borehole information, whereas GERDA and MARTA contain measured data as well as geophysical interpretations for mostly shallow on- and off-shore data.

- Netherlands: The Dutch geological survey (TNO) has developed the DINO database that provides an underpinning for 3D geomodelling. Additionally, in 2015 legislation placed subsurface data and information in a system of key registries to be managed by TNO. This data framework manages subsurface data of 28 different data types, four jurisdictional models, and provides information on permitting and subsurface infrastructure.
- Germany: The Germany geological survey (BGR) initiated the Infra3D project which is facilitating data use and integrating it with cognitive interpretation to produce re-usable and sustainable 3D geological models. The Infra3D project objective is to upgrade the technical infrastructure to improve support for semi-automated model development and updates. Additionally the Geosciences in Space and Time (GST<sup>®</sup>; <https://www.giga-infosystems.com/products>) framework is a pillar of the Survey's 3D infrastructure.
- Bavaria: The Bavarian geological survey is building on the success of the previous GeoMol project to support two integrated projects for the Bavarian Molasse Basin, an internal project Infra3D and HotLime, one of 15 projects under the umbrella of GeoERA (European Research Area, <http://geoera.eu/>).
- European Community: European countries are benefiting from initiatives to standardize data for a variety of scales and applications. Illustrative European initiatives include the GeoERA Information

Platform EGDI (<http://www.europe-geology.eu/>), and sub-elements such as the GeoERA project HIKE that is consolidating a fault database (<http://geoera.eu/projects/hike/>). Another example is the European Sub-Urban program (<https://www.sub-urban.eu>) which is part of the European Cooperation in Science and Technology (COST, <https://www.cost.eu>). Sub-Urban is a collaboration of geological surveys, cities and research partners to improve the management of the subsurface of cities.

A summary of database management subjects from Part 2 is presented below. Not all contributions discuss or reference supporting datasets in the same manner; however, much of the information presented below is, in general, common across many jurisdictions.

### **Surface Topography Databases**

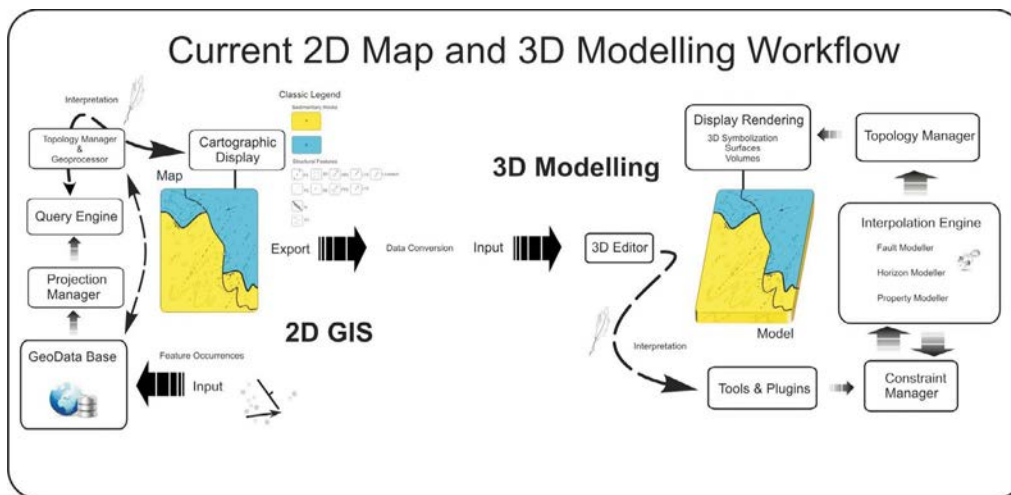
Topographic information in the form of a Digital Elevation Model (DEM) provides the highest resolution and, in many cases, most reliable dataset of a 3D model. Besides providing a surface boundary and an elevation datum for all model data, the modern land surface provides a geomorphic context for the shallow subsurface, particularly where it represents paleogeography (e.g., glaciated terrain). In some instances, this information is managed within the GSO; however, it is commonly collected and managed in companion organizations. Countries are using digital topographic data from one of global (e.g., Shuttle Radar Topography Mission - SRTM), national (e.g., National Elevation Dataset - NED) and with increasing frequency LiDAR coverage and various bathymetric sources.

Representation and encoding of the topographic surface are critical in the 3D modelling process. Scale dependencies, resolution of meshes, and accuracy of the DEM all impact the way

geological features are extracted from map sources and can radically increase or decrease geological accuracy and plausibility of modelled geomorphology. Efficient storage and extraction of relevant topographic data are vital operational requirements for GSOs conducting 3D modelling. The key technology pieces under active research in this area are 3D spatial indexing, property, and feature mapping to DEMs, image texture mapping, rapid and accurate updating and real time solids representation, and for cross-section representation. All of these rapidly evolving components and their implementation impact how models are constructed, represented, and distributed.

### **Geological Map Databases**

A common thread is the importance of the surface 2D geological mapping to both guide and constrain subsurface modelling. In other words, the subsurface geology should coordinate seamlessly with 2D geological mapping at the surface boundary of the 3D model (Figure 1). A number of contributions have geological map databases that are used to support regional to jurisdictional modelling (e.g., Catalonia, New South Wales, USA). An ongoing challenge reported with geological map databases is maintaining, updating, and developing the 3D component. The current notion of a 2D geological map is that it is the surface expression of three-dimensional geology projected to a planar coordinate system. Geological mapping requires interpretations and generalizations of observational data that could be quite biased. Moreover, as 2D models are a manifestation of a geologist's conceptual understanding of 3D geology, 3D models based on 2D maps are therefore also based on a pre-existing conceptual 3D model. Extracting 3D model input from 2D map information is somewhat suspect in being a circular process. In the future, as GSOs move toward operational 3D modelling capacities, the geological map will likely become a

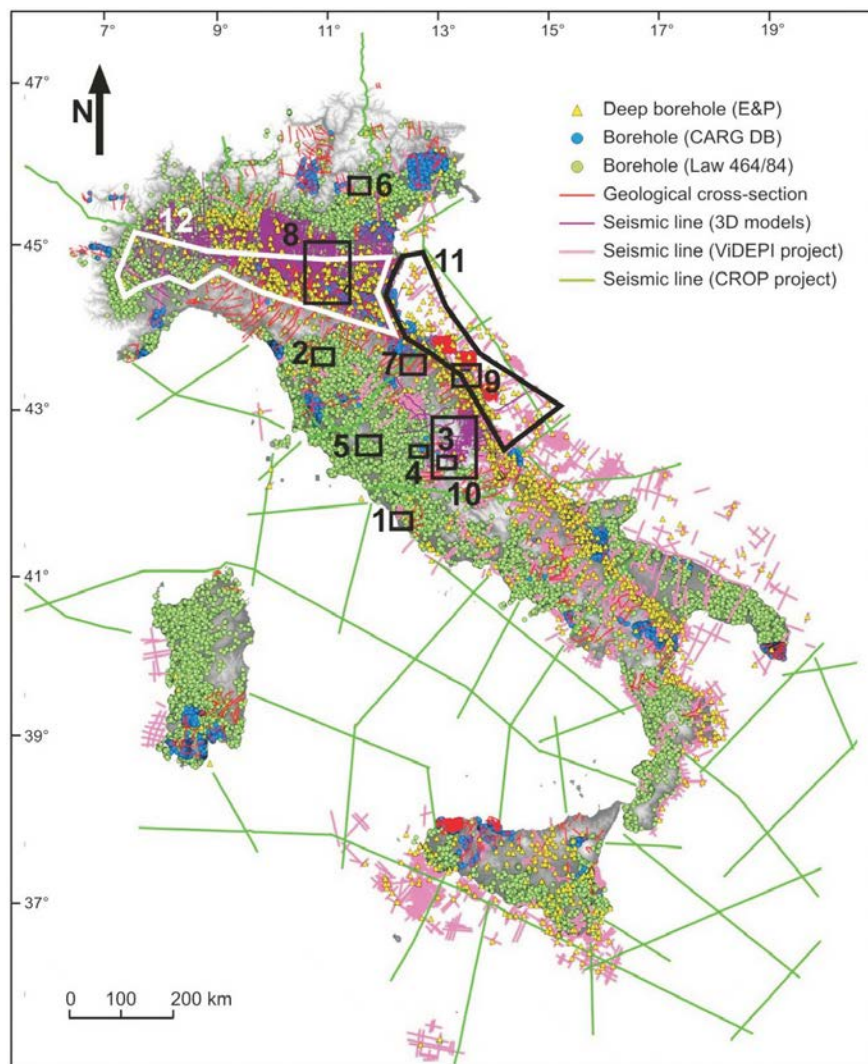


**Figure 1.** Illustrative workflow of 2D geological mapping that is transitioning to support for 3D modelling efforts. From de Kemp et al. (2017).

3D model suite of reproducible realizations based on knowledge and data, much of which could be sampled with the topographic surface DEM to produce 2D map analogues that are internally consistent with the subsurface geological model (de Kemp et al., 2015).

### Subsurface Data

The cornerstone to 3D mapping and modelling is the extent, geological content, and accessibility of subsurface data. There are common themes across the Part 2 contributions regarding data support that reflect the geological conditions being modelled. Commonly used borehole datasets include: water wells, geotechnical, petroleum, geothermal, and mineral boreholes. Additional subsurface data sources include geophysical data, particularly seismic (reflection, refraction, teleseismic) and potential field datasets and geological field observations (e.g., faults and horizons, structural measurements, map units, facies and unit contacts). The most useful data holdings are those in the public domain or freely accessible by GSOs for derivative products (Figure 2; e.g., Alberta, Austria, Illinois, Italy). Management of these databases is not necessarily within the jurisdiction of respective GSOs thus complicating curation and limiting the potential enhancement of the data holdings (e.g.,



**Figure 2.** Distribution of principal publicly available geological data in Italy for national modelling. Note combination of borehole and seismic data, both onshore and offshore. Purple lines indicate seismic data available under a confidentiality agreement. Black polygons are areas of completed 3D models, and in white models under construction. (From D’Ambrogi et al., this vol., Chapter 11).

Austria, Canada, Ontario, UK, USA). In many jurisdictions water wells meet both of these conditions, they are freely available to support 3D mapping of GSOs; however, they commonly are not under the purview of GSOs, thus complicating data management and data enhancement. Some of the European initiatives are attempting to rectify this problem. Differences in legislation and privacy concerns can also constrain the scope and nature of data that can be accessed. A common theme is the proprietary nature and limited accessibility to petroleum drilling records (e.g., Alberta, Canada) and more importantly the inaccessibility of petroleum seismic data (e.g., Alberta). A similar situation often exists with mineral exploration borehole log data that is often protected to varying degrees depending on local governing legislation. In some jurisdictions this is changing (e.g., Netherlands, UK).

Jurisdictional (e.g., national, provincial, state) or regional airborne potential field geophysical data is commonly within the purview of GSOs

and is generally available from managed databases (Figure 3; e.g., Denmark; Jarna et al., 2015). Additional geophysical data includes downhole geophysics and shallow unconsolidated subsurface cone penetration tests (e.g., Illinois, Netherlands). Onshore and offshore seismic data can be collected by both the GSO (e.g., high-resolution offshore, crustal) and the private sector (e.g., petroleum basins). In the offshore environment there is in many cases abundant marine seismic of both shallow high-resolution and basin scale (e.g., Canada, Italy). Within petroleum basins this can often fall under the purview of organizations other than a GSO, for example in the United Kingdom it is the UK's Oil and Gas Authority (OGA), whereas in Canada it is commonly controlled by the contracting party and the data collector. Similar issues arise in multiple jurisdictions for access to basin scale seismic data (e.g., Germany, UK). First arrival time seismic data from both permanent and transient stations are also valuable data for mapping

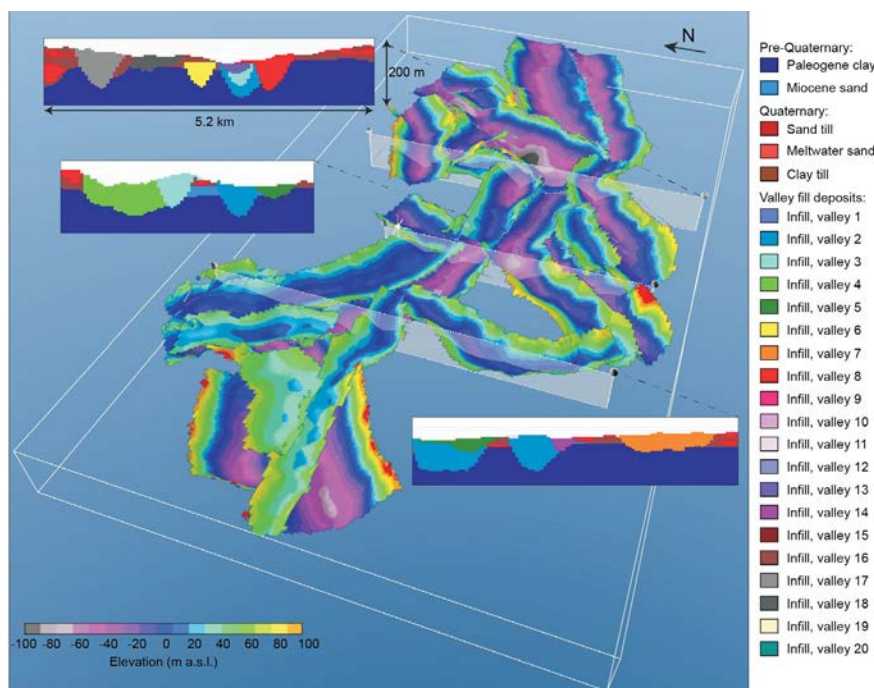
deeper crustal structures (e.g., Canada, Italy, New Zealand, USA).

### Model Databases

A number of jurisdictions have recognized and initiated plans to assess the feasibility of storing 3D models within a retrievable database structure (e.g., Bavaria, Canada, Denmark, Germany, Netherlands). Models derived from geological integration and interpretation, geophysical inversion products, and forward models all fit into this category. Denmark is using an open source data management solution that is able to support different models and metadata storage, including information on feature versions, development history, associated features, attributes, and geometry. In the Netherlands, model management will soon be under the purview of the 2015 legislation for subsurface information management. In Germany and in several German state geological surveys (e.g., Bavaria), the GST<sup>®</sup> framework is being developed as both a data and model management system.

### Data Standardization and Exchange

There is limited coverage of this subject in the volume, particularly with respect to international norms and more specifically those related to 3D data standards. An excellent point was raised by Diepolder et al. (this vol., Chapter 7) highlighting the contrasting challenges between technical interoperability and content-related interoperability. Eventual intermodel correlations can only be achieved by harmonization of the stratigraphic nomenclature prior to the modelling process. There is reference in a number of contributions regarding participation in European Union funded and sanctioned activities that saliently indicates that efforts are underway toward technical interoperability. However, these efforts may be predominantly focused on 2D data holdings. The EuroGeoSurveys (EGS) is an international non-profit organiza-



**Figure 3.** Integration of borehole and geophysical data to model buried valley in the Kasted area, Denmark. Valley generations highlighted by different colours. (From Sandersen et al., this vol., Chapter 11).



tion representing the national GSOs from 36 European countries (<http://www.eurogeosurveys.org>). It is interested in the development of a Geological Service for Europe and the Geological Surveys Research Area (GeoERA) is a major initiative. GeoERA (2017-2021) is a collaboration of 45 national and regional GSOs from 33 countries in Europe. One of the four core components is the development of a European Geological Data Infrastructure EGDI (<http://www.europe-geology.eu/>) via which GeoERA projects will be distributing data. One of the 15 projects that will be delivering data via EGDI is 3D geomodelling for Europe (3DGEO-EU). Other data harmonization initiatives in the European Community include INSPIRE, COST, etc. A number of European contributions (e.g., Italy, Poland, Sweden) plan for, or are compliant with, the INSPIRE (<https://inspire.ec.europa.eu>) standard for much of their geological data. Individual contributions highlight various approaches that connect to broader international initiatives. Finland references the use of GeoSciML to support geological mapping. GeoSciML is an international data transfer standard for geological map data developed by the IUGS Commission for the Management and Application of Geoscience Information (CGI). The Swiss have a national database that is OGC compliant and interfaces with European initiatives such as GEOMOL. The Netherlands reviewed the development of internal standards for various data components to facilitate integration of disparate datasets. They bring home to the reader the long-term challenge of such work which took decades to develop, and which without, modelling would not have been possible. In Germany the Geosciences in Space and Time (GST<sup>®</sup>) framework is central to the German Survey's 3D infrastructure and is able to store and serve 3D models using open standards defined by the Open Geospatial Consortium. It is an outshoot of a European Union Initiative ProMine

(2009-2013) that involved 11 EU member states and 30 collaborators from geological surveys and industry. The U.S. Geological Survey has maintained a standardized archive of geoscience information through its National Geological Map Database Program (<https://www.usgs.gov/core-science-systems/national-cooperative-geologic-mapping-program>) since the early 1990s, and is now implementing a new geological map schema (GeMS) for additional standardization. However, to date, there is no common standard for 3D data or model exchange. The current but changing tendency is for each GSO to embed data into the model through proprietary systems similar to the model followed in 2D for cartographic production.

### **Data Legislation**

Many of the countries of contributing GSOs in Part 2 have enacted legislation to ensure the preservation, management, reporting, and accessibility of subsurface and other geoscience data. Depending upon the governmental structure, roles between state/provincial and federal GSOs, including the division of power and responsibility, GSOs can have varying degrees of problems with access to data. Data responsibility may be legislated to government agencies other than the GSO. Furthermore the management and accessibility of both private sector and contracted government data generally follow different models. Where private sector data is submitted to government agencies, it is often held under a confidential status for 2–5 years depending upon jurisdiction. For example, in New South Wales legislation requires that all drilling, geological, geophysical, and geochemical data acquired by companies on mining and exploration titles be submitted to the Geological Survey of New South Wales (GSNSW). In the Netherlands, legislation covering all subsurface borehole data requires submission to the National GSO. In contrast, in Germany the BGR lacks

the proprietary rights to the relevant data which are often owned by industry and there is no legislative requirement for companies to share data. Enhancements in legislation toward more data sharing for public benefit would further support what is evolving into an Earth Science Commons. Such changes in legislation would definitely benefit jurisdictions ability to conduct better policy development, supported by increased model accuracy and ultimately have more sustainable socio-economic impacts.

There are three broad groupings of datasets; petroleum, mining, and geotechnical. Petroleum data consists largely of borehole information and seismic data collected on- and offshore. In many jurisdictions this data group is managed by government or independent agencies and is controlled through permitting. Petroleum repositories can often be the most completely reported, managed, and accessible, although in numerous jurisdictions, access requires a user fee. Petroleum seismic data is commonly managed and accessed under a different model from borehole data (e.g., Alberta, Canada, Germany, UK), commonly due to the industry contracting model. Mining data is predominantly borehole and physical parameter information along with property scale geophysics that has a range of reporting and data management models across GSOs. Geotechnical data includes mostly shallow and clustered geotechnical, geological, and hydrogeological data collected for infrastructure development (e.g., urban, transportation corridors). This data is well managed in some European countries (e.g., Netherlands), while in North America (e.g., Canada, Ontario, USA) it is largely unreported, and hence inaccessible.

## Three-Dimensional Modelling

### Overview

A significant development since the 2011 publication is the emergence of implicit approaches to modelling. In Berg et al. (2011) implicit modelling is mentioned in only 3 contributions - in Chapter 3 on modelling software it is referenced in relation to GeoModeller and SKUA-GOCAD™ (Kessler et al., 2011) and by two contributing authors from France (Castagnac et al., 2011) and Bavaria (Diepolder, 2011). In contrast, within the 2019 synopsis, implicit and explicit modelling is referenced in the 22 contributions by 12 and 10 contributors, respectively. In more than half of the contributions, GSOs use both implicit and explicit methods or hybridized approaches are used to maximize geological plausibility and confidence (Table 1) in the resulting model surfaces and volumes (e.g., Alberta, Bavaria).

### What is Explicit vs Implicit Approaches

Both explicit modelling and implicit modelling approaches are strongly constrained by knowledge of the geology and geological concepts. The major difference between the two is the manner in which geological concepts are integrated into the modelling approach. Explicit modelling is highly reliant on the interaction and implementation of geological concepts by the geologists, such as with manual cross-section construction. It is time intensive and consequently expensive in terms of human resources and expertise. By contrast, in implicit modelling the geological concepts are formalized in the modelling software (e.g., layer chronology, layer contact types) while layer contacts are implied by mathematical functions that are based on geologically-interpreted data and structural measurements.

Implicit modelling relies more extensively on mathematical functions and

rules to constrain the interpolation of either abundant, sparse, or secondary data, such as potential field geophysical data (Wellman and Caumon 2018). It is inherently a more complex approach, more reliant on computer algorithms, and available in limited software packages. An objective of implicit modelling research is to extend modelling beyond the classically modelled areas that are rich in data to areas with sufficient geological knowledge, but lacking geological data.

The terminology used for data interpretation vs data interpolation can be a source for confusion in describing modelling approaches. For both implicit and explicit approaches, data interpretation and classification may be completed by a geologist or by machine-learning processes (Silversides et al., 2015). The question is the degree and nature of intermediate steps in the protocol and rules related to interpolation can vary widely. Explicit approaches, such as the cross-section approach, rely on the creation of an

intermediate data interpretation by the geologist prior to interpolation. Subsequent interpolation is then highly constrained to secondary derivative datasets. In addition, confusion arises between the traditional use of 3D constraint data (e.g., borehole ‘picks’) to interpolate surfaces with kriging, IDW, Nearest Neighbour etc. and surface estimations using implicit mathematical functions. The former have been referred to as implicit stochastic or sometimes ‘automated’ or ‘unbiased’ estimators and can be the basis of simulation approaches such as Sequential Gaussian Simulation. The later ‘implicit’ estimator refers strictly to algorithms that perform an implicit calculation to create a directed distance-based 3D scalar potential field where the zero values represent the surface to be extracted from within the scalar field that is then rendered as a 3D mesh or point set (see Hillier et al., 2014 and references therein for background).

**Table 1.** Illustrative modelling approaches and examples employed at GSOs.

Modelling Approach	GSO Example	Summary	Example Ref(s)
Explicit	Bavaria, Canada, Catalonia, Finland, Illinois, Minnesota, Ontario, Switzerland, UK, Sweden, USA	User defined boundary contacts (geological units, faults) are manually defined.	Gratacós et al., 2012; de Kemp et al., 2007; Schetselaar et al., 2016; Pan et al., 2018
Implicit	NSW, Bavaria, Canada, Finland, Germany, Netherlands, Poland, Finland	Component surfaces are calculated from on-contact and orientation observation constraints.	Wellmann and Caumon, 2018
Hybrid explicit and implicit	Alberta, Bavaria, Germany, Canada	Input includes elements from geological interpretations, maps and cross-sections.	Montsion et al., 2017
Expert system	Canada	Rule based (geological, geometric, and spatial) constraints on stratigraphic interpretation.	Logan et al., 2006
Machine learning	Alberta, Canada	Stratigraphic classification using SVM.	Smirnoff et al., 2008
Stochastic	Alberta, Canada, Finland, Germany, UK, USGS	Spatial estimation using variants of geostatistical (Kriging) approaches.	Journel and Kyriakidis, 2004; Snyder et al., 2018

## Explicit Modelling

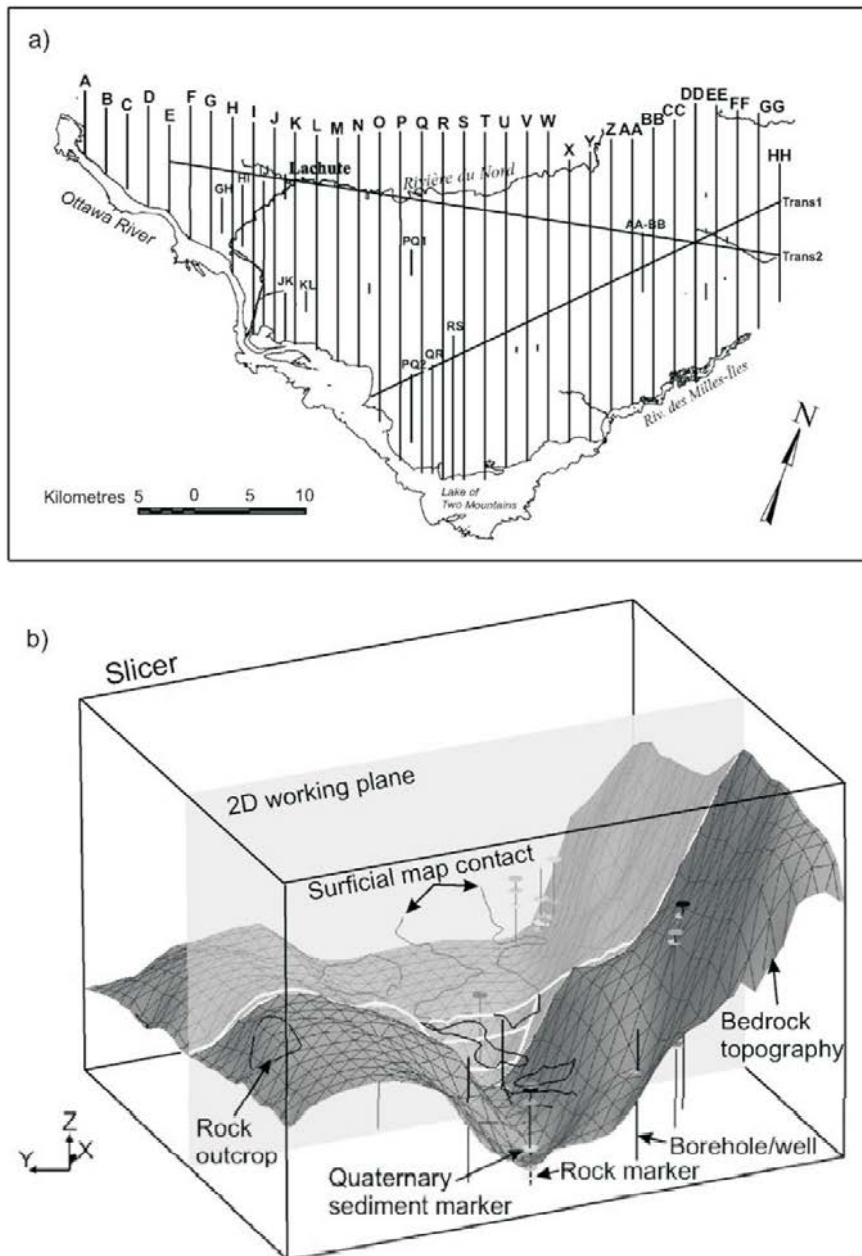
Explicit modelling is the common entry point for geological modelling. It is commonly supported by abundant data with a high-degree of geological content and cognitive engagement of geologist(s). Evolving from pre-digital approaches, this method commonly involves cross-section development in either a digital or non-

digital environment (Figure 4). It is an approach familiar to field mapping geologists and can easily facilitate user interaction to maximize the geological plausibility of the surfaces. Deterministic explicit models are singular realizations with limited options for model rebuilds in the future, or implementation of stochastic realizations.

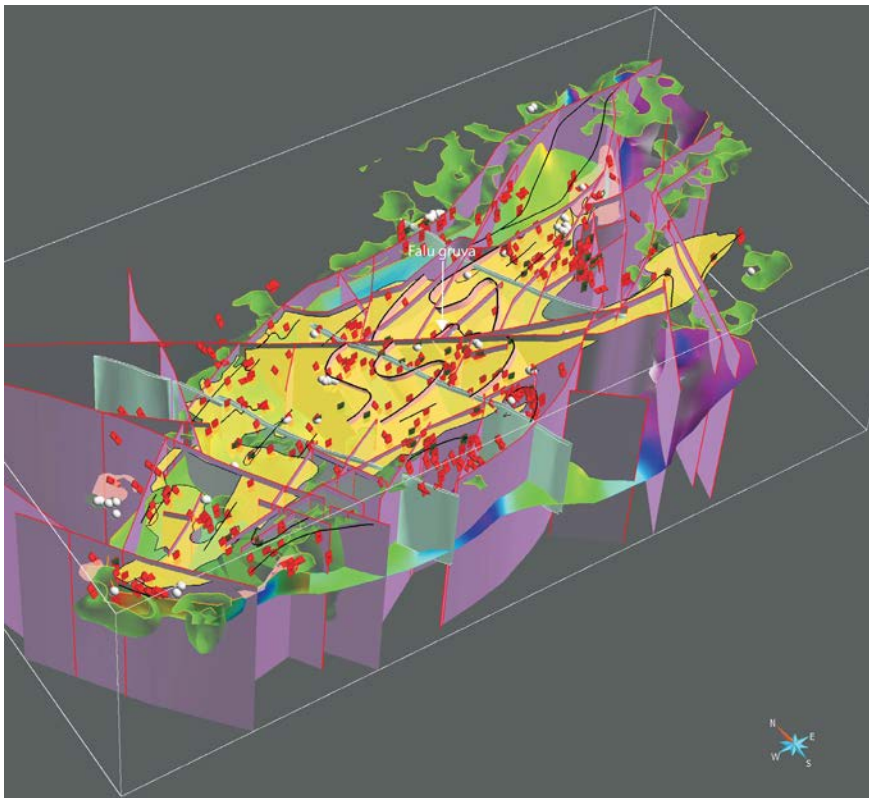
The explicit modelling approach is the tried and true approach used to simplify geological complexity into relatively simple lithostratigraphic or sequence stratigraphic units. For the basin stratigrapher and sedimentologist, and certainly those less numerically-inclined, this approach has a high degree of familiarity. Cross-sections can be developed outside of a digital environment, digitally scanned and registered in a 3D environment and then converted to vector objects. This approach is effective in areas with abundant data support, and for characterizing geological scenarios from layer-cake to complex geology with folding and faulting. Explicit modelling has been implemented across a broad spectrum of geological settings from surficial geology (e.g., Illinois, Ontario, UK), sedimentary basins to even complex fault and fold domains of orogenic belts (de Kemp et al., 2015), and crystalline and metamorphic terrains (Figure 5; e.g., Bavaria, Canada, Italy, Sweden).

The most commonly discussed approach to explicit modelling is the cross-section approach. Multiple approaches have been developed with Keller et al. (2011) detailing an approach adopted in Manitoba and various approaches adopted in this volume (e.g., Austria, Bavaria, Catalonia, Denmark, Minnesota, Ontario). Further example of commitment to and the success of the explicit cross-section approach is provided from surficial geological modelling and framework modelling for geothermal applications (e.g., Poland). The utility of the cross-section approach from site scale to national scale in the Lithoframe model has been demonstrated (e.g., UK). In areas with abundant drillhole and geophysical data, explicit approaches have supported well-constrained 3D modelling approaches (Figure 6; e.g., Bavaria, Canada, Illinois, Sweden).

Numerous software packages are able to support the cross-section approach. Ontario has maintained a multidec-



**Figure 4.** Cross-section approach for explicit deterministic modelling in GOCAD used to develop the input data for interpolation. Cross-sections were constructed interactively in GOCAD. (From Ross et al., 2005).



**Figure 5.** Three-dimensional model of a mineral deposit in a folded and faulted volcanic setting. Model constructed from multiple datasets derived from field surveys, with geological and geophysical modelling combined into a single model. The yellow area corresponds to the volcanic domain. The red tablets refer to the strike and dip of the main foliation, which can be traced as form lines (dark solid lines). White balls symbolize the occurrence of sulfide mineralization. The purple surfaces are faults or shear zones. The iso-density-surfaces are shown in green (relatively high density) and yellow (modest density high). Model dimensions are 20 km in length, 5 km in width and 5 km in depth. (From Stölen et al., this vol., Chapter 23).

adal commitment to the use of Datamine Studio with a set of customized scripts, and Manitoba has relied on GOCAD (Keller et al., 2011). The BGS has pursued development of the tools necessary to maximize the efficiency of the organization’s workflow and model construction. BGS software development has advanced GSI3D (Kessler et al., 2009) and the Groundhog Desktop GIS focused on the display of geological information and the construction of cross-sections through stratigraphic correlations (e.g., UK).

### **Implicit Modelling**

Explicit modelling is gradually losing pre-eminence to implicit modelling and often hybrid approaches integrating both styles of modelling are now

being used. A comparison with the 2011 volume (Berg et al., 2011) indicates a tenfold increase in contributions referring to implicit modelling. For an excellent review of state-of-the-art methods for implicit approaches see Wellmann and Caumon (2018). Implicit modelling is being used not only in data rich areas (e.g., Netherlands), but also in data sparse settings (e.g., Canada, New South Wales, New Zealand). In addition, implicit approaches are being used where primary data support involves geophysical data (e.g., Poland). There is current active methodological research addressing the challenge of improved integration of geophysical data and this will hopefully have an impact in developing the next generation of tools for 3D geological model-

ling for GSOs (See <https://loop3d.org/>). Recognizing the limitations of both methods and the desire for maximum geological reasonableness, hybrid approaches are on the increase (e.g., Alberta, Denmark). Highlighting one of the prime advantages of implicit modelling from Sweden is modelling national soil depth on an annual up-date cycle and integrating new information from boreholes, geophysical measurements, and surface mapping.

Much of the implicit modelling is being completed in GOCAD/SKUA (e.g., Bavaria, Canada), Leapfrog (e.g., Finland, New Zealand, Canada; Cowan et al., 2002) and Geomodeller (e.g. NSW, GSWA, BRGM; Calcagno 2008). This software is also being complemented by plug-in software development (e.g., SURFE; Canada) to accommodate more structural and stratigraphic constraints, regional and local anisotropies.

### **Expert System**

Geological Survey Organizations, as experts in geoscience issues, recognize the need for expert geological input into the modelling exercise. This is in fact a consistent and persistent argument made by many for explicit modelling approaches. It is thus surprising to see the limited mention or identification of approaches that formalize this approach. This could be that to some extent the subject is cached in the terminology of implicit modelling. For example, expert knowledge is a crucial part of the “Loop” project within the Knowledge-Event Management component (Ailleres et al., 2018). Logan et al. (2006) describe a rules-based expert system used to model the surficial geology in Ontario, Canada. The approach used control datasets to produce training surfaces to then help constrain stratigraphic assignments to low-quality archival data through use of stratigraphic, spatial, and geometric (thickness) rules. This work was completed in traditional 2D GIS sys-

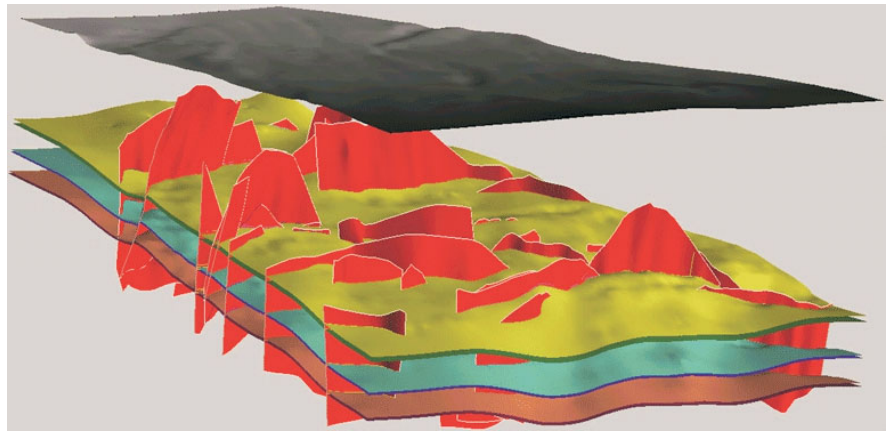
tems and then assembled within 3D visualization software.

### **Machine Learning**

Machine learning or Artificial Intelligence (AI) approaches appear to be in an embryonic stage of development within 3D mapping workflows at GSOs (e.g., Alberta, UK). The Support Vector Machine (SVM) learning model has been applied to data classification (Smirnov et al., 2008) as an aid in the development of a number of geological models (e.g., Canada). In this volume, Alberta details more recent work on the application of machine-learning approaches to assist in the refinement of bedrock elevation surfaces. Machine learning approaches are also coming into use for extracting data from unstructured sources (e.g., manuscripts, tables, maps), as well as narrative information for semantic analysis and capture (e.g., UK).

### **Stochastic Property Modelling**

Submissions to the volume overwhelmingly document the development of deterministic models. In only a few instances are GSOs producing stochastic models. Reported modelling applications of stochastic approaches are related to lithofacies variability (e.g., Alberta, Canada, Denmark, Germany) for example in VMS systems (Schetselaar et al., 2018), fault networks (e.g., Finland), and hydraulic conductivity (e.g., Canada, UK). In some cases, the stochastic modelling was completed for purposes of integrating geophysical data with borehole data (e.g., Denmark). Stochastic modelling has also been applied to model shallow, heterogeneous surficial deposits (e.g., Canada, UK). Where stochastic modelling has been completed and reported on it is commonly completed to model volume attributes such as hydraulic conductivity (e.g., Canada, UK). The future may well see this change as there is increasing interest in understanding the potential of model variability and



**Figure 6.** Discontinuous, nonlinear, and blind fault patterns in a 2000 km<sup>2</sup> area from the GeoMol project framework model in eastern Bavaria. Layers are pre-Tertiary surfaces of the sedimentary sequence, view from SW, total depth is >5 km. For clarity the Tertiary units are omitted and grey layer is topographic surface. (From Diepolder et al., this vol., Chapter 7).

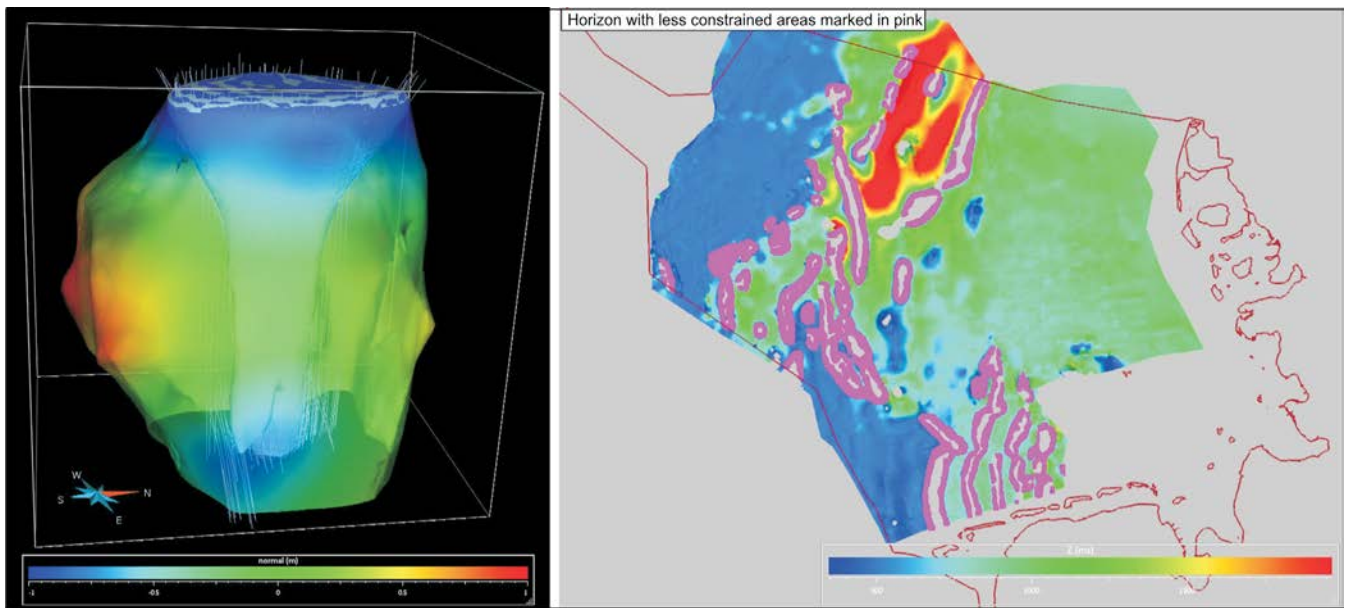
expressions of confidence in the model realization. Stochastic modelling can provide a powerful and comprehensive approach to supporting confidence measures. Stochastic realizations are often constrained in explicit modelling environments, but the growth of implicit modelling approaches will facilitate the adoption of stochastic methods. Furthermore, optimization in computer processing will reduce the computation obstacle inherent in stochastic realizations of large models through increased CPU speed and CPU/GPU parallel processing implementations.

### **Modelling Considerations**

#### **Uncertainty Analysis**

Three-dimensional geological modelling at many geological surveys is maturing and there is increasing interest by both the GSO and other disciplines to optimise the downstream use of such models. Many geological mapping applications are accustomed to high levels of uncertainty; however engineering, hydrogeological, and other disciplines increasingly require uncertainty to be identified both qualitatively and quantitatively. Mineral exploration studies are increasingly interested in modelling uncertainty far

beyond the head frame targeting (mine site), especially when combining geophysical inversions and implicit modelling studies (Giraud et al., 2017). Uncertainty analysis is often focused on the end products and quantification of interpolative error or uncertainty related to data support, referred to as the aleatory uncertainty. Of equal importance is the uncertainty related to geological interpretations that underpin model development or epistemic uncertainty. From the contributions in this volume, it is clear that many GSOs are grappling with approaches (e.g., Germany) to quantify uncertainty, particularly the aleatory component. A range of approaches are detailed in the contributions and it is likely that this subject is under represented in the contributions. The documented approaches include basic statistical measures (e.g., Alberta), stochastic and probabilistic methods (Figure 7; e.g., Canada, Germany), data density maps (e.g., Illinois, Swiss), and user developed hybrid approaches (e.g., Ontario). An additional benefit of uncertainty analysis is also as a valuable metric in orientating future data collection to maximize the cost – benefit of scarce resources. As geological modelling and visualization increase in sophistication, particularly for example, with



**Figure 7.** Uncertainty visualisation for interpreted salt structures in the Germany Basin, North Sea. Left: 3D model of a salt structure (blue) surrounded by a semi-transparent envelope indicating the seismically less constrained area. The color code on this envelope refers to the distance between the envelope and the interpreted salt body. Right: Modelled horizon for the base of the Upper Buntsandstein. Regions (pink) are obtained by intersecting the horizon with the uncertainty envelope around the salt structure. These regions indicate areas where the depth and structure of the horizon are less constrained by seismic data. The depth of the horizon is indicated by the color code. For details see (From Steuer et al., this vol., Chapter 13).

augmented and virtual reality tools, the expectations associated with models can be unrealistically high. The importance of uncertainty measures will increase where modelling hybridized methods are employed. There will also be an increasing challenge to communicate uncertainty integrated within the visualization model process, particularly where immersive technology is employed.

### **Collaboration and Software Development**

An area that is completely reliant on collaboration is development and adoption of data standards. GSOs have been involved in standards development such as GeoSciML a long-term CGI initiative and Resource ML originally developed by the Australian Geoscience Committee and subsequently transferred to CGI (<http://www.cgi-iugs.org>). Beyond the GSO structure, examples from industry include RESQML from Energetics, an industry consortium (e.g., Hollingsworth and Schey, 2018). Additionally,

there is research occurring in academia, for example on 3D standards such as Geo3DML which has been released by the Chinese Geological Survey as a standardized data-exchange format for 3D geomodels (Wang et al., 2014).

Software development for a new generation of geomodelling software, for example the Loop initiative, a multinational initiative of OneGeology involving Australia, Canada, France, Germany, and the United Kingdom (<https://loop3d.org/>; Ailleres et al., 2018), will be most efficiently employed when supported by a standardized data foundation. Additional collaborative software initiatives are being pursued by Germany to ensure the validation of codes and modelling approaches through benchmark initiatives. The United Kingdom is actively engaged in developing Groundhog.

Examples from the Australian geological surveys demonstrate that it is entirely possible and advantageous to combine forces to provide shared data

infrastructure and modelling expertise with federal, university, and industry organizations (i.e., CSIRO, UWA, Curtin, GSWA and 9 other companies) in the Capricorn project to deliver high quality and timely geoscience data and models (Hough, 2016). Coverage of the lessons learned from these examples is beyond the scope of this summary. However, future investigation is warranted in this era of reduced human resources and rare skills for 3D data management and modelling within GSOs.

### **Summary**

A comparison of content in Berg (2011) and this volume (MacCormack et al., 2019) indicates GSOs are moving forward. There has been a significant increase in the number of GSOs embracing 3D mapping and modelling from 2011 to 2019. The 22 contributions on the subject provide an incomplete picture of the status of GSO activity in this area. Nevertheless, the methods, case studies and

collaborative examples documented provide a solid representation of the status of work taking place. The contributions demonstrate advances in data management, data integration, and modelling approaches. The complexity of geology being modelled has increased with modelling examples from a range of geological settings. The use of implicit modelling approaches, often within a hybrid implicit – explicit approach, has experienced considerable growth. Methods are increasingly being developed to go more regional, beyond mine headframes or local aquifers to municipal, state and national scales. There is increasing interest in stochastic modelling, particularly for improved uncertainty characterization. GSOs are also addressing the societal needs for this type of work through increased collaboration to support transboundary harmonization and data exchange.

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# Chapter 4: Benefit-Cost Analysis for Building 3D Maps and Models

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## Introduction

The economic benefits derived from having a national or jurisdictional geological survey have been well documented. The first national geological survey, the British Geological Survey (BGS), was founded in 1835. It was established to address issues associated with the Industrial Revolution, a time of intense economic development that required considerable earth resources for industrial applications. Information on access to minerals and development of mines, including aggregate for construction as well as coal, was essential. Geological knowledge also was needed for road and canal building, groundwater resource identification, and discovering sources of fertilizer and minerals that supported food production for a growing population. A significant catalyst for geological investigations by the BGS was William Smith's 1815 geological map of England and Wales (Allen, 2003). The map's cross-sectional depictions of the subsurface, and portrayal of strata ages, differences in lithology, and structural relationships permitted, for the first time, predictions of rock occurrences in regions of sparse data. This 1815 foundational map even included various uses for the geological data. It is indeed the blueprint for modern mapping, as well as 3D geological modelling.

Geological Survey Organizations (GSOs) worldwide were founded on the premise of economic development, whether it be development of mineral and energy resources within jurisdictional boundaries or discovering resources elsewhere and bringing them home. When the environmental movement took hold in the 1960s (Frye, 1967), GSOs not only maintained their more traditional role of basic mapping in support of the mineral resource industry and research-driven science, they also became active in identifying groundwater resources and promoting environmental protection. Both of these new GSO emphases also made significant contributions to the economic well-being and prosperity of their jurisdictions. They gave rise to the need for more detailed information of the subsurface because resource-based land-use decision making for groundwater and mineral resource extraction would be based on this geological information. The premise was (and still remains) on avoiding or mitigating risks associated with geological hazards or the increased potential for contamination, and identifying areas of emerging resource potential or development opportunities. This approach, minimizes future and potentially costly liabilities resulting from poor land-use and development decisions.

## Benefit-Cost Investigations

The use and benefits of geological information has been touted for over 200 years, mainly occurring through anecdotal examples. However, beginning in the 1980s, some governments demanded a more comprehensive understanding regarding how tax-payer money was being spent and began to require agencies to justify their various activities. Included in these demands was a quantifiable justification for conducting geological mapping. The earliest economic assessment of geological mapping was done by Cressman and Noger (1981), following the completion of the only jurisdiction within the U.S. to be completely mapped (from 1960-1978) at 1:24,000-scale (Kentucky, Anderson, 1998). Kentucky's statewide mapping program cost ~\$21M USD (1978 dollars) to complete traditional 2D mapping. The Cressman and Noger (1981) report acknowledged that it could not place a value on the economic benefit of the mapping endeavor, but there were some examples of benefits provided, including newly discovered minerals and the wide use of the mapping for coal, oil, gas, fluorspar, limestone, and clay exploration, money saved by government and industry, as well as use of maps for infrastructure evaluations, preparing environmental impact statements, engineering geology, and land-use

planning. The most striking example was the discovery of a 70-80 M ton coal field worth >\$1B USD (using 1974 prices), which represents approximately \$48 USD of developed resource for every \$1 spent characterizing the geology.

To address the need for more detailed geological information of the subsurface, modern stack-unit mapping was developed in the 1970s, and then as computer technology advanced, 3D geological modelling emerged in the 1980s. In response to an Illinois State Senate resolution to justify the costs of geological mapping, the Illinois State Geological Survey performed a benefit-cost study of detailed 1:24K-scale surficial and subsurface geological mapping (Bhagwat and Berg, 1991). It was based on 3D stack-unit mapping completed for two counties in 1984 (Berg et al., 1984), where costs were well documented because the counties funded the project. Questionnaires were sent to 80 map users (55 interviewed) regarding money saved because of the mapping. The economic premise was that geologic maps were a “public good”, and the benefit-cost assessment was based on future cost avoidance because of knowledge gained through mapping. The only quantifiable benefit chosen was the cost of cleaning up contaminated sites. Benefits were also reduced 50%, 75%, and 90% to account for environmental regulation efficiency. In other words, if regulations worked 100%, then mapping was not needed. At the 50% benefit reduction, the benefit-cost ratio was 24:1 to 55:1 and at the 75% reduction, it was 12:1 to 27:1. Even when benefits were reduced a full 90%, the benefit-cost ratio was still quite high at 5:1 to 10:1 (Bhagwat and Berg, 1991). The entire assessment was very conservative, and justified 3D mapping as a viable and cost-savings activity.

In addition to the benefit-cost assessment provided above, Bhagwat also authored three other economic assessments of geological mapping in Ken-

tucky, Spain, and Nevada. In all three cases, the products evaluated were traditional 2D mapping, but similar to the study above, included extensive questionnaires regarding map use.

- 1) With the Cressman and Noger (1981) report in hand for Kentucky, and admission that the authors could not place a value on the entire Kentucky mapping program, the Kentucky Geological Survey contracted the Illinois State Geological Survey to conduct a very rigorous economic assessment for that state (Bhagwat and Ipe, 2000, and also discussed by Cobb, 2002). Using very conservative assumptions, there was a return of \$25-39 USD for each dollar invested in mapping. Completed originally to boost Kentucky’s mineral and energy industries, at a cost of >\$130M USD (year 2017 dollars), the maps were primarily used for water supply/ protection issues, development, environmental problems, and mitigation of natural hazards.
- 2) Garcia-Cortés et al. (2005) reported on Bhagwat’s analysis of Spain’s national mapping program. Here, there was a benefit-cost ratio of 18:1. An investment in mapping of €122M (\$148.5 USD) produced savings for the Spanish economy of €2,200M (\$2,677M USD).
- 3) In 2014, Bhagwat assessed the value of mapping for the State of Nevada, where the total value for maps sold over a 40-month period was \$13M USD. The questionnaires revealed that map user’s “willingness to pay” (a measurable economic benefit factor) was \$6,414 USD (on average) for each map. With an estimated cost of \$90K USD to produce each map, the benefit-cost ratio was 147:1. This was the highest benefit-cost of Bhagwat’s assessments, primarily due to the high value of Nevada’s mineral resources (e.g., gold and silver vs. Kentucky’s coal).

The U.S. Geological Survey also was one of the first agencies to generate a benefit-cost assessment of geological mapping. The first evaluations (Bernknopf et al., 1988a and b) assessed the benefits due to losses that could be avoided from landslides. They used a combination of topography and the regional distribution of surficial materials with differing shear strengths to estimate the probability for landslides. The analysis resulted in a yearly net benefit of \$1.7M USD, based on benefits (derived from costs that were avoided) of \$3.1M USD and a cost of \$1.4M USD. They also determined that an optimum mitigation rule could be adopted and by selectively applying building codes to susceptible parcels, significant increases in net benefits were possible. Bernknopf et al. (1993 and 1997) also performed a very sophisticated evaluation on the use of new and improved geologic maps, with more detail, versus existing or older geologic maps (scale 1:100,000) for siting a waste disposal facility and a transportation corridor in Loudoun County, Virginia (outside of Washington DC). The expected net benefit of using the improved geologic map was \$2.44M to \$4.66M USD minus \$1.16M USD for the cost of map production, yielding a net benefit between ~\$1.28M and \$3.50M USD. The benefit-cost was estimated at 2-4:1. Finally, Haling et al. (2004) studied the economic benefits of the USGS’ National Map and estimated net benefits at \$1-3B USD. The National Map is aimed at improving and delivering topographic information and is a collaboration between the USGS and other Federal, State, and local partners. Accurate topographic data is an integral component essential for accurate production of geological maps and models.

The British Geological Survey (BGS) has been particularly active in assessing the value of geological information. A 2003 report (Roger Tym & Associates) sums up their reason for conducting these analyses as it justi-

fies the BGS' contributions toward providing a public good that adds wealth to the UK economy. The first economic evaluation at the BGS was by Ellison and Calow (1996) who assessed geological mapping information in the UK based on a value that was calculated using reasonable and conservative assumptions regarding the frequency of geological map usage and the output value attributable to having initial access to the information. The calculations showed a national baseline value of geological mapping of £18.9M (\$29.4M USD) per year, while the BGS budget allocation for geological mapping was about £3.2M (\$5M USD). This 6:1 benefit-cost ratio is similar to the results identified in Canada (Boulton, 1999), discussed later. BGS also identified 17 sectors (aggregates, other industrial minerals, waste management, environmental assessment, land and regional planning, coastal management, water resource management, water protection management, site investigations, road building, insurance and risk, research, education, offshore hydrocarbons, onshore hydrocarbons, health, and coal) for which cost savings were estimated by virtue of having geological mapping, and they presented two case-study benefit-cost examples.

Reedman et al. (1996) reported on a Kenyan study of mapping that was conducted between 1980 and 1987. This new mapping allowed for targeted drilling that reduced exploration costs more than £200,000 (\$307,000 USD). Reedman (2000) and Reedman et al. (2002) further reported on an evaluation of the value of geological information in other less developed countries. Assessments were based on several large projects funded by the UK that produced geological and other information used for mineral exploration in South America, Africa, and Asia, and also the use of geological information for groundwater exploration in Nigeria. As an example of mining benefits, new geo-

logical information in Peru, with an initial mapping investment of <\$500K USD, resulted in the discovery of almost 1.75M ounces of gold valued at >\$500M USD. A Nigeria project produced a groundwater potential map that improved drilling success rates in several geological settings, and the net benefit was >£750,000 (\$1.15M USD).

The BGS' Project Iceberg (BGS 2017) had a long-term goal to evaluate the subsurface and its infrastructure which is extensive, with >1.5M km of underground services, and >4M km of data lines in the UK. When coupled with a lack of coordination and collaboration, the Department of Transport estimated that street works costs were ~£4.3B (\$5.6B USD) per year, and the Treasury estimated in 2013 that greater cross-infrastructure collaboration could save ~£3B (\$3.9B USD). Project Iceberg's goal was to provide optimum information for understanding and developing underground space and ensuring that subsurface geological information was an essential component of all assessments.

The UK's Natural Environment Research Council (2006) and later Hughes (2011) reported on significant benefits of environmental research, particularly ground stability hazards, including (1) better informed decisions and avoidance/mitigation of potential hazards, (2) accurate and relevant information for users, (3) cost savings by investing in areas lacking risks, and (4) avoidance of stress and disruption often associated with property loss. They estimated that the cost of subsidence hazards to insurance companies in the UK was about £300M (\$551M USD) per year, and reported that BGS ground stability data potentially could save this industry between £70M and £270M (\$129M and \$496M USD) between the years 2006 and 2030.

Most recently, the BGS (2019) reports specifically on the value of 3D geomodels:

- A Chalk aquifer model below London supported risk-based decision making on new groundwater withdrawal licenses, and that resulted in additional withdrawals valued between £27M and £40M (\$36M and 53M USD).
- A geological model in the Oxford region helped to forecast groundwater flooding, and risk mitigation valued at >£46M (\$45M USD), was the estimated cost for the affected properties.
- A geological model in northern Scotland helped to alleviate a groundwater flooding risk to properties, and that exercise was valued at £112M to £130M (\$148 to \$172M USD).

A more global perspective on the value of geoscience information by the BGS was provided by Ovadia (2007), who evaluated various published materials to help establish a monetary value for collecting, managing, and disseminating geoscience information. He estimated that the value of geological information to national economies, in general, had a benefit-cost of 100-1000:1.

An extensive review of more than 30 reports and peer-reviewed articles on the value of geological information and closely related earth observations (e.g., Landsat) was conducted by Häggquist and Söderholm (2015). In addition to those discussed above, are citations specifically reporting the tangible economic benefits derived from geological mapping and/or access to geoinformation. Cocking (1992) reported that geological mapping in Kenya had a net benefit of >£0.2M (\$0.4M USD) per year. It was not based on the value of avoided costs, but rather on the costs of collecting data from private enterprise as opposed to a public entity. Scott et al. (2002) reported that regional geological mapping for mineral exploration in Australia had a net benefit of

\$4.3M AUD (\$2.4M USD) mainly by enhancing exploration potential by improving the areas of focused activity and thereby reducing risk during early stages of mineral exploration. Castelein et al. (2010) evaluated the economic worth of geo-information in The Netherlands at €1.4B (\$1.7B USD), based on economic indicators of turnover of funds from geoinformation products and services, employment, various activities (measuring, collecting, and storing geographic data), and the market.

Kleinhenz & Associates in 2011 performed an economic impact analysis of products and services of the Ohio Geological Survey. A user's survey reported that respondents saved \$65,800 for each project in the State of Ohio using the Survey's products. There were an estimated 8,740 projects, based on products requested, and therefore a minimum benefit of \$575M (USD) per year of the Survey's information. The economic analysis measured the costs that were avoided as a result of having the Survey's information.

In 2015, the annual report of the Geological Survey of Norway stated that interviews from 2,200 map users concluded that every euro invested in geological maps produced a return of 18 euros (\$20 USD). New industries, with developing needs for infrastructure, required a logical approach to manage natural resources (including minerals and water) and the environment, and subsurface information was critical to decision making. In addition, a seafloor mapping project that encompassed 12 municipalities had a savings for industry and ocean managers of >30M NOK (>\$3.8M USD).

In 2017, Robertson provided a comprehensive assessment of Canada's National Geoscience Mapping Program conducted between the years of 1991 and 2002. In that report, he cited several published and unpublished studies on the value of geologi-

cal mapping for supporting the mineral extraction industry. Boulton (1999) reported that every government dollar invested to improve geoscience knowledge had a 5:1 return of investment, but years later had the potential for a 125:1 return of investment. Bernknopf et al. (2007), focused on mapping of the Flin Flon Belt of Manitoba and Saskatchewan and the South Baffin Island area of Nunavut. For the Baffin Island region, the cost of the mapping was \$1.86M CAD (\$1.7M USD), and the economic value of exploration that resulted from new and more detailed mapping was calculated between \$2.28M CAD (\$2.05M USD) to \$15.21M CAD (\$13.68M USD), and therefore a benefit-cost of 8:1, with added value resulting from more options and less risk by industry for exploration, as well as increased efficiency and mineral productivity. Finally, Maurice et al. (2009), evaluated mineral industry investments in regions where major mapping had been conducted in northern Québec. Exploration expenditures in one region increased almost continually from essentially \$0 in 1988, at the outset of the mapping program, to over \$25M CAD (\$23.7M USD) by 2007. Over a 10-year period at another region, industry expenditures increased from less than \$20M CAD (\$14.5M USD) in 1997 to nearly \$100M CAD (\$94.8M USD).

Lastly, the Alberta Geological Survey during the last few years has had a robust and aggressive program of modelling their provincial jurisdiction, and is in the process of completing an economic impact assessment of their 3D modelling program to identify the costs saved and opportunities that have been realized to highlight the value proposition. Some early observations show that due to the availability of open-source software and open-access data, the costs associated with constructing 3D models are decreasing. At the same time, increases in computational power have provided

the opportunity to integrate larger and more diverse datasets to enhance stakeholder communications and the decision-making value of these models. As a result, single 3D geological models are being used to support decision making with respect to a wider range of applications, thus increasing the value for the cost and effort expended to generate 3D geological models.

## Summary / Conclusions

Estimates of benefit-cost for geological mapping and modelling have been conducted since the early 1980s, with a steady increase in the number of GSOs developing these benefit-cost analyses to highlight the value and economic impact of their work. While methodologies for conducting the various economic assessments have many similarities, they do differ in scope and detail, but all show a very positive valuation for the mapping and modelling activity ranging from benefit-cost ratios of 4:1 to >100:1. The large range in benefit-cost ratios reflects the scope of the respective studies, and critically the timeframe over which the benefits were estimated to accrue, as well as the value of the commodities that were assessed. All of them were conducted to report on the need for geological information to address resource, hazard, and other societal issues, and with the specific intent to justify the activity. They importantly (1) market the value of geological mapping/modelling to customers, stakeholders, and potential funders, and (2) promote the need for mapping/ modelling within jurisdictions that lack a dedicated mapping/ modelling program, thereby providing a significant economic incentive for conducting the activity.

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# Chapter 5: The Alberta Geological Survey 3D Geological Modelling Program

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## Introduction

The Alberta Geological Survey (AGS) is responsible for providing geological information and advice about the geology and resources to the Government of Alberta, the Alberta Energy Regulator (AER), industry, and the public to support public health and safety, exploration, sustainable development, regulation, and conservation of Alberta’s resources. The AGS delivers geoscience in several key areas, including surficial mapping, bedrock mapping, geological modelling, resource evaluation (hydrocarbons, minerals), groundwater, and geological hazards. We also are responsible for providing geoscience outreach to stakeholders ranging from professional colleagues and academia to the general public.

The objective of our 3D Geological Framework program is to develop a single-source of geological truth for Alberta, and for the AGS and AER to provide a single location for accessing consistent and reliable geological data within a credible geospatial context. This operational approach allows for a more efficient and effective evaluation of the relationships between surface and subsurface properties and interactions ensuring that risk-based strategic and operational decisions are based on sound science and credible evidence.

We are making the 3D Geological Framework (including sub-models) accessible to our external stakehol-

ders to improve regulatory efficiency and competitiveness by improving access and transparency of the data and information used to inform regulatory decisions. This will significantly improve our ability to effectively integrate and evaluate geospatial data to facilitate science-based decisions in support of land-use planning, safe and sustainable resource development, environmental protection, economic diversification and public safety.

## Organizational Structure and Business Model

The AGS was created in 1921 by Order in Council of the Alberta Government, and was established as a core part of the Scientific and Industrial Research Council, and later the Alberta Research Council. In the late 1990s, the AGS was transferred to the

Alberta Energy and Utilities Board to (1) provide geoscience expertise to support the regulatory process, (2) provide necessary geoscience information and knowledge to the Government of Alberta, and (3) fulfill the need for unbiased, credible public geoscience information. The AGS is the official provincial geological survey of Alberta and currently resides within the Alberta Energy Regulator (AER), providing world-class geoscience support for Alberta’s regulatory processes.

The AGS has approximately 59 permanent full-time employees working on 4 teams (Figure 1). The majority of AGS and AER 3D modelling activities occur within the Modelling and Resources Team, which is composed of 15 geologists, geomodellers, geostatisticians and geophysicists.

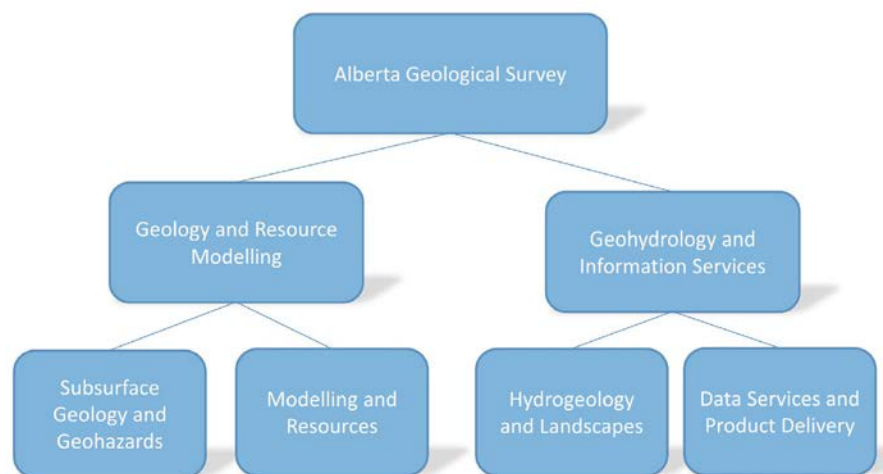


Figure 1: Overview of the organizational structure of groups and teams within the Alberta Geological Survey.

The AGS is responsible for describing the geology and resources in the province and provides information and knowledge to help resolve land use, environmental, public health, and safety issues related to the geosciences. Our work is primarily focused on enhancing the scientific understanding and characterization of Alberta's geology, resources, and environment. However, on occasion we will collaborate with neighbouring provinces, territories, and states to investigate cross-border geological entities, opportunities, or risks. In recent years, the collaborative studies that the AGS has participated in have been related to groundwater protection, distribution of shallow gas plays, and characterizing the susceptibility of certain regions to induced seismic events. We have also signed a number of Letters of Intent with other international geological surveys to formalize and facilitate the exchange of information and knowledge on strategic topics of mutual interest.

## Overview of 3D Modelling Activities

The 3D Geological Framework modelling project was initiated in 2010 and began with the development of independent 2.5D grid surfaces for 8 well known geological units, and was resourced with a 0.25 FTE. In 2012, the project was resourced with 1.0 FTE, the number of 2.5D surfaces increased to 23, and the transition began toward development of a full 3D geological model (MacCormack, 2014). The current 3D Geological Framework model of Alberta covers 602,825 km<sup>2</sup> and includes both provincial- and local-scale 3D models (Figure 2). These models have been constructed at a grid cell resolution of 500 m x 500 m or less. Our current provincial-scale model (version 2) contains 62 geological units and was interpolated using approximately 1,235,761 data points (Figure 3), which represents a two-fold increase over Version 1 (released in 2018) that

leveraged 620,812 data points to characterize 32 units (Alberta Geological Survey, 2019). Both of these provincial scale models are available at [www.ags.aer.ca](http://www.ags.aer.ca) for download.

In conjunction with our provincial-scale model, the team is also developing local-scale models that cover smaller regions of the province. These local-scale models are typically built to support specific investigations that require either higher-resolution geological characterizations, or require additional geological units to be modelled that are not already available within the provincial-scale model. Although it is necessary to build models at a variety of scales to capture the required level of detail, a key objective of our 3D Geological Framework program is to combine and leverage all of the work done by our geologists and geoscientists on both local and provincial-scale models to combine them into 1 holistic model representing the most current single-source of geological truth for the province. Working towards this objective has spurred the team to make great strides towards developing sophisticated functions that have facilitated the integration of a variety of data types from multiple sources. This required the development of adaptable multi-scalar grids with built-in feedback mechanisms, and workflows to allow individual components of the model to efficiently adapt and evolve as our knowledge and understanding of the subsurface evolves and additional data and information becomes available.

As of 2018 our Geology and Resource Modelling Group (Figure 1) consists of 31 staff that work with teams consisting of geologists, geomodellers, groundwater numerical modellers, geostatisticians, and other scientists or data professionals that support building multi-scalar models for the following applications:

- Conventional and unconventional hydrocarbon resource characterization (Figure 4A),

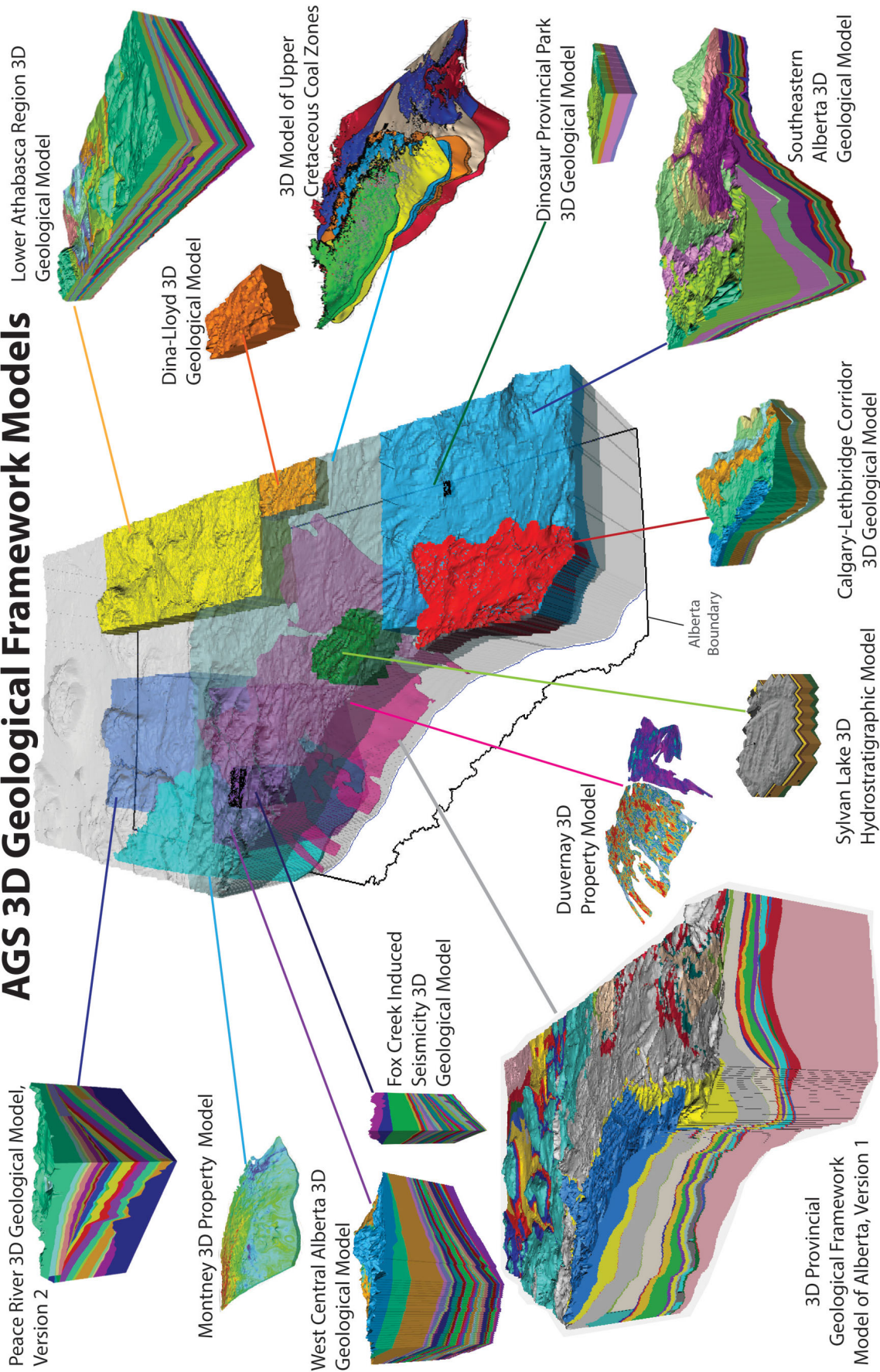
- 3D hydrostratigraphic models to support groundwater quantity and quality assessments,
- 3D rock property characterization (Figure 4B),
- Subsurface cavern storage potential,
- Assessing the relationship between geological features and induced seismic susceptibility,
- Mineral potential,
- Stakeholder communication and geoscience education (Figure 5A and B),
- Holistic integration of Alberta's natural resources.

## Resources Allocated to 3D Modelling Activities

When the 3D geological modelling program was initiated in 2010, the only costs to the program were the salary for 1 FTE and for a single GoCad license (approximately \$5,000 CDN). As the program grew, it was discovered that the AER had access to 4 Petrel licenses, which although they were quite costly to maintain, were much better suited to the type of data we were using to build and integrate within our 3D models.

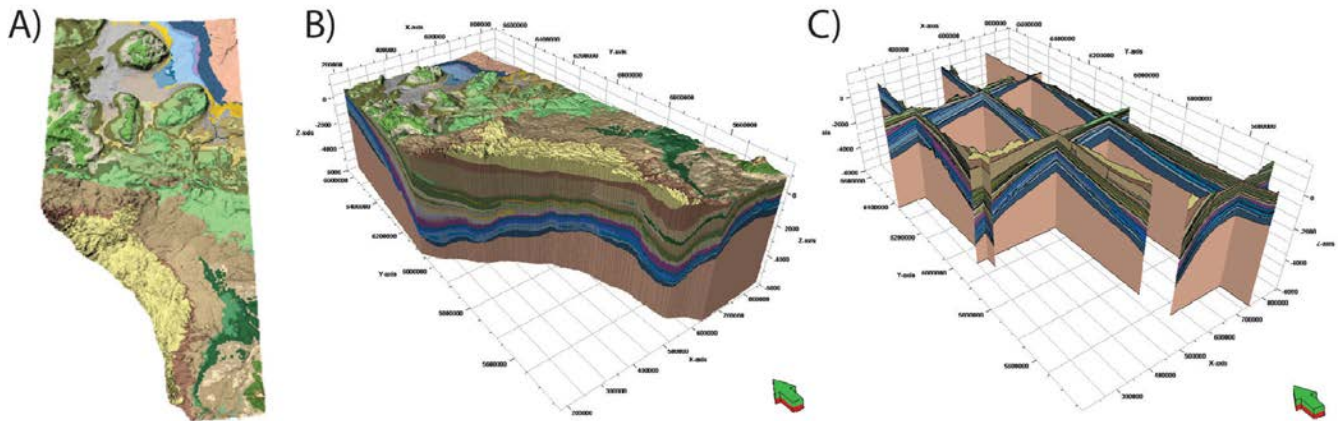
As of 2019, our Modelling and Resources team consists of 15 geomodellers, geostatisticians, geologists, and geophysicists that have access to multiple 3D modelling and visualization software packages including Rockworks, Viewlog, ArcPro, Petrel, and iMOD. Each software package has different strengths in how they allow the user to integrate, query, interpolate, and QA/QC the data and modelled horizons. Our geologists primarily use Rockworks and Viewlog to visualize, evaluate and model surficial geological units. ArcPro is used primarily to visualize and QA/QC the geological picks, horizons, extents, and visualize geospatial data within the 3D models. The majority of the 3D model construction is done by workflows that the team has built within Petrel. These 3D models and

# AGS 3D Geological Framework Models

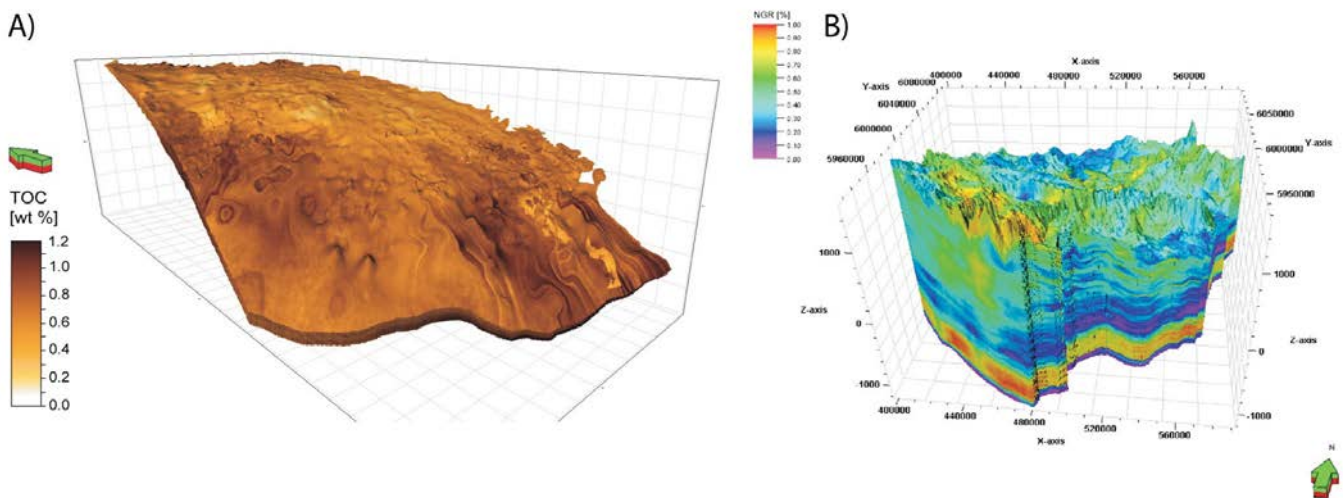


**Figure 2:** 3D geological and property models that are all contributing to the 3D Geological Framework of Alberta.





**Figure 3:** Version 2 of our 3D provincial-scale geological model from **A)** birds-eye view, **B)** oblique view, and **C)** cross-sections showing the internal stratigraphy.



**Figure 4:** **A)** Three-dimensional property model of total organic carbon used to characterize resources within the Montney Formation (Lyster et al., 2019), **B)** 3D property model of porosity within the upper geological units of west-central Alberta to help identify potential groundwater aquifer units (Babakhani et al., 2019).

model components (horizons/grids, extents, and points) are exported from Petrel and saved in an ESRI compatible format. This model information is also made available in iMOD, which is a free open-source software program that allows users to visualize and interactively explore our 3D models, as well as import and visualize their own data and information within our models.

## Overview of Regional Geological Setting

The geological units characterized within our 3D models range from the top of the Precambrian basement to the modern day ground surface (Fig-

ure 3B). The crystalline rocks of the Precambrian basement are more than 542 million years old and just over 5 km deep along the western edge of Alberta (Figure 3C). During the Paleozoic Era, Alberta was covered by warm water in which supported the growth of reefs and deposition of extensive carbonate units. Many of Alberta's deeper oil and gas reservoirs were emplaced during this time (Figure 6D). During the Mesozoic Era, Alberta's western edge was impacted during an extensive period of mountain building that resulted in the creation of the Rocky Mountains (Eyles and Miall, 2007). The Mesozoic Era was also a time when the inland seas retreated and much of the province

was exposed resulting in a transition to the deposition of primarily clastic sediments with intermittent periods of erosion resulting in multiple extensive unconformities (Figure 6A, B and C). Overlaying the major unconformity surface of the bedrock topography are the deposits of the Neogene-Quaternary, which represent a relatively thin deposit (1/4 of the province is covered by 2 m of sediment or less), however can reach depths of over 400 m in some areas (MacCormack et al., 2015).

Although the majority of Alberta is a sedimentary basin, there are many areas of significant deformation and faulting, and complex features, such



**Figure 5:** **A)** Picture of an exhibit at Dinosaur Provincial Park, a UNESCO World Heritage Site in southern Alberta showcasing the Minecraft model of the parks shallow geology, **B)** Child playing with Minecraft models and 3D prints of a 3D geological model at an Alberta science center.

as salt-dissolution induced collapse, caverns, reefs, folds, and faults. Alberta is also fortunate to have numerous natural resources such as oil, gas, coal, bitumen, condensates, groundwater, minerals (diamonds, lithium brines, rare earth metals), and geothermal potential.

## Data Sources

The data used to build our models typically comes from stratigraphic picks from geophysical well logs (primarily oil and gas wells), maps, cross-sections, water wells, and seismic data where available. We have relied heavily upon the >500,000 wells that have been drilled throughout the province by the petroleum industry. Our staff are fortunate to be able to evaluate and compare well log profiles with core stored in our Core Research Centre (CRC; Figure 7). Core from over 70,847 of these wells (stored in over 1.6 million boxes), and drill cuttings from >159,500

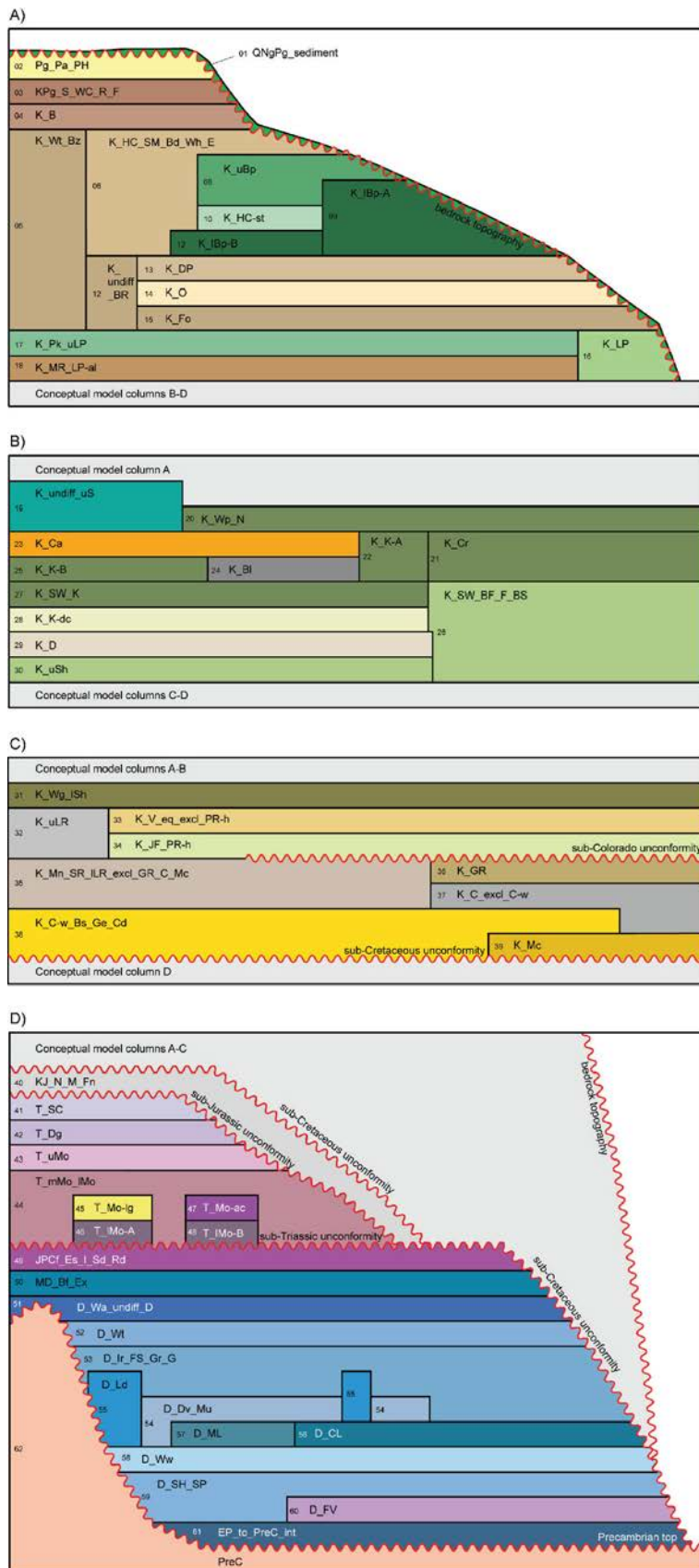
wells are stored within the CRC. These wells range from shallow (tens of metres) to over 5 km deep with an average depth of 1.2 km. We provide users with all of the data that we use to build our models to encourage trust and transparency with our modelling processes. Therefore, it is important that we use data that is available to the public. Newly drilled wells have confidential status for 1 year and then are made publicly accessible unless a request for extension is requested, which rarely occurs.

The majority of seismic data within Alberta is not publicly accessible, and therefore AGS is only able to incorporate a small amount of information from seismic surveys during the construction of our 3D models. However, in a few places we have been able to acquire 2D and 3D seismic to support specific investigations. In most cases, we have been able to incorporate the derivative data from these seismic surveys into our 3D models.

To support shallow geology characterization and modelling, the AGS has access to approximately 430,000 water wells that have been drilled throughout the province. The difficulty with the water well data is that the quality of the information provided in the logs and reports is highly variable. Fortunately, many of the modern oil and gas wells are now being logged to land surface (rather than stopping the log data collection below the surface casing), and is providing another source of data to support characterization and modelling of Alberta's shallow geology (Mei, 2019).

## 3D Modelling Approach

Our approach to 3D geological modelling has been evolving over the past few years in response to the growing demand and diversity of requests for our 3D models. Previously, the geological horizons that we used to build our 3D models were implicit



**Figure 6:** Schematic section showing the **A-C)** Mesozoic and **D)** Paleozoic geological units that are contained within version 2 of our provincial-scale geological model.

geostatistical algorithms, and with only minor modifications to incorporate unique geological characteristics for specific units. Today, we apply a wide range of algorithms depending on the amount of data that is available to model each geological unit, as well as the complexity of the surface being modelled in order to create the most realistic representation possible. Once the 2.5D grids for the top and base of each geological unit have been built, the grids were evaluated for fit with their neighbouring geological units. This can be challenging especially in areas of unconformities, faulting and deformation, or when modelling reefs or other geological units that exhibit significant variability over short distances. Ensuring that the geological surfaces (grids) fit together properly can require additional modification to the grids to make sure that they conform to the available data. These geological surfaces are then combined to create 3D geological models, for which we define the relationship of each surface to the others (conformable, erosional, etc.). This process can take a long time to complete, and therefore we have created workflows for each of our models to make model updates much more efficient. Generating workflows has reduced the amount of time required to rebuild some 3D models from 2 days to less than 2 hours, which represents an 87.5% reduction in time. The workflows have not only proven to save time, but also help reduce the chance of introducing user error by not requiring the modellers to manually recombine grids to build models every time we want to test or update a surface.

The modelling team has been working on developing and updating multiple 3D models within the province as new data becomes available. However this can lead to confusion and duplication of effort in areas where both provincial and sub-models exist. To avoid this, and ensure that we are as efficient as possible with our staff re-



**Figure 7:** Photo of core boxes stored at the Core Research Centre.

sources, we have started the process of combining all of our models into a single, multi-scalar geological model of the entire province.

The team is also building more 3D property models for geological units which require further investigation for resources (e.g., groundwater, oil and gas, or lithium) using a variety of geostatistical algorithms ranging from simple kriging to simulation algorithms such as Gaussian Random Function Simulation (Babakhani et al., 2019; Lyster et al., 2019; Figure 4A).

Another new development in our modelling program is the use of machine learning and deep learning to enhance our modelled results. The team has successfully applied machine learning techniques to predict areas of landslide susceptibility across the province (Map 605; Pawley et al., 2017), and evaluate the geological parameters associated with seismic susceptibility (Pawley et al., 2018). A machine learning approach was also used to leverage a variety of data from multiple sources to create a

much improved bedrock topography for the province that used a randomized tree regression model trained to different subsets of predictors (Atkinson and Pawley, 2019). Although the root-mean-square-error (global measure of uncertainty) of the provincial bedrock topography created with a machine learning method is slightly better (11.8) than the surface interpolated using an Empirical Bayesian Kriging approach (12.8), a key benefit of the machine learning approach is that this methodology allowed terrain-related features to be included in the surface prediction, which resulted in a significant increase in spatial detail and geomorphic plausibility versus other interpolation algorithms that relied only on coordinate information (Figure 8).

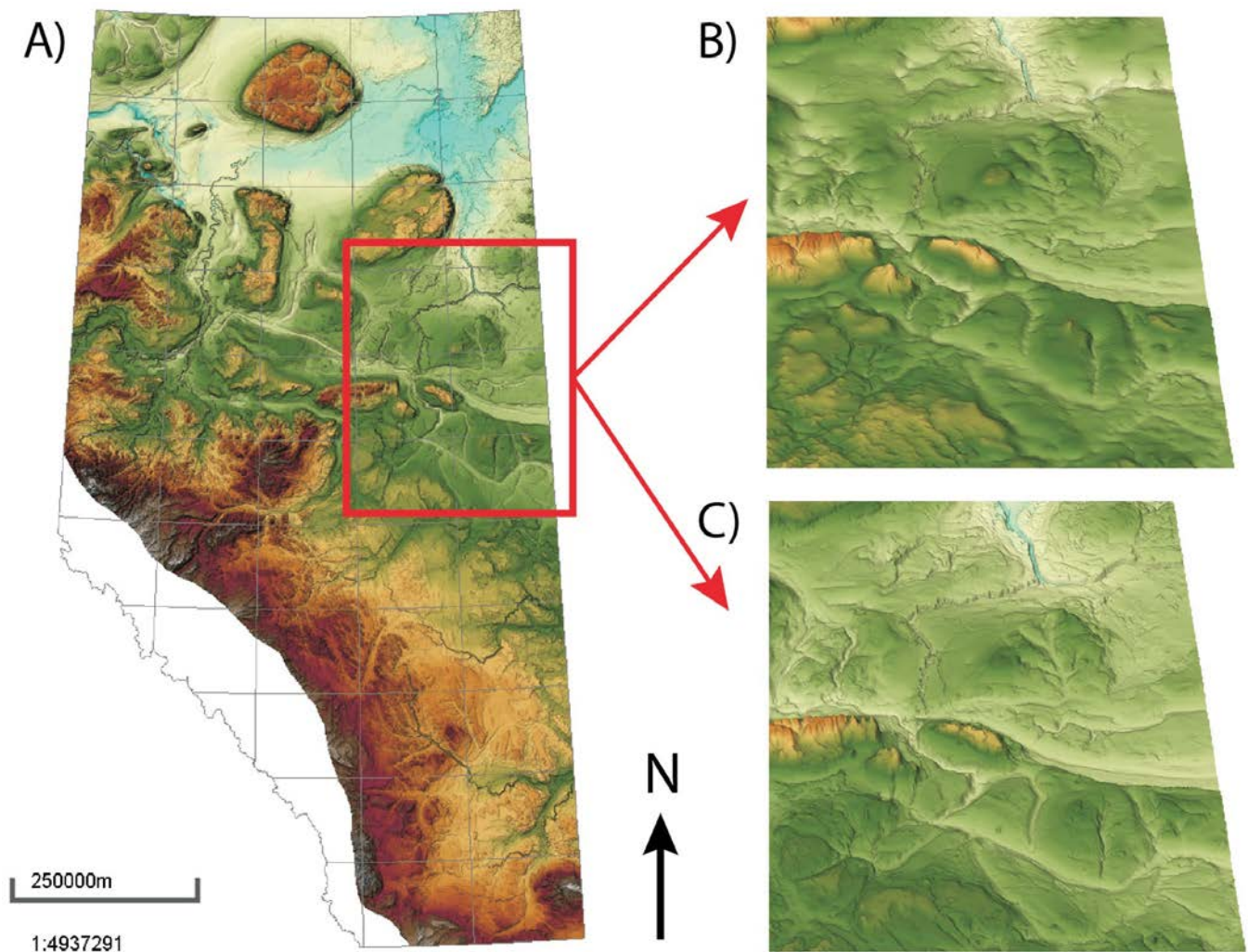
## Clients

Over the past few years we have seen increased uptake and usage of our 3D models to support a wide variety of investigations and applications from

both internal and external clients and stakeholders.

Internally, our models are frequently used to support other teams within the AGS to conduct resource assessments, such as groundwater quantity, quality, and source water protection studies. The models are also shared with a variety of teams within the Alberta Energy Regulator to support science- and evidence-based decision making with respect to regulating and protecting Alberta's energy resources; for example, investigating the occurrence of natural and induced seismic events, and assessing the potential for subsurface gas migration in proximity to potable groundwater resources (see Case Study #2). We are also leveraging our 3D models to help communicate information about the subsurface to our stakeholder groups and the public, which often have quite variable levels of background knowledge, to facilitate understanding and enhance discussion in areas of concern, emerging opportunity, or to support decisions on land- and water-use or economic development.

Our external clients include a variety of groups within the Government of Alberta such as Economic Development and Trade, Alberta Environment and Parks, and Alberta Education, for which we provide information about the geology to highlight Alberta's natural resource potential, support environmental investigations and research, and provide information to enhance education about Alberta's subsurface geology, natural resources and environment. We are also in the process of engaging with science and education centers across Alberta to showcase our 3D models and some emerging technological developments from these models, such as virtual reality (VR) and augmented reality (AR) applications, Minecraft (Figure 9A), 360 videos of Alberta geology in Minecraft, and tactile 3D prints (Figure 9B and C). We have found that communicating information about Alberta's geology and en-



**Figure 8:** **A)** Provincial bedrock topography surface created using a machine learning approach. **B)** shows the previous surface from which the data was interpolated using a kriging algorithm, versus **C)** the improved characterization of surface features such as incised valleys delineated using a machine learning approach.

vironment using emerging and interactive technologies such as VR and AR has increased people’s interest in the information and often leads to questions about how we collect information about the subsurface geology and create these models. Allowing stakeholders to engage and interact with the models and data has shown to increase their interest in the information and enhance our ability to communicate complex geological information to stakeholders with a variety of background knowledge.

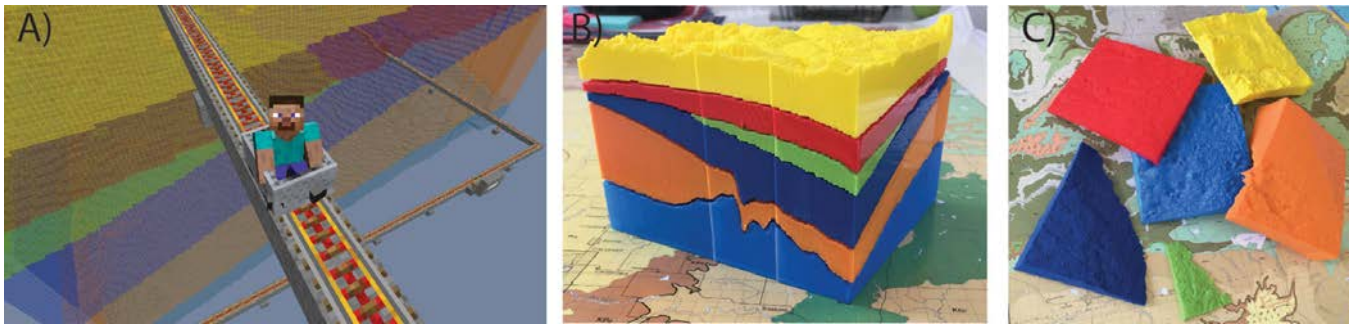
### Recent Jurisdictional-Scale Case Studies Showcasing Application of 3D Models

The case studies presented within this section were selected to highlight the diversity of applications in which our 3D models are being used to meet the needs of various clients and stakeholder groups.

#### ***Case Study #1: Investigating the Occurrence of Induced Seismic Events in West-Central Alberta***

In 2015, the AGS initiated a study to investigate if there was a relationship

between locally occurring seismic events, hydraulic fracturing operations, and subsurface geological features. This investigation required a detailed 3D geological model to be built for a 10,014 km<sup>2</sup> study area using 38,823 picks generated from 16,039 wells to characterize 50 geological units from the ground surface to the top of the Precambrian basement (Figure 10). We had access to some 2D and 3D seismic data which were used to help refine the geological model as well as identify 38 faults within the study area. The 3D model was used to integrate hydraulic fracture wells, seismic events, and faults to assess whether there was a



**Figure 9:** A) Minecraft character in mine cart on tour through our Peace River 3D model, B) 3D print of Peace River model put together and C) taken apart.

geospatial correlation between the location of induced seismic events and certain geological features, such as pre-existing faults or underlying reef structures in close proximity to the Precambrian basement.

The results of this investigation determined that based on the hydraulic fracturing operations in this region to date, there was little direct correlation between the hydraulic fracturing operational parameters and the occurrence of induced seismic events, however a relatively strong correlation was identified between the location of induced events and proximity to a reef-edge immediately underlying the target formation (Corlett et al., 2018). This information was critical to providing decision makers with the scientific data and evidence to support the development of a subsurface order and traffic light protocol to help manage the risk of large-magnitude induced earthquakes in the region (Shipman et al., 2018; Schultz et al., 2016). The 3D model proved to be an important component of this work as it allowed our scientists to efficiently integrate numerous geospatial datasets in order to assess spatial correlations, and it facilitated communication of the investigation results to regulatory decision-makers and the public. This work also provided information on other areas that could also have a higher potential likelihood for induced seismicity based on similarities in the subsurface geological conditions (Pawley et al., 2018).

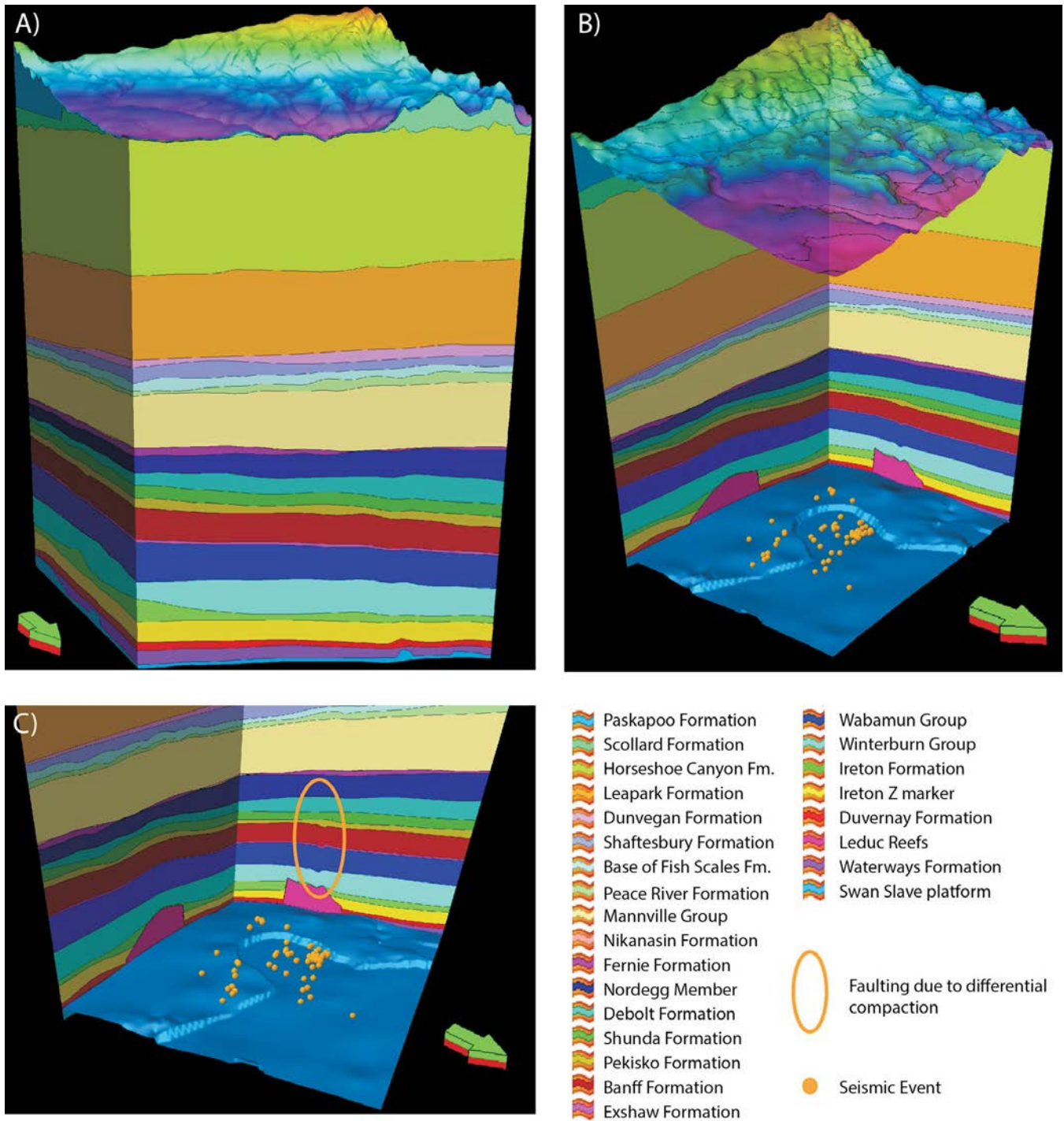
The public was also quite concerned about whether hydraulic fracturing and induced seismic events were having an impact on their source of drinking water. We were able to leverage the 3D model to integrate and display all known water wells, oil and gas wells, faults, and the location of seismic events within a robust scientific 3D geological model to show the public the exact distance and number of confining layers between the target formation and the shallow aquifer (Figure 11). Rather than trying to communicate complex geoscience information and relationships using cartoons and hypothetical drawings, our 3D model enabled us to use visuals that were built using scientific data and evidence to communicate our understanding of the geological setting and seismic events based on the available data.

### ***Case Study #2: Assessing the Impact of Commingled Well Abandonment on Nearby Groundwater Aquifers***

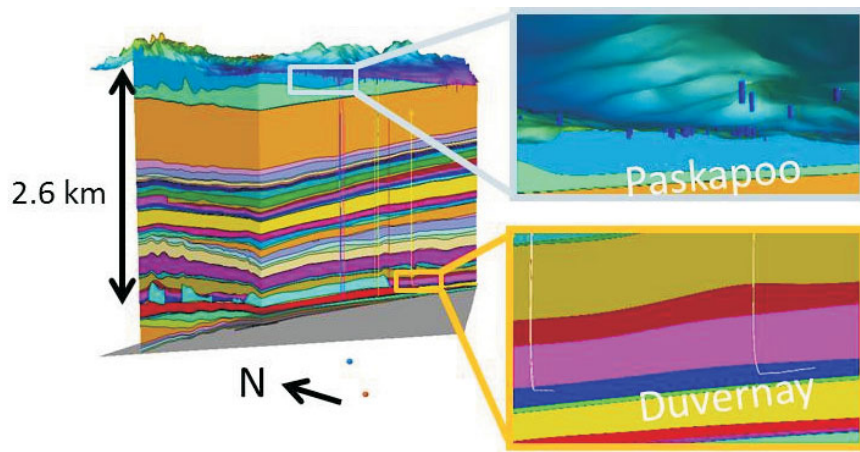
In 2015 a small team consisting of a geologist, geomodeller, hydrogeologist, and groundwater modeller were tasked with doing a 30-day study to investigate the potential impact of well abandonment of 2 large commingled gas plays on a nearby groundwater aquifer. The first step in this project was to create a 3D geological model of the region (88,768 km<sup>2</sup>) that included the pertinent geological units (Figure 12). Thankfully, a number of AGS geologists had previously done field work

and evaluated thousands of well logs in this region; therefore, the team was able to leverage this high quality dataset to build their 3D geological model in just 7 days! With the geological model complete, the team integrated well production data and created a 3D representation of both gas plays, as well as integrated hydrologic and geochemistry data to evaluate and characterize the primary groundwater aquifers. The completed model was tremendously valuable for ensuring efficient and effective communication on the complexity of the geological setting (which included an unconformity, a meteorite impact structure, and 47 offset lineaments), and the geospatial relationship of the aquifers and gas plays to other subject matter experts working on the project. The results of this 30-day project were used to communicate our understanding of the subsurface conditions and areas of varying potential risks to executive decision-makers, industry partners, and stakeholders to gain support for a longer-term, more in-depth study into the risks of gas migration into aquifers in this region (Lemay et al., 2019).

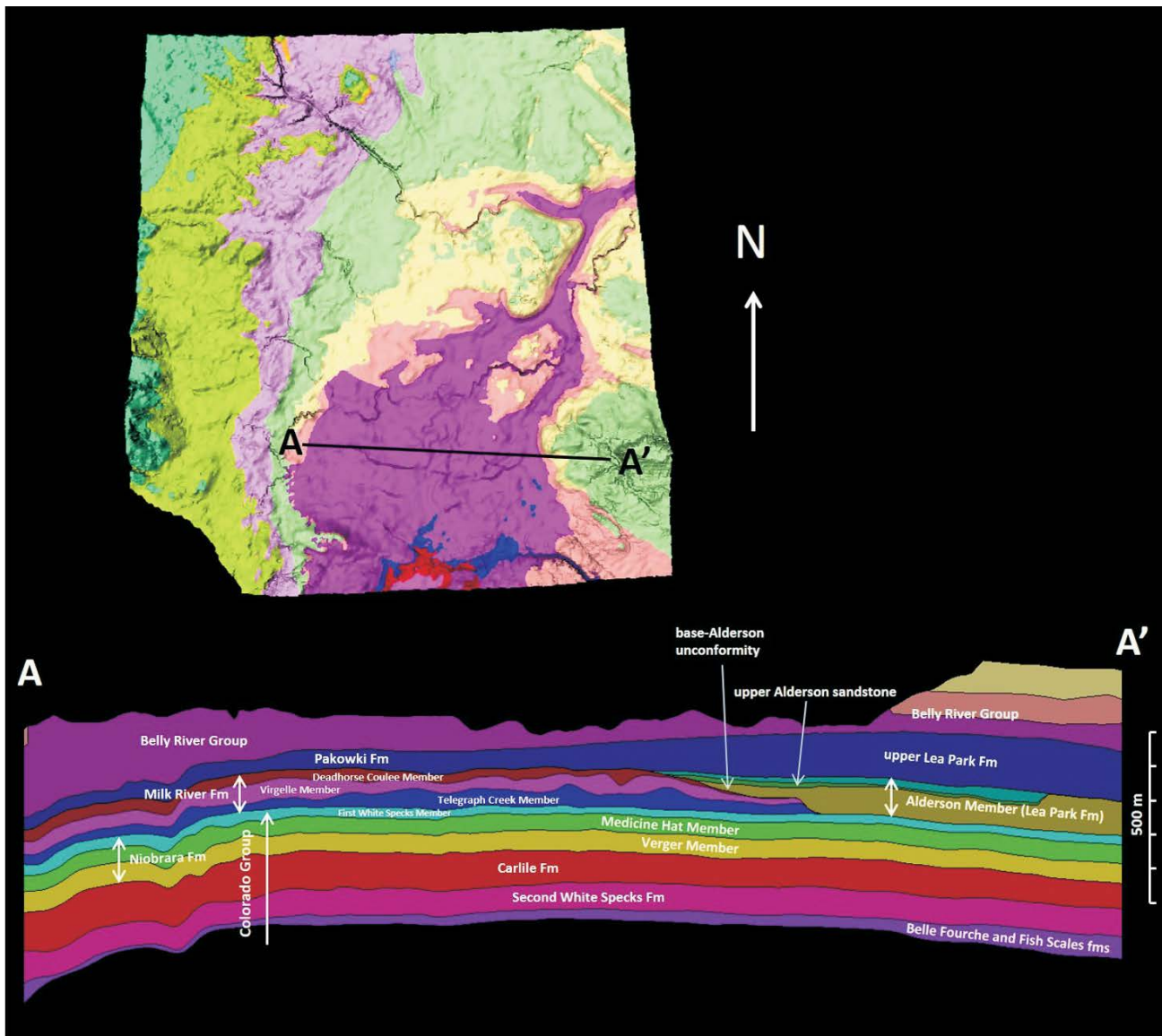
This study highlighted the benefit of having a 3D model of the geology ready for use within a short period of time in order to quickly address an environmental investigation. This was only possible because many of the geological units had already been modelled in 3D, and the data for the other units were stored within a well managed database. It would not have been possible to provide a high-quality



**Figure 10:** **A)** 3D geological model of the Fox Creek study area. **B)** Integration of seismic event data within the model showing the spatial distribution of the events within an embayment of the Swan Hills Formation. **C)** Cross-sections through Fox Creek study area showing the internal complexity of the 3D geological model. Areas of differential compaction faulting are highlighted within the orange circles. The model was created using a grid cell size of 100 m x 100 m, and is shown at a vertical resolution of 50 times.



**Figure 11:** 3D geological model showing the location of wells that were hydraulically fractured in the Duvernay, location of seismic event in the Precambrian basement, and the location of municipal and private water wells.



**Figure 12:** 3D geological model of southern Alberta and cross-section showing the internal stratigraphy. Model was built at a 500 m x 500 m resolution and is shown in a vertical resolution of 50 times.



ity model of the geological setting if we had needed to search for data, QA/QC, and create an entirely new model. Thus, this investigation highlighted the need for proper management of both raw data and 3D models to allow timely response to high-priority investigations.

## Current Challenges

We have recently made a number of organizational changes to support the increased demand for 3D modelling, such as centralizing our modellers on 1 team. However, we are still working to overcome a number of challenges, which are primarily related to hardware, software, data, number of available geomodellers, and complexity of Alberta's geological setting.

Most of our geomodellers are using computers with a minimum of an Intel Xeon 8-12 core 2.9 GHz clock speed processor, 64GB RAM, and Nvidia Quadro K5000 (4GB) GPU. However, our efforts to build higher resolution models in areas that are strategically important and where sufficient data exists, and to ensure they are integrated within the provincial-scale model, often supersedes the computational power of these machines. To ensure that our geomodellers are able to continue with their work, we are in the process of upgrading components (RAM and GPUs) within their computers, and evaluating options to move our geomodelling activities to the cloud environment.

Another challenge is software interoperability and ensuring that our models can be easily and accurately transferred to other software programs. Unfortunately, not having a standardized format for transferring (exporting and importing) 3D models between 3D software packages is a current limitation that we hope will be resolved by the 3D modelling community, including model and software developers. Getting our models into the hands of users can be very chal-

lenging, therefore improving software interoperability and web accessibility would likely result in a significant increase in the uptake and use of 3D geological models.

In Alberta, we are fortunate to have a large amount of subsurface data. However, a significant issue is that duplicate subsets of this data are often stored within multiple datasets in numerous locations within our organization. Thus, we are making great efforts to ensure that the AER, AGS, Government of Alberta, and Albertans have access to a single-source of current, and validated geological data that includes a quality assessment. This leads into another challenge, which is the need to build models at a variety of resolutions that support the multiple needs of various decision-makers. Our solution is to build multi-scalar models where the grid cell resolution is based on both the needs of our stakeholders and the availability and distribution of data. This will allow the models to be higher resolution in areas where it can be supported by sufficient data and is considered strategically valuable by our stakeholders, while maintaining a lower resolution model in areas with fewer data and of lower priority to our stakeholders.

A significant challenge that our modellers are working to overcome is integrating the highly deformed and faulted portion of western Alberta (Rocky Mountains), which covers approximately 78,000 km<sup>2</sup> (Figure 13). The Modelling and Resources Team is currently evaluating the best approach to modelling this region with the data that is currently available.

## Lessons Learned

We have learned so much about the needs and requirements for building and disseminating 3D geological models to support geoscience applications, education, and decision-making. The demand for 3D geological models to support a wide variety of

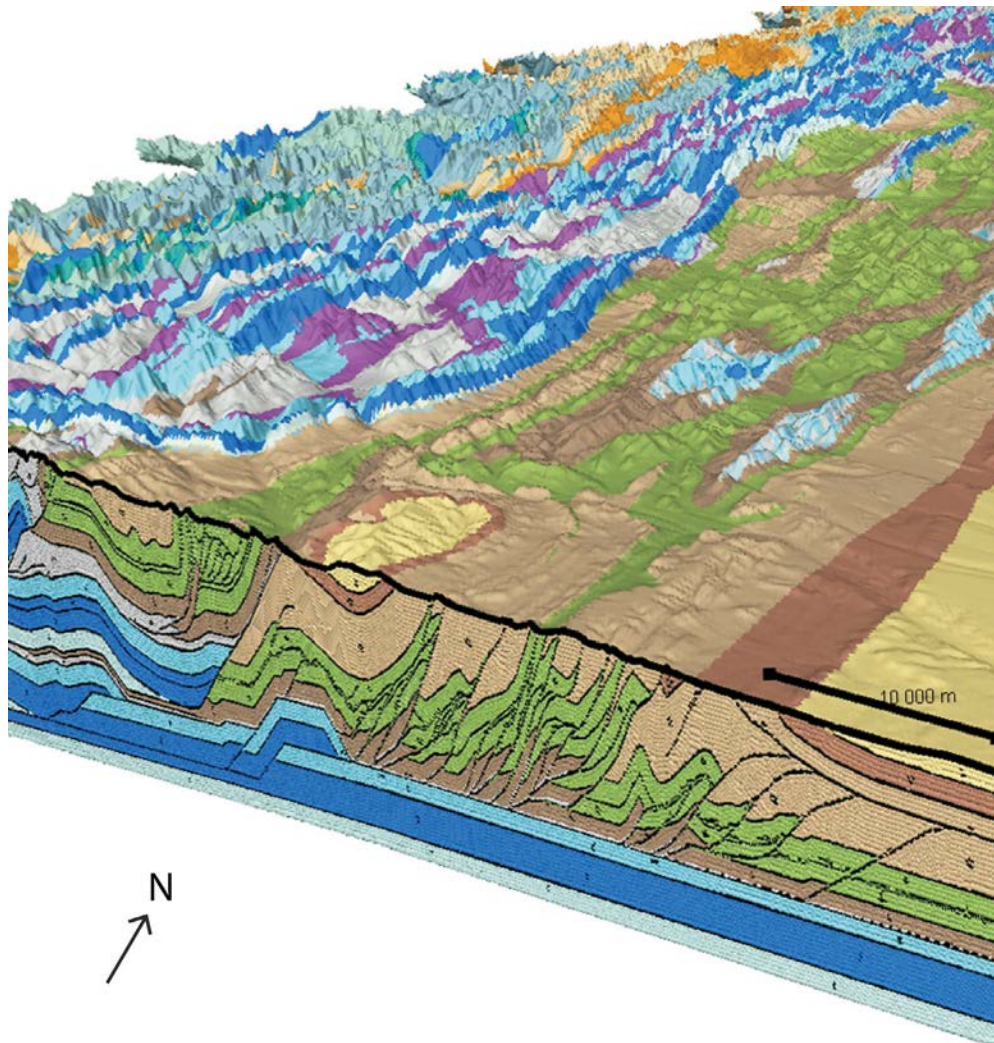
applications continues to grow. We are observing increased occurrences of competing interests in the subsurface (hydrocarbon extraction, mineral exploration, groundwater extraction, management, groundwater protection, waste disposal, carbon capture and sequestration, geothermal energy capture and storage, etc.) that has increasingly led to a necessity for pore-space management within a 3D context.

We use our models to build trust and confidence in regulatory systems to stakeholders, GoA, indigenous groups, and the general public by facilitating transparent communication of compiled geological and environmental issues using tangible graphics and visualizations, which are easy to understand and are based on the scientific evidence.

Creating semi-automated workflows is a major development that has allowed the team to significantly decrease the time and effort required to update our models with new information. Therefore, we are constantly looking for ways to increase the efficiency of our model construction phase.

We characterize the local and global uncertainty for every geological unit within our 3D models. This was initially done to help communicate areas of the model that the geologists and modellers were more or less comfortable (certain) in the model predictions. However, we found that the uncertainty models were also very helpful to identify areas of high uncertainty to management and justify the need to do additional geological work in areas of emerging development or geological sensitivity (Figure 14).

As we incorporate more data within our models, build more sub-models, and update our regional-scale models at a faster rate, we have realized that the necessity for good data and management practices are critical. To en-



**Figure 13:** Cross-section through the Rocky Mountains of Alberta showing the complex and faulted geology of the mountains that the modelling team is working to integrate into our provincial-scale 3D model.

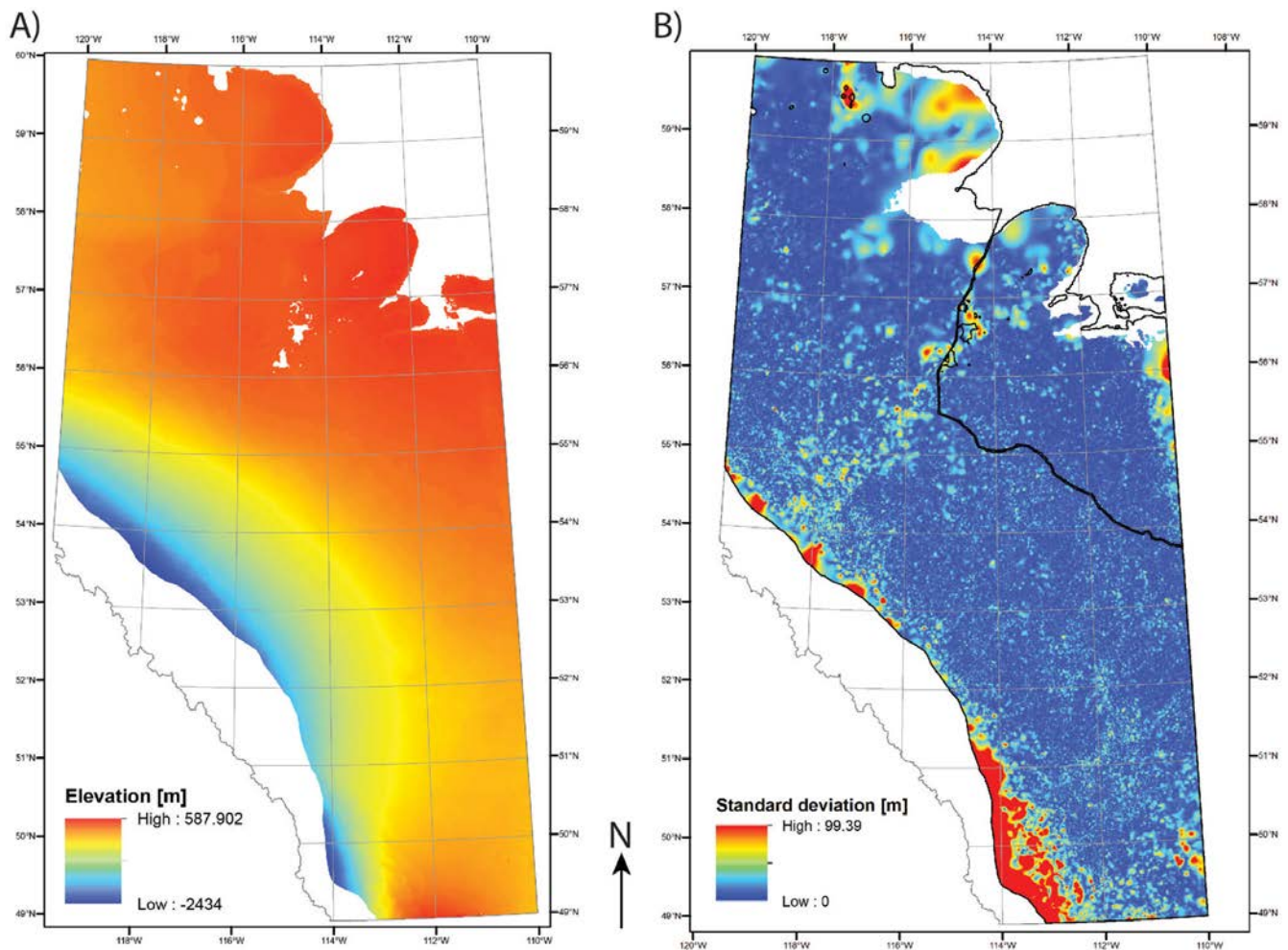
sure transparency in our models, we publish all of the data that is used to build our models. It is also important that our data management system is able to manage all of the points, extents, grids, and model files for all of the models and subsequent update versions. This has required us to develop data and model repositories to store and provide easy accessibility to all of our models and information. To make sure that users are able to assess the suitability of our models and are comfortable using our models will require us to provide informative metadata, which we currently provide in a report document that is published with all of our 3D models.

## Next Steps

The AGS is initiating a number of projects within the Geological Framework Program to advance development and innovation of our 3D models and associated products. Some near-term objectives of the program include integrating all of our local-scale submodels within our large provincial-scale model to create a single multi-scalar source of geological information that can be easily updated as additional information becomes available. The team is also working to improve upon our current modelling methodologies and look for efficiencies within our workflows as we continue to refine our geological

characterization in areas of strategic importance, and integrate surface and subsurface resources. Our plan is to continue to evaluate opportunities to leverage machine learning and deep learning methods to optimize our data and enhance our mapping and modelling products.

Similar to the competing interests in the deeper subsurface, Alberta is also seeing increased interest in creating shallow subsurface models in urban areas to support evaluation of surface water and groundwater interactions and availability, contaminant migration, urban infrastructure (planning new and replacing old), and near-sur-



**Figure 14:** Map showing the **A)** elevation of a surface from the 3D model, and **B)** map of the local uncertainty (represented by the standard deviation) associated with the model prediction of the surface shown in A).

face geohazards such as landslide susceptibility.

In order for our 3D models to be used to support investigations and decision-making both within and outside our organization, we need to ensure that people have easy access to software programs or online applications that can be used to integrate, and evaluate a variety of geospatial data within our 3D geological models. The AGS will be identifying and evaluating open-access software or online options to increase accessibility and applicability of our maps, 3D models, and geospatial data. Another objective for the AGS is to leverage innovative and emerging technology (augmented reality, virtual reality, serious-gaming, and 3D prints) to enhance communication of our geoscience

information and products to stakeholders.

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# Chapter 6: Three-Dimensional Geological Modelling at the Geological Survey of Austria

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## Introduction

This paper gives an overview of 3D geological modelling activities at the Geological Survey of Austria (GBA). Activities started as early as 1991, and for the following 16 years continued in the form of small, isolated studies constructing surfaces – so-called “flying carpets” – in GIS. Due to the project-based nature of these studies, irregular funding and high fluctuation of staff, modelling expertise did not increase significantly until 2010, when a modelling team was established and professional 3D modelling software acquired. Regular funding was secured in 2015.

The focus then shifted from modelling for a specific, applied geoscientific purpose to modelling as a geological exercise in its own right. In cooperation with field geologists, large sedimentary basins were modelled at first, as their horizontal, layer cake structure is easy to map and data such as drillings and seismic sections are abundant. In the central Alps, geological modelling started only in recent years and follows a more conceptual approach, as the tectonic setting is complex and subsurface data scarce. Geological models in both sedimentary basins and Alpine tectonic units are now often used for numerical models to study e.g. groundwater flow or geothermal heat distribution.

Today, the modelling team consists of experts from the Applied Geosciences Department but is closely linked to field geologists and data managers. In the Geological Mapping Department, 3D modelling has yet to be established as a regular tool to map and visualize geology in three dimensions. While other Geological Survey Organizations already deliver 3D models in conjunction with 2D maps, the Geological Mapping Department at GBA still restricts itself to publishing maps, accompanied by a vertical cross-section constructed outside any 3D modelling software. 3D data such as strike and dip measurements of structural surfaces, borehole logs, as well as derived products such as cross-sections and structural maps, do not find their way into a common data storage system. Current plans strive for the establishment of an integral workflow and data management system, which would facilitate the modelling.

## Organizational Structure and Business Model

The Geological Survey of Austria is a federal institution under the Ministry of Education, Science and Research and is organized in three main departments – Geological Mapping, Applied Geosciences and Central Services. Geological Mapping comprises the Departments of Hard Rock Geology, Sedimentary Geology and Paleontology & Stratigraphy, while Applied

Geosciences consists of the Departments of Mineral Resources, Engineering Geology, Hydrogeology & Geothermal Energy, Geochemistry and Geophysics. Central Services include Administration, Geoinformation, IT & GIS, Public Relations and the Library, Archive and Publishing Unit. Approximately 135 persons are employed at GBA, 85 of them as geoscientists.

The geological mapping at GBA forms the basis for the applied geological research on mineral deposits, groundwater, natural hazards and geothermal energy. All activities are grouped into either basic research, applied projects or methodological and experimental development. Data, maps and reports on all aspects of Austrian geology are provided to public administrations, universities, research centers, industry and to the wider public through a geological information service.

The geological modelling team currently consists of five scientists in the Departments of Mineral Resources and Hydrogeology & Geothermal Energy. The team cooperates closely with colleagues performing numerical modelling (groundwater flow, heat flow, geochemical interpolation, geohazard modelling and geophysical inversion) as well as with field geologists and experts on data definition and management.

## Overview of 3D Modelling Activities

3D geological modelling at GBA started with individual projects focusing on applied geoscientific topics such as the distribution of coal seams (Lipiarski and Heinrich, 1992), the thickness of groundwater protecting layers (Moser and Reitner 1998), the structure of Vienna's building ground (Pfleiderer and Hofmann 2001) or the geothermal potential of the Eastern Alps (Götzl et al. 2007). The modelling entailed the interpolation of formation tops from drill logs to create structural maps and was performed in GIS (ArcInfo). Later projects, e.g. on the geothermal use of tunnels (Rockenschaub et al. 2009), applied professional software (GeoModeller) to aid the structural modelling.

In 2010, structural modelling started to be recognized as a geological exercise in its own right, preceding applied geoscientific studies, and GOCAD<sup>®</sup> was introduced as the modelling software of the Geological Survey of Austria. Large sedimentary basins outside the Alps were modelled, such as the Vienna basin (Götzl et al. 2012a), the Styrian basin (Götzl et al. 2012b) and the Molasse basin (Pfleiderer et al. 2016). Recently, work also started to focus on inner-alpine sedimentary basins or valleys (Götzl et al. 2016) and on alpine regions or tectonic units such as the Tauern window (Götzl et al. 2015), the Arzberg region (Götzl et al. 2017), or the Dachstein region (Porpaczy et al. 2017).

In 2017, SKUA<sup>®</sup> was acquired and is now gradually replacing GOCAD<sup>®</sup>. Ongoing modelling work centers on two themes. On one hand, bedrock structures *beneath* sedimentary basins are investigated, e.g. in the greater Vienna area and in the border region between Austria and the Czech Republic. On the other hand, a simplified, pan-Austrian framework model is being developed, displaying major tectonic units down to the Mohorovičić

discontinuity (Pfleiderer et al. 2018). Altogether, 14 models have been finalized and three are in progress as of 2018.

## Resources Allocated to 3D Modelling Activities

3D geological modelling is partly supported by federal funds, which are not tied to any specific project and currently amount to 43,000 Euros per year. These funds cover e.g. the work on the pan-Austrian framework model as well as the development of web-based visualization tools and costs arising from data management or software licenses. Additional funds come from national and international projects that include modelling activities. These projects are financed by European and national funding agencies as well as by government contracts. Summing up the budgets allocated to modelling within these projects, the funds amounted to 36,000 Euros in 2018. In total, the modelling team had a budget of 79,000 Euros available in 2018.

While the federal funds remained constant for the last few years, project money varies from year to year. Nevertheless, the resources are sufficient to cover employment costs for approximately 1.5 persons per year. Hardware costs are paid by in-house budgets and do not impact on either of the two funding sources mentioned above.

## Overview of Regional Geological Setting

Schuster et al. (2014) describe the Austrian geology in an easy-to-read, richly illustrated publication, which can also be viewed online (<https://www.geologie.ac.at/rocky-austria>). Figure 1 gives an overview of the geological / tectonic setting.

The Variscan orogene in the North of the country is composed of granitic and gneissic rocks of the Moldanubian and Moravian

superunits, their Mesozoic cover, which is not exposed at ground level, and of Neogene sedimentary rocks of the Autochthonous Molasse.

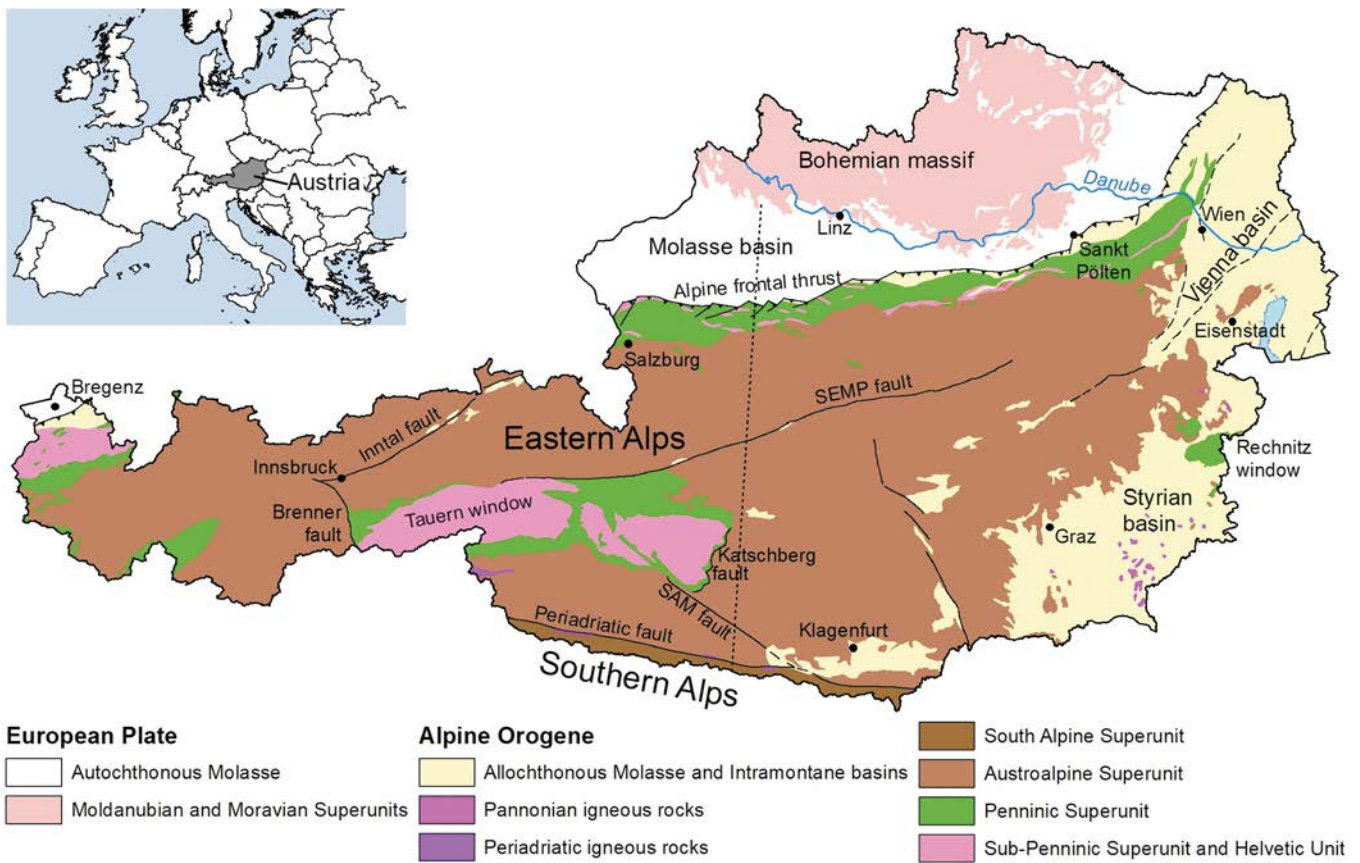
South of the Alpine frontal thrust, the Alpine orogene is characterized by thrust-and-fold tectonics and includes three superunits. These are (a) the South Alpine and Austro Alpine superunits, which are derived from the Adriatic continent, (b) the Penninic superunit, which represents remnants of the Penninic ocean and continental fragments, and (c) the Sub-Penninic Superunit, which is derived from the European continental margin deformed during the Alpine orogeny. In the East, the Styrian and Vienna basins cover the Alpine orogene with Neogene sediments.

The cross-section in Figure 2 illustrates the tectonic structure along a North-South transect across Austria. Further details on the geology of the Eastern Alps are given by Schmid et al. (2004), Froitzheim et al. (2008) and by Schuster and Fritz (2013).

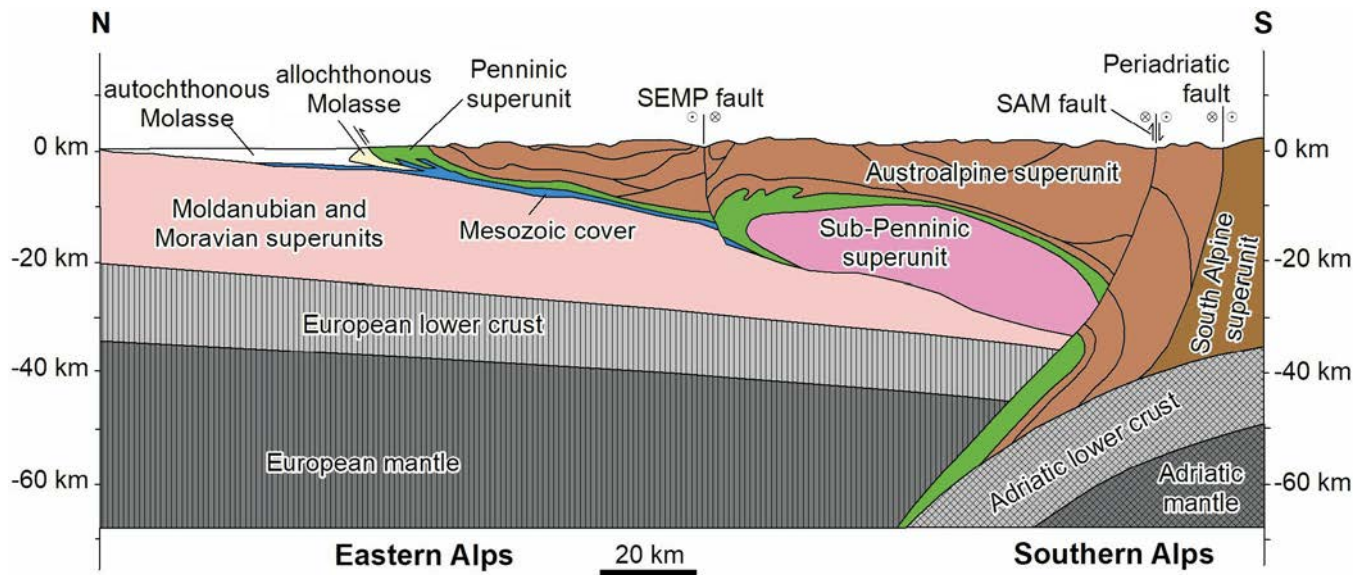
## Data Sources

Data used for 3D geological modelling at the Geological Survey of Austria are listed in Table 1. In Austrian sedimentary basins, most of the data types listed in Table 1 exist with high data densities due to extensive oil and gas exploration. In the central Alps, the only available data are commonly strike and dip measurements as well as outcrop boundaries and fault lines from geological maps. From these, cross-sections are constructed by field geologists using their knowledge gained through mapping together with scarce borehole data.

Borehole data in Austria are currently collected in databases of the federal states and accessible via online web services. Some states offer public, free-of-charge access, others have granted GBA password-protected access. However, the services only provide individual drill logs in image or



**Figure 1:** Geological overview based on the Multi-thematic Map of Austria 1:1,000,000 (Krenmayr, 2017; Hintersberger et al., 2018), modified after Froitzheim et al. (2008).



**Figure 2:** Cross-section through the Eastern Alps after Schuster and Fritz (2013) and Schmid et al. (2004) (for location of cross-section see dotted line in Figure 1).

**Table 1:** Data types and sources used for 3D geological modelling at the Geological Survey of Austria.

Geometric Type	Data	Source
Point data	Strike and dip	Field measurements
	Formation tops	Drill logs
Line data	Outcrop boundaries	Geological and structural maps
	Fault lines	Geological and structural maps
	Layer boundaries	Cross-sections
	Fault sticks	Seismic sections
2D data	Cross-sections	Literature
	Seismic sections	Oil and gas companies
	Structural maps of surfaces	Literature
	Thickness maps of layers	Literature
	Digital ground elevation models	Open government data

table format, and entire data sets cannot be imported directly for modelling purposes. Only two of the nine federal states share their entire borehole databases with GBA.

Data sharing practices of oil and gas companies in Austria are restrictive with respect to drill logs and seismic sections. Although federal laws prescribe that any exploration data are handed to GBA, the data often remain with the companies. However, agreements exist which allow GBA to obtain data for specific projects. Data can then be used internally but publication of raw data is prohibited without prior consent of the data owners, and derived information can only be published if the exact location of the underlying data is concealed. For the interpretation of seismic sections, GBA relies on subcontracted, external consultants, as no internal expertise exists in-house.

Drill logs and cross-sections published in maps and journals of the GBA, are made accessible to the public through data viewers on the website ([https://gisgba.geologie.ac.at/gbaviewer/?url=https://gisgba.geologie.ac.at/ArcGIS/rest/services/AT\\_GBA\\_PROFILE/MapServer](https://gisgba.geologie.ac.at/gbaviewer/?url=https://gisgba.geologie.ac.at/ArcGIS/rest/services/AT_GBA_PROFILE/MapServer)) and through OpenGIS<sup>®</sup> web map services. These services show the location of drill holes and

cross-sections, provide a preview, list metadata on the title, scale and year of publication, and offer a direct link to the library catalogue.

A countrywide, digital elevation model of the ground surface, constructed from airborne laser scan data with a resolution of  $10 \times 10$  m, is available as open government data (<https://www.data.gv.at/katalog/dataset/dgm>).

### 3D Modelling Approach

Currently, the 3D geological modelling team of the Geological Survey of Austria is in a transition phase between explicit and implicit modelling. Some models are still being finalized using GOCAD<sup>®</sup>, constructing surfaces explicitly through discrete smoothing interpolation between points and subsequent manual editing to achieve plausible results with respect to stratigraphic sequence, layer thickness and fault displacements (Pfleiderer et al., 2016). In 2017, SKUA<sup>®</sup> was acquired and the implicit modelling approach adopted. Following the structure and stratigraphy workflow, volumes are now constructed by defining litho-stratigraphic sequences, building fault networks, and then modelling horizons.

For further numerical modelling, results from both modelling approaches are exported in the form of surfaces. The computation of geologic grids, the assignment of petro-physical properties to cells and the simulation of e.g. groundwater or heat flow are performed by other software applications such as FEFLOW or COMSOL Multiphysics<sup>®</sup>.

### Clients

The Geological Survey of Austria does not operate commercially. Geological modelling is carried out within research projects and performed for stakeholders of these projects rather than for clients. Stakeholders include water and mining authorities, engineering departments, spatial planning institutions and geothermal energy providers. As these stakeholders represent end-users of the models and usually have little geological expertise, there is no collaboration between them and GBA as such when creating the models. The modelling team therefore rather seeks collaboration with field geologists who can provide expert knowledge in the area under investigation.

Modelling areas are most often defined by the respective funding bodies, e.g. cross-border model areas by European Regional Programs or



model areas of inner-alpine valleys by provincial governments. For European research projects, stakeholders' interests are commonly collected at the start of the project and regular stakeholder meetings organized to inform about the projects' progress. For projects commissioned by provincial governments, a much closer interaction exists. Before modelling, base data are often provided by these governments, and regions (and layers) of interest are defined in cooperation. During modelling, feedback is given regularly and any problems encountered are discussed together to ensure satisfactory results.

After project completion, and without remaining funds, there is no continuing support of end-users. Once the model has been delivered, they are responsible for storage, maintenance and ongoing use. When new data become available or new interests of users are expressed, updating or refining of existing models is performed within new projects. These cases however have so far rarely occurred.

Apart from the use by stakeholders, finalized models are stored on a GBA server and made accessible to in-house staff. For public use, a web-based viewer was developed which accesses the models stored internally and provides an interface for visualizing 3D models, querying them with virtual drill holes and slicing through them in any browser, without the need for downloading any data or software. This viewer went online in 2016 and quickly became one of the most visited pages of GBA's website (<https://gisgba.geologie.ac.at/3dviewer/>). Currently, it shows only one model, Vienna's underground geology (see Figure 3), but plans are well advanced for a front page allowing the selection of one of the 17 models, before viewing (Figure 4).

To present 3D geological models to the wider public, two types of physical representations were realized, a glass block and a 3D print (Figure 5).

The former was produced by a laser engraving technique, etching 80 million points into a glass block to make surfaces, fault planes and drill holes visible in three dimensions (Schimpf and Wycisk, 2016). The latter was made by sending four simplified, closed surfaces to a 3D printer, which produced four plastic shapes which can be stacked upon each other.

## Recent Jurisdictional-Scale Case Study Showcasing Application of 3D Models

Information on this topic is currently not available.

## Current Challenges

Approximately half of the funds for 3D geological modelling constitute project money. These projects typically last one to three years. To secure continuous funding, and to keep the staff and their experience, new projects have to be acquired constantly. As project money varies from year to year, this can pose a financial challenge. In addition, the modelling team depends to some degree on in-house data managers and programmers whose contribution, time and costs have to be planned well in advance. This sometimes adds an organizational challenge.

Concerning the acquisition of base data, the modelling team often faces significant challenges as ownership of seismic sections and most borehole data lies outside GBA. Only if projects are commissioned by institutions which hold and provide the necessary data, or if data owners are part of the project team, these problems are solved easily.

On the data management side, GBA is still lacking an integral workflow and data management system for 3D modelling. Base data are currently stored in dispersed data bases and modelling products are filed individually. This makes maintenance and update of

data and models difficult. When new base data are collected and previous modelling results are refined in the course of new projects, it becomes a challenge to know which version was based on what subset of data and which layers represent the latest result. Current plans at GBA strive for the establishment of a central data archiving system. Keeping a detailed log file of modelling activities and results in a central system would increase transparency and facilitate modelling, especially for new staff joining the team.

3D data collected by field geologists, such as strike and dip measurements of structural surfaces, do not find their way into a common data storage system. Considerable time is spent to gather and prepare base data before modelling. The Geological Mapping Department has yet to recognize and embrace 3D modelling as regular tool to map and visualize geology. This department's main objective still is to publish 2D maps, accompanied by vertical cross-sections constructed outside any 3D modelling software. The conceptual and organizational challenge here is to promote closer cooperation and to make field geologists and modellers "grow together".

## Lessons Learned

The adoption of an implicit modelling approach with SKUA<sup>®</sup> proved a promising step to facilitate modelling and to introduce a transparent and verifiable workflow. Although introduction of the method and software requires training (and time), the approach will soon fully replace explicit modelling at GBA.

To build bridges between the modelling team and mapping geologists, the software tool Subsurface Analyst (part of the ArcHydro Groundwater suite by Aquaveo) was acquired to prepare and visualize 3D data (cross-sections, logs) in GIS as well as to derive cross-sections from finalized 3D models in GIS. This has led to a

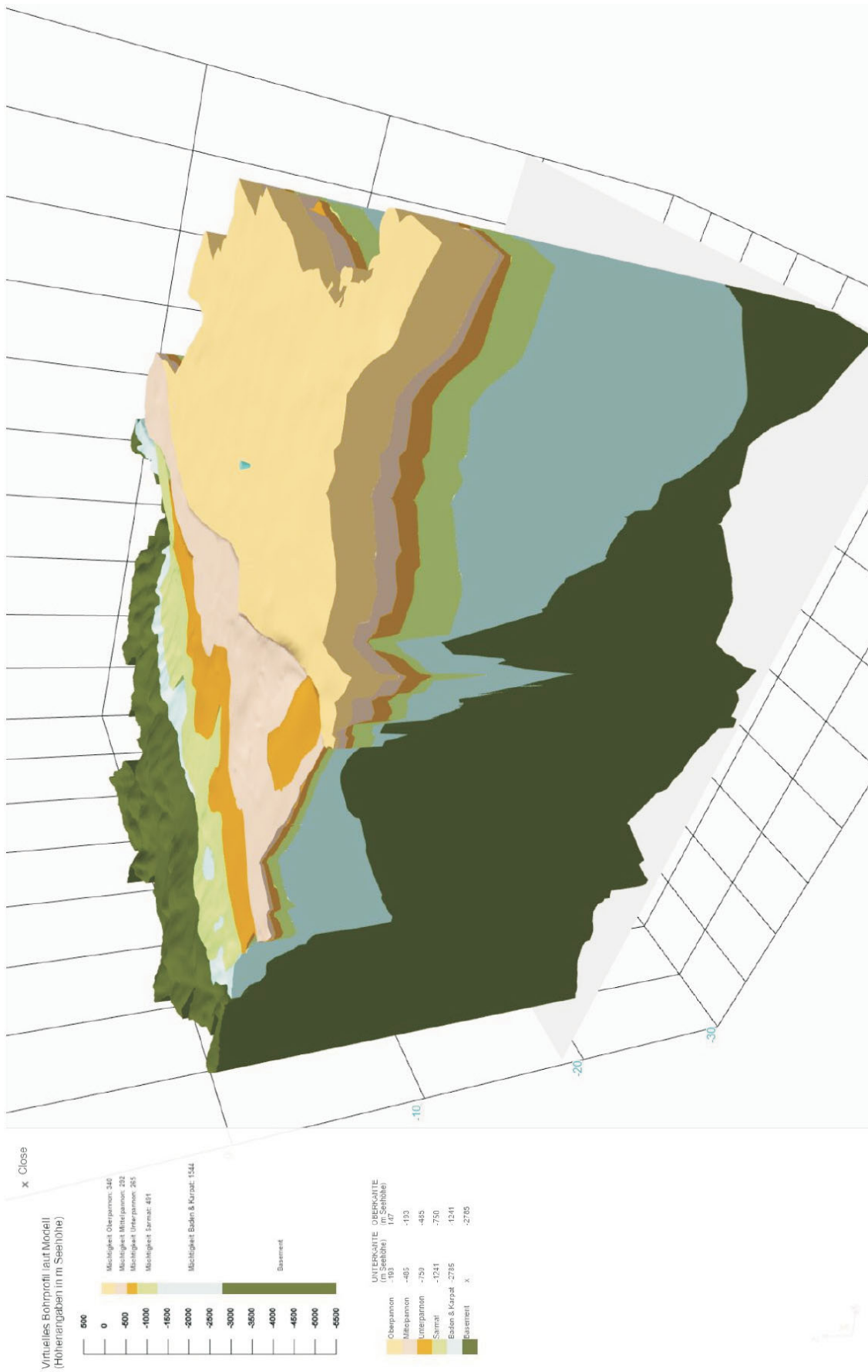
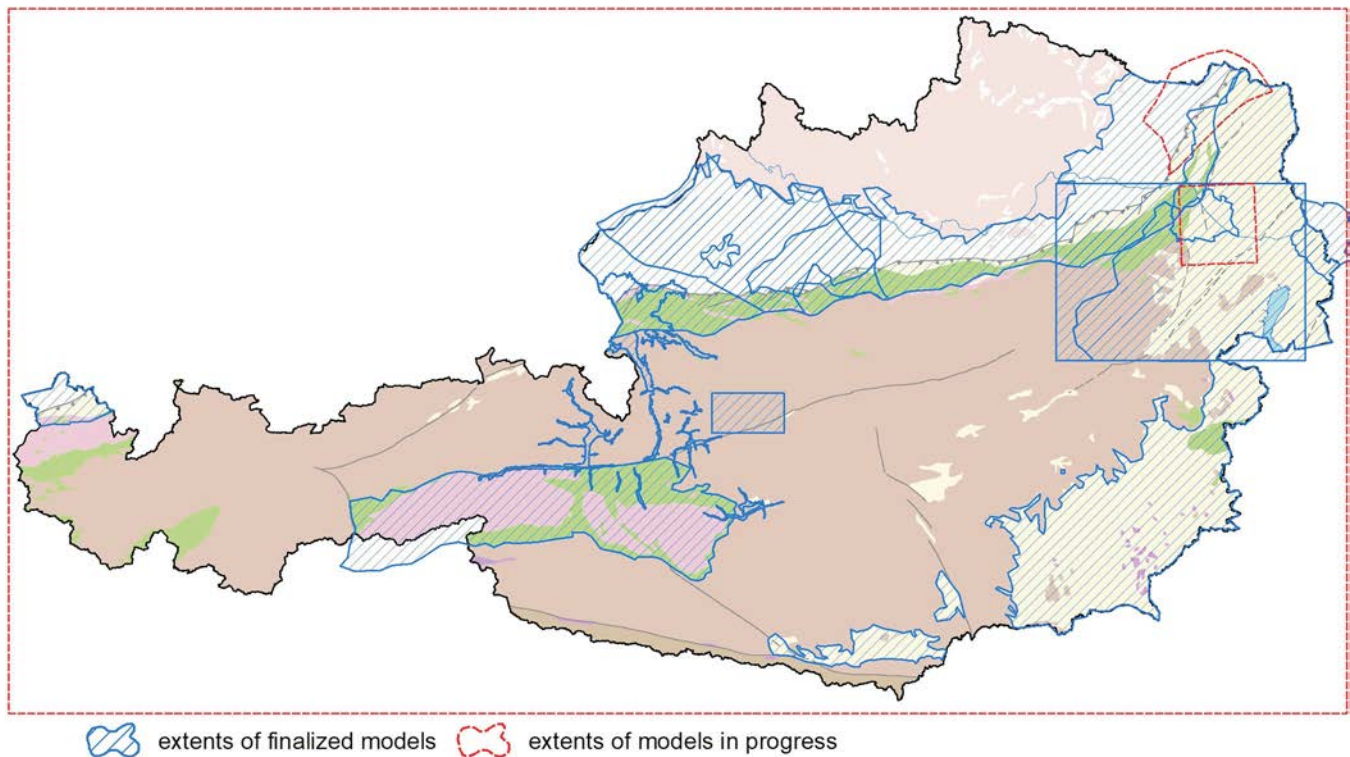


Figure 3: Screenshot of the 3D viewer on the homepage of the Geological Survey of Austria.



**Figure 4:** Extents of 3D geological models constructed at the Geological Survey of Austria.

situation profitable to both sides, as geologists can make cross-sections drawn on paper available to modelers, and modellers can make their models useful to colleagues who work in 2D GIS.

The 3D viewer developed by in-house programmers became a success story not only by showing 3D geological models to the outside world and boosting the popularity of GBA's homepage but also by sharing the source code on GitHub (<https://github.com/geolba/3dViewer>). The Hungarian Geological Survey for example used the code and, with the help of GBA's IT & GIS Department, further developed it to present their geological models.

## Next Steps

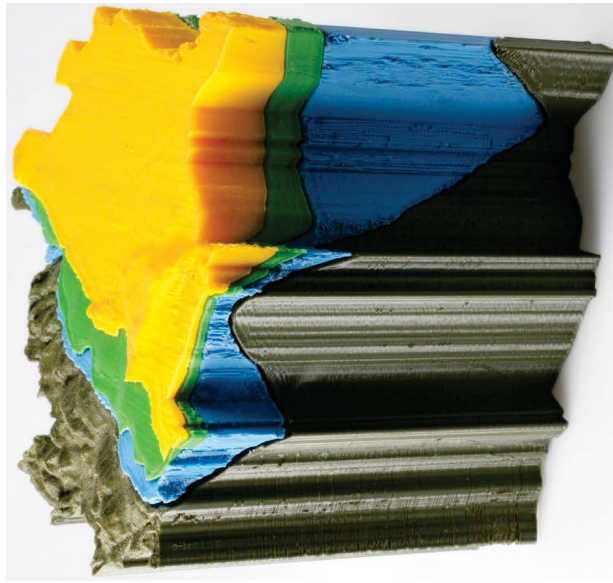
With respect to model creation, current work will produce three new models. Two models focus on the bedrock structures beneath sedimentary basins to aid the use of thermal groundwater and geothermal energy, while a third model will shed light on

Austria's deep tectonic structures on a pan-Austrian framework scale.

Concerning methodology, the explicit approach will be phased out and fully replaced by implicit modelling. In addition, planning and implementation of a central data storage and management system for 3D data and models will be carried out as a future step.

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**Figure 5:** Physical representations of a 3D geological model of Vienna's subsurface: left, glass block (30 x 27 x 12 cm); right, 3D print (15 x 11 x 12 cm).

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# Chapter 7: Advancements in 3D Geological Modelling and Geo-Data Integration at the Bavarian State Geological Survey

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Diepolder, G.W., Pamer, R., and Großmann, J. 2019. Advancements in 3D geological modelling and geo-data integration at the Bavarian State Geological Survey; Chapter 7 in 2019 Synopsis of Current Three-Dimensional Geological Mapping and Modelling in Geological Survey Organizations, K.E. MacCormack, R.C. Berg, H. Kessler, H.A.J. Russell, and L.H. Thorleifson (ed.), Alberta Energy Regulator / Alberta Geological Survey, AER/AGS Special Report 112, p. 48–61.

## Introduction

After more than a decade of producing digital 3D geological models and model applications tailored to the requirements and scope of a wide range of projects, 3D modelling has become a routine business of the Bavarian State Geological Survey. The guiding concepts and workflows have been incrementally improved and practice-approved over years in various geological settings with disparate data background. Presently the advanced workflows are applied in two product lines of distinct scale, objective and scope. Over the course of augmentation, revision, and upgrade of the 3D geo-models it has become clear that safeguarding sustainability in further progression of model building requires a substantial redesign of those parts of the 3D modelling cascade beyond the 3D modelling procedure as such: We identified the increasing importance to further develop an IT- and geo-information infrastructure that supports integrated data storage and barrier-free data availability. Since all principal data for geological model building is held available in digital repositories, peripheral processes like data integration and evaluation, model documentation and version control must be interlinked and tied in on the fly, thus forming an integral part of the modelling procedure. To facilitate knowledge sharing, models and associated data sets must comply with the principles of FAIR data – Findable,

Accessible, Interoperable, and Re-usable, whereby all concepts have to be supported by controlled vocabularies as part of the Semantic Web.

## Organizational Structure and Business Model

Similar to the USA, Canada, and Australia, Germany is a federation of states. For geological mapping, surveying, and data storage this means that each state has a jurisdictional geological survey organization as the legal custodian of the subsurface (cf. Diepolder 2011a).

In charge of the largest German federal state covering a territory of about 70,500 km<sup>2</sup>, the Bavarian State Geological Survey (hereinafter referred to “the Survey”) is among the larger ones of Germany’s 16 State Geological Survey Organizations (Staatliche Geologische Dienste, SGD). Dating back to 1850 and reorganized several times, the Survey, since 2007, is a department of the Bavarian Environment Agency (LfU), a subordinate authority to the Bavarian State Ministry for the Environment and Consumer Protection (StMUV). Unlike some other German SGD the Survey does not incorporate the Mining or Water Administration Authorities. As the central authority providing geoscientific advice to the Bavarian government, e.g. the Mining Authority and geo-energy regulator, it is tasked to acquire, store, process and synthesize geoscientific data, and to

make this data available for economic and societal needs.

Basically, LfU overall is financed by the StMUV. A minor support for the Survey is provided by the Bavarian State Ministry of Economic Affairs, Regional Development and Energy (StMWi) specifically for programs related to raw materials and geothermal issues. Many projects, especially cross-border projects with neighboring countries or in a pan-European context are acknowledged by co-funding of the European Union or its regional funding schemes. Entirely run by public money the Survey is a public sector, non-profit organization and not entitled to accept private commissions or to compete otherwise with consultants and planners of the private sector. Accordingly, and pursuant to the Environmental Information Law, product distribution follows non-commercial principles as well. Digital products retrievable via web map and information services or the online shop are free of charge for non-commercial use and printed material against payment of only a nominal fee. However, data privacy requirements imply that not all products are freely available.

## Overview of 3D Modelling Activities

All multi-layer 3D models produced so far or presently under development pertain to the Scarpland (Cuesta Region) and the Molasse Basin that alto-

gether cover more than two-thirds of the Bavarian territory (Figure 1). The intensely folded and thrust Alps as well as the terrains of exposed crystalline basement are only included in their marginal areas and, due to the complex internal structure, are just captured as undivided and unstructured bodies. Kept generic and not tailored to any specific application, all 3D geo-models in their original version are lithostratigraphic layer models featuring the general geological setup and characteristics. However, through conversion into volume models and specific parameterization they can be made useful for many geoscientific and cross-cutting applications.

The first 3D geological framework models have been built in the 2000s, conceived to supplement thematic map sets of holistic mapping campaigns addressing administrative units (Regionen). These first exercises in digitally stacking lithostratigraphic layers for making clear the spatial relationship of the subsurface layers and the principal faults have been elaborated in a regional scale corresponding to the 1:100,000 scale thematic maps of the holistic mapping. For a concise synopsis of the early years of 3D modelling at the Survey see Pamer and Diepolder (2010). With new regions added, adjusted to an overarching concept evolved over time and refined with substantial new information coming up, the 1:100,000 scale models are now integral parts of the LOD2 framework model product line of the Survey. The LOD2 geo-models provide the framework to integrate smaller, more detailed models and form the nuclei for incrementally setting up a statewide 3-dimensional overview – still waiting for capacity increase of computer power to be fully implementable. The first step towards an all-encompassing statewide model is the harmonization and integration of various 3D geo-models into a supra-regional, cross-border

Molasse Basin model (cf. Figures 1 and 2).

Local to regional scale detailed models, which focus on lithostratigraphic and structural features for characterizing the near-surface sedimentary sequence and the shallow bedrock, are generally considered to be of most use in urban planning and development (Kessler et al. 2005). At the Survey, such 3D models (Figure 3) are developed for specific agglomeration areas and growth axes surrounds (LOD3 in Figure 2), based on a resolution equivalent of about 1:25,000 scale. Aimed at a stratigraphic subdivision to group or formation level these geo-models synthesize all available geoscience information from boreholes, geological maps, cross-sections as well as contour plans and, where implemented, the interpretations of ground- and air-borne geophysical surveys. This accumulated knowledge underpins geological advice for construction and engineering projects, draws attention to potential hazards and impacts, in particular regarding groundwater and foundation conditions, and helps to unlock the subsurface potential e.g. with respect to geothermal use (Figure 4). At present, this second product line of the Survey consist of overall 23 mostly interconnected 1:25,000 scale map grid tile 3D models of 8 principal agglomeration areas and environs (Figure 2).

The largest challenge of 3D modelling activities the Survey is presently facing includes compiling a consistent structural model of the Bavarian part of the Molasse Basin (cf. Figures 1 and 2). Representing an important reservoir for drinking water production but also hosting central Europe's most prolific hydrothermal aquifer that presently features more than 25 geothermal installations >3,000 m in depth, it also holds a high potential for underground storage and economic residual quantities of oil and gas. Thus, the Molasse Basin is a paramount example for the imperative

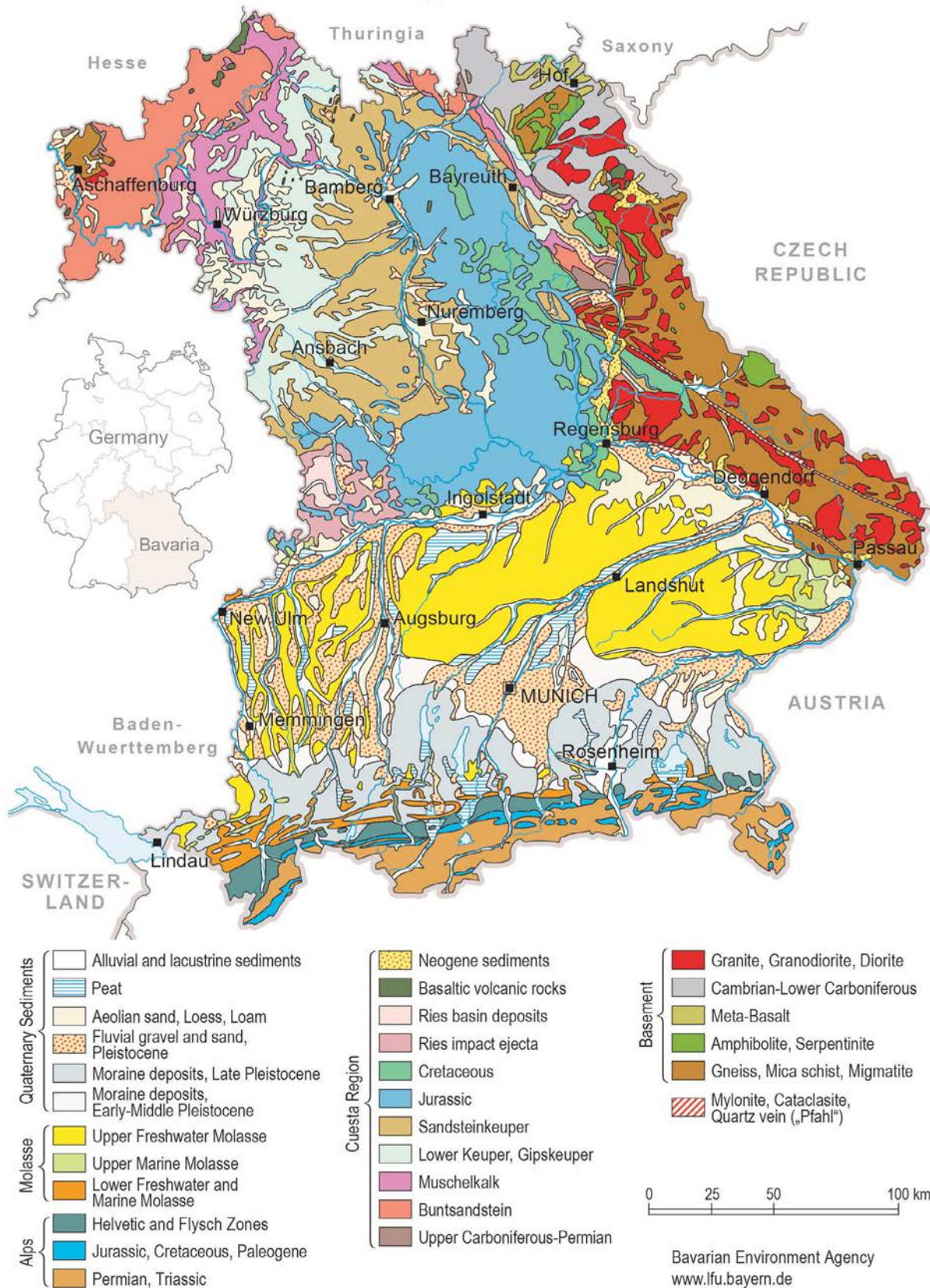
necessity of an unbiased and holistic subsurface management system.

Aimed at assisting the regulators in their task to avoid use conflicts and to ensure resource efficiency, the Bavarian Molasse Basin has been the principal focus of 3D modelling activities for almost a decade, resulting in a vast variety of regional and sub-regional 3D geo-models of varying coverage, resolution and depth (Figure 2). The effort of integrating these segments, filling the gaps in between, adding marginal areas, and ultimately compiling one homogenous and seamless “super”-model, is hampered by various obstacles. They list an uneven distribution of baseline data, different modelling approaches – borehole-based for shallow, seismic-focused for deep portions of the basin – and the lithostratigraphic disparity with neighboring territories. Furthermore, the ongoing boom in geothermal exploration continuously generates new state-of-the-art datasets (3D seismic surveys, deep well downhole data) that make a rigorous revision of the legacy models inescapable.

The first 3D geo-models addressing parts of the Molasse Basin have been implemented in the marginal (Reg. 10) and shallow (Reg. 13) parts of the basin (cf. Figure 2), geared to hydrogeological applications, and are entirely based on borehole evidence or contour plans derived thereof. Modelling the deeper portions of the basin (down to about 4 km depth) started in 2010, focused on the hotspots of geothermal exploration at that time (5-Seen, München; cf. Figure 2). These models are based on a selection of digitized seismic sections and a few “golden spike” downhole data.

The transnational project GeoMol (Diepolder et al. 2014, GeoMol Team 2015, see also <http://www.geomol.eu>), running from 2012 to 2015, was spearheading the Survey's efforts to put all 3D geo-models of the Molasse Basin in a common context. Aimed at the cross-border assessment of the

# Geology of Bavaria



**Figure 1.** Geological overview of Bavaria portraying the principal geological units and the location of Bavaria within Germany (inset). See section ‘Overview of regional geological setting’ for discussion.



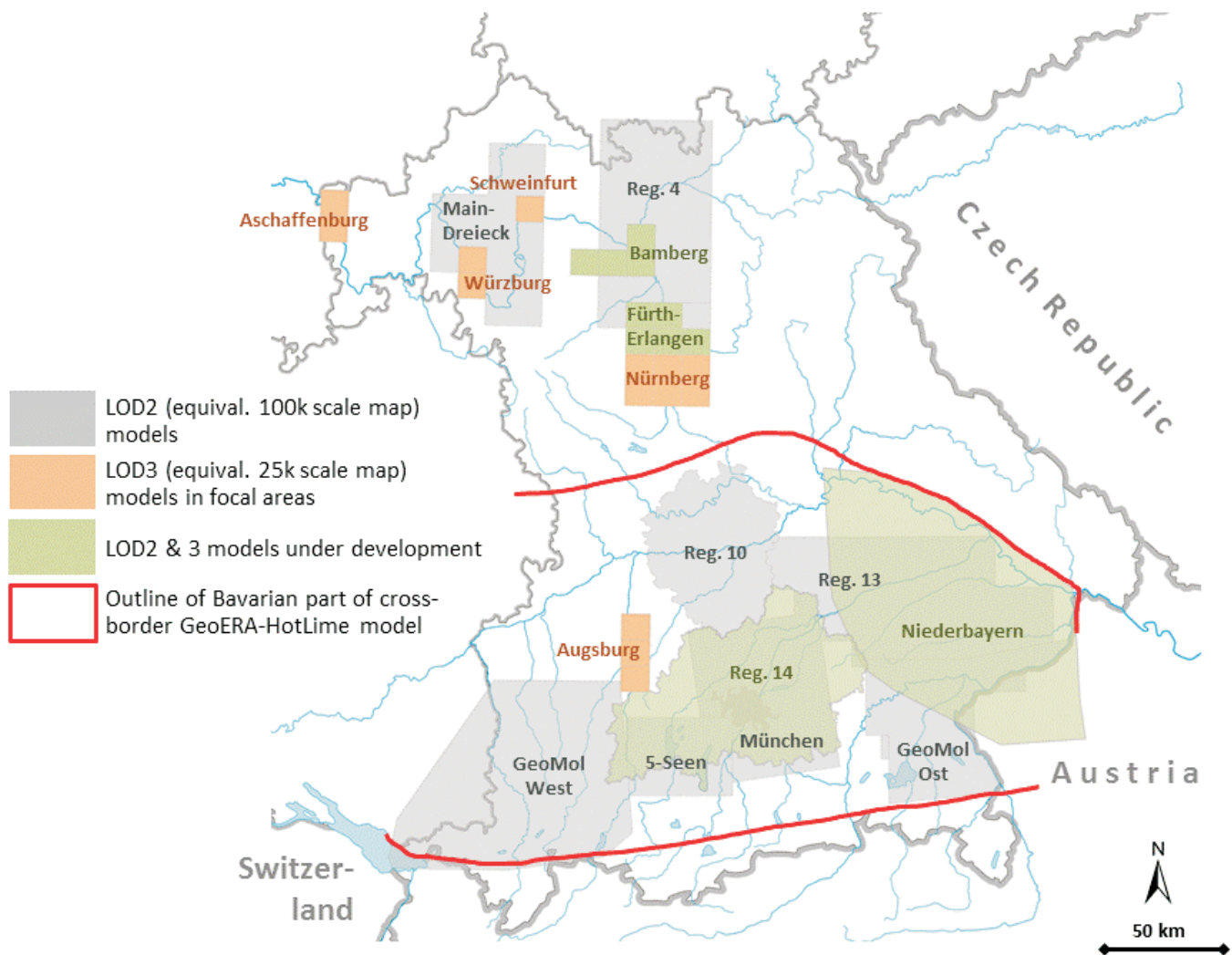
subsurface potential for various utilizations based on common criteria, a 3D geological model was set up to elucidate the structural controls of the resources. Funded by the European Union’s Alpine Space Programme, the project offered the opportunity to substantially enlarge the areal backdrop and to develop a harmonized 3D model of the entire Molasse Basin including a cross-border concerted lithostratigraphic subdivision.

A major challenge in 3D modelling of basin structures that reach down to more than 5 km, is the availability of data with an adequate distribution and resolution to address issues properly.

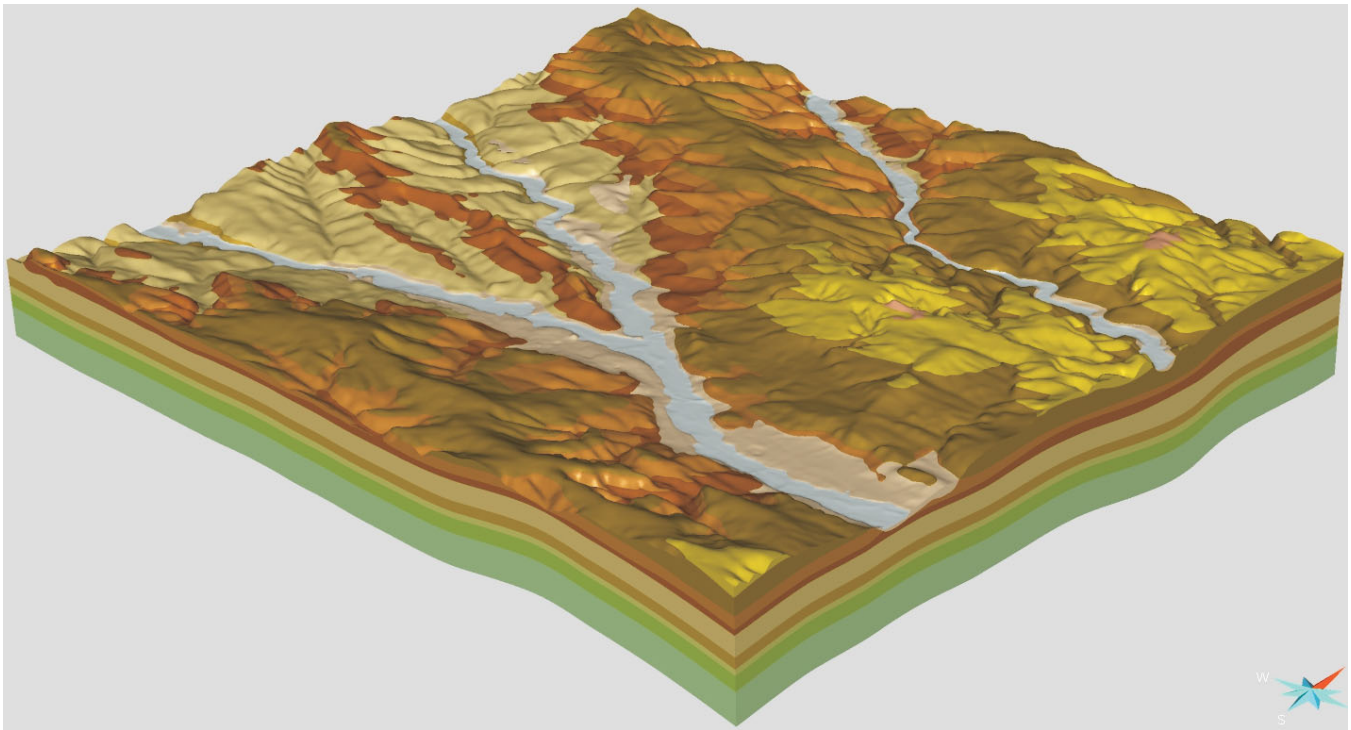
Principal baseline data for GeoMol’s 3D geological models have been seismic data, scattered and clustered deep downhole data (Figure 5) – both originating primarily from the 1960s and 1970s hydrocarbon exploration and production and secondarily from the investigations for geothermal installations that commenced in the early 2000s – and contour line drawings, all held together by the conceptual model of the Molasse Basin evolution. The use of different baseline data originating from multiple sources and various dates of origin imperatively required data harmonization from the very beginning of the model building workflow starting with the

selection and preparation of the input data. Applying consistent methods and common parameters for model preparation and fault assessment (Figure 6), the integration of data in time domain and information in depth domain imposed particular requirements on the velocity models employed and the modelling workflow that requires toggling back and forth between depth and time domains depending on the point of departure (Maesano and the Italian GeoMol Team 2014).

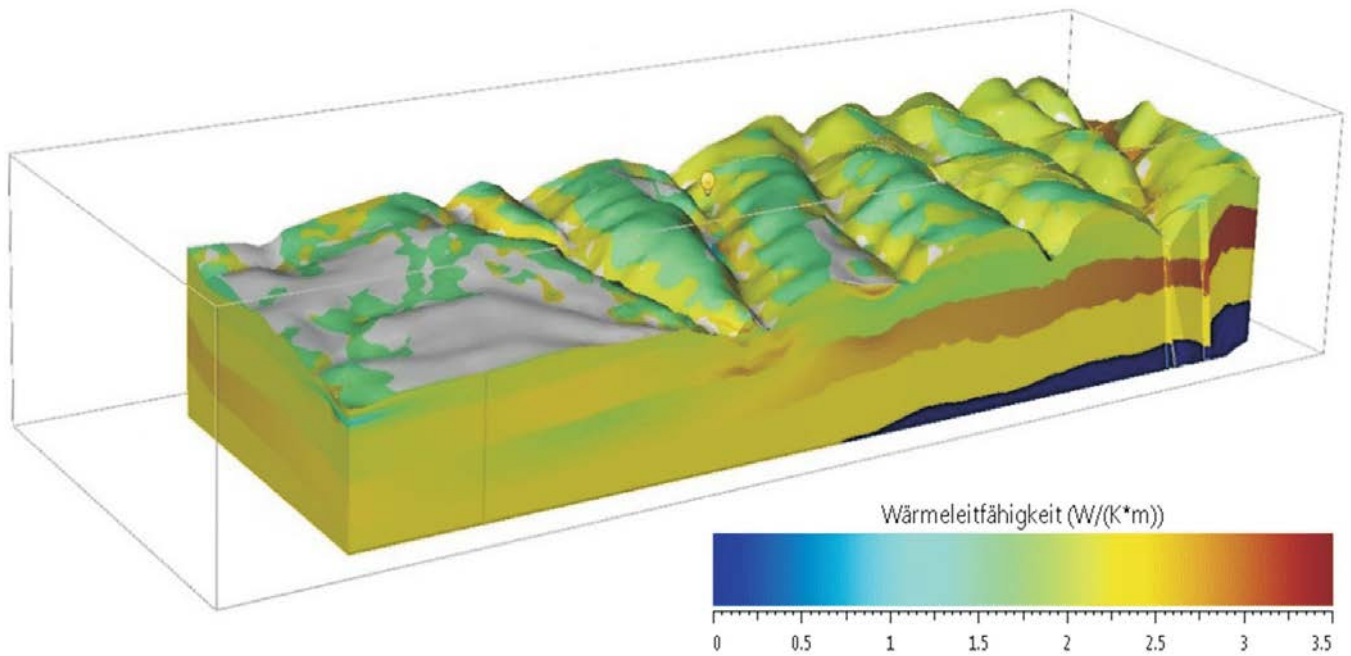
Data preparation and the 3D modelling workflows applied in GeoMol are described in detail in the GeoMol



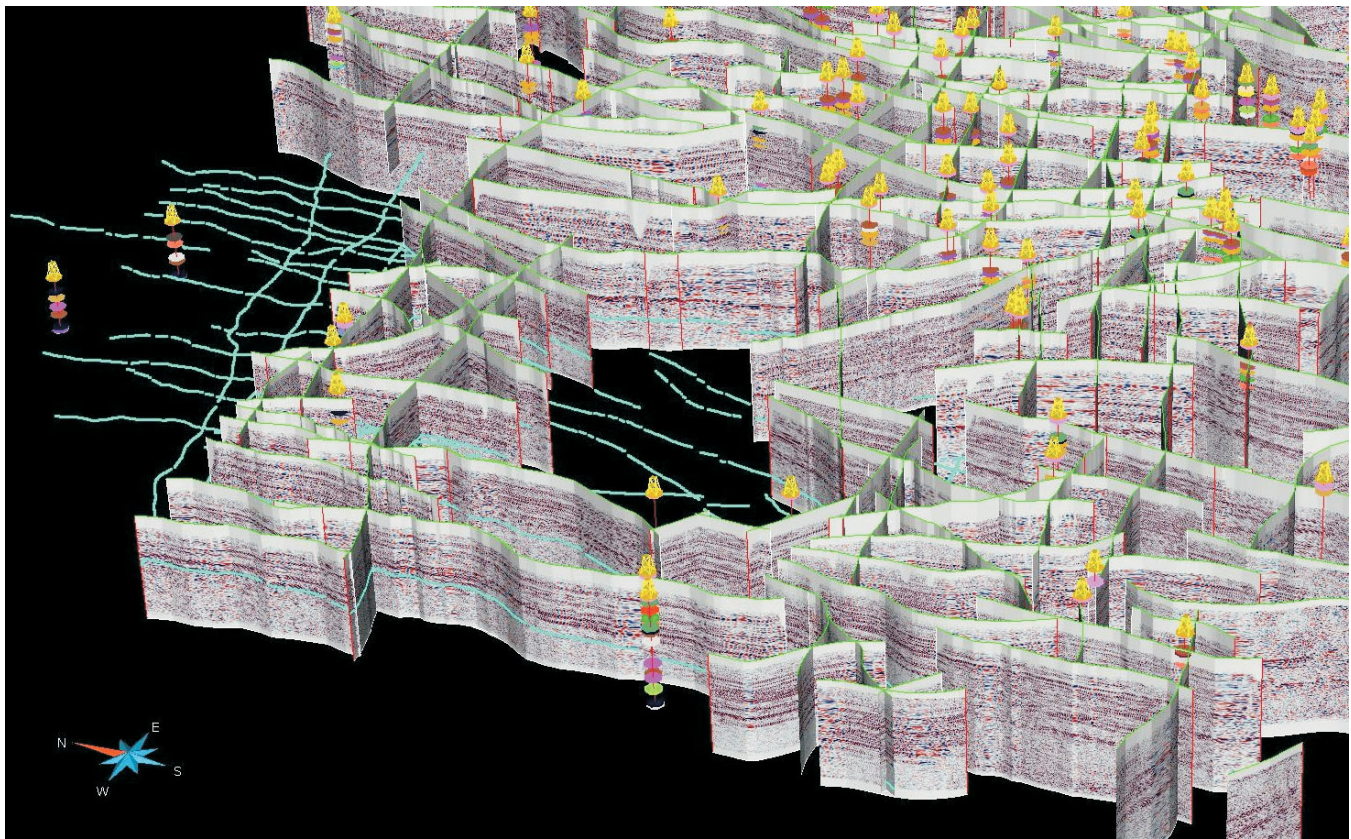
**Figure 2.** Outline of the model areas of the 3D geological models prepared at the Bavarian Survey. All LOD3 models and “Niederbayern” are prepared within the BAB (Subsurface Atlas of Bavaria) project. Modelling of “Reg. 14” is commissioned to the Technical University of Munich and comprises a shallow LOD3 part and a deeper LOD2 part connected to the deep models “München” and “5-Seen”. See text for details.



**Figure 3.** 1:25,000 scale map grid Burgebrach tile (part of Bamberg focal area) as an example for a LOD3 geological model. In addition to 11 lithostratigraphic units of the Keuper group (upper part of the Germanic Trias) Pleistocene fluvial terraces and Holocene valley fill are differentiated. Detailed structural modelling revealed that the faults inferred in bordering areas are just flexures of the strata.



**Figure 4.** Example of a LOD3 model application: Cut-out of the Schweinfurt 1:25,000 scale geological model parameterized with the rock specific heat conductivity. Such heat conductivity distribution models are the basis for assessing the downhole heat exchanger efficiency with regard to rock specific properties as provided in [http://www.umweltatlas.bayern.de/mapapps/resources/apps/lfu\\_angewandte\\_geologie\\_ftz/](http://www.umweltatlas.bayern.de/mapapps/resources/apps/lfu_angewandte_geologie_ftz/).



**Figure 5.** Screenshot of the larger Munich area GoCAD<sup>®</sup> scene while GeoMol model preparation featuring an exceptionally dense seismic network and borehole information. Borehole markers were used to derive regionalized depth constraints for areas with no significant seismic signature or without stratigraphic control and to overall calibrate the scene. The cyan lines trace the top of the Upper Jurassic hydrothermal aquifer, one of the principal target horizons of modelling (from GeoMol Team 2015).

Project Report (GeoMol Team 2015, <http://www.geomol.eu/report/>).

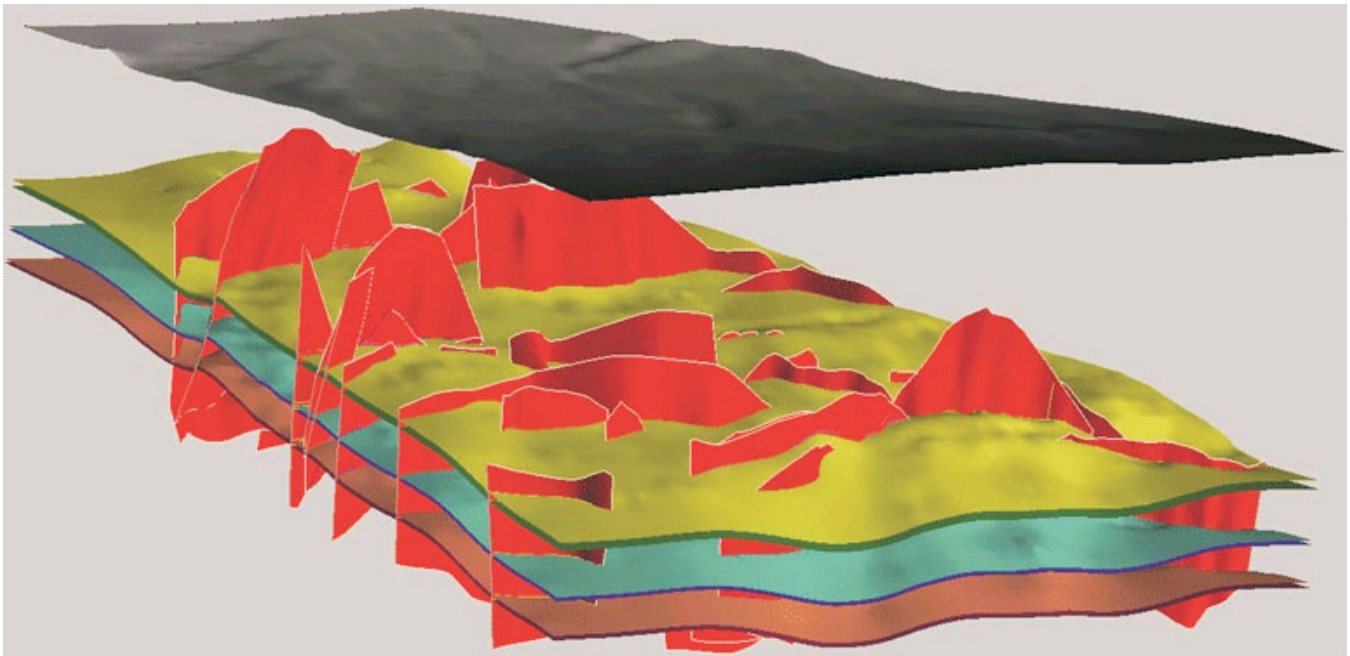
Undoubtedly successful with respect to knowledge exchange and fine tuning of methods and workflows – from baseline data processing, specifically seismic interpretation, to distributed organized model delivery (GeoMol Team 2015) – the project had to exclude “Niederbayern” (cf. Figure 2) due to the limitations of the Alpine Space Cooperation Area and revealed fundamental constraints with respect to cross-border lithostratigraphic harmonization. Nevertheless, for the Bavarian territory it delivered two detailed cross-border harmonized geo-models of pilot areas (GeoMol West and GeoMol Ost in Figure 2) and a downscaled framework model of (al-

most) the entire Molasse Basin, roughly 1,000 km in length, from Grenoble in France to Vienna in Austria.

Methodologies approved in and lessons learned from the GeoMol project are the guidelines for the current efforts that finally include the preparation of an all-encompassing geo-model of the Bavarian Molasse Basin and its connected terrains. This endeavor interlaces two projects: the Survey-internal project Infra3D and HotLime, one of 15 projects under the umbrella of GeoERA (European Research Area on Applied Geosciences, <http://geoera.eu/>) that has received funding from the European Union’s Horizon 2020 research and innovation programme.

Infra3D started in 2015 and is geared towards further systemization of 3D modelling processes and setting up an IT- and geoinformation infrastructure that supports data integration and model documentation. (Infra3D’s data integration efforts are further discussed in the “Data” section below.) Implementation and evaluation of these processes is most suitable controlled in real case testbeds featuring a wide range of baseline data and different approaches of integration of downhole data with seismic data. Consequently, the revision and aggregation of the Molasse Basin has been chosen for Infra3D testbed. With this, Infra3D comprises topics that comply with the objectives and scope that have been prioritized in the GeoERA call, specifically the Geo-energy and

*All tradenames ( /<sup>®</sup>) in this paper are marked with a postposed °. This use of tradenames is for descriptive purposes only and does not imply endorsement.*



**Figure 6.** 2,000 km<sup>2</sup> tile of GeoMol Ost pilot area model, vertical extension ca. 5,400 m, view from SW. Depicted are six Mesozoic layer surfaces of the south dipping footwall sedimentary sequence and the fault network reflecting the complex tectonic evolution of the basin. Tertiary units are omitted for clarity. Modelling blind faults was a principal objective of GeoMol as these intrinsically control resources through forming hydrothermal fluids conduits, structural traps and reservoir compartmentalizing offsets.

Information Platform Themes. Thus it appeared obvious to propose the relevant parts of present work of the Survey as contributions in-kind to GeoERA projects and put it in a wider European context.

Core of the 3D modelling activities of the Survey in GeoERA is the HotLime project (<http://geoera.eu/projects/hotlime6/>), geared towards identifying the generic structural controls of hydrothermal plays in deep carbonate formations, through the comparison of geological situations in 10 case study areas across Europe. Similar to GeoMol but in a larger area including also the outcrop and subcrop (recharge area) of the Upper Jurassic hydrothermal aquifer, the capture of the structural inventory is the gist of the German-Austrian Molasse Basin cross-border study area (red outline in Figure 2). In HotLime, running from July 2018 to June 2021, all existing geo-models within the HotLime areal coverage are refined, extended to close the gaps, supplemented with missing ar-

eas and finally intertwined to form a single harmonized model. To this end an improved velocity model for time-depth conversation is applied. Model integration also includes segments where new approaches have been tested in areas with an inadequate coverage of seismic and downhole data, like the LOD2 model “Niederbayern” (Figure 7), prepared within the generic scope of the BAB (Subsurface Atlas of Bavaria) project.

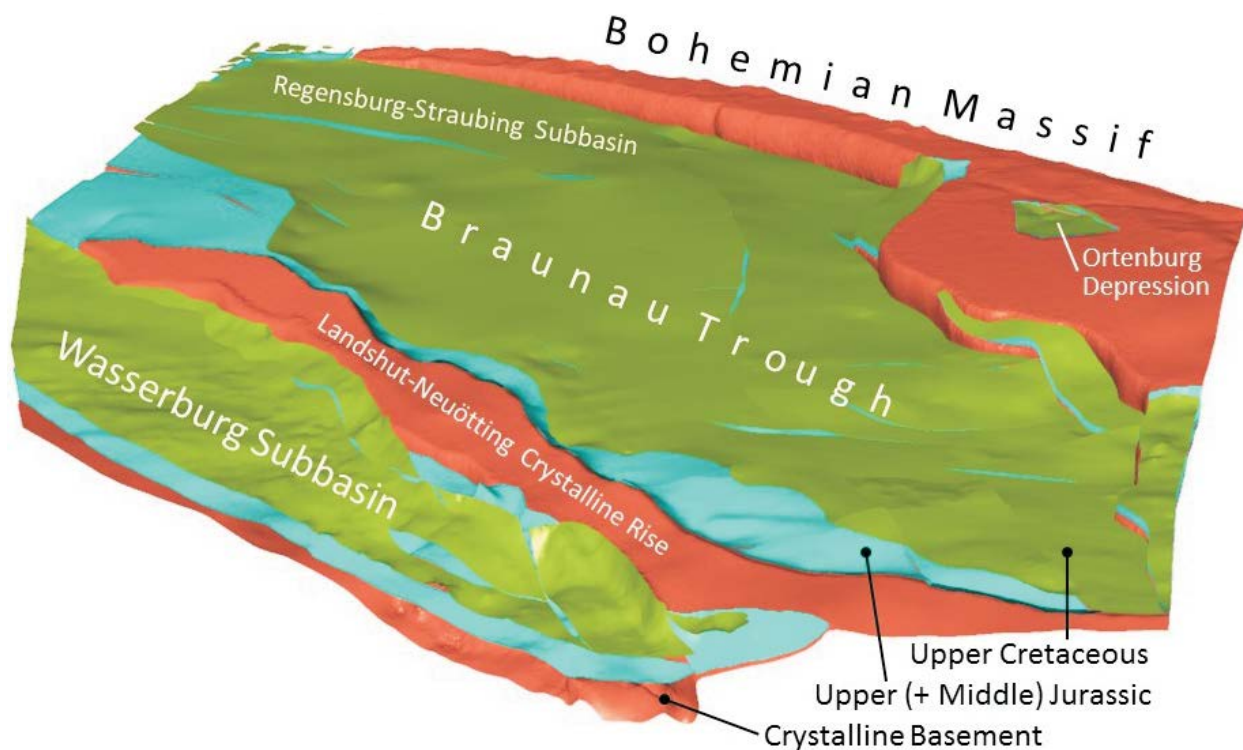
For all deeper parts of the basin seismic data are the pivot for modelling both, layers and blind faults. Deep downhole data is used to calibrate the scene. Combining both, the modelling workflow requires switching repeatedly between time and depth domain. Thus, special emphasis is placed on the refinement of the velocity model quality by utilizing a layer-specific 3D property modelling workflow that responds to lateral changes in rock characteristics and yet velocities in a mostly automatized way. This update and refinement exploits methodologies developed by the Italian GeoMol

Partners rounded up in the Vel-IO 3D tool (Maesano and D’Ambrogi 2017).

The spatial outcomes of all HotLime case studies will feed into the GeoERA Information Platform EGDI (<http://www.europe-geology.eu/>), supplemented with the HotLime knowledge base and project vocabulary as part of the Semantic Web. Likewise, the fault network modelled and parameterized will feed into the European fault database, a principal delivery of the GeoERA project HIKE (<http://geoera.eu/projects/hike2/>).

## Resources Allocated to 3D Modelling Activities

All active 3D modelling is implemented by project staff contracted on a maximum 8-years basis. At present the 3D-modelling team consists of 5 geologists (see Acknowledgement) and permanently employed coordinators only marginally involved in routine modelling. The resulting volatility in human resources is one of the driving forces for the efforts to make



**Figure 7:** Preliminary LOD2 geological model Niederbayern (for outline see Figure 2) presently under revision and refinement (view from SW, Tertiary layers omitted for clarity). Due to the lack of hydrocarbon prospectivity and a low geothermal potential few seismic surveys have been carried out in the southern (deeper) part of this shallow to medium-deep portion of the Molasse Basin only. Hence, a Bouguer gravity residual anomalies map was used to accentuate the structure of the pre-Mesozoic basement and the >2,000 m throw fault system along the edge of the Bohemian Massif basement complex (cf. Figure 1).

the Survey's 3D geo-models sustainable through preserving the implicit knowledge and experience of the modellers in detailed model documentations.

## Overview of Regional Geological Setting

Situated at the southern margin of the European Plate Bavaria is characterized by a Mesozoic sedimentary sequence overlying and framed by Paleozoic rock suites on crystalline basement and the Alpine Orogen to the south (Figure 1). Four structural domains can be distinguished: the Alps, the Molasse Basin, the Scarpland (Cuesta Region) and the crystalline basement terrain. Quaternary sediments are common to all regions.

The Alpine-Carpathian Orogen evolved owing to the collision of the Adriatic and European plates during

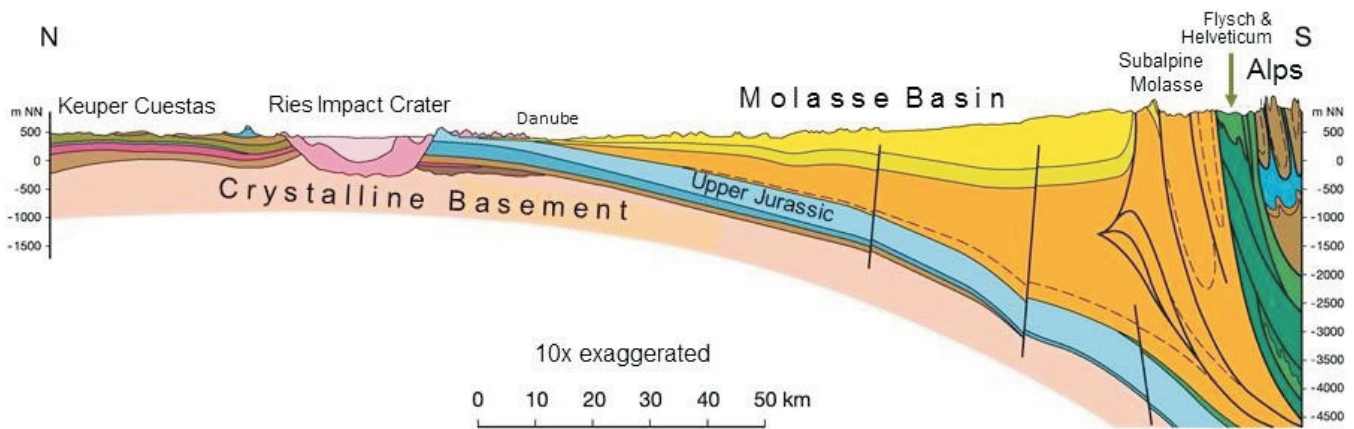
Cretaceous and Tertiary, bequeathing four principal tectonic units on Bavarian territory. The nappes of the Northern Calcareous Alps, built up of Adriatic plate shelf formations, overthrust the oceanic trench fill (Flysch), the European plate shelf sediments (Helveticum), and the southern rim of the foreland basin fill, the Subalpine or Folded Molasse (Figure 8).

Along the forefront of the emerging orogenic belt, due to the large-scale downwarping of the European plate, a foreland basin developed progressively infilled with 'Molasse' sediments eroded off the northward thrusting Alps during Tertiary. In the south and west of the Alpine piedmont the top of the Molasse is shaped by several phases of Pleistocene glaciation.

Jurassic and Triassic sedimentary sequences make up the footwall of the,

up to 5 km deep, Molasse Basin. Hosting central Europe's most prolific hydrothermal aquifer at great depth, the karstified carbonate rocks of the Upper Jurassic on the surface feature the 15 Ma old Ries asteroid impact crater (Figure 8), and form the uppermost escarpment of the Scarpland revealing increasingly older strata towards the northwest.

The lowermost cuesta forming sequence, Buntsandstein, rests upon non-metamorphic Permian sediments in post-Variscan troughs or directly overlays older medium-grade to high-grade metamorphic rocks associated with plutonic rocks, both formed during the Variscan orogenesis. This crystalline basement crops out in the very northwest of Bavaria and along its eastern border, partly covered by low-grade metamorphic rocks of Paleozoic age (Figure 1).



**Figure 8.** Geological section across the southern Cuesta Region, the Alpine Foreland and the Pre-Alps in western Bavaria (from Doppler et al. 2004, modified; color coding refers to the legend of Figure 1). The south-dipping Upper Jurassic karstified carbonate rocks forming the footwall of the Molasse Basin feature the most prolific geothermal aquifer in Central Europe thus being a principal target of 3D geological modelling. See text for details.

### Data (Type, Abundance, Availability, Confidentiality Issues, Integration)

In Germany the federal law on geological resources (Lagerstättengesetz) enacts the reporting obligation for all geological findings towards the authorised GSO in order to support their mandate to gather, store and evaluate information on the subsurface. This statutory duty for data provision covers borehole data (since recently feasible through digital notification and report) as well as seismic surveys. At present index and downhole data of roughly 228,000 boreholes (about 950 deeper than 1,000 m), 1,770 seismic lines (overall length 12,230 km) of that 1185 in SEG-Y format, and 30 3D-seismic surveys in SEG-Y (overall coverage 3,550 km<sup>2</sup>) are stored in the data repositories of the Survey. Auxiliary data for larger-scale structural models are gravity, magnetics and electromagnetics data from state-wide airborne geophysical surveys.

The vast majority of the seismic and deep borehole data comes from exploration and production (E&P) activities mainly for oil and gas, of late increasingly for deep geothermal. These data are subject to business interests and are thus classified confidential or

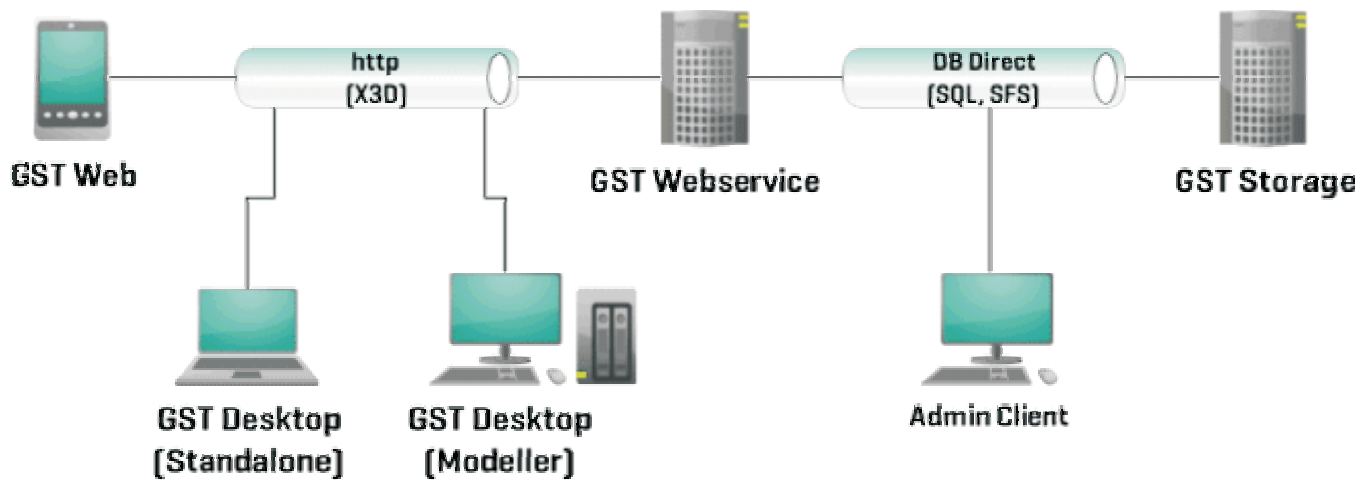
commercial. A framework agreement with the E&P association allows us to utilize the data for interpretation and generic modelling, but no primary data may be displayed in detail nor may disclosed models be suitable for back-engineering. This imposes special requirements on the disclosure of 3D geological models and their mode of distribution.

Datasets of both, borehole index and downhole data and the digital repository for geophysical data are consolidated in the central database (BIS) of the Survey and are on the way to be supported by controlled vocabularies for lithological, stratigraphic and structural terminology. Virtually all the Survey's paper records had been scanned and most legacy data had been geo-registered. The retrieval and subsequent use of all these data is aided by data indices and associated metadata. Streamlining the linkup and synchronisation of this data thus facilitating their use and intertwining with the implicit knowledge in the scientists' brain, to produce re-useable hence sustainable 3D geological models, is the objective Infra3D project. Infra3D aims at the upgrade and extension of technical infrastructure assisting in semi-automated model development and update. Besides BIS and MIS (metadata database), the GST° (Geosciences in Space and

Time, <https://www.giga-infosystems.com/products>) framework is the pivotal pillar of the Survey's 3D infrastructure (Figure 9).

To support the automation of the processes, certain custom programming features are developed, based on international standards for information exchange and data description. Their main purpose is to check, correct and improve the consistency of the underground data. The programming features include the development of ArcGIS° Python toolboxes, of a custom Python° library and standalone scripts. The GST° API Python module GSTPy provides capabilities to enhance the data processing. Since Infra3D is oriented to open source technologies Eclipse° is used as an integrated development environment. All programming modules are stored in Git code repository, SmartGit° is used as a graphical Git° client. Additionally an ETL-Process for data synchronization via FME platform is developed.

Examples of applications in automated model documentation and controlled vocabulary integration are addressed in the chapter "Current Challenges" and "Lessons Learned" sections.



**Figure 9.** GST° provides collaborative environment for software independent storage, administration and visualization of spatial data. The GST° DesktopClient assists modellers in organizing 3D geo-models. GST° WebClient, a Web 2.0 application, forms the back end component which allows presenting the open source models of GST°Storage in web-based 3D browser-analyst (as exemplified in Figure 10). Beyond visualizing 2D and 3D geometries the browser analyst is capable to display corresponding baseline data objects retrieved on the fly (for data privacy internal version only). Figure courtesy of GiGa infosystem.

### 3D Modelling Approach

Confined to static modelling 3D model building at the Survey is based on the SKUA-GoCAD° software package, applied to implicit as well as explicit techniques at all scales and levels of detail. This software proved to be capable of regional stratigraphic modelling the majority of geological terrains encountered in Bavaria at acceptable productivity rates and capable of dynamic revision when new data or interpretive insight becomes available.

We learned that there is no universal best practice applicable to all geological regions or project settings. With scarce baseline data, modelling is driven by geological concepts and implicit knowledge guided by the modeller and the software’s algorithms. In contrast, when baseline data is sufficiently available and expert knowledge is on-hand explicit modelling is the means of choice, particularly based on geological cross sections. In practice, both extremes and all facets in between may occur in the same modelling area. In any case, modelling is controlled by the field geologist’s expertise and modelling results feed back into the “hard” baseline

data, manifested in repeated revision and re-evaluation especially of the stratigraphic interpretation of downhole data, but also for improving the conceptual model. In the long term, 3D geological models will be the datum for calibrating all new spatial data and geological evolution concepts.

### Clients

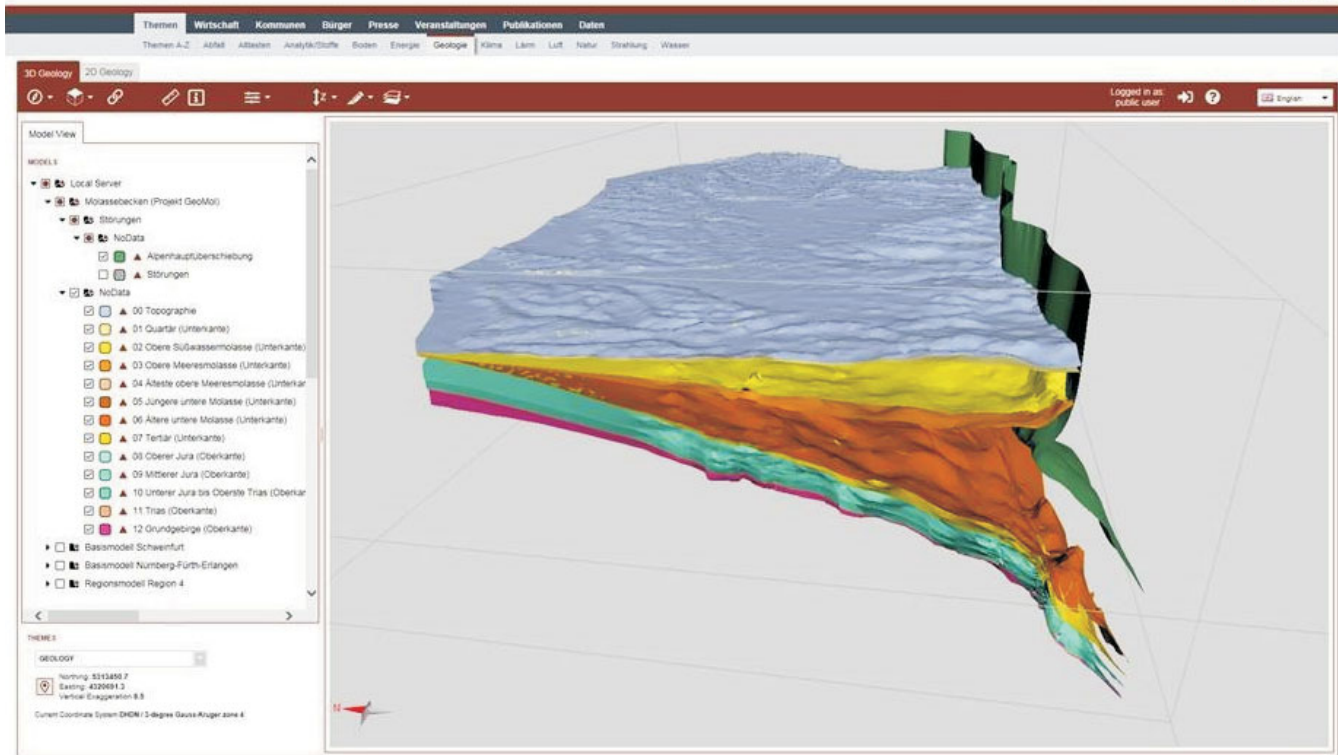
In line with the statutory mandate to counsel the Bavarian public authorities on geoscience issues principle clients of the Survey are planners, regulators and decision makers of the public sector. However, these stakeholders require justiciable “frozen-state” information and only rarely have capability to interpret basic geoscience data, let alone to evaluate the merits of 3-dimensional interpretations, in short: they desire “solutions, not data” (Turner and D’Agnese 2009). Accordingly, these clients are served by 2D or 2.5D information derived from 3D geological models rather than by the full 3D information itself.

In Germany there are considerable reservations of the general public regarding the utilization of the deeper

subsurface. Specifically deep geothermal energy or underground energy storage, which both are crucial to achieving the energy transition for the mitigation of global climate change, are under general suspicion to induce or trigger seismicity. To de-bias the public’s awareness of underground operations, hence, it is a core role of the Survey to unveil “the hidden landscape beneath their feet” by providing straightforward insight into the subsurface. To this end a public access 3D explorer (Figure 10) was implemented for visualization and query of down-scaled 3D geo-models at a restricted zoom-in range.

The 3D browser-analyst for exploring open source models is based on GSTWeb° technology (<https://www.giga-infosystems.com/products>). It allows for spinning the model and exploded views as well as to toggle surfaces and faults, to slice through the model, to generate arbitrary cross-section and virtual drill holes, and to drape geospatial information from other WMSs. With the next release of GST° it will also be able to depict volumes grids.

The disclosure of 3D geo-models for further processing is limited to stake-



**Figure 10:** Screen dump of LfU's 3D explorer (<https://www.3dportal.lfu.bayern.de/webgui/gui2.php>) portraying the eastern portion of the Bavarian Molasse Basin of the GeoMol framework model. Fault planes (except for the Alpine orogenic front wedge in dark green) and the topographic overlay are disabled for clarity.

holders from academia and research institutions for further evaluation, parameterization and thus valorization of the models, and to GSOs of neighboring territories for cross-border adjustment and trans-regional investigations. In all cases, to comply with the statutory provisions on data privacy, the 3D geo-model is made available only upon request and in recognition of the case specific terms of use. One recent example is the collaboration with the Leibnitz Institute for Applied Geophysics (LIAG): The framework model of the Bavarian Molasse Basin has been deployed for the assessment of the main fluid and heat transport processes for a better understanding of thermal anomalies induced by gravity-driven groundwater flow and the long-term effect of Pleistocene glaciation (Schintgen et al. 2019). This negative temperature anomaly (cf. Figure 11) affecting the Upper Jurassic hydrothermal aquifer is a major constraint for the further boost of

deep geothermal energy production in the Bavarian Molasse Basin.

### Recent Case Studies Showcasing Application of 3D Work

As the Alps and the terrains of exposed crystalline basement are not covered by 3D models so far, there is no truly statewide case study application of 3D modelling results. However, the available models of the Molasse Basin and the Scarpland are shared for various thematic applications of different supra-regional coverage.

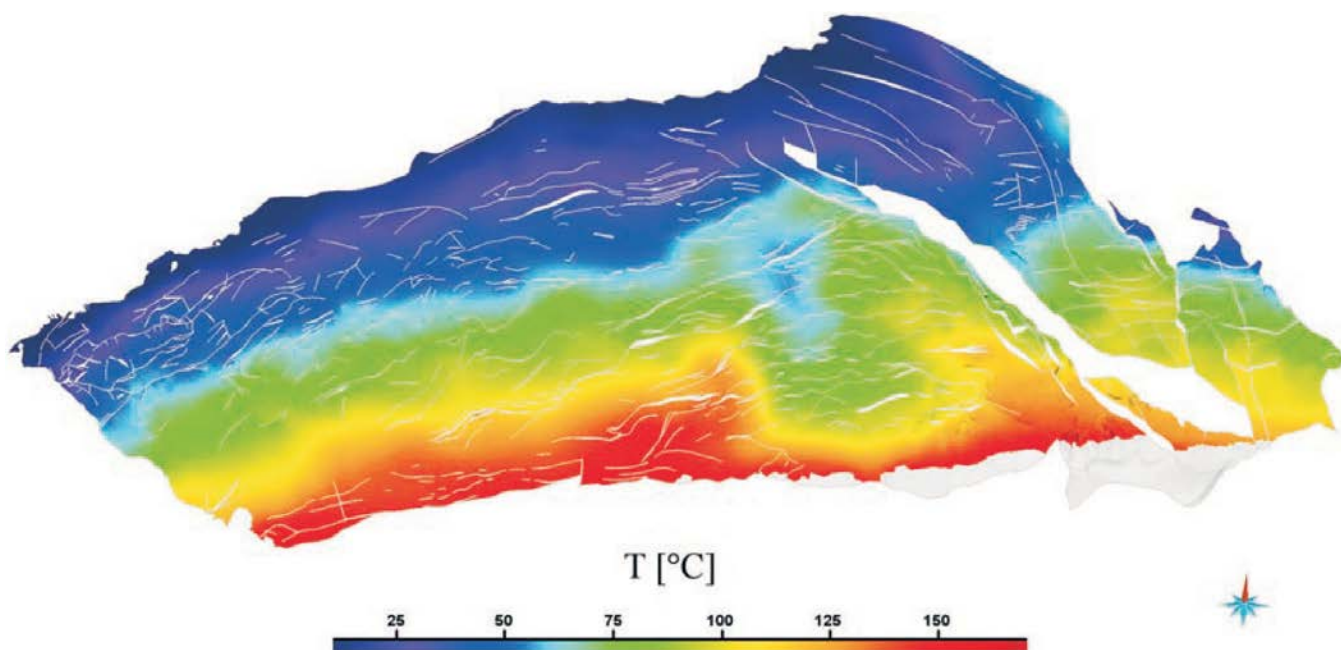
Implemented by LIAG, the Molasse Basin framework model was exploited to model the temperature distribution at the top of the Upper Jurassic hydrothermal aquifer in a cross-border approach including the Baden-Wuerttemberg, Bavaria and Upper Austria territories (Figure 11).

LfU's web-based information system "Umweltatlas" (<http://www.umweltatlas.bayern.de>) features various maps on the appropriateness and efficacy of downhole heat exchange including a map on the depth-related rock specific heat capacity. Presently building on flat-rate value 2.5D information it will incrementally be refined by tiles of parameterized LOD3 models as depicted in Figure 4.

### Current Challenges (Organization, Technological, Conceptual)

Over the course of augmentation, revision, and upgrade of the 3D geo-models as described above we identified the increasing importance to improve our geo-information infrastructure towards supporting integrated data storage and facilitating knowledge sharing. One of the principal issues to achieve the latter is making





**Figure 11:** Temperature distribution in the Molasse Basin at the top of the south dipping Upper Jurassic, based on 3D structural models of the states of Baden-Wuerttemberg, Bavaria and Upper Austria and the 3D temperature model of LIAG (from Agemar and Tribbensee 2018). The white gaps represent the Landshut-Neuötting Crystalline Rise aka “Zentrale Schwellenzone” bare of Upper Jurassic and the fault tears in the Upper Jurassic surface. The south-trending bluish to green bulge indicates a marked negative temperature anomaly of unresolved origin, possibly a long-term effect of Pleistocene glaciation.

our models and associated data sets FAIR – Findable, Accessible, Interoperable, and Re-usable (Wilkinson et al. 2016), exploiting the functionalities of the Semantic Web.

**Findable:** The key for making information findable is discovery metadata. Well established for 2D geographic information and services, ISO 19115 provides information about the identification, the extent, the quality, the spatial and temporal schema, spatial reference, and distribution of digital geographic data. This standard is not yet adjusted to 3D geo-models. It lacks an input option for the key information clients might search for, the lithostratigraphic units modelled as the gist of 3D geological models. ISO 19115, though, allows the indication of multiple keywords thus making possible an approach as outlined in Kondrová and Diepolder (2018), by tagging all modelled geological formations in *KeywordTypeCode:stratum*. However, such keywords are just empty shells if not underpinned by a controlled

vocabulary that glosses synonyms and similar concepts as well.

This approach, initially conceptualized by the German SGD 3D modelling work group, has been recognized by the OCG and is proposed for interoperability tests within the OGC/CGI-IUGS GeoScience DWG (<http://www.opengeospatial.org/projects/groups/geosciencedwg>).

**Accessible:** ISO 19115 provides various data items describing the mode and constraints for distribution. Open disclosure geo-models can be furnished with a *dataSetURI* for direct retrieval via web services, and *distributionFormat* to ensure beforehand that the client has available the suitable equipment for model exploitation. Models being subject to data privacy, as stated in *accessConstraints* and *useLimitations* can be made available upon request via the *distributorContact*, in recognition of the case specific terms of use.

**Interoperable:** Technical interoperability among the German SGD, e.g. for cross-border harmonization, is not an issue as all SGD are utilizing (among others) the SKUA-GoCAD<sup>o</sup> software package. File-based model transfer, however, is outdated since GST<sup>o</sup> Storage (<https://giga-infosystems.com>, cf. Diepolder 2011b) has become a quasi-standard for model storage and exchange at the SGD. GST<sup>o</sup> also allows the frictionless exchange with other software packages like MOVE<sup>o</sup> or Petrel<sup>o</sup>.

Unlike technical interoperability, content-related interoperability, the cross-border fit of the model layers, can only be achieved by harmonization of the lithostratigraphic subdivision at the very beginning of the modelling process. As one of the principal lessons learned from GeoMol project, the approach to tackle this challenge is discussed in the following chapter.

**Re-usable:** Model documentation and versioning is the crucial pre-requisite

to make 3D-geo-models re-usable. With fluctuating staffing it is also essential to preserve the implicit knowledge of the model builder and to keep track of the modelling process applied and the data used, thus facilitating future model updates. Recently, each model prepared or revised at the Survey is described in standardized digital templates stored in the Geo3D database. By database exports this formalized records can be compiled for various publication formats or can be re-used in other data bases. All relevant information is supported by controlled vocabularies for lithological, stratigraphic and structural terminology. In addition to formalized records, the model documentation (Figure 12) also admits free text for an unconstrained, individual appraisal of the modelling process and the conceptual background.

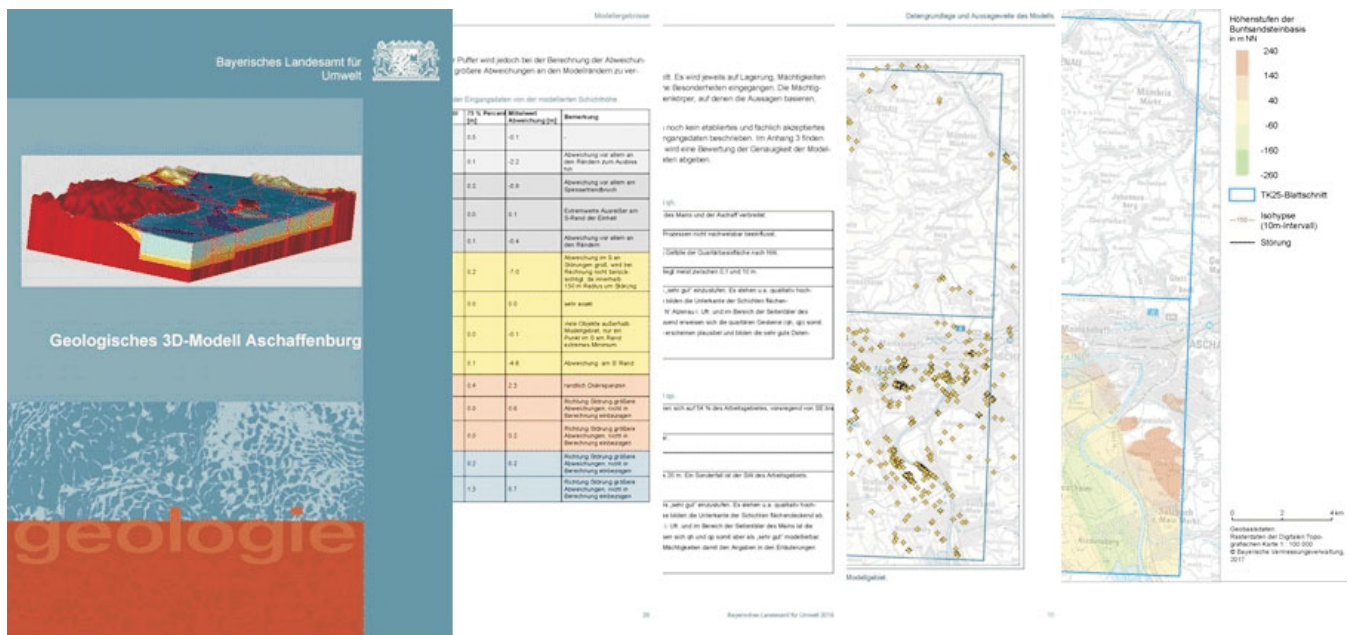
## Lessons Learned

Cross-border harmonization of the lithostratigraphy and correlation with seismic reflectors, in order to achieve content-related interoperability among

cross-border models, was the most underestimated issue during the implementation of GeoMol. Lithostratigraphic subdivisions are standards with limited areal validity evolved from regional approaches reflecting regional peculiarities and are subject to semantic changes in historical evolution of terms. Full standardization of such geological interpretation terminologies is virtually impossible as pluralism of terms is fact-based, well-established and has been used in geoscientific publications over decades (Kondrová and Diepolder 2018). Furthermore, in geology, semantics defines the delimitation of units, e.g. depth of strata. Thus, shifts in lithostratigraphic subdivisions often require realigning, or even re-surveying of geological units.

Rather than attempting to harmonize lithostratigraphic concepts, the Survey's present approach is to elucidate the differences by contrasting juxtaposition of these concepts. Lithostratigraphic concepts collated in a general legend and linked to external classification schemes, using the

standard relations (same as, broad match, etc.) of semantic triples in the Resource Description Framework (RDF) data model allow for the straightforward comparison of the geological interpretation terminologies. Embedded in a Semantic Web exploiting the functionalities of the Simple Knowledge Organization System (SKOS) and using unique web addresses (URIs), such controlled vocabularies can be related to other web resources like code lists of established definitions and standards thus constituting a comprehensive web-based thesaurus of geoscientific concepts like the advanced GBA-Thesaurus (Hörfarter and Schiegl 2016, <http://resource.geolba.ac.at/>). The Survey's general legend now is used for tagging discovery metadata, the formalization of model documentations, etc. As soon as the SKOS modelling is fully implemented the unique ID of the concepts will be converted into an URI and uploaded to a registry, thereby integrated into the Linked Open Data Semantic Web serving both, the SGD lithostratigraphic concepts thesauri network in the



**Figure 12:** Example of the print copy of standardized model documentation. Tables and annexes are featuring mandatory information directly integrated from the GEO3D database using templates in a machine-readable format based on CGI Geoscience Vocabularies (<http://resource.geosciml.org/def/voc/>) and other standard code lists. The documentation's annex comprises thematic 2D extracts (maps, contour line plans) derived from the geo-model described including information to assess uncertainty like data density distribution maps for all modelled units.

making and the GeoERA project vocabularies as part of a comprehensive knowledge base.

## Next Steps

Next steps planned at the Survey are to continue and complete the present plans as set out above. Sparse staffing levels do currently not allow for ambitious new plans and rather we try to disburden our modellers from secondary work by fully automating data handling processes. Likewise, it is not our ambition to single-handedly deal with all advancements in 3D geological modelling. To mitigate shortcomings caused by sparse staffing we rather further on promote knowledge sharing through inter-SGD and transnational exchange as spearheaded by the Survey for more than a decade. However, despite the tacit appreciation of the mutual benefits of such collaboration, succession planning to secure the continuity of the SGD task group on 3D modelling and its international involvements, now, as the chair is approaching retirement, is a challenging task.

## Acknowledgement

This synopsis on 3D modelling and geo-data base integration cannot be complete without the acknowledgement and appreciation of the staff carrying out the spadework of model building but usually is generalized in blanket terms like the Infra3D Team, the BAB Team or et al.: Silvia Beer, Eric Donner, Dirk Kaufmann, Nils Landmeyer and Stephan Sieblitz. The same applies to Iveta Atanasova and Lisa Lutterschmid at the forefront of programming and data modelling for geo-data integration and the Semantic Web.

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# Chapter 8: Geological Survey of Canada: Geological Mapping in Three Dimensions

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## Introduction

The Geological Survey of Canada (GSC) has a long history of both terrestrial and offshore (marine) geological studies at local, regional and national scales. With the rise of powerful new 3D mapping methods and technologies, the GSC has increased 3D mapping activities at all scales in recent years. These efforts have built upon 25 years of outcrop-scale and subsurface 3D geological modelling in support of bedrock mapping, mineral exploration, hazard assessment, and groundwater studies. Three-dimensional mapping is recognized as a high priority by the GSC and, as such, it is highlighted by a relatively new national flagship project, Canada-3D. This project aims to develop a comprehensive 3D geological framework and associated knowledge-base for the Canadian subsurface (Figure 1; Brodaric et al. 2017; 2018). As a national mapping agency, the GSC has developed this initiative in collaboration with provincial and territorial surveys through the National Geological Surveys Committee (NGSC). The NGSC provides guidance and coordination between the 10 provincial and three territorial geological surveys and the GSC. It is anticipated that Canada-3D will become the authoritative state of knowledge for the geology of Canada at a national scale. Canada-3D is a prime example of the continuing focus on scientific innovation by the GSC in contempo-

rary digital times. Canada-3D is a response to shifting scientific methods, emerging opportunities that favour digital techniques, as well as a response to the demands of the Canadian government's open data strategy and global open data concerns. Such concerns are escalating alongside rising data volumes and accompanying challenges to manage new and old data. Indeed, 70 years from the initiation of the post-war acceleration in geological mapping and geophysical developments, the GSC has an enormous repository of legacy data, mostly analogue. This data volume has caused a requirement for significant resources to be allocated to data management and integration in order to

fulfill goals for scientific analysis and communication. The advent of global positioning systems and the conversion of many systems to digital data capture is also rapidly expanding the geological data repositories of the GSC. This has significant impact on GSC's 3D mapping activities, which function optimally when the data is well-structured and readily accessible. This report provides an update and an expansion on documentation in Berg et al. (2011) on 3D mapping activities at the GSC, and uses the Canada-3D initiative, to highlight ancillary GSC activities in data management, 3D model development, data visualization and related case studies.



**Figure 1.** Canada-3D vision as authoritative source of knowledge on the geology of Canada. Supporting elements of geological mapping, analysis and data in attribute databases with reporting and geological knowledge.

## Organizational Structure and Business Model

Founded in 1842, the GSC is the oldest research agency in Canada (e.g., Zaslow 1975; Lebel 2018). It is part of the Lands and Minerals Sector of the Department of Natural Resources within which it is one of a number of branches related to earth science, geodesy and surveying, and mining. The GSC has traditionally focused on the production of geoscience knowledge to support economic development, primarily in the realm of mineral and energy exploration. More recently its mandate has expanded to include issues pertaining to geological hazards, groundwater, the environment, and climate change. Since the 1950's the GSC has also supported Canadian strategic interests in the Arctic and offshore through targeted geoscience programs. The GSC operates in all 10 provinces and three territories on a cooperative basis with respect to federal government mandates and objectives (e.g., Lebel 2018). To fulfill this mandate, the GSC has six offices across Canada: a central office in Ottawa and 5 regional offices. A seventh office in Iqaluit, the Canada-Nunavut

Geoscience Office is co-led with the territorial government. The GSC maintains a staff of approximately 400 researchers and support personnel (GSC 2018), with an annual operating budget in 2017 in the range of 74 million dollars (GSC 2018). This amount fluctuates annually depending upon the ratio of base funding and other governmental and external allocations. GSC has a matrix management framework consisting of Divisions responsible for human resource management and Programs that are designed to align with government priorities and objectives. The number of active programs fluctuates, but typically there are around 11. To supplement limited capacity, the GSC develops partnerships with provincial and territorial government geological surveys, other federal government departments, industry, universities, and other state and national geological surveys. GSC publications are available under the Canadian Government open data initiatives. It operates under a non-cost recovery basis, though it can, and frequently does, seek collaborative funding from interested partner groups from all sectors.

## Overview of 3D Modelling Activities at the GSC

Prior to the advent of Canada-3D, geological modelling efforts at the GSC had been scattered amongst various programs, often reflecting dramatically different research agendas (Table 1). Modelling had been performed to address specific research questions, support derivative activities (e.g., numeric groundwater modelling) and support operational activities. To enhance regional geological and mineral deposit understanding, targeted 3D modelling has been completed in the complexly deformed areas of the Canadian Shield (e.g., Flin Flon, Schetselaar et al. 2018) and within orogenic belts (e.g., Purcell, de Kemp et al. 2016). Modelling of sedimentary basins (Carter et al. 2017) and surficial sediment (Logan et al. 2006; Nastev et al. 2016) have been completed to support groundwater and public safety geoscience programs. Offshore, high-resolution reflection seismic studies have supported 3D modelling in structural isopach studies during the 1990s (e.g., Syvitski and Praeg 1989) and

**Table 1.** Illustrative examples of 3D modelling by programs, geological setting and scale.

Program	Geological setting	Area	Area km <sup>2</sup>	Reference
Public Safety Geoscience	Surficial	St Lawrence Lowlands	72,000	Nastev et al. 2016
Targeted Geosciences Initiative	Complex folded and faulted Orogenic belt	Sullivan, British Columbia	7000	de Kemp et al. 2016.
Targeted Geosciences Initiative	Deformed volcanogenic massive sulphide	Flin Flon Manitoba	80	Schetselaar et al. 2018.
Groundwater	Surficial geology, buried valley	Spiritwood, Manitoba	3300	Logan et al. 2006.
	Paleozoic sedimentary basin	Southern Ontario	110,000	Carter et al. 2018.
	13 regional hydrostratigraphic 3D models across Canada	Distributed across Canada	<11,000	Bedard et al. in prep.
Targeted Geosciences Initiative	Paleozoic sedimentary basin	Saskatchewan	30	White et al. 2016
Resource assessment	Marine estuary	St Lawrence	8000	Duchesne et al. 2010
	Continental shelf	Scotian Shelf	50,000	Campbell et al. 2015

fully digital models since the 2000s (e.g., Duchesne et al. 2010; Campbell et al. 2015). These are primarily seismo-stratigraphic models with limited integration of geological stratigraphy.

Canada-3D has emerged since 2016 as a unifying project for the integration of geological mapping in 3D. It is designed to be continuously supported (“evergreen”), multi-resolution, inter-disciplinary, collaborative, and updated regularly upon acquisition of new data both internally and from collaborators (Figure 2). To address visualization issues due to the enormous scale differences from local (i.e., 1-2 km<sup>2</sup>) scale models to the national model, and support efficient visualization, the Canada-3D framework will vary in resolution (Hillier and Brodaric 2018). Notably, scalability concerns dictate a sophisticated modelling approach that is in its nascent stages. Consequently, at this time local to regional models in blank areas are being imported into the Canada-3D database as is, while retaining provenance links to original sources. In cases where new models overlap with existing data in Canada-3D, either (1) the new models replace the existing Canada-3D model fragment,

with replacement occurring in collaboration with partner agencies in cases where partner 3D models are affected, or (2) the new models will be integrated into the Canada-3D model, by treating the new models as additional control points and triggering re-modelling for the area. The resultant Canada-3D model contains full modelling provenance as well as links to detailed information on rock units, and will be visualized in desktop and on-line environments (Hillier and Brodaric 2018).

### Resources Allocated to 3D Modelling Activities

Approximately 5 to 10 staff are involved in 3D geological modelling within individual projects. Staff are commonly geologists with an interest and experience in numeric and computer science applications. Explicit mineral deposit or groundwater model construction is accomplished by a geological expert with a geophysics team. For Canada-3D, a more structured team environment is emerging consisting of implicit modelling experts with both geological and computer science backgrounds. Geological mappers, crustal and mantle geophysicists are providing data input

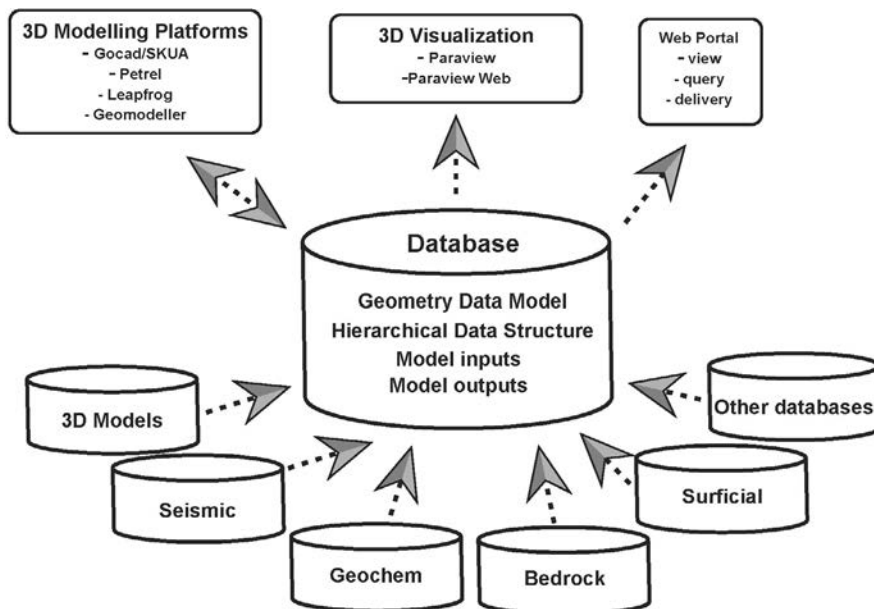
guidance and coordination with other government science organizations and GSC staff. Budgets vary according to program and project cycles and the scope of included costs, data collection, legacy data capture, or just interpretation and model creation.

To-date, little emphasis has been placed on public communication of models, with visualization commonly handled by viewing tools supplied by modelling software. With Canada-3D, the development of a more accessible web-based visualization environment has become a more important activity for both 2D map and 3D model presentation. To address challenges of the large size of the Canada-3D datasets, R&D is being undertaken to develop visualization methods that are hierarchical, analogous to 2D tiling in which greater resolution is seen with deeper zoom levels (Hillier and Brodaric 2018). The emerging Canada-3D web portal will enable 2D maps and 3D models to be viewed, interrogated, and portions downloaded. The 2D components are slated for release in 2019, while the 3D components are expected to be released in future years.

### Overview of Regional Geological Setting

Canada spans the North American continent from the passive continental margin of the Atlantic Ocean to the active Pacific margin and from its southern extremity at 41.7 degrees northward, to include the Arctic archipelago, and the northern extremity of Ellesmere Island at 83 degrees north, plus the contiguous offshore continental shelf. It has 9,984,670 km<sup>2</sup> of terrestrial land cover and 7,100,000 km<sup>2</sup> of marine offshore.

The bedrock geology of Canada includes the oldest dated rocks in the world (St-Onge et al. 1984; Bowring and Williams 1999), and a rock record that tracks the formation and breakup of three supercontinents since the end of the Archean Eon.



**Figure 2.** Schema of database management with data source inputs for Canada-3D and output modelling, visualization, and web-based dissemination.

The first supercontinent is referred to as either Nuna or Columbia (Piper 1976; Hoffman 1988; Park 1995). There are approximately 35 known fragments of Archean-aged crust preserved on Earth (Bleeker 2003) and these would appear to have been largely cohesive at around 1.8 to 1.7 Ga. The evidence for Nuna is based on comparative geology and is observed through alignment and synchronicity of features such as mafic dyke swarms, suture zones and orogenic belts. The existence of numerous compressional orogenic belts in the period 2.1 to 1.7 Ga (e.g. Taltson-Thelon, Wopmay, New Quebec, and Trans-Hudson in Canada; St-Onge et al. 2015) provide the evidence that amalgamation of the Archean continental fragments was near global in its extent. Reconstructions of Nuna attest to the long-lived duration of the supercontinent creating lithospheric stability for around 400 million years (between ca. 1.8 and 1.4 Ga; Evans and Mitchell 2011; Zhang et al. 2012). Breakup of Nuna is evidenced by rifting along continent margins (e.g., accumulation of the Belt-Purcell Supergroup in western Canada) and by the emplacement of mafic dyke swarms such as the 1.27 Ga Mackenzie dykes (LeCheminant and Heaman 1989).

The supercontinent cycle repeated itself during the latter stages of the Proterozoic Eon with a second supercontinent referred to as Rodinia (McMenamin and McMenamin 1990), which started to assemble from about 1200 Ma, and then dispersed again by about 700 Ma. As with Nuna, it is the global extent of compressional orogenic belts active in the period 1400 – 1000 Ma - the so-called ‘Grenvillian’ belts that include the type Grenville orogen in eastern Canada – that attest to the re-amalgamation of dispersed Nuanan continents by the early Neoproterozoic (Nance et al. 2014). The supercontinent broke up episodically over a pro-

tracted period that may have exceeded 200 million years (Scotese, 2009).

The most recent supercontinent, Pangea, coalesced from the fragments of Rodinia, and assembled as Laurasia (a combination of Laurentia and Eurasia as witnessed by the Appalachian orogen in eastern Canada) and Gondwana re-united by progressive subduction of the Rheic Ocean in late-Paleozoic times. The geological, paleontological and paleomagnetic evidence for the existence of a combined landmass in late Permian-Triassic times is robust, but the details of how it was assembled are complex (Torsvik and Cocks 2013). Pangea has now dispersed and its remnants occur as 5 major continental landmasses of today. Some continents are already undergoing reassembly and growth, with the impingement of Greenland and NE Canada (leading to the Eureka orogen in Arctic Canada; St-Onge et al. 2015), and the evolution of the Cretaceous North American Cordillera and associated Western Canada Sedimentary basin.

Canada has been glaciated multiple times and little of the landscape was not glaciated during the Quaternary (e.g., Dyke et al. 2002). Most of the Canadian Shield has been stripped bare of weathered regolith exposing relatively unweathered bedrock overlain by extensive areas of glacial sediment. Sediment thickness increases dramatically over the Phanerozoic sedimentary basins where sediment thickness can rapidly increase from 10s of meters to over 200 m. The landscape is defined by extensive tracks of streamlined landforms and poorly developed juvenile drainage systems.

## Data Sources

The GSC has a wealth of legacy data that has largely been archived through the publication process in individual reports (e.g., Open Files, etc.). In excess of 30,000 GSC documents have been scanned and are available online

as PDF files. Map publications have also been scanned and captured digitally as PDF files. Little of this data has been captured in structured relational databases. Digital data capture has become progressively more common over the past 25 years and numerous databases exist for geochemical, geochronology, and geophysical datasets. Internal legacy data capture from unstructured to structured formats remains a challenge. In the 1990’s the National Mapping Program had an emphasis on digital methods and this initiated a change from analogue to digital data capture that continues to evolve (Robertson, 2010). A series of field data capture (e.g., Fieldlog, Brodaric 2004) and modelling initiatives were pursued to support structural geological interpretations, mineral exploration and groundwater studies. Projects in these domains, in addition to geophysics, have provided the framework and vision for Canada-3D to emerge. These projects and data notwithstanding, Canada-3D has a serious data gap issue, inasmuch as there are many parts of the country where the data required for 3D models is quite sparse, or inadequate for the complexity of the geology. This has required an investment in methods development to address sparse data and modelling of complex geological environments (de Kemp 2004, 2005).

Effective data management is crucial to the success of 3D programs. Because almost any geological information can impact the national model, Canada-3D has chosen to differentiate itself from core data management activities. Because the Canada-3D framework draws from several sources, the project relies on existing corporate data infrastructure and collaborative data custodians (e.g., Ontario Oil, Gas and Salt Resources Library, provincial surveys). Canada-3D manages only the 3D model data, with links to original sources (e.g., borehole data, geological maps).

Surface (2D) bedrock and surficial geological mapping continue to be a cornerstone of 3D activities at the GSC. This recognizes the accessibility of the outcrop geology of Canada, the profundity of data available and the ability to use such data to project knowledge into the subsurface. Both bedrock and surficial mapping is coordinated with provinces, with the GSC mandated to manage a national synthesis. Much of the map products only exist in raster formats and efforts are being explored as to how to capture, map polygon information, point observation and structural measurements into a structured geospatial database.

Geophysical data sets are collected in all three domains of water borne (marine), terrestrial, and airborne. Surveys may involve controlled source (seismic, electromagnetics), passive (seismic, magnetotellurics), and potential field surveys (gravity, magnetics). Datasets in each of these domains is variable in coverage, and resolution, with datasets often constrained by spatial extent or data collection parameters (line spacing). Primary (geophysical) 3D modelling of this data is not included within this review. Progressively more effort is being made to interpret and integrate geophysical signals with geological knowledge to support geological interpretations and understanding.

Terrestrial geophysical surveys have been primarily controlled source seismic and electromagnetic, most prominently those data acquired as part of the Lithoprobe program (Clowes et al. 1992; lithoprobe.eos.ubc.ca). Lithoprobe seismic reflection sections and field records are available via Open Government (<https://open.canada.ca>) as well as similar older and newer seismic surveys (e.g., Discover Abitibi). Seismic reflection profiles are placed section by section into 3D models to provide context for interpretation. Key aspects of published interpretations are being translated to

3D models (e.g., LITHOPROBE, <http://lithoprobe.eos.ubc.ca>).

Passive teleseismic and magnetotelluric field data (e.g., Roots and Craven 2017) are available through web portals Earthquakes Canada (<http://earthquakescanada.nrcan.gc.ca>) and Open Government respectively. Processed teleseismic data used in structural seismic studies of the lithosphere are documented in journal publications (Snyder et al. 2014) as are 3D conductivity models from magnetotelluric data. Structural interpretations of mantle discontinuities are captured and further interpreted in the 3D geological models.

Marine geophysics data is being progressively captured and documented in the Expedition database for marine seismic and swath bathymetry (Courtney 2013). Extensive marine activities mapping the continental shelf and coastal water using swath bathymetry are being completed on all Canada's coasts, commonly in conjunction with shallow reflection seismic (e.g., Shaw and Potter 2015).

The most commonly employed data for 3D modelling are various types of drillhole datasets (water well, geotechnical, mineral, petroleum). Data quality, reliability and degree of both physical and observational data curation of these datasets is variable, as is accessibility. Issues of confidentiality, liability, industrial competitiveness, and personal privacy can limit access for periods of time and portions of datasets. For areas of surficial sediment across southern Canada provincial water well databases are the most common and accessible dataset. Lithological data and access to water wells has been coordinated through the Groundwater Information Network (GIN, Brodaric et al. 2016). In areas of infrastructure development, geotechnical data are prevalent but controlled by a disparate variety of agencies (hydro, transport, municipality, geotechnical firms) much in analogue format, and with limited re-

cord access and/or confidentiality issues. Despite early attempts to coordinate geotechnical data (Belanger 1975), such data remains difficult to access and integrate. In areas of mineral exploration and resource delineation there is abundant drillhole data; however; this data lacks public curation, accessibility and is considered proprietary. Documentation beyond the files of exploration companies and consultants is very limited except where submitted for mineral assessment reports.

Numerous datasets of both geological and geophysical data are collected and curated by organizations other than the GSC. Many modelling initiatives access either the primary data or through pre-existing models. For example, the most comprehensively managed drillhole datasets are in petroleum provinces of Phanerozoic basins (e.g., Alberta, Saskatchewan, Ontario). Such datasets underpin the model development in southern Ontario (e.g., Carter et al. 2017) and provincial development in Alberta (MacCormack et al., this vol., Chapter 5). The records are attribute rich with geophysical records, core samples, and drill chips. Unfortunately, this data is proprietary and accessibility is commonly through a user pay system.

## 3D Modelling Approaches

A range of modelling approaches have been adopted by individual studies at the GSC. Illustrative examples are provided in Table 2, but are not exhaustive. In the 1990's modelling was completed in a range of conventional GIS platforms (e.g., MapInfo®, ArcInfoTM) and 3D modelling software (e.g., GOCAD®). Since 2015 modelling activities have been undertaken using the LeapFrog® software platform for many groundwater studies. LeapFrog® has proven to be a cost effective software option with manageable learning curve for modelling use. Conversion of geological



models into hydrostratigraphic models for numeric groundwater modelling has been completed for both internal (Benoit and Paradis 2015) and external activities (e.g., Frey et al. 2018) and use in a range of numeric flow modelling software (MODFLOW, FEFLOW, HydroGeoSphere).

In the sparse data setting of regional geological mapping, tools have been developed for interactive and implicit modelling (e.g., de Kemp et al. 2017a; Hillier et al. 2017). In contrast, mineral camps with abundant drillhole and geophysical data, including 3D seismic cubes, have enabled well-constrained 3D modelling approaches (Schetselaar et al. 2018).

The development of an efficient visualization mechanism is an integral part of Canada-3D. Visualization of such geo-models is challenged by several things: (1) massive geo-model sizes, (2) file-based data management that treats geo-models as single entities, (3) the inability of popular geo-modelling software to calculate and render massive models, (4) variability in 3D geometry structures, as key 3D data types are often unsupported; and (5) efficient and effective web-based access to large geo-models. Solutions being developed in Canada-3D include the use of hierarchical visualization to address (1), database-driven spatial decomposition and spatial indexing of geo-model files to address (2), incorporation of hierarchical-sensitive streaming and rendering to address (3), the adoption of the sophisticated VTK geometry standard to address (4), and investigation into standards-based 3D web visualization systems. Integration of these results in

both desktop and web-based visualization systems is ongoing.

## Clients

The GSC supports Government of Canada priorities of economic development and public safety. To-date the principal clients for 3D geological modelling have been groundwater, mineral exploration, and public safety agencies. Clients range from watershed water managers to provincial ministries and other federal government departments.

Models are currently available through GSC publication series, as well as through the Groundwater Information Network web portal ([www.gw-info.net](http://www.gw-info.net)), and are licenced for reuse through the government of Canada open data policy online. In the case of the groundwater program, models have been converted to a set of standard formats (e.g., ASCII grid, GeoTIFF, 3D PDF, GOCAD) and layers (Bedard et al. in prep). To-date no models are available for online viewing. In the past three years animations have been created to allow public previewing of model geology and applications (e.g., Russell et al. 2017b). Subsequently virtual reality and augmented reality visualizations have been developed since 2018 to enhance visualization and outreach for Canada-3D, groundwater, and mineral deposit models.

## Recent Case Study Applications of 3D Models

The GSC is addressing the 3D geology of Canada in a hierarchical framework that is premised on an evergreen

approach. In this section we overview Canada-3D and provide two applications in mineral exploration and groundwater demonstrating how regional scale models will infill a coarse resolution Canada-3D framework.

### Case Study 1. Canada-3D

Canada-3D is consolidating GSC and provincial – territorial geological data into a seamless national geological model. Recognizing the geological complexity of Canada, as well as the diverse and commonly sparse data support in the subsurface, Canada-3D has taken an hierarchical approach, including geo-models at all resolutions, from mineral camp to national scale. It is building upon the wealth of 2D geological mapping (e.g., Wheeler et al. 1996; Fulton 1993) and emerging national compilations (St-Onge et al. 2017). The intention is not only to develop a 3D framework for Canada, but enable frequent updates as new information becomes available, making it “evergreen”.

To help prioritize and communicate the complexity of the challenge, parts of Canada and North America can simplistically be assigned to one of three broad geological domains with a thin surficial cover that is near ubiquitous across Canada (Figure 3). Canada-3D is fundamentally a geological model and thus will ingest stratigraphic interpretations from disparate data coded to provincial and national stratigraphic norms from outcrop, geophysical, drill logs, 2D and 3D geological models, and other sources.

Given the scale and sparsity of data support, a lithoframe approach, such as developed for the UK, was not

**Table 2.** Illustrative modelling approaches and examples employed at GSC.

Modelling Approach	Application	Reference
Explicit	mineral camp	Schetselaar et al. 2010
Expert system	hydrostratigraphy	Logan et al. 2006
Machine learning	hydrostratigraphy	Smirnoff et al. 2008
Implicit	mineral camp	Hillier et al. 2017
Stochastic	hydrostratigraphy	Benoit et al. 2017

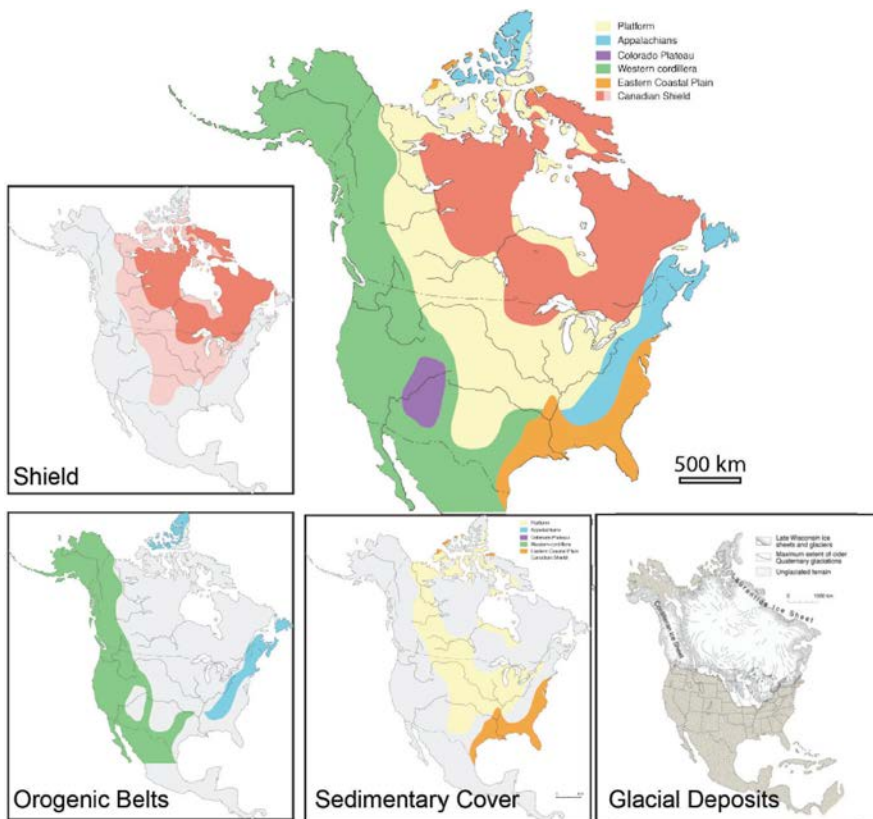
considered practical. Instead, a model of three units or four surfaces was initiated, consisting of the surficial, bedrock and mantle (and sub-mantle) layers. Initial focus is on development of surfaces separating the layers, i.e., the topographic surface, the bedrock surface, Phanerozoic-Precambrian surface, and the mantle surface (i.e., Mohorovicic discontinuity MOHO), with preliminary products created. Progress on these national surfaces is proceeding asynchronously as data support and resources permit.

The topographic surface is provided by the Canada Digital Elevation Model (CDEM; Figure 4a). This elevation surface is augmented by either the bedrock or surficial geology mapping where appropriate (e.g., Wheeler et al. 1996; Fulton 1993). The bedrock surface consists of depth to bedrock extrapolations beneath the surficial coverage (Figure 4b). This

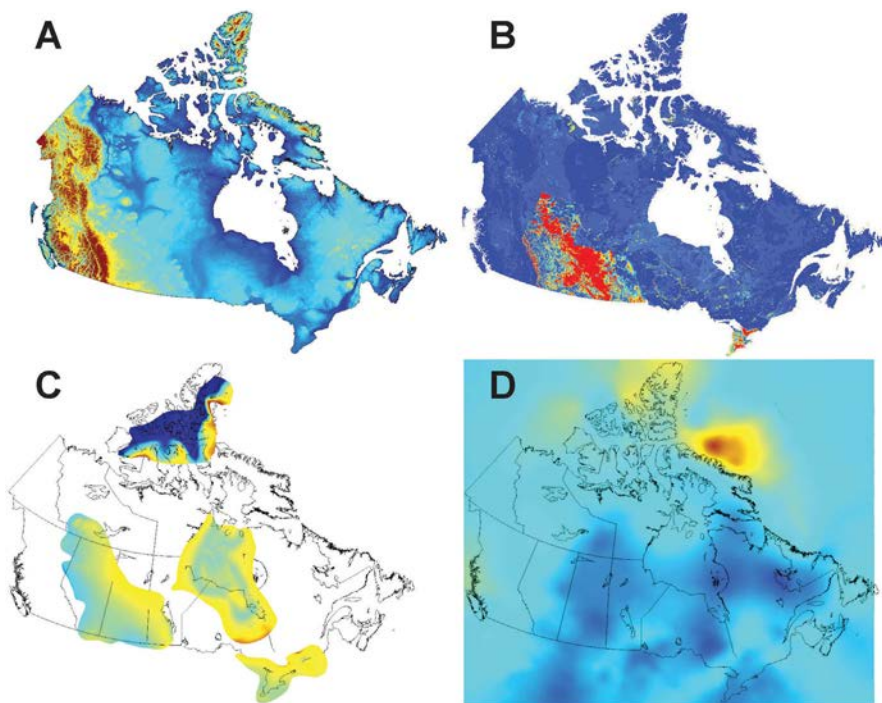
surface is a synthesis of existing provincial coverages derived from data-driven modelling integrated with a rules-based approach for shield and orogenic areas (Russell et al. 2017a). It is expected this surface will be useful in bedrock resource assessments, groundwater studies, geophysical interpretation, geohazards, permafrost degradation, and geotechnical work for infrastructure development. The Precambrian - Phanerozoic contact surface separates cover rocks of the Phanerozoic Eon and older basement rocks (Figure 4c). This surface development is being undertaken through the application of data-driven geostatistical, implicit modelling (GOCAD/SKUA and SURFE; Figure 5) and knowledge-driven (SPARSE) methods (Figure 6; de Kemp et al. 2017a, b). It can help separate bulk rock properties into cover and basement classes useful for geophysical and mineral potential modelling. Com-

bined with heat flow and fracture density estimates it could help develop national-scale 3D maps for geothermal energy and CO2 sequestration potential. The deepest surface is the (MOHO), corresponding to the transition in P-wave seismic velocity from 6-7 km/s to 8 km/s that commonly occurs at  $\pm 30$ -35 km depth (Schetselaar et al. 2017). This surface provides a first-order characterization of crustal thickness variations underneath Canada's landmass and offshore domains. It is of increasing interest for understanding the construction of the continent and origin of certain types of mineral deposits (e.g., diamonds).

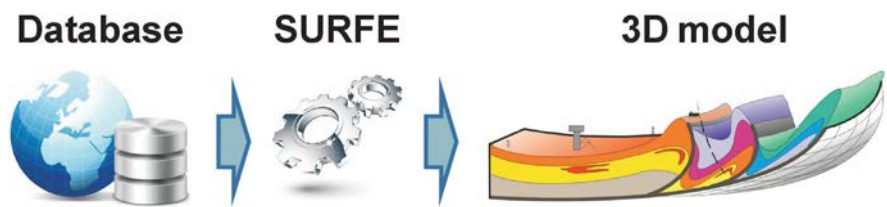
Incorporation of existing regional and local 3D models is occurring simultaneously with national surface development, to fill the volumes between the national surfaces. This largely builds on areas of simplest geology and most abundant data support, for example in order of increasing complexity and data scarcity: Phanerozoic basins, Canadian Shield, Orogenic belts and offshore. However, there remain large gaps in 3D model coverage, often coinciding with geological data sparsity. For these parts of the country with minimal data support, methods are being investigated and developed to propagate geological mapping structural information into the subsurface. Multilayer models at regional scale of 100,000s km are being integrated for Phanerozoic basins as the next phase of the initiative. Higher resolution models of <10,000s km<sup>2</sup> are being integrated for complex mineral deposit terrains, and areas of thick surficial sediment cover modelled for groundwater studies. In complex terrains mining camp scale (<10,000s km<sup>2</sup>) and Phanerozoic sedimentary basins (100,000s km<sup>2</sup>) sufficient drill holes, geophysics, geological maps may exist to construct data-driven models. In remote areas and at regional scales and depths greater than a few kilometres, sufficient observations cannot exist and model interpolation must be knowledge-



**Figure 3.** Tectono-stratigraphic framework of North America in outcrop (dark colour) and subcrop (pale colours). Thumbnails highlight extent of simple geological domains that can provide a framework for prioritization of Canada 3D progress. Modified from Barton et al. (2003).



**Figure 4.** Emerging national surfaces for Canada-3D. **a)** Topographic DEM of Canada (from NRCan 2012, CDEM 3.0). **b)** Depth to bedrock surface, base of surficial cover (Russell et al. 2017). **c)** Precambrian – Phanerozoic subcrop contact (de Kemp et al. 2017b). **d)** Depth to Mohorovicic discontinuity (Schetselaar et al. 2017).



**Figure 5.** Conceptual progression of SURFE implicit modelling (from de Kemp et al. 2017a).

driven, with geological formations inferred by manual interpretation, mathematical down-dip extrapolation of key surfaces, or from key physical properties such as potential field properties.

### **Case Study 2. Mineral Camp Models**

Early computer aided 3D methodology work was initiated at the GSC in the 1970's with initiatives such as calculating trend surfaces with uncertainty estimates (Agterberg and Chung 1975) using 3rd order polynomials for pluton geometry estimation. Subsequently, through the 1990's and

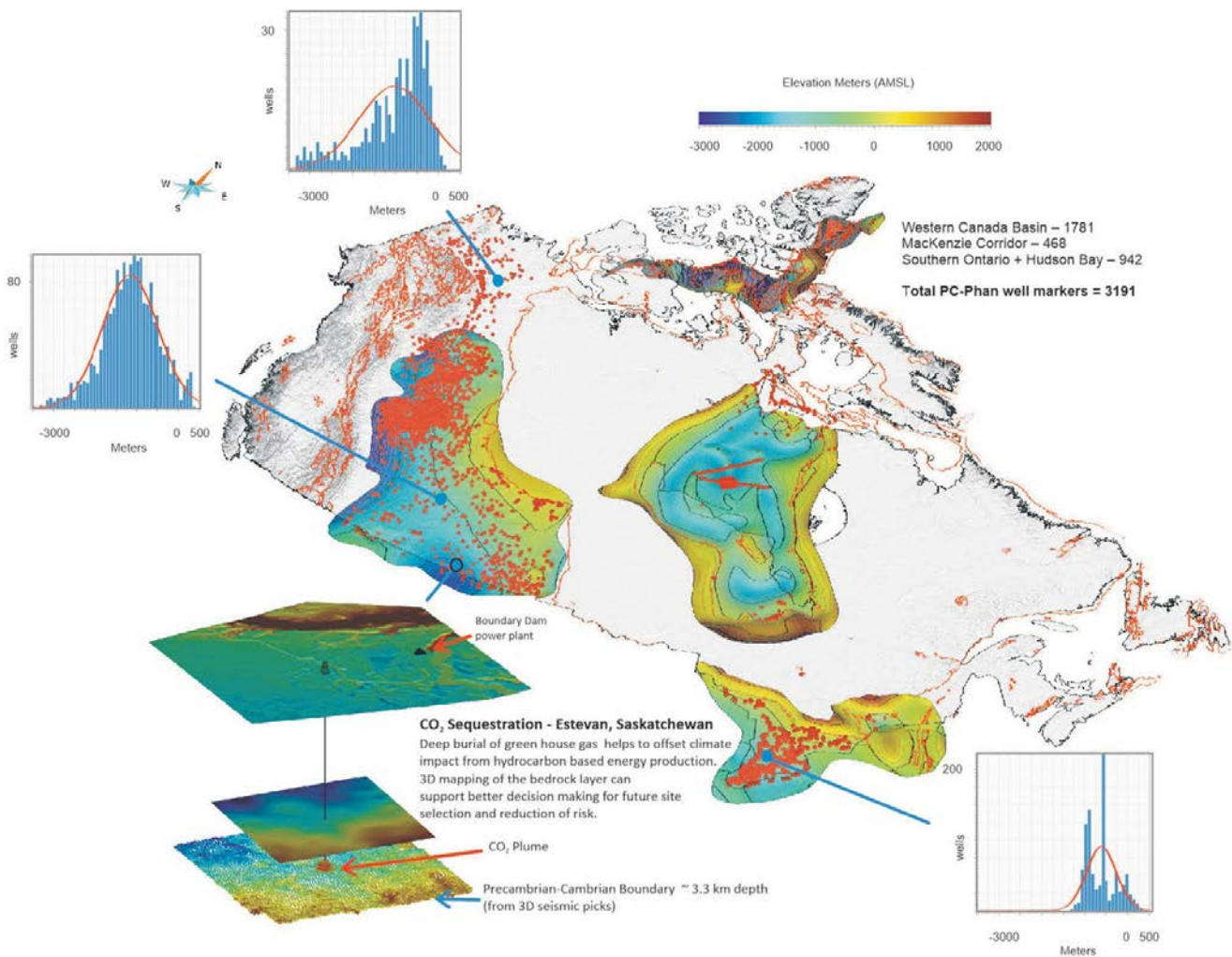
into this century, methods have evolved using explicit interpretive tools and propagation approaches for complex folding (de Kemp 2000, Hillier et al. 2013) to implicit approaches for complete structural and stratigraphic constrained systems based on co-kriging and radial basis functions (Hillier et al. 2014). Interpretive regional models at 1:250,000 and 1:100,000 scales demonstrated 3D visualization of field-data constrained models consistent with the map products and cross-sections developed for northern Canadian regions in Baffin Island and Québec (de Kemp et al.

2001 2002; de Kemp et al. 2007; de Kemp and St-Onge 2007).

Several comprehensive 3D GIS compilations combining mine-scale and regional-scale lithostratigraphic, structural, geochemical, geophysical information have been conducted within the Targeted Geoscience Initiative Program focusing on VMS systems including the Blake River Group and Giant Horne mine in the Abitibi, Flin Flon (Schetselaar et al. 2010), Laylor mines (Schetselaar et al. 2013) in the Snow Lake belt and the Heath Steel mine in the Bathurst camp. Other 3D models from gold mines Musselwhite (Northern Ontario) and Eskay Creek (British Columbia) (de Kemp et al. 2004), nickel PGE deposits in an Archean Ultramafic intrusive complex in the Ring of Fire (Northern Ontario; Laudadio et al. 2017), and porphyry copper systems at the New Afton Mine (Schetselaar et al. 2017; 2018) focused on seismic and geological integration for exploration using alteration signature detection (Figure 7).

One of the most comprehensive Canadian examples to date of a larger regional scale (1:100,000) bedrock model integrated with a detailed mine data set is the Mesoproterozoic Purcell Anticlinorium (de Kemp and Schetselaar 2015) and the Giant Sullivan SEDEX (Pb, Zn, Ag) (Montsion 2012). These models are now being incorporated in Canada-3D along with Lithoprobe deep seismic data and map compatible interpreted cross sections (de Kemp et al. 2016). The data along with the current well constrained Western Canada Basin basement-cover (Precambrian – Phanerozoic) surface will potentially be able to support the 3D extension of Western North American bedrock stratigraphy in the more complex faulted and folded Cordilleran geology.

The core challenge in going forward with these studies has been the fundamental lack of data in the subsurface



**Figure 6.** Emerging national Phanerozoic – Precambrian surface beneath Canada (de Kemp et al. 2017b).

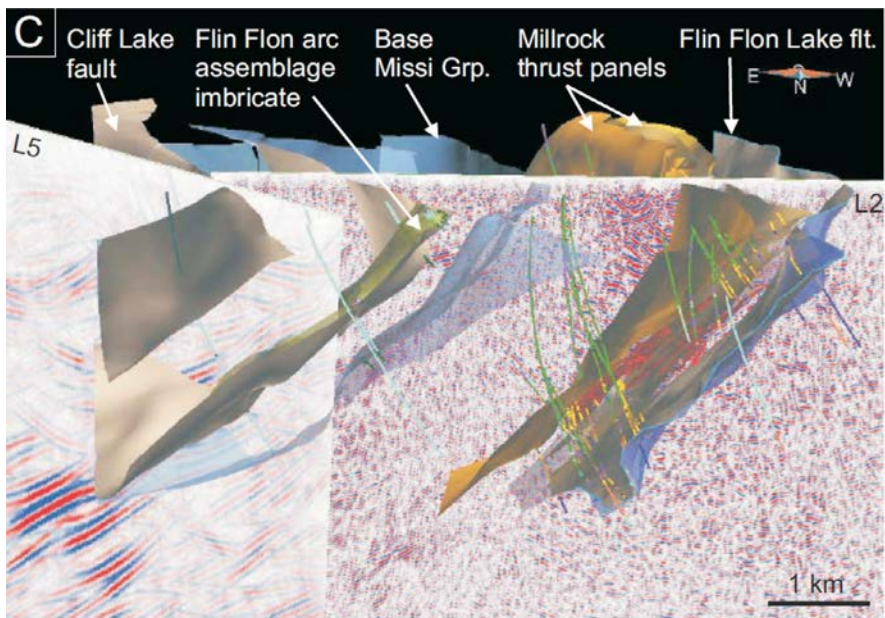
for extending deposit scale structural and stratigraphic features when using solely data driven methods. In the future, hopefully it will be possible to capitalize on existing knowledge of process behaviour and new methods for simulating scenarios given the limited data and increased complexity presented to us in the deeper orogenic regions of Canada where our mineral wealth is yet undiscovered.

### **Case Study 3. Groundwater Models**

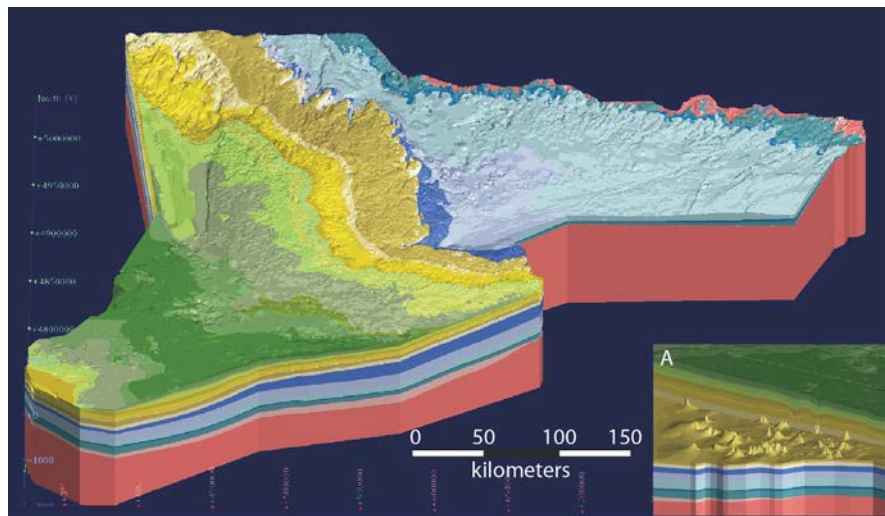
The GSC groundwater program completes regional groundwater studies with an emphasis on the delineation and characterization of potable groundwater resources at municipal scales. Studies are generally completed for areas of 700 to >100,000 km<sup>2</sup>

(e.g., Russell et al. 2011; Carter et al. 2017). Most exploited potable groundwater resource are hosted in surficial sediment in Canada and thus the focus of most of the program modelling has been on multilayer stratigraphic models of unconsolidated sediment which is generally <200 m thick. A small number of studies have focused on the stratigraphy of sedimentary bedrock successions (e.g., Carter et al. 2017; Pétré et al. 2015). The approach to model development has been a basin analysis approach with the collection of high-quality geological and geophysical data that would permit an analysis of the paleogeography of the basin and development of a predictive geological model (e.g., Sharpe et al. 2002). Supported by a process-based concep-

tual model, geological knowledge guides the interpretation and integration of disparate archival and legacy data. Three cases studies of this approach were overviewed in Berg et al. (2011) by Russell et al. (2011). Since the 2011 review, the approach to model development has not changed significantly. Data collection for surficial modelling has remained focused on integration of low-reliability water well data (Russell et al. 1998) with more rigorous seismic reflection profiling (e.g., Pugin et al. 2013), sedimentological drilling with continuous core, and downhole geophysics (e.g., Crow et al. 2015). In two pilot studies airborne electromagnetic (AEM) surveys were flown to enhance delineation of the bedrock valley geometry and the surficial stratig-



**Figure 7.** Mine camp model of the Flin Flon massive sulphide deposit illustrating data integration with 3D seismic and modelling of faults, geological units, and ore deposit (Schetselaar et al. 2017).



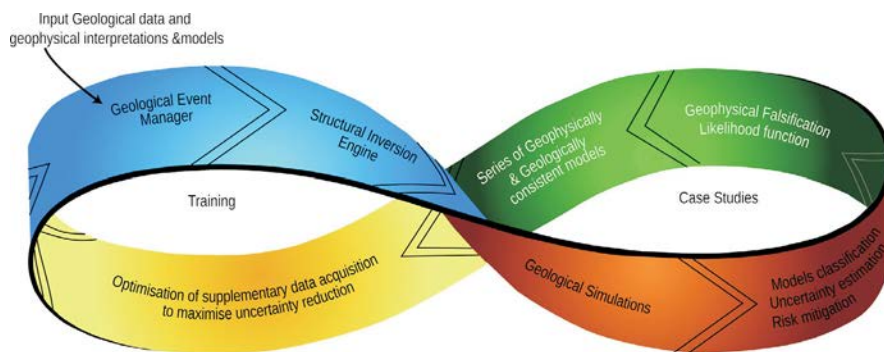
**Figure 8.** Model of sedimentary geology of 110,000 km<sup>2</sup> area of southern Ontario with 59 layers from Precambrian to Devonian age strata. **A)** Inset highlighting local detail in model surface of the Silurian Guelph pinnacle reefs.

raphy (e.g., Oldenborger et al. 2016). For regional studies, the cost of this survey technique has inhibited broader application by the GSC. A significant component of each study has been the quality assurance and checking (QA/QC) of legacy and archival data. For example, in the southern Ontario bedrock study (Figure 8), over 50,000 formation top picks have been reviewed. The iterative model development and associated data cor-

rections have been incorporated by the Ontario Oil, Gas and Salt Resource Library to ensure that all of this information is available for future modelling initiatives (e.g., Carter and Costillo 2006). Local watershed modelling has been completed to investigate stochastic methods for rendering lithofacies models and parameterization of hydraulic properties (e.g., Benoit et al. 2017).

## Current Challenges

The primary challenge faced by development of national 3D geological models in Canada is data scarcity or clustering – there is lack of adequate data support, such as drill holes and field observations, in many parts of the country. A coincident challenge is the lack of 3D modelling methods for regions of complex geology. Additional challenge exist with the need for interoperability and the challenge to overcome issues related to systems, syntax, structure, semantics, etc. (Brodaric et al. 2016). Combining these challenges leads to difficulties in developing 3D models in large parts of the country (e.g., orogenic belts, Canadian Shield). Canada is rich, however, with geological knowledge in the form of geological interpretations, such as geological maps, cross-sections and associated conceptual models. The challenge is to leverage this knowledge, in combination with available data, for augmented 3D model creation. This involves a three-fold approach: (1) recovering legacy data, to minimize data sparsity, (2) improving integration with related data (e.g., geophysics), and (3) investing in 3D modelling research, to build hybrid data-driven and knowledge-driven systems that can address complex geological environments. An example of the latter is GSC participation in the LOOP initiative (<https://loop3d.org/>; Ailleres et al. 2018), to build next-generation 3D modelling algorithms and software. This multi-agency, multinational collaboration is coordinated through OneGeology ([http://www.onegeology.org/what\\_is/home.html](http://www.onegeology.org/what_is/home.html)). It is a collaboration of geological surveys and research institutions in Australia, Canada, France, Germany and the UK. The objective is to develop an Open Source modelling solution that will model the subsurface, characterise model uncertainty and test multiple geological scenarios (Figure 9).



**Figure 9.** Graphic depiction of the proposed Loop project workflow that will support the next generation of implicit geological modelling. The platform is proposed to be OpenSource, scalable and capable of modelling problems from local to jurisdictional scale. (Graphic from <https://loop3d.org>; e.g. Ailleres et al. 2018).

An associated challenge is the lack of well-established 3D modelling infrastructure that allows models to be managed in a rigorous way. Currently, models are file-based outputs that are largely disconnected from the input data, assumptions and methods. As files, they cannot be easily searched or compared, so model contents become opaque and not queryable. A model management approach is required, as developed in other modelling domains, that integrates models into a wider modelling lifecycle. This would allow query within and across models, and bring order to the chaos of the massive number of files. As GSOs shrink in size and competition for HR resources increases it is challenging, but essential, that organizations are able to recognize, hire and integrate skill sets required in a digital big data AI environment with traditional geological personnel. As a government research laboratory, within a large government ecosystem it is often difficult to develop the recognition and understanding of computing and IT support necessary to support research-oriented objectives. With increasing consolidation and centralization of such services this challenge is increasingly constraining and reducing the GSCs ability to adapt to research needs.

## Lessons Learned

A key lesson learned concerns the maturity of 3D modelling methods and availability of data. While 3D modelling algorithms have progressed significantly, especially with the signature advance of implicit modelling, there still remains knowledge gaps in modelling complex geology, leveraging knowledge, and in the overall management and visualization of related 3D modelling data. Thus a key lesson is the need to maintain a balance between leveraging existing technologies and methods while developing improvements. Modelling to-date at the GSC has received positive client acceptance and engagement for this type of product and highlights the need for geological survey initiatives in 3D mapping and modelling.

## Next Steps

Canada-3D through the course of a two-year pilot project demonstrated the feasibility of a national scale geological model implemented incrementally and with areas of prioritization. Next steps include continued advances in all aspects of the realization of the national 3D model. Canada-3D also provides a framework for high-resolution, regional models which previously lacked context, while integration of such work provides a platform for continued en-

agement and dissemination to broader and new clients. There remains a continuing need for sustained funding to support data collection in the subsurface, for example geophysical surveys. There is also a real need for improved data management and accessibility across a number of sectors of the economy (e.g., mining, geotechnical, hydrogeological). Research modelling initiatives are providing the methods development (e.g., de Kemp et al. 2017a; Hillier et al. 2017) to make regional modelling more feasible. New methods and tool development are essential and initiatives such as Loop (<https://loop3d.org/>) will advance our ability to complete implicit modelling. Experience has also indicated that such initiatives need to be multiagency, commonly multi-national, and increasingly multidisciplinary. Canada-3D will support the New Economy for energy resources (geothermal, tidal), water resources (critical for climate change etc.), and infrastructure development (seismic zonation) by better defining broad framework for subsurface resources and hazards.

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# Chapter 9: Institut Cartogràfic i Geològic de Catalunya: Synopsis of Three-Dimensional Geological Mapping and Modelling

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## Introduction

The Earth is three-dimensional (3D) and heterogeneous as a consequence of the succession of different geological processes throughout time. For this reason, to understand Earth's nature and processes, as well as to predict the effects of human activities on the ground, it is necessary to study it from a 3D/4D perspective. Therefore, one of the main challenges for geological survey organizations (GSOs) is to gather subsurface data and predict the nature and behavior of the subsurface from the available data.

The Cartographic and Geological Institute of Catalonia (ICGC), as a public organization of the Government of Catalonia, aims to provide formally homogeneous geological and geomatic information, appropriate to support territorial and urban planning, the execution of civil engineering works, the reduction of risk, as well as other activities of public management that require knowledge of subsurface structures and compositions.

3D geological mapping and modelling has been embraced at the ICGC during the past 10 years as data collection, analysis, visualization, and presentation methods have evolved with the advent of personal computers equipped with fast video cards, vast

storage capacity, and 3D software programs (CAD, GIS, and other specific applications). As a result of this work, a series of 3D geological models have been developed at different resolutions, and with varying approaches, geographical areas, and objectives.

This contribution describes the state of the art of 3D geological mapping and modelling at the ICGC. This overview will help us to explain the organizational challenges that we hope to achieve in the coming years as 3D modelling and visualization will allow us to best assess the benefits of the ICGC to the society that it serves.

## Organizational Structure and Business Model

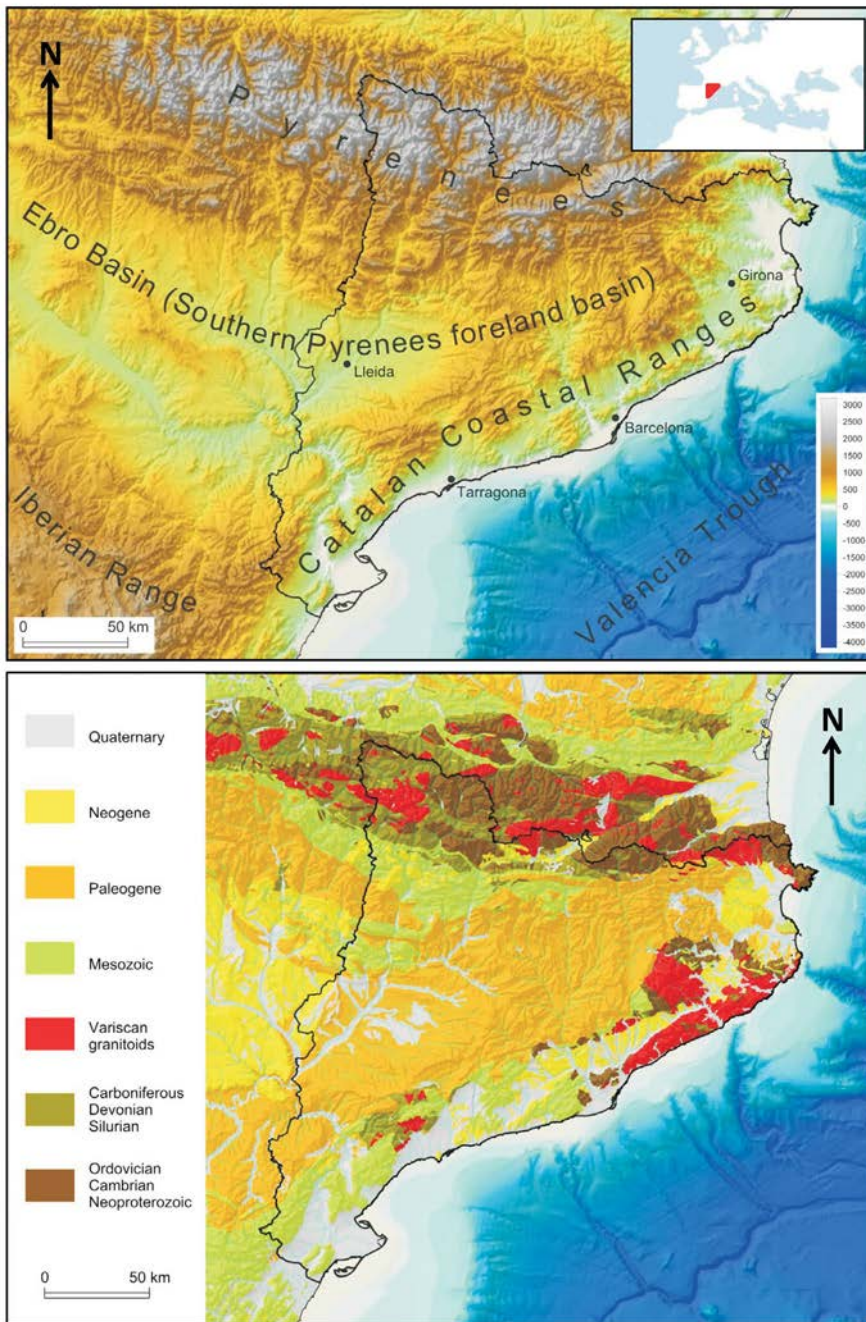
The ICGC represents a public organization whose purpose is to promote and carry out actions related to knowledge, exploration, and information on the soil and the subsoil, within the scope of the competencies of the Government of Catalonia (Figure 1).

The ICGC was created in 2014 from the merger of the Institut Cartogràfic de Catalunya (the national mapping agency) and the Institut Geològic de Catalunya (the geological survey organization). In accordance with arti-

cle 152 of Law 2/2014 of the Government of Catalonia, the ICGC adopted the legal form of a public entity; it has its own legal status, as well as administrative, technical, and economic autonomy, and it maintains a full capacity to perform functions congruent with its goals and mission. The ICGC reports to the Ministry of Territory and Sustainability that is responsible for territorial policy and urbanism.

At the time of drafting this document (November 2018) the ICGC has a staff of 267 employees. About 20% of the staff focus scientific-technical tasks specific to a Geological Survey Organization. This group of Earth science professionals roughly is organized into 11 teams addressing regional geology, geological mapping, earth surface processes, hydrogeology and geothermal energy, geotechnics and geological engineering, geological hazards and risk assessment, urban geology, soil science, avalanche prediction, seismology, geophysical exploration, environmental geology and geological heritage.

Apart from these activities, the ICGC performs other tasks related to geodesy, topography, cartography, remote sensing, and geographic information systems, all of which support the geological survey. In particular, are tasks



**Figure 1.** Physiography (top) and geology (bottom) of Catalonia and neighboring areas.

related to 3D geological mapping and modelling.

Some ICGC tasks within geological projects are outsourced, while other activities are carried out in collaboration with the academic community and other public and private institutions.

The production and technical objectives of the ICGC are defined in a contract established with the Government of Catalonia. This contract covers ~85-90% of the annual budget and includes tasks that the ICGC plans to execute in order to comply with its functions as established by law. The remainder of the budget comes from

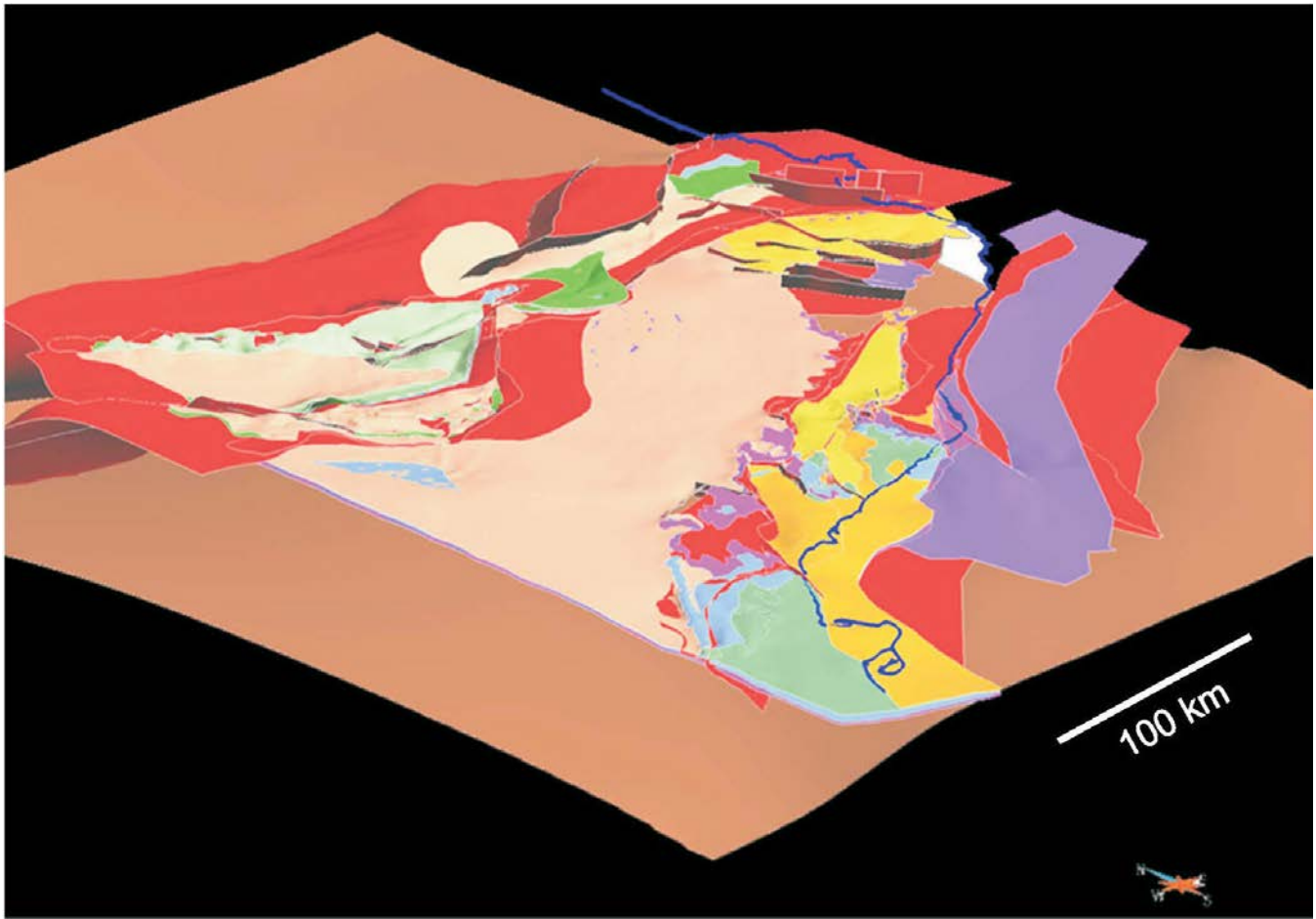
commissioned work from the public and private sectors.

## Overview of 3D Modelling Activities

Over the past 10 years, a very significant part of the 3D geological modelling activity at the ICGC has been conducted within the framework of a specific project called the 3D geological model of Catalonia. Its main objective was the development of a 3D geological model of Catalonia at a resolution of 1:250,000 scale, and it was based on the collection, classification, homogenization, and reinterpretation of available surface and subsurface geological information. This 3D geological model of Catalonia was developed through collaboration with the Geomodels Research Institute of the Universitat de Barcelona (Gratacós et al. 2012). The first version of the 1:250,000-scale 3D geological model of Catalunya was completed in 2013 (Figure 2).

In addition to the 3D geological model of Catalonia, the ICGC has performed other 3D geological modelling endeavors for specific geographic regions. Two representative examples of these activities are:

- The 3D geological modelling related to the development of the 1:5,000-scale Urban Geological Map of Catalonia (Pi and Vilà, 2013). A pre-Quaternary basement map, cross-sections, and an isopach map of surficial materials (Vilà et al. 2015) were components of the 3D modelling and portrayed on geological map sheets that covered 8 km<sup>2</sup>.
- The 3D reconstruction of the architecture of the Holocene deposits of the Ebro delta plain (Figure 3). This model was developed within the framework of a larger project called LIFE EBROADMICLIM (<http://www.lifebroadmiclim.eu>), which advocates for pilot actions related to adaptation to and mitigation of climate change in the Ebro Delta



**Figure 2.** General view of the 3D geological model of Catalonia (version 1.0).

(south Catalonia), an area vulnerable to sea level rise and subsidence. The main objective of this 3D model was to evaluate the distribution of areas susceptible to subsidence (Rodríguez et al. 2018).

In addition, 3D geological modelling in recent years also has concentrated on the development of methods and techniques, as for example:

- Programming CAD applications for the 3D analysis of geological traces, outcrop data, and borehole logs to facilitate the reconstruction of geological surfaces and cross sections.
- Determination of soil-rock boundaries and some Quaternary sedimentary horizons from the analysis of passive seismic data (e.g., Macau et al. 2015).

- Development, most recently of specific tasks of ICGC projects related to geo-resources, natural hazards, and engineering geology.

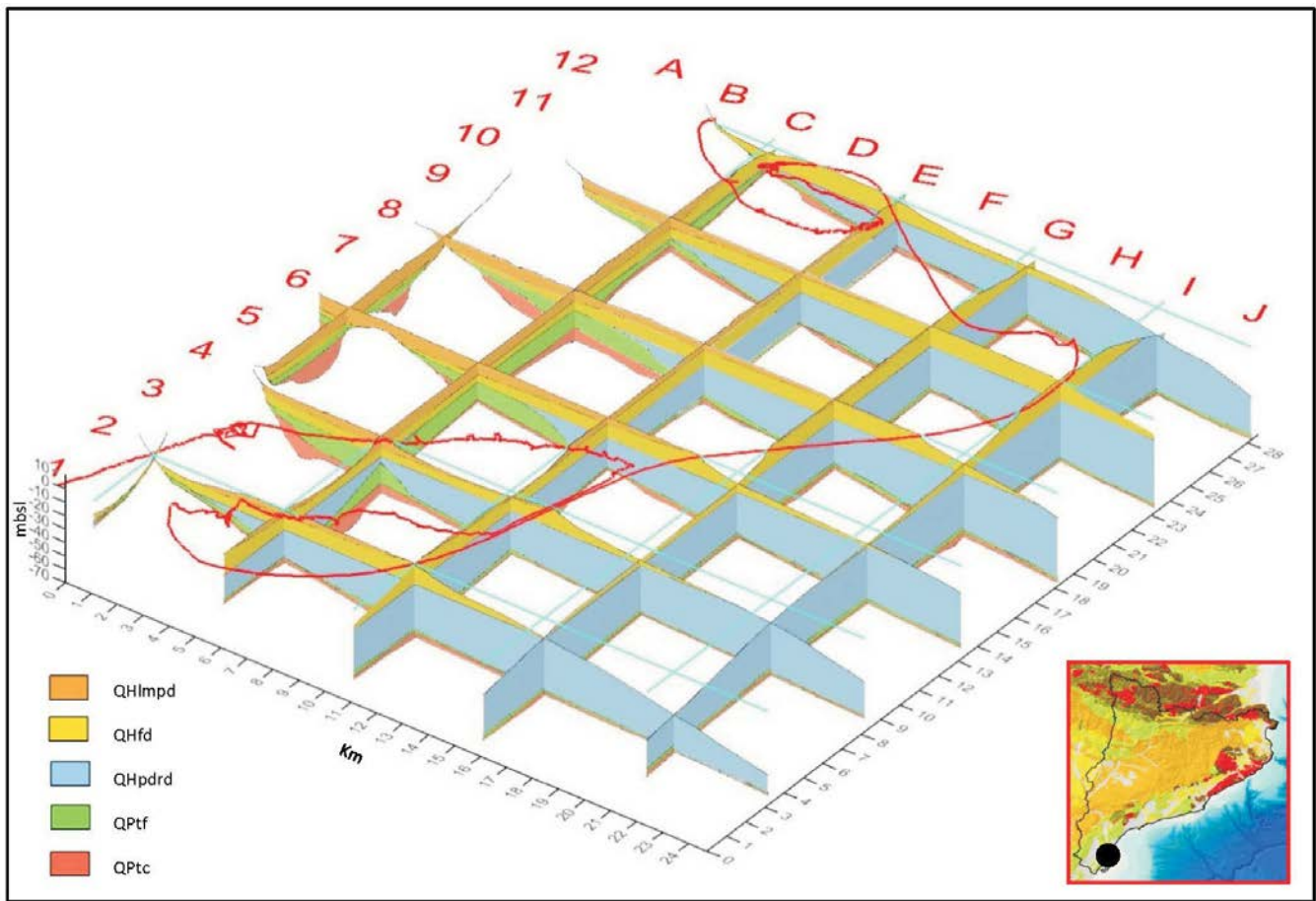
### Resources Allocated to 3D Modelling Activities

The 3D geological model of Catalonia project represents one of the 33 lines of work included within the strategic programme 2014-2018 (and the 40 of the 2019-2022 programme). The total yearly budget of this project is ~150,000 €. These annual resources allow for the dedication of ~3,200 hours related to 3D modelling (approximately equivalent to the full dedication of two geologists) and the outsourcing of some specific work.

These resources are relatively small compared to those dedicated to over-

all geological mapping projects. However, the development of 3D models is dependent upon and benefits from traditional 2D geological mapping. Broadly speaking, in the last 5 years, about 10-14 geologists have been dedicated, full time, on the development of traditional 2D geological maps. Their efforts mainly have been focused on constructing and publishing geological maps at 1:25,000-scale, as well as, associated thematic maps (Figure 4). From an administrative point of view, the development of these maps has not been explicitly considered to be related to 3D geological modelling.

Despite advances in the development of specific software for depicting the 3D geology, activities related to digital geological mapping in the ICGC have been done using standard CAD and GIS tools (basically Microstation



**Figure 3.** 3D view WNW-ESE cross sections (2, 4, 6, 8, 10 and 12) and SSE-NNW cross sections (A, C, E, G and I) showing the structure of the Holocene and Upper Pleistocene deposits of the Ebro delta plain. QHlmpd: Holocene lagoon, marsh, and alluvial plain deposits; QHfd: Holocene delta front deposits; QHprdr: Holocene prodelta deposits; QPtf: Upper Pleistocene fine grained transgressive deposits; QPtc: Upper Pleistocene coarse grains transgressive deposits.

and ArcGIS). The investment in 3D geological modelling software and associated training has been low. Currently the ICGC has 9 GOCAD licenses, 2 Move licenses and 1 GeoModeler license. Over the last 10 years the ICGC has offered only one generic training course (2015) for 3D geological modelling. It involved 35 hours of teaching and 10 ICGC geologists participated by initially learning GOCAD and Move. However, since then, there has not been continuity in the systematic use of these softwares, and geologists have been training on their own.

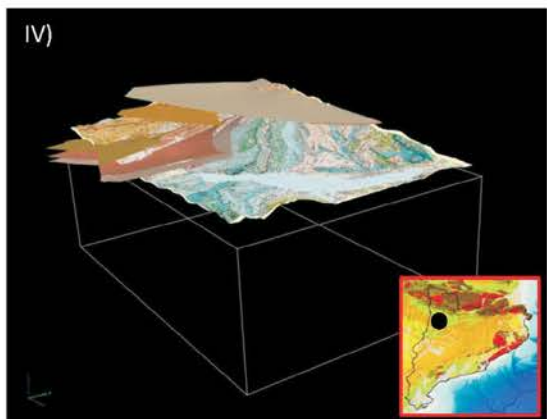
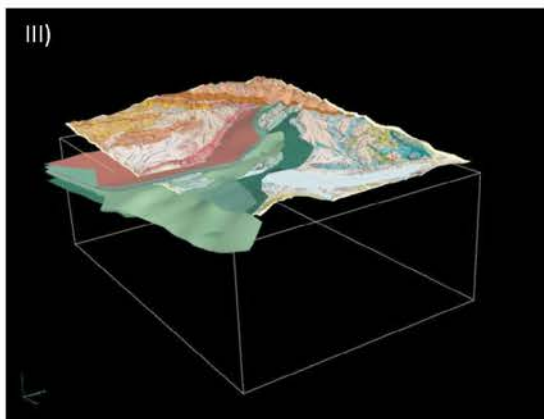
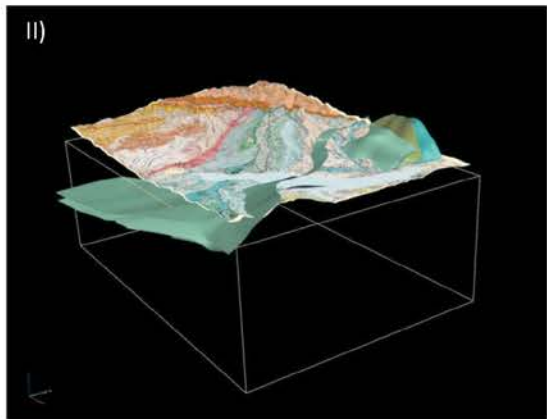
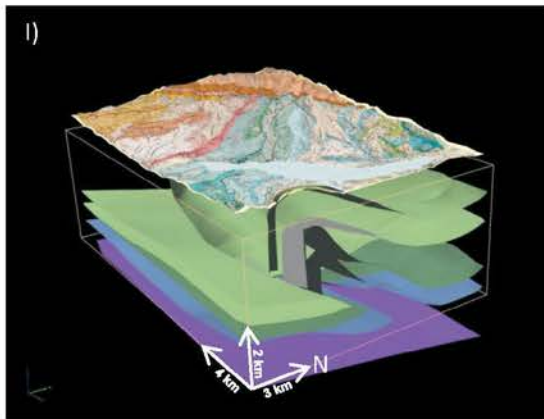
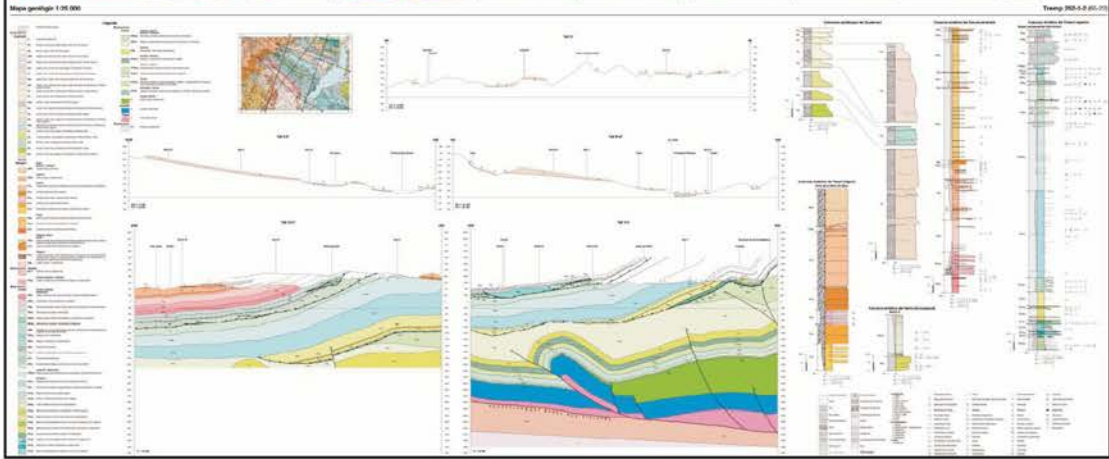
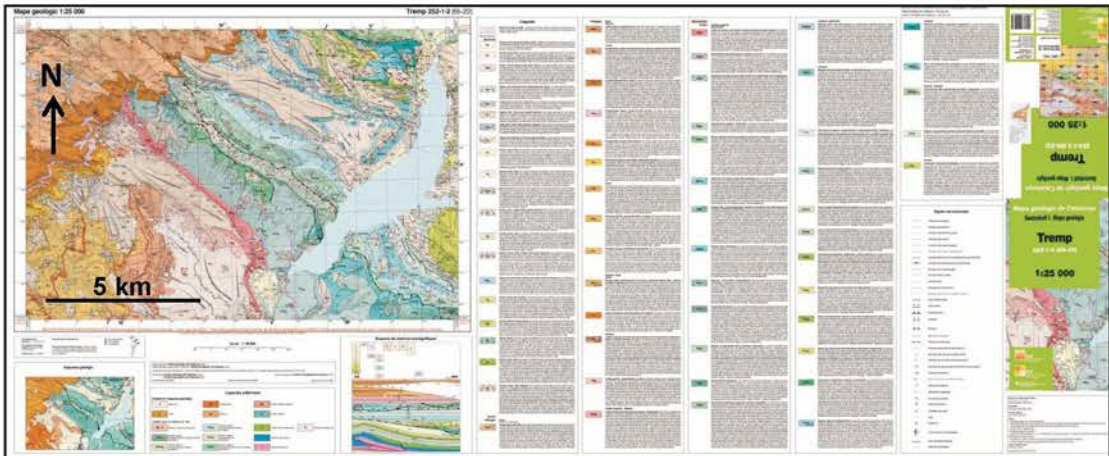
It is difficult to quantify the total resources that the ICGC commits to 3D modelling activities. Broadly speaking, it is estimated that the resources allocated to the 3D geological model of Catalonia project represented approximately 25% of the total resources that the ICGC dedicates to 3D geological modelling activities. It is important to note that a significant part of the results related to 3D geological modelling has been performed mostly based on individual initiatives, where modelling has been used as a tool to solve specific aspects of projects, but not explicitly labeled as 3D.

### Overview of Regional Geological Setting

Covering an area of 31,895 km<sup>2</sup>, Catalonia has significant physiographic diversity that directly reflects the underlying geology (Figure 1). The geomorphology reflects Cenozoic events linked to the Alpine Orogeny and the subsequent opening of the Valencia Trough in the western Mediterranean (Losantos and Berástegui, 2010).

The territory of Catalonia can be subdivided into three main morphostructural domains: (i) The northern do-

**Figure 4.** Top: Example of a printed map sheet of the 1:25,000-scale Geological Map of Catalonia series, the Tremp map sheet (Cirés et al. 2009) from the Central Pyrenees. Bottom: 3D reconstructions of pre-Campanian Mesozoic horizons (I), Campanian reference horizons (II), Maastrichtian reference horizons (III) and Paleogene reference horizons (IV) of the Tremp area developed after the publication of the Tremp geological map sheet 1:25,000-scale (Institut de Recerca Geomodels, 2012).



main, is a mountainous region that belongs to the southern limb of the central and eastern part of the Pyrenees; (ii) the coastal domain, named the Catalan Coastal Ranges, includes a system of mountain ranges separated by basins parallel to the present coastline, and (iii) the central domain, a relatively depressed region that defines the eastern sector of the Ebro Basin, represents the Cenozoic foreland basin of the Pyrenees, the Iberian Range, and the Catalan Coastal Ranges.

The Variscan basement has a sedimentary cover outcrop in the Pyrenees and the Catalan Coastal Ranges. The Variscan basement includes Lower Palaeozoic clastic-dominated sedimentary sequences, Upper Palaeozoic carbonate-dominated sequences, and late-Variscan intrusions of granitoids. The sedimentary cover primarily consists of Mesozoic carbonates, terrigenous red beds and Triassic evaporates, and Palaeogene clastics and carbonates. The general structure of the materials outcropping in the Pyrenees and the Catalan Coastal Ranges is governed by several systems of folds and faults related to the Alpine Orogeny. In addition, the basement rocks are affected by ductile structures and metamorphism related to the Variscan Orogeny.

Generally, the fill of the eastern Ebro Basin consists of a composite succession (up to 5 km thick) of alternating continental deposits of Palaeocene and late Eocene-lower Miocene age and marine sediments of early-middle Eocene. The Palaeogene deposits located at the margins of the current day Ebro Basin were affected by compressive structures related to the Alpine Orogeny.

In the eastern Pyrenees and the Catalan Coastal Ranges, the Alpine structures have been overprinted by Neogene extensional structures related to the opening of the NW Mediterranean margin. As a result of this extensional period, a series of basins were

formed, which were gradually infilled by continental and marine deposits. In NE Catalonia, at the intersection of the eastern Pyrenees, the Ebro Basin and the Catalan Coastal Ranges, there is a volcanic province also related to the development of these young extensional basins.

The Quaternary record in Catalonia encompasses many environments, including alluvial, fluvial, colluvial, lacustrine, glacial, aeolian, coastal, estuarine, and marsh deposits. In the coastal and fluvial plains, there are outcrops of upper Pleistocene-Holocene deposits that are related to the last global sea level rise. Also present are the Pleistocene alluvial-colluvial deposits related to the climatic cycles previous to the last glacial period that cover many plains and foot slopes.

Apart from the geological configuration, throughout history, the territory of Catalonia has undergone intense landscape modifications related to human activity (agrarian, urban, etc.). It is important to note that since the Classical Greek period, Catalonia represents an important strategic crossing point that links the western Mediterranean region with the rest of Europe. Urban zones represent the areas where anthropization has a significant impact on the ground. Catalonia has a population of 7,534,813 inhabitants spread over 947 municipalities ([www.idescat.cat](http://www.idescat.cat) retrieved 1 January 2018), and 131 of these municipalities have more than 10,000 inhabitants, mainly located in the coastal area. The Barcelona Metropolitan Area, including Barcelona City and 35 neighbouring municipalities (~3.3 million people in an area of 636 km<sup>2</sup>) is the most heavily populated region. Other urban areas with more than 100,000 inhabitants include Terrassa-Sabadell, Tarragona-Reus, Lleida, Mataró and Girona.

## Data Sources

Catalonia has had a geological map at 1:250,000 scale since the mid 1990s.

Associated with this map and the associated database are 228 cartographic units differentiated as follows: 22 Quaternary, 24 Neogene, 56 Paleogene, 55 Cretaceous, 4 Jurassic, 9 Triassic, 1 Permian, 5 Carboniferous, 15 Devonian, 1 Silurian, 7 Cambrian-Ordovician, 15 Variscan plutonic rocks, and 14 metamorphic rocks. This geological map represents the basic geological conceptual reference for the initial construction of associated more detailed models.

In 2007, the ICGC completed a geological map at 1:50,000-scale for the whole territory of Catalonia. The map, which is available in shp format, was derived from synthesizing and harmonizing the geological information of the MAGNA project (geological maps sheets 1:50,000 scale made by the Geological and Mining Institute of Spain), that was conducted between 1997 and 2007. This larger-scaled geological map homogenized 84 map sheets, and it covered an approximate area of about 500 km<sup>2</sup> for each 1:50,000-scale map. The 1:50,000-scale geological map of Catalonia, and its associated database, have not been updated since 2007. The map includes 1047 cartographic units. The distribution of these units undoubtedly represents an essential source of geological data of reference to build 3D reconstructions throughout Catalonia.

The geological database associated with the 1:50,000-scale mapping represents a detailed source of information covering the entire territory of Catalonia. However, the ICGC has more detailed information that covers a considerable part of the territory. Much of this information derives from the development of a 1:25,000-scale geological map of Catalonia. Currently (November 2018) there are 92 published map sheets of this cartographic series that cover a total area of ~10,000 km<sup>2</sup>. These map sheets include a considerable number of structural measures, geological cross sections, and stratigraphic columns. The

development of this 1:25,000-scale project entails the compilation and homogenization of a large volume of data from outcrops and boreholes. In parallel to this effort, the ICGC also has conducted other regional mapping projects, but oriented towards the inventory of geothematic data (e.g., geomorphological, hydrogeological). These products have also been useful contributions to the 3D modelling effort.

In urban areas, in general, there is a considerably higher density of available data, especially geotechnical. The 1:5,000-scale geological map sheets from the Urban Geological Map of Catalonia project include a large volume of geological information (Pi and Vilà, 2013). At present (November 2018), 38 map sheets have been published, covering 310 km<sup>2</sup>.

In addition to the information related to geological maps, the ICGC has other sources of geological information that have been useful to build 3D geological models. Currently the ICGC's document management system stores 11,046 technical reports that can be consulted upon request. The ICGC also hosts a borehole database with ~31,000 logs and a geophysical database that includes the results from various surveys (gravity, electric, magnetotellurics, active seismic, passive seismic, well-logging) that have been conducted during the last 40 years.

Apart from the geological information, it should be noted that the ICGC is the national mapping agency of Catalonia. Through the Vissir application (<http://www.icc.cat/vissir3/>), a large number of layers of topographic information useful for the development of 3D geological models can be viewed and downloaded:

- Topographic maps of the entire territory up to 1:5,000 scale.
- Topographic maps at 1:1,000 scale for urban areas.

- Current orthophotos up to 25 cm pixel size of the entire territory.
- Digital elevation model with a 5-meter grid size of the entire territory derived from the 1:5,000-scale topographic database.
- Digital elevation model with a 2-meter grid size of the entire territory derived from LiDAR data. The point cloud, in las format, is also provided.

It should be noted that topographic cartography is available in 3D formats (e.g., 3D dgn files). This facilitates the reconstructions and the integration of buildings and other topographic features in 3D geological models.

Apart from these cartographic data sources, which are periodically updated, the ICGC makes available a large volume of historical topographic maps, photogrammetric frames, and satellite derived images that can be used to identify ground surface changes over time and landscape evolution.

### 3D Modelling Approach

As described in the Overview of 3D Modelling Activities section, the main objective of 3D geological modelling has focused on the geometric reconstruction of geological structures. Recently, the ICGC began to develop more sophisticated models, with physicochemical parameters, in order to make more realistic simulations and predictions. These advanced models are in a preliminary stage, and can be envisaged as one of the current challenges of the ICGC.

The reconstructions carried out to date are basically deterministic, and most of them have been obtained by applying explicit methods. Broadly, the explicit method reconstructions imply (1) establishing 3D geometric relationships between initial data, (2) the use of the initial data in its original xyz position, (3) and applying geological knowledge in the data

analysis. The explicit reconstructions have the disadvantage that they are laborious, and by contrast provide greater control and understanding over each reconstruction step. On the other hand, it is important to emphasize that by means of the explicit method, any type of geologic structure can be reconstructed regardless of its complexity. In addition, explicit reconstructions can be obtained using current CAD tools, as they do not require the application of very specific software. This is important because the reconstructions easily can be merged with many kinds of specific projects (e.g., ground and environmental engineering, natural hazards, municipal operations, reality modelling, roads and other types of infrastructure).

As has been discussed in the previous section, the nature of the primary geological surfaces that divide the subsurface of Catalonia are very diverse. This fact influences the way that the ICGC has reconstructed surfaces. Some of the more common methods are:

- 1) Comparing digital terrain models. The comparison of topographical documentation of different periods highlights the impact of human activities on the ground through time (Vilà et al. 2015). Thus, from a 3D geological modelling perspective, it is possible to define the geometry of certain artificial deposits by comparing detailed pre- and post-urbanisation digital terrain models, such as infilled river channels. This method is also useful to detect 3D landscape evolution related to natural processes such as coastal or alluvial dynamics.
- 2) Surface contouring. This method basically consists in interpolating the locations of selected contour elevations honouring the information at a number of places (e.g., Groshong 2006). For a long time, surface contouring has been widely applied to 3D geological modelling as it allows for the re-



construction of the geometry of surfaces in an easy way. The surface contouring method is especially useful to model the geometry of near surface deposits that are relatively thin (e.g., Anthropocene, Quaternary and Neogene units).

- 3) Dip domain. The segmentation at different scales of geologic surfaces into planar domains using the dip domain method (e.g., Fernández et al. 2004, Carrera et al. 2009) is one of the most useful strategies to build internally consistent geological models of multi-layer sequences, especially where extensive surficial exposures exist (e.g., the Paleogene and the Mesozoic units in the Pyrenees).
- 4) Interpolation of 2D sections. The interpolation between closely spaced 2D data, such as seismic sections or geological cross-sections (e.g., De Donatis 2001, Kessler et al. 2009) is one of the most applied methods of 3D reconstruction of geological surfaces from field and subsurface data.
- 5) Gridding structural orientation data. The interpolation of spatially distributed measures of regional planar geological structures allows for obtaining of the continuous distribution of such structures on a grid cell basis (e.g., Meentemeyer and Moody 2000, Günther 2003). The application of this method, based on regionalisation of structural orientation data, is useful, for example, for predicting the orientation in the near surface of the Variscan regional foliation of the Cambro-Ordovician successions.

The reconstruction of 3D subsurface structures that represent the diverse types of environments of Catalonia can be obtained by applying and utilizing the above methods. These methods were used for the development of the 1:5,000-scale Urban Geological map of Catalonia (Vilà et al. 2015). However, other methods of reconstruction have been used and, of-

ten the most effective way to build a particular surface is applying a hybrid procedure by combining different methods. The ICGC's modelling approach is to build 3D models that involve applying a combination of explicit methods.

## Clients

Major users of ICGC data and information include the ministries and agencies of the Government of Catalonia, and the councils and other public organizations that focus their activity on the management Catalonia's municipalities.

Because of the national scope of the ICGC functions, land management agencies use its surveys in developing policies that help them meet their administrative responsibilities. For example, the Ministry of Territory and Sustainability rely on ICGC geothematic information to develop the land-use policies that are within its jurisdiction. The ICGC also provides information that helps other government organizations develop and enforce regulations. For example the Catalan Water Agency relies on ICGC assessments of groundwater levels and quality across the territory. The ICGC provides information that helps develop policy and provides warnings or mitigation strategies related to hazards such as landslides, floods, subsidence and collapses, avalanches, and earthquakes. The ICGC is focused on providing geoinformation to the citizens of Catalan, and it also provides impartial advice to academia and industry.

Usually, the general customers of the ICGC information do not directly use 3D geological models, but they use the results. Academic users are usually collaborators in 3D modelling helping to improve modelled resolutions and checking the correct shapes of the modelled structural features.

Concerning the prioritization of the modelled regions, for the general 3D

model of the whole territory, the ICGC continues to improve its spatial resolution in the areas where there is new available information.

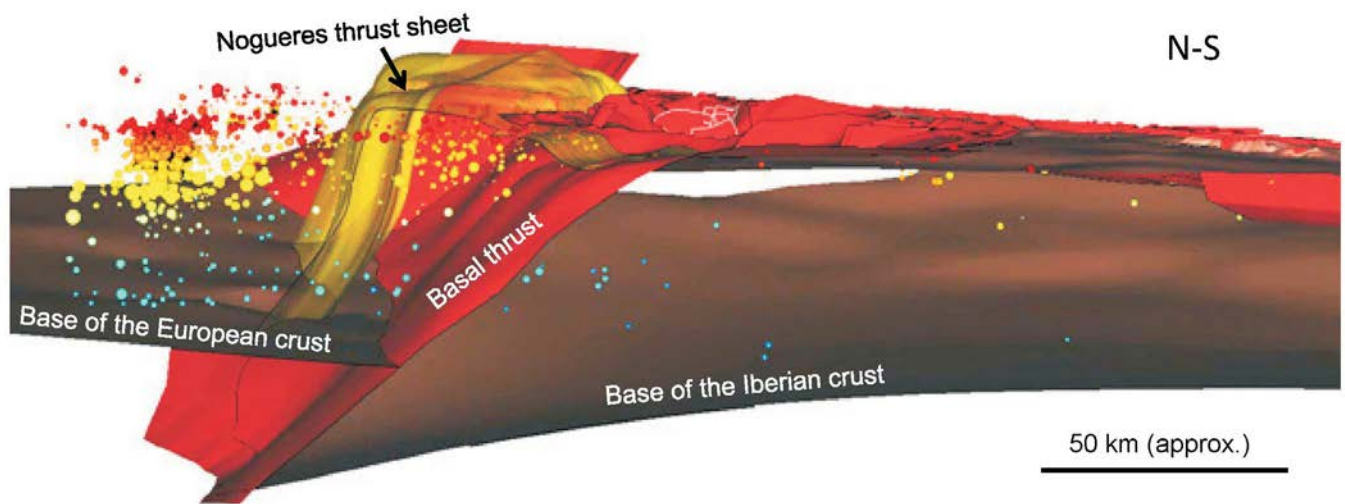
## Recent Jurisdictional-Scale Case Study Showcasing Application of 3D Models

As previously stated, in 2013 the ICGC, in collaboration with the Geomodels Research Institute of the Universitat de Barcelona, finalized version 1 of the 3D geological model of Catalonia at 1:250,000-scale (Figure 2). According to Gratacós et al. (2012), the methodology used to generate the 3D geological model of Catalonia is summarized as follows:

- Adequacy of information. Collecting information from different sources involved different data formats. All this data was transformed in a common digital format for its use in a common 3D graphic environment.
- Database. A database was generated including some properties (type, quality, format, authors, etc.).
- Information was added in a common 3D graphic environment. Collecting and visualizing of all available information was accomplishing using a single software (GOCAD).
- 3D reconstruction. A deterministic geological surface and 3D reconstruction was made honoring all available data and incorporating geological constrains.

The 3D geological model of Catalonia covers the entire territory and differentiates 11 main stratigraphic discontinuities:

- Base of the Triassic
- Base of the Jurassic
- Base of the Lower Cretaceous
- Base of the Upper Cretaceous
- Base of the Upper Santonian (initiation of the Pyrenean deformation)
- Top of the Garumnian materials
- Base of the Lower Eocene



**Figure 5.** N-S view of the 3D geological structure of west Catalonia, with accompanying earthquake hypocenters.

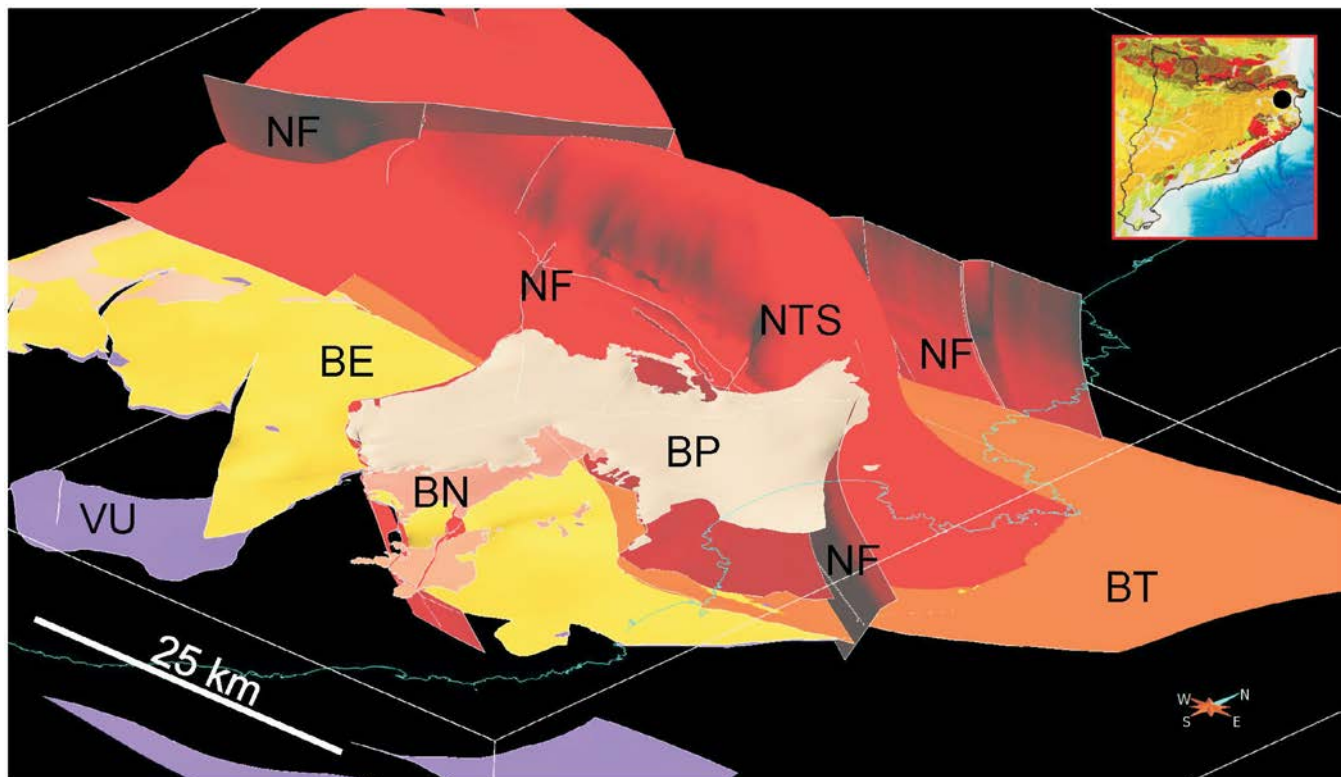
- Base of the Lower Priabonian
- Base of the Neogene
- Base of the Middle Miocene
- Top of the Paleozoic basement (Variscan unconformity)

Moreover, the realization of the model involved the reconstruction of 30 major structural discontinuities (indi-

vidual faults and fault systems) as well as the base of the crust of the Iberian plate and the European plate (Figure 5).

The 3D geological model of Catalonia only includes the reconstruction of the most important surfaces (stratigraphic and structural discontinuities), leaving the volumes between

them as empty spaces. This model, which can be downloaded in 3D pdf format from the ICGC web page ([www.icgc.cat](http://www.icgc.cat)), represents an important improvement in the visualization of the structure and the composition of the subsurface of Catalonia and allows for an improved disclosure of geological knowledge. Over the last 5



**Figure 6.** Detail of the geological structure of the Empordà Basin (NE Catalonia). BP: Base of the Pliocene deposits; BN: Base of the Neogene deposits; BE: Base of Paleogene deposits; VU: Variscan unconformity; NTS: Nogueres thrust sheet; BT: Pyrenean basal thrust; and NF: Neogene normal faults.

years, the model has served as a basic geological reference in numerous specific studies.

Since its completion, the 3D geological model of Catalonia (version 1) has been improved in the Neogene Empordà Basin (Gratacós et al. 2015), taking into account data from 1:25,000-scale geological maps and new available data (Figure 6). The Institute foresees the update of the model. However, during the last 3 years it has not had significant modifications.

## Current Challenges

The primary current challenges that the ICGC must face regarding 3D geological mapping and modelling are:

- Fostering the use of 3D geological modelling tools by geologists engaged in geological mapping projects. There are currently a large number of 3D geological modelling tools that can facilitate the development of many common tasks in geological mapping projects (e.g., making geological cross sections). However, the available tools commonly are underutilized, although their use in the near future would be very beneficial. Encouraging 3D geological modelling is a challenge for those geologists that have been engaged with traditional 2D geological mapping.
- Taking advantage of the technological infrastructure and 3D topographic databases. Over the last few years, the ICGC has devoted considerable effort to the generation of high resolution 3D topographic geoinformation for the management and sustainability of the territory (e.g., LiDAR surface model with a minimum density of 0.5 m<sup>2</sup>), and in particular urban and peri-urban areas (e.g., topographic cartography of urban areas at a scale of 1:1,000). The acquisition of this information and the know-how generated should be

used in the development of 3D geological models.

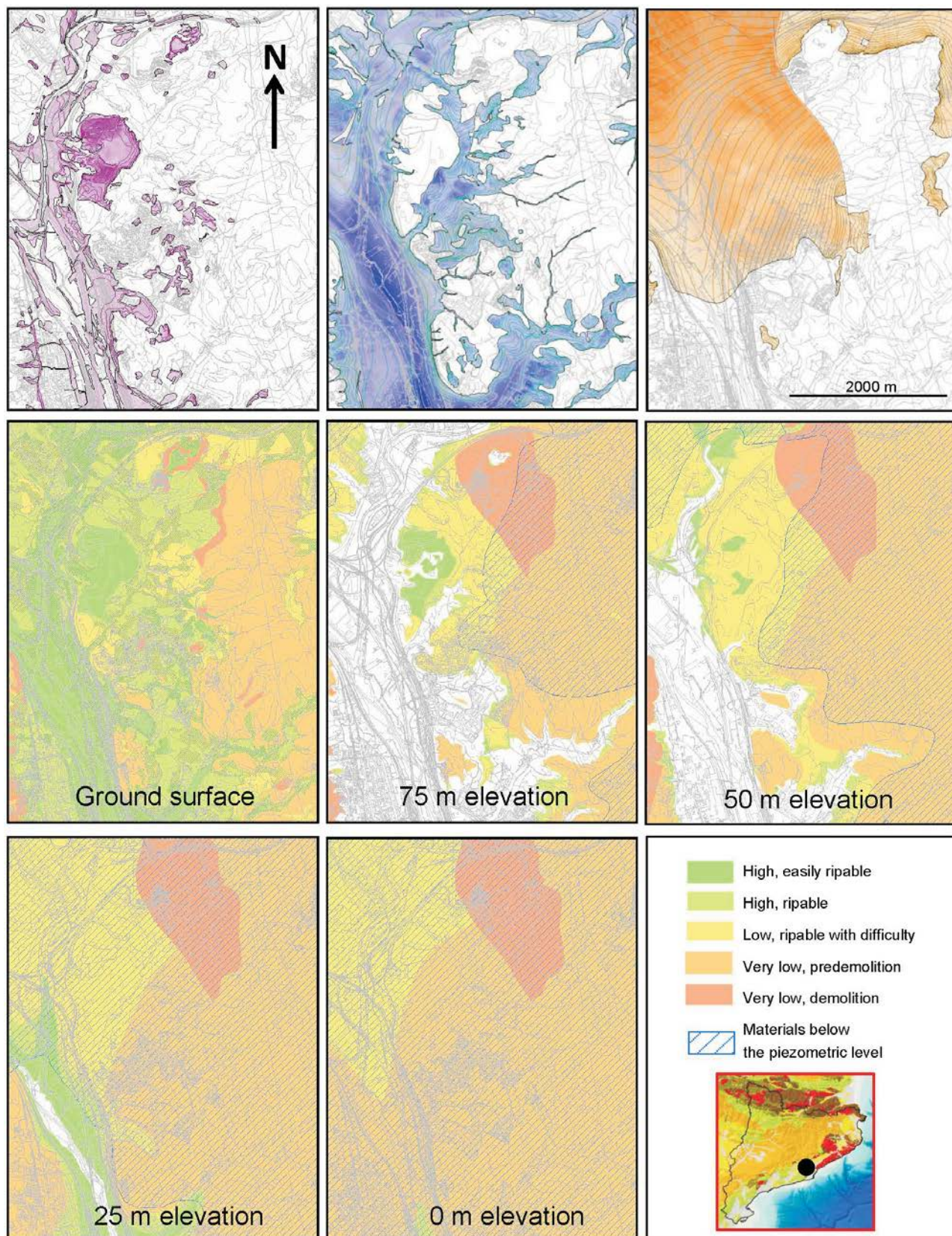
- Ensuring that the 3D geological models that are being developed have maximum interoperability with topographic information and subsurface infrastructures (e.g., transportation tunnels or commodity storage caverns). If geological models can visualize subsurface structures and allow for predictions in areas of sparse data, it is essential that the models be able to integrate into the information system used for planning and territory management.
- Implementing 3D reconstructions in applied projects. Regardless of the types of models that are constructed, it is the duty of the geological survey to use them and be able to apply them in more specific projects related, for example, to hazard management and safety, sustainable development, geo-resource management, adaptation and mitigation to climate change, archaeology/cultural heritage, environmental pollution, underground storage, and integral planning.
- Fostering the realization of models that incorporate physical and chemical parameters. To date, the ICGC's 3D geological models have basically corresponded to geometric models of the subsurface. The ICGC has begun developing projects that foresee the realization of more sophisticated 3D geological models that incorporate physical and chemical parameters of geological units. These more advanced models will allow obtaining more robust subsurface reconstructions from adjusting geophysical potential fields, simulating geodynamic processes and/or performing more accurate predictions (Figure 7). For the ICGC, it is a challenge to foster lines of work focused on the development of more robust 3D geological models that not only adjust the geometry of the units, but also the

physicochemical conditions of the subsurface.

## Lessons Learned

The development of the 3D geological model of Catalonia represents an important improvement in the visualization of the structure and the composition of the subsurface. For the ICGC, the completion of this innovative model was considered a milestone. However, the geological survey projects over time are varied; therefore, 3D geological modelling should not be considered as an end but rather as a tool that serves to improve the knowledge of the structure of the subsurface or to support projects for which knowledge of the subsurface structure is important. Apart from this general reflection, other lessons that the ICGC has learned while developing 3D modelling products or programs are:

- To plan the models taking into account the regional geological setting. The regional geological knowledge in the technical body of the ICGC is the main asset for developing 3D geological models.
- To develop models that integrate and honor information derived from different techniques, as far as is practical. For example, combine data from outcrops, boreholes, and geophysical techniques. In this way the models will be more robust and consistent.
- To avoid relying excessively on specific software and computer formats. The developed models must be easily exportable and able to integrate into standard systems. The GSO must have sufficient infrastructure to effectively disseminate the models that are constructed.
- The realization of 3D geological models often requires a multidisciplinary approach. For this reason, collaboration between different groups of experts must be encouraged. It is not necessary for all members involved in the real-



**Figure 7.** Example of 3D geological reconstructions used to predict terrain excavatability conditions. Isopachites of the Anthropogenic deposits (I), Quaternary deposits (II) and Miocene deposits (III); and excavatability conditions at ground surface (IV), 75 m (V), 50 m (VI), 25 m (VII) and 0 m (VIII) elevation above sea level. These predictions come from the urban geology pilot project of el Papiol municipality of the Metropolitan Area of Barcelona (ICGC, 2016).

ization of a 3D geological model to master computer tools, to have a thorough knowledge of the geological structure of the region or to be experts in geo-resources or ground engineering. This works, just so long as the person who is responsible of the reconstruction has the geological background to assess the geology as the model is being developed.

- In the ICGC, there should be a formal work group for 3D geological modelling that promotes the implementation and use of modern 3D geological modelling techniques.
- For each model it is important to make clear its objective, the methodology used, and to explain its virtues and weaknesses. The utility of the model will depend on these characteristics.
- When planning jurisdictional-scale models, it is important to decide whether these will be updated and, if so, how the update will be conducted.

## Next Steps

In the future, the ICGC will continue to concentrate on improving the geological knowledge of Catalonia. In the next four years, specifically in the field of geological mapping, there is a plan to focus the work around three main activities:

- To update the 1:250,000-scale and 1:50,000-scale geological databases.
- The geological characterization of specific morphodynamic domains.
- The detailed geological characterization of specific urban areas.

On the part of the technical team, there is the commitment for 3D geological modelling to play an important role in the development of these activities, specifically to:

- Improve the 3D geological model of Catalonia at 1:250,000-scale. This means modifying the geometry of existing surfaces, adding new horizons, generating the vol-

umes of the units and introducing the petrophysical parameters of the units.

- Reconstructing in 3D the sedimentary deposits associated with recent dynamics (since the last glacial maximum) of the main Catalan coastal-plains.
- Developing a methodological guide for the agile reconstruction of 3D geological structures based on the 1:50,000-scale geological database.
- Building the 3D geological models of 3 morphostructural domains (of the order of 100 km<sup>2</sup> of horizontal plan and few kilometres of depth).
- Building detailed 3D geological models of the near surface (of the order of 1 km<sup>2</sup> of horizontal plan and depths of the order of 100 m) of urban areas of interest (mainly from the Metropolitan Area of Barcelona) integrated with the 3D topographic databases and the available information related to subsurface infrastructure.

It is expected that 3D geological modelling will also have an important role in the development of other activities: geophysical, hydrogeology, geothermal, geotechnical, subsidence, surface geodynamic processes and the dissemination of geological knowledge. But, today, it is difficult to establish its weight. For this reason, it is recommended to set up an ICGC working group to collect the information related to the 3D geological modelling activity at the Institute and, ultimately, optimize resources and offer a better geological survey.

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# Chapter 10: 3D Geological Modelling at the Czech Geological Survey

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## Introduction

The Czech Geological Survey (CGS), established in 1919, provides the state geological service for the Czech Republic. Even though the structure of the institution and its name have changed several times, its main mission and related unique social status have remained. CGS has the statutory responsibility to gather, store and interpret geological information so that the state administration can take appropriate decisions about national economic and environmental issues. It provides the results of systematic regional geological mapping and investigation to all interested persons.

The Czech Geological Survey pays increasing attention to building 3D geological models as a part of the research and commercial projects and provides definition of a unified systematic approach to their storage, administration and presentation.

## Organizational Structure and Business Model

The Czech Geological Survey is a state contributory organization that belongs to the structure of the Ministry of Environment of the Czech Republic. The organizational structure of the CGS consists of six divisions within the frame of eight local offices: four in Prague and one in each of Brno, Kutná Hora, Jeseník and

Lužná u Rakovníka. These divisions include the Directorate, Geochemistry and Central Laboratories Division, Economic Division, Geological Division, Geofond Division and the Division of Informatics.

## Overview of 3D Modelling Activities

As the administrator and owner of large geoscientific datasets from the whole territory of the Czech Republic, CGS is involved in numerous applied research projects dealing with various kinds of use of the subsurface rock environment. High-speed railway tunnels, reassessment of mineral resources, assessment of geothermal energy potential, carbon capture and storage (CCS) and, last but not least, location of a deep radioactive waste repository are among priority projects of the national importance.

## Resources Allocated to 3D Modelling Activities

There is no dedicated yearly budget allocated to 3D modelling activities within the CGS. Geological models are built within different projects or contracts (ca. 9 FTE) and standardization activities related to the data storage and administration are partly covered by an internal project with limited capacities (ca. 0.7 FTE).

## Overview of Regional Geological Setting

A majority of the territory of the Czech Republic is built by crystalline rocks of the Bohemian Massif consolidated during the Variscan Orogeny. The Massif is partly covered by Permian, Carboniferous, Cretaceous and Tertiary sedimentary basins and in the East it is buried below the Carpathian overthrust units since Middle Miocene. The Bohemian Massif is conventionally subdivided into the Saxothuringian domain in the West, the Teplá-Barrandian and Moldanubian domains in the central part of the Massif and the Brunovistulian (Brunia) Neoproterozoic lithospheric plate in the East. Presently it is interpreted as a Gondwana-derived Variscan collisional domain characterized by: 1) relics of a two-stage SE-directed subduction at the Saxothuringian–Teplá-Barrandian boundary; 2) a magmatic arc genetically related to the subduction represented by the Central Bohemian Plutonic Complex in the centre; and 3) the rigid foreland represented by the Brunia plate in the SE. Large Variscan strike-slip zones (e.g. the Elbe Fault Zone) strike NW–SE dismember the NNE trending Variscan structure of the Bohemian Massif.

## Data Sources

The input data for creation of a regional structural geological model usually includes: geological map 1:50,000 or 1:25,000, archival purpose-specific geological maps, tectonic data from the rock outcrops, cross sections and maps from the mineral exploration (e.g. extensive uranium surveys), subsurface data in digital and printed form (borehole data, geological profiles, archival or new geophysical data and interpretations). A problematic aspect is often the scarcity of deep borehole data (especially in crystalline parts of the territory of the Czech Republic), or the absence of high-quality geophysical survey.

## 3D Modelling Approach

The 3D geological models built in the Czech Geological Survey cover a broad spectrum of scales and lithotectonic environments. Concerning scale, they range from meters in the case of outcrop fracturing quantification for Discrete Fracture Network models, to regional scale covering areas of hundreds of square kilometres and up to 1.5 km depth. They depict structurally complex high-grade metamorphic units that exhibit several episodes of pervasive ductile deformation, partial melting and emplacement of magmatic bodies, as well as simple overlying sedimentary formations. Each model includes an initial assessment of model reliability, used especially for purposes of risk/safety analysis. The scarcity, heterogeneity and complexity of available archived and newly acquired geological data often do not allow for any semi-automatic techniques of model construction; the models usually need to be created purely manually.

Models of sedimentary basins are put together based on 2D and 3D seismic surveys, well logs and all other supporting data, such as lithological core samples description and laboratory

analysis. First, the well logs are converted from depth to time (TWT) domain and linked with the seismics, then the horizons and faults are mapped using different interpretation techniques and tools.

## Clients

The 3D geological models are used either for presentation purposes, or in further research and exploration as a geometrical basis for numerical simulations and other engineering applications. Based on the 3D geological models, e.g. 3D hydraulic and transport numerical simulations are performed to estimate groundwater flow. Additionally, the models are used by engineering companies in CAD-type SW as natural limits for technical design of underground facilities (Figure 1).

Another application is the use of 3D models for the evaluation of geological structures focused on reservoir volumes, permeability, and seal efficiency. The results serve as a basis for further scenario testing of future technological actions and related environ-

mental risks, e.g. subsurface gas or CO<sub>2</sub> storage (Figure 2).

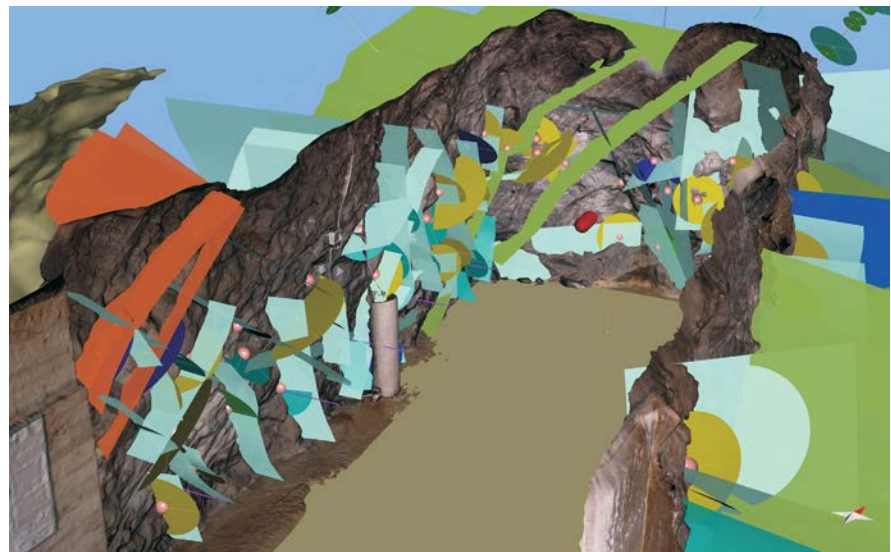
As the models are often created for a specific purpose, their construction comprises numerous meetings with customers and continuous adaptation of the data processing and modelling workflow to fulfil their needs. Even after finishing a particular project or contract, the CGS is eventually engaged in further use of the resulting model(s) as a geological or hydrogeological consulting expert team.

## Recent Jurisdictional-Scale Case Study Showcasing Application of 3D Models

Information on this topic is currently not available.

## Current Challenges

3D geological models are often created from ambiguous and uncertain data which are subject to error propagation during measurement and interpretation. In addition, they are often



**Figure 1.** 3D structural geological model of the ZK-3S niche in the underground research facility Bukov operated by SURAO. The model with dimensions of about 10 x 10 x 4 m represents compilation of a laserscan and photogrammetric model. The lithology and structures in the nearby boreholes are plotted into this model, individual brittle structures on the walls of the niche (cracks in blue, faults in orange) were created manually, along with schematic main lithological boundaries (green). Based on all these data, position of 10 horizontal wells (purple color) was proposed for in-situ interaction experiments with bentonite and heaters.

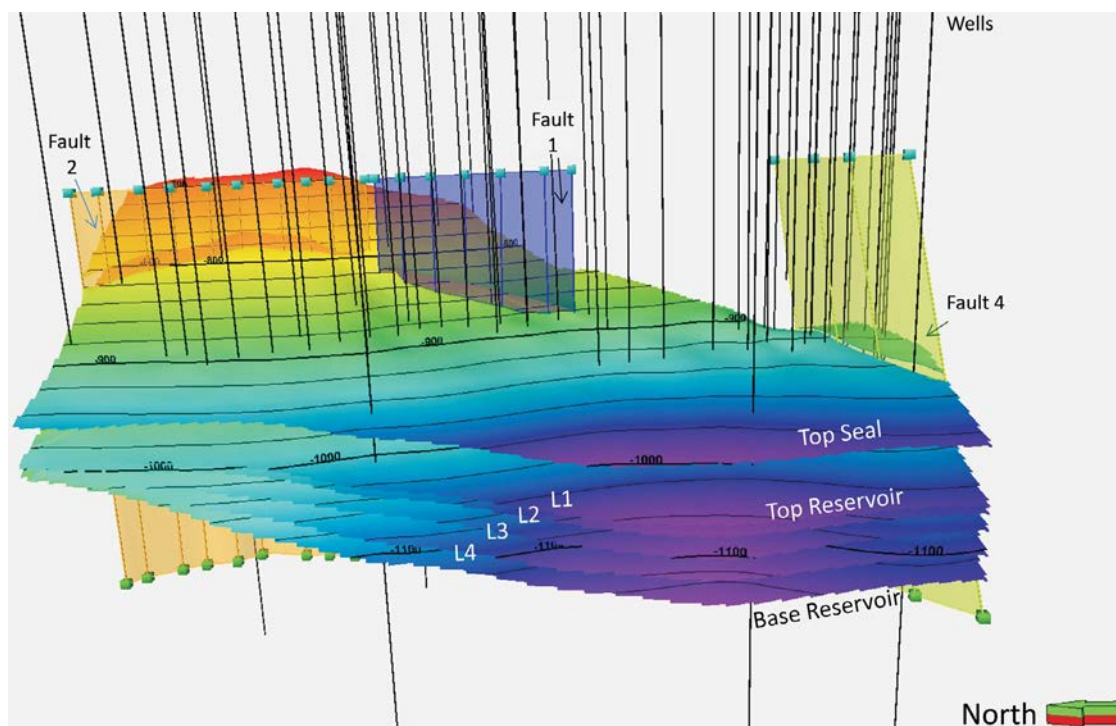


scarce and heterogeneous, so that the modeller has to rely on a model-based interpretation, e.g. by assuming a certain tectonic regime or deformation style. Currently, the challenge is to evaluate the uncertainties mentioned above and provide them to the model users and stakeholders in an easily understandable and precise form. More challenges are related to

dynamic simulations of the processes which happened in the past, e.g. oil, gas or water production, and which are going to happen, such as underground gas storage. The key words are: the volumes or amounts of produced or stored fluids, the velocity of the fluid movement, and the associated risk.

CGS is currently working on the development of a customized web viewer (based on Esri API for Javascript) for a satisfying visualization of models without the need to install any plugins. This viewer should be publically available in 2019 and should be interlinked with an interactive map overview of the modelling activities of the CGS (described by proper metadata according to the ISO 19115 standard).

A continuous challenge is to set the topic of the creation of the 3D geoscientific information system as one of the priorities of our institution and have a dedicated team with capacities to work on it systematically.



**Figure 2.** Geological 3D model of LBr-1 storage complex built based on well and seismic data: five surfaces define top of the seal (impermeable rock), tops of four partial reservoirs (sandstones L1 – L4) of the Láb horizon, and base of the reservoir - Lower Badenian shales (Francu et al. 2017). The reservoir is ca. 3 km long and max. 600 m wide; depths are shown in metres.

## Lessons Learned

First steps have been done in developing a 3D modelling system in our geological survey organization. The selection of the modelling software has been done based on a careful analysis of available solutions for the future needs, e.g. their presentation possibilities, modelling workflow, and flexibility in import and export of various data sets. New 3D models require some important changes in existing database structures and applications. New ways of financing of such supporting activities need to be sought, especially in cases where particular regions or smaller areas are not strictly involved in certain projects or contracts but, at the same time, they are important on the national scale.

## Next Steps

The long-term CGS mission is to create a 3D geoscientific information

system that would include a spatial database for the central storage, administration and use of 3D data and models (GEOCR3D), methodology for a standardized creation of the 3D models from existing or newly acquired data, quality assurance processes, and sharing of the modelling results. In the short term, we would like to advance with the standardized metadata description of the models, making the models accessible via a web viewer, and customization of the applications to retrieve relevant input data from the CGS central databases.

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# Chapter 11: Geological Survey of Denmark and Greenland - Targeting Current 3D Model Needs

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Sandersen, P.B.E., Vangkilde-Pedersen, T., Kallesøe, A.J., Høyer, A.-S., Andersen, L.T., Pedersen, C.B., Mathiesen, A., Møller, I., and Svennevig, K. 2019. Geological Survey of Denmark and Greenland - targeting current 3D model needs; Chapter 11 in 2019 Synopsis of Current Three-Dimensional Geological Mapping and Modelling in Geological Survey Organizations, K.E. MacCormack, R.C. Berg, H. Kessler, H.A.J. Russell, and L.H. Thorleifson (ed.), Alberta Energy Regulator / Alberta Geological Survey, AER/AGS Special Report 112, p. 92–108.

## Introduction

In Denmark and Greenland, there is a growing need for 3D geological models within the fields of aggregate prospecting, resources and vulnerability investigations of groundwater, geothermal investigations, urban planning, and geotechnical investigations, and specifically in Greenland, geohazard investigations, mineral prospecting, and mapping. For decades, consultants and authorities have constructed geological models to provide a scientific base for dealing with challenging issues related to the subsurface. Consequently, a large number of models exist – models that are of different types, constructed with different purposes, and for use at different scales. When opting for high 3D model detail e.g., for assessments of contaminant transport, adequate coverage with data that resolves the geological details is required.

The Geological Survey of Denmark and Greenland (GEUS) has over a long period of time developed a range of databases that serve as a repository for data used in 3D modelling (Hansen and Pjetursson 2011). GEUS has produced 3D geological models for several years and has initiated the construction of a national 3D geological model for Denmark with the purpose of making all existing geological interpretations available for relevant

end-users and the society in general (Sandersen et al. 2016). The foundation of the model is a 3D database that can manage and present the full potential of the geological data and interpretations. Apart from containing national scale geological model elements, the 3D database will also be able to store a variety of existing local and regional models. The 3D database will act as a repository of geological interpretations capable of maintaining its value and continuously being attractive to a wide range of end-users.

## Organizational Structure and Business Model

The 3D modelling activities at GEUS are generally related to research projects, consultancy work, and scientific assistance for other authorities. The geological modelling work is done both in connection with projects related to activities in individual departments as well as in connection with projects across departments. GEUS has a large number of geoscientists working with issues either directly or indirectly related to 3D models targeting subsurface resources or subsurface storage potentials (e.g., groundwater, aggregates, geothermal energy, CCS storage or storage of radioactive waste).

Building a national 3D geological model for Denmark is a highly com-

plex undertaking that activates several departments and requires a high degree of collaboration (Sandersen et al. 2015). No overall national 3D model organization is set up because activities until now have been focused on specific sub-topics in work groups or departments. Work groups and individual departments have worked with, for example, testing of alternative 3D modelling methods and workflows (e.g., Høyer et al. 2015a, Jørgensen et al. 2015), 3D database construction, and creation of a coherent national lithostratigraphy.

GEUS performs and participates in research and consultancy work for private companies, private and public research funds, and the public sector related to 3D geological modelling projects, but currently does not receive governmental funding specifically for 3D mapping and modelling of the subsurface. Thus, funding for work on 3D geological modelling is currently related to research applications and consultancy work on specific projects. In order to establish a detailed and comprehensive national 3D geological model for Denmark, substantial external funding is needed. A large range of both private and public stakeholders is expected to benefit from a national 3D model in a variety of applications. Therefore, it will be important to build a strong business case demonstrating the total

cross-sector socio-economic benefits of having such a model to generate the necessary funding.

## Overview of 3D Modelling Activities

### *National 3D Models and Model Elements*

#### **Development of a 3D Database for the National 3D Geological Model**

As a part of GEUS's 3D strategy (Sandersen et al. 2016), a 3D model database with the aim of storing all publicly available 3D geological models has been developed. The primary objective of the 3D model database has been to store the national 3D geological model, but the database will also be a central storage facility for outputs from other 3D model projects. The database has been designed to meet a platform-independent standard that can secure data in the future and make it possible to better share the models internally as well as externally. The database is able to support different model and feature versions and will therefore be capable of storing models, which will include information regarding development history and all the associated features, attributes, and geometry within a versioning management system.

Initially, a conceptualization of the elements of a 3D digital geological model was described, including all of the related geological principles and properties. The assessment of a platform-independent storage facility for 3D geological models was done with the best-suited technology in mind, including open source possibilities. Testing and implementation phases of different import and export scenarios were executed to validate suitable features for the model storage as well as executing various spatial and topological operations. See Figure 1 for an example visualized directly from the database.

On the technical side, the database is based on a PostgreSQL database with

the spatial PostGIS extension. Another extension used is the `pg_pointcloud` extension by Paul Ramsey from OpenGEO for storing point cloud data (LiDAR). The point cloud extension gives the database a unique possibility to store non-fixed dimensional data, so that in principle, the database can store billions of points with multiple dimensions for various properties like porosity, permeability, lithology, biostratigraphy, chronostratigraphy, gravity etc. This provides great possibilities for voxel data, because voxels are made of regular or irregular XYZ-points. For storing polygons or TIN's, the geometry is stored as separate definitions as vertices points, and the edge definitions of the lines that combine them.

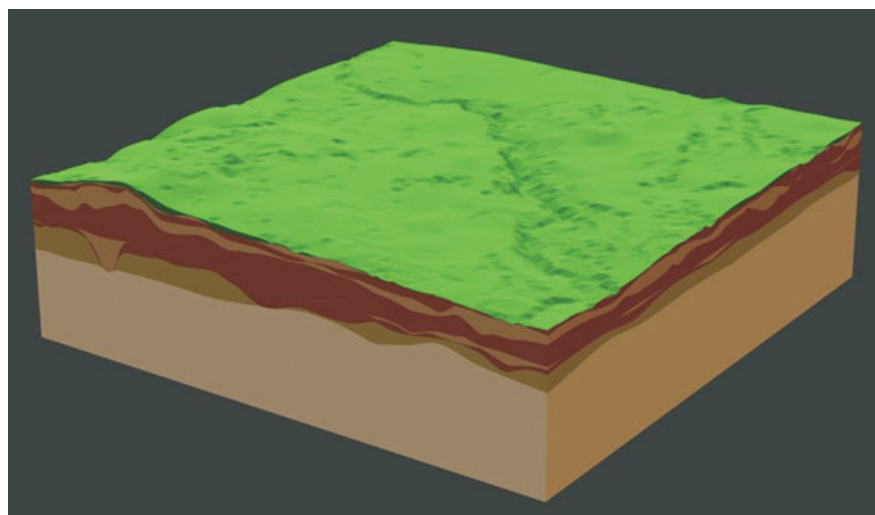
#### **Updating 3D Hydrostratigraphic Input for the National Hydrological Model**

In connection with the national groundwater mapping project (e.g. Thomsen et al. 2004, Thomsen 2013), a large number of geological and hydrostratigraphic models have been constructed in areas with special drinking water interests in Denmark.

The models were generally made without merging with neighbouring models and without necessarily having the same hydrostratigraphy. However, with the finalization of the national groundwater mapping project in 2015, the models are now being merged into a nationwide, 45-layer, hydrostratigraphic model intended as input for the national hydrological model (DK-model; Kidmose et al. 2011). The work is led by the Environmental Protection Agency and the primary stitching and re-interpretations are being made by a group of consultants. GEUS performs QC reviews of the merging process and is responsible for updating the DK-model. The work was completed in early 2019.

#### **3D Geological Modelling of the Deep Subsurface**

The deep geothermal resources in the Danish subsurface are expected to contribute to a mixed energy supply in the future. To facilitate the use of geothermal energy, a part of the initiatives has been to establish an overview of the amount and quality of existing and interpreted geological and geophysical data, as well as to pro-



**Figure 1.** A closed 3D volume model example loaded and visualized directly from the database in a web browser. The volume is located near the city of Odense, measures 10 × 10 km and shows the subsurface down to around 300 m below the terrain surface. The two deepest layers represent Pre-Quaternary limestone and clay (Upper Cretaceous to Palaeocene), whereas the layers above represent a Quaternary succession dominated by clay (dark red-brown colour) and sand (light red-brown colours). The view is towards northeast.

vide an overview of the geological composition of the deep Danish subsurface (Vosgerau et al. 2016).

Data from deep wells and seismic surveys from primarily oil and gas exploration have been used for mapping the depth, thickness, and lateral extent of lithostratigraphical units and for mapping major faults. A number of nationwide maps of important boundary surfaces covering the Danish onshore outlines the structural-stratigraphical evolution from the Top-Pre-Zechstein and up to the Top Chalk Group. The maps are based on patchy and uneven data coverage and constructed to give regional representation of the subsurface and are therefore only meant for regional use. New well and seismic data or refined local geological models may lead to modifications. However, the present depth maps give a good indication of where in Denmark deep geothermal future exploration is relevant. The depth maps can be visualized through an in-

teractive 3D-viewer providing an overview of the subsurface geology; see Figure 2 (<http://dybgeotermi.geus.dk>).

### Mapping and Modelling of the pre-Quaternary Surface

The boundary between the pre-Quaternary and the Quaternary is an important surface in the upper part of the Danish subsurface that is highly demanded by consultants, researchers, and administrators when working with geotechnical issues, groundwater, and aggregates. An update of the existing map of the Pre-Quaternary surface topography (Binzer and Stockmarr 1994) is planned to be one of the important elements of the National 3D geological model (Sandersen et al. 2016). The erosional character and the intricate topography of the pre-Quaternary surface makes it an important element in the National 3D geological model.

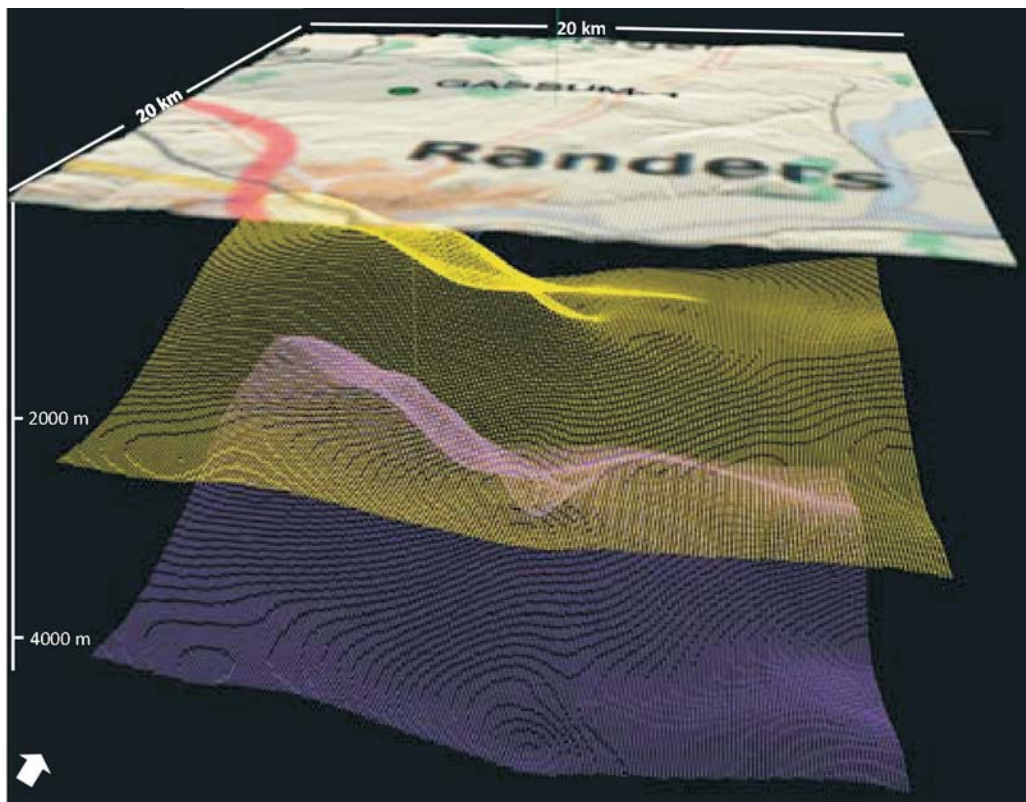
### National Guidelines

To secure common procedures and workflows GEUS has developed guidelines for constructing 3D geological models (Sandersen et al. 2018a). This guideline is one of a series of guidelines funded by the Environmental Protection Agency to be used primarily when working with projects related to groundwater.

### 3D Geological Modelling Projects

#### Examples of Research Projects (Denmark)

GEUS participates in a range of research projects where mapping and modelling of 3D geology is an important element. The projects are typically related to groundwater modelling, contaminant transport modelling, or urban subsurface planning, all of which require detailed interpretations of the geological subsurface architecture. To construct models with a sufficient degree of detail, dense coverage with high-quality data and develop-



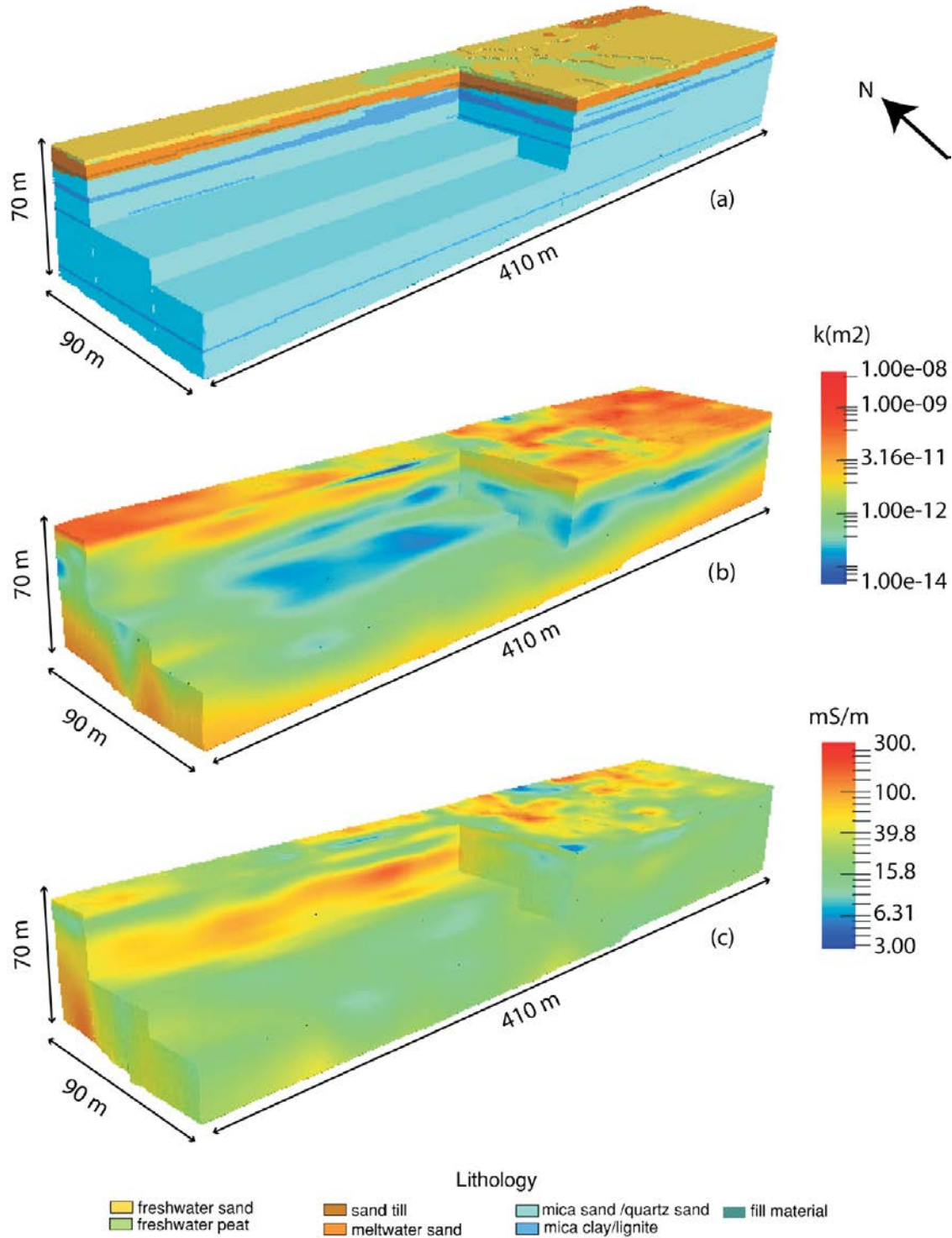
**Figure 2.** Interactive 3D tool available in the WebGIS portal, visualising selected mapped surfaces. Modified from Vosgerau et al. (2016).

ment of new mapping and modelling approaches are necessary (e.g. Mielby and Sandersen 2017, Sandersen et al. 2018b). At contaminated sites for instance, knowledge about geology and hydraulic properties of the subsurface

and the extent of the contamination is needed for risk assessments and for designing potential site remediation.

At a contaminated site close to the city of Grindsted, a local 19-layer 3D

geological model was used as a basis for developing a new approach for characterizing contaminated sites through time-domain spectral induced polarization (Maurya et al. 2018). Figure 3 shows the 3D geological



**Figure 3.** The Grindsted case: (a) 3D Geological model, (b) 3D permeability model and (c) 3D water electrical conductivity model. From Maurya et al. (2018).

model (a) together with a 3D permeability model (b) and a 3D water conductivity model (c). The imaging of permeability and water conductivity allowed for a better discrimination of lithology from the water conductivity, and the geophysical models were actively used as support for the geological modelling.

At a landfill site at Pillemark on the island of Samsø, six different data sources were combined to gain an updated geological understanding of the subsurface (Figure 4; Høyer et al. 2019). A high-resolution 3D geological voxel model was constructed with the purpose of performing a renewed risk assessment in relation to the groundwater resources. The study included analysis of geomorphology data, spear-auger mapping data, near-surface electromagnetic induction data, borehole data, geoelectrical profiling, and Transient Electromagnetic measurements. The 3D geological model was constructed to provide information about the vulnerability of the aquifer below the landfill site.

Buried tunnel valleys are common features in formerly glaciated areas, and because of their abundance and size, they can have a large impact on groundwater recharge and flow. Delineation of the buried valleys and modelling of the infill is therefore very important in relation to groundwater (Sandersen and Jørgensen 2003). Densely covering airborne electromagnetic data in combination with borehole data has proven to be very useful for mapping buried tunnel valleys and their complexity (Jørgensen and Sandersen 2006). A good example is from the Kasted area, where a 3D geological model of a highly complex network of buried valleys has been made based on borehole data and Airborne Electromagnetic data (AEM) (Høyer et al. 2015b). The model includes twenty different buried valleys in a complex cross-cut setting indicating the presence of up to eight valley generations (Figure 5).

In a study area in southwestern Denmark, a novel strategy for 3D multiple-point statistics (MPS) modelling was performed on a succession of Miocene sediments characterized by relatively uniform structures and a domination of sand and clay (see Figure 6; Høyer et al. 2017). The strategy focused on optimal utilization of geological information and the use of 3D training images rather than 2D or quasi-3D training images typically used for MPS modelling. A workflow for building the training images and effectively handling different types of input information to perform large-scale geostatistical modelling was constructed. The study showed how to include both the geological environment and the type and quality of input information in order to achieve optimal results from MPS modelling.

#### **Examples of Research Projects (Greenland)**

Compared to Denmark, Greenland has an excellent degree of exposure of bedrock, but a general lack of subsurface data (detailed geophysics, drill-holes etc.). Three-dimensional work has been tied to the application of oblique photogrammetry to map geological structures (faults, and bedding) as detailed 3D polylines (Dueholm, 1992, Svennevig et al. 2015, Sørensen and Guarnieri 2018, Sørensen and Dueholm, 2018). This method has been used in several areas for several purposes, e.g., to produce geological 3D models of complex faulted and folded strata at Kilen in northeastern Greenland mainly for the purpose of structural validation by 3D modelling helping to the restoration of the deformed strata (Svennevig et al. 2016, 2017) (Figure 7). Another application was to produce onshore 3D models for reservoir analogues for offshore basins for the oil industry (Vosgerau et al. 2010, 2015), with the main product being annotated 3D polylines for which the oil industry customers themselves build 3D models. Furthermore, the method has been used to produce high accuracy and

structurally validated geological maps (e.g., Svennevig 2018a, b). This work is also ongoing in a large project in the Karat Group of central west Greenland to produce several 1:100,000-scale map sheets (Sørensen and Guarnieri 2018).

#### **Consultancy Work**

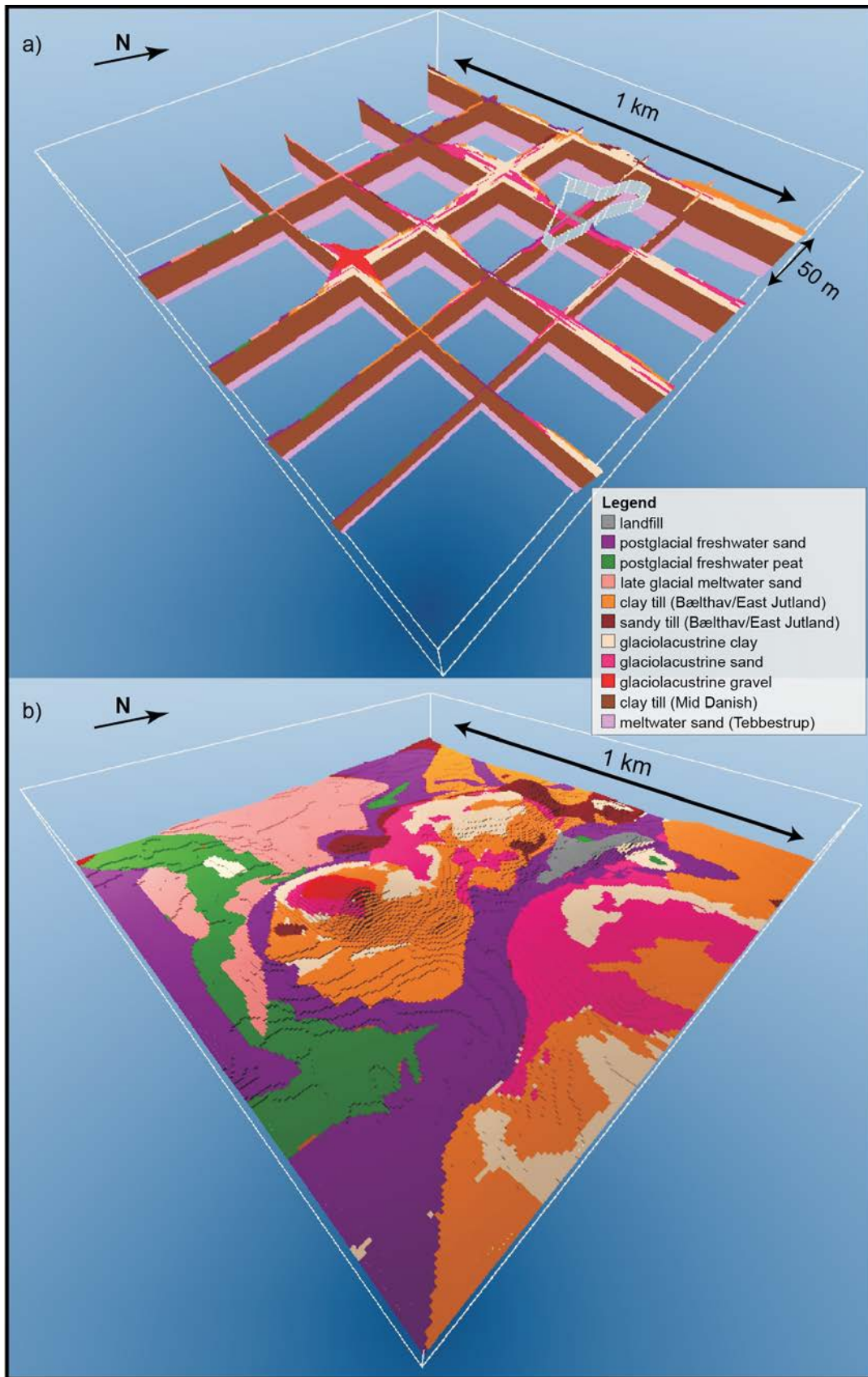
GEUS is currently producing 3D models in a number of consultancy or partnership projects that have participation by typically waterworks and regional and local authorities. The projects have their focus on solving challenges to issues related to groundwater resources and contamination, groundwater abstraction, and climate change. The 3D geological mapping and modelling is performed at a local scale usually with a high degree of detail.

#### **Resources Allocated to 3D Modelling Activities**

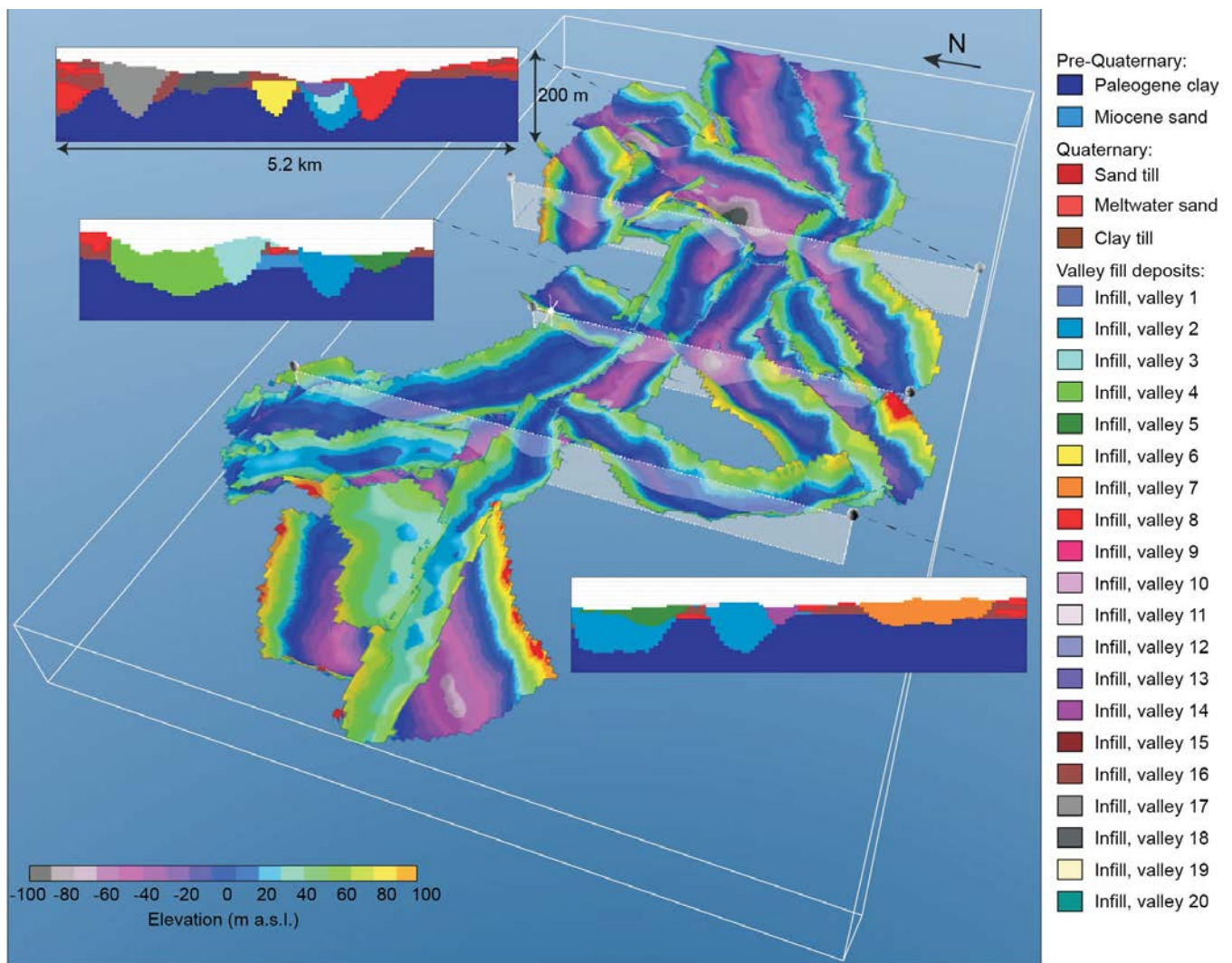
Based on activities in 2018, around 12 scientists (man-years) are occupied with activities related to 3D geological modelling.

#### **Overview of Regional Geological Setting**

The Danish Kingdom comprises the Danish area (43,000 km<sup>2</sup>), the small Faroe Islands in the North Atlantic (1,400 km<sup>2</sup>) and the world's largest island, Greenland (2,175,000 km<sup>2</sup>). The northern part of Denmark, together with southern Sweden, comprises the boundary between the Fennoscandian Shield and the European sedimentary province (Figure 8). This zone, the Sorgenfrei-Tornquist Zone, is characterized by fault tectonics and horst/graben structures (Figure 9). To the southwest, the Danish basin is an elongated trough, which toward the southeast crosses Poland (Mogensen and Korstgaard 2003). The sediment thickness in the basin is up to 10 km (Vejbæk and Britze 1994). Towards the southwest, the basin is separated from the North German Basin by the Ringkøbing-Fyn



**Figure 4.** The Samsø case: View of the 3D voxel model a) N-S and E-W slices through the 3D grid. A polygon marks the landfill area, b) The 3D model seen from above. From Høyer et al. (2019).



**Figure 5.** Kasted 3D model: 3D view of the modelled buried valleys. Three slices through the model are shown where the different colours represent the different valley generations. Modified from Høyer et al. (2015b).

High, where the Precambrian basement is found as high as around 1 km below the surface (Nielsen 2003). The southwestern part of Denmark is a part of the North German Basin.

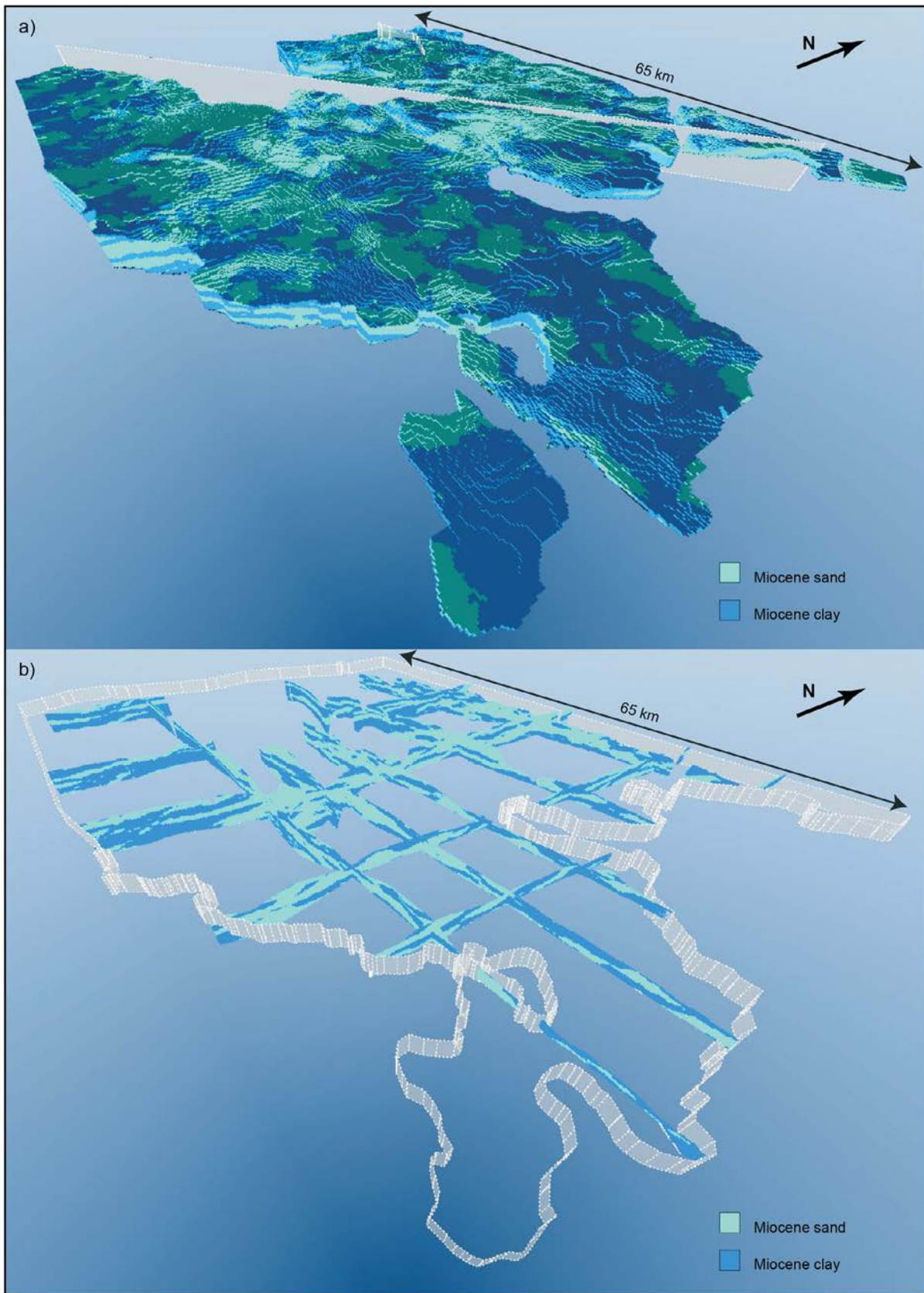
The oldest sediments are Cambro-Silurian sequences (Nielsen and Schovsbo 2007). Devonian deposits have not been found, but occurrences of Carboniferous sediments are present. Above, Permian volcanics and conglomerates form the basis of the upper Permian salt-deposits that can attain thicknesses of ~1 km or more. The Mesozoic sediments consist mostly of marine sands, clays, chalk, and limestone (Nielsen 2003). During the Tertiary, limestone sedimentation

was followed by sedimentation of marine clay while sandy materials were more common in the younger Tertiary. The Miocene succession comprises fluvial sand deposits and sand deposited in prograding deltas. Between the sandy units are marine mud-dominated deposits (Rasmussen et al. 2010). The Miocene succession ranges in thickness from a few meters to more than 200 m.

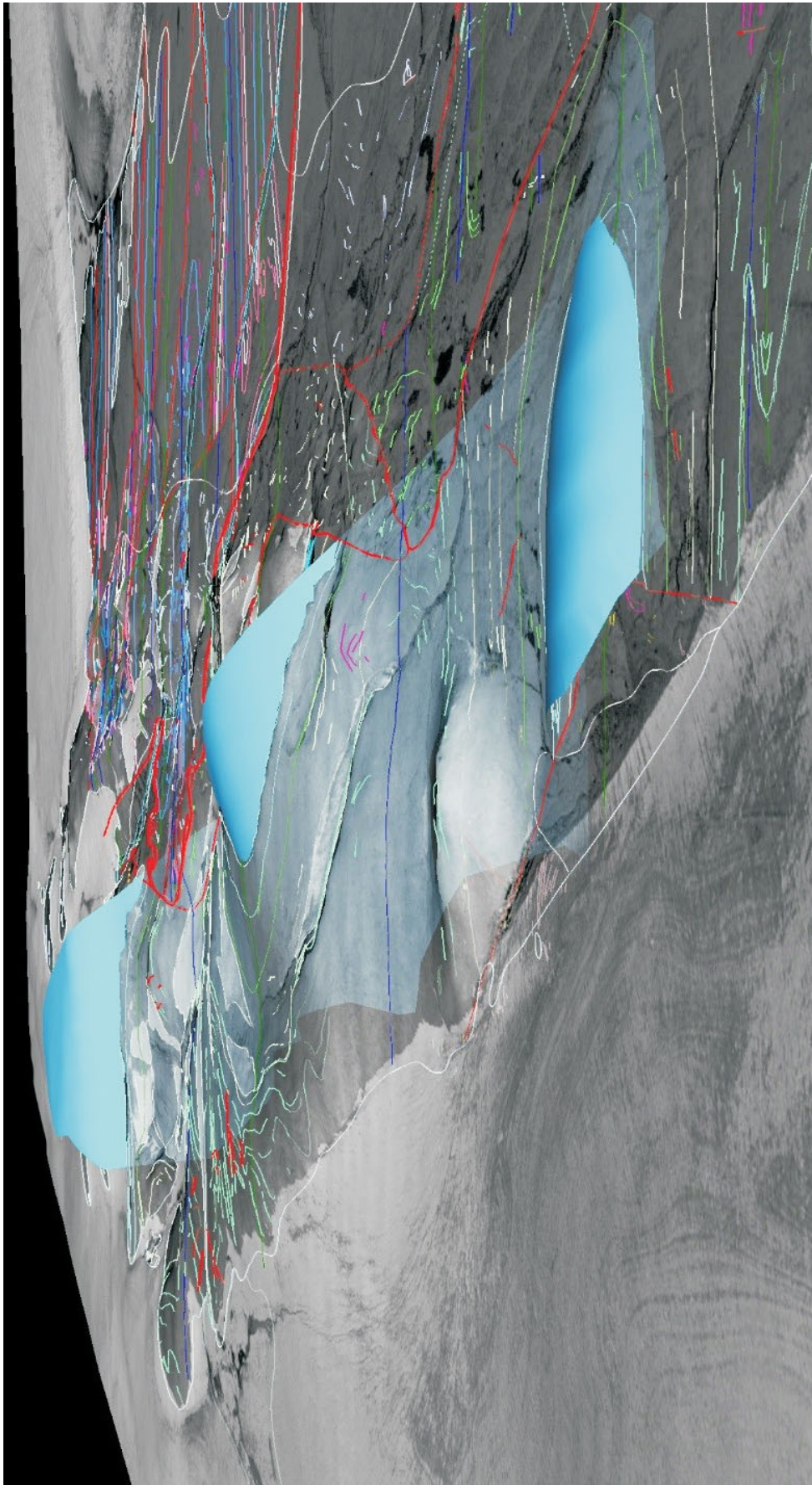
During the Quaternary, glaciers advancing from northerly and easterly directions repeatedly covered Denmark. During the glaciations, deposition of tills and meltwater sediments were dominating, whereas marine and freshwater sediments were mainly de-

posited during the interglacials. The cover of glacial and interglacial sediments is on average around 50 m thick, but ranges from a few meters to more than 300-400 m in buried tunnel valleys. In many areas, the uppermost sediments were intensely deformed during the numerous ice advances and several occurrences of large glaciotectonic complexes have been found (e.g. Pedersen 2005, Høyer et al. 2013, Jørgensen et al. 2012). The buried tunnel valleys are found as several cross-cutting generations, thus adding to the complexity of the subsurface (Jørgensen and Sandersen 2006).

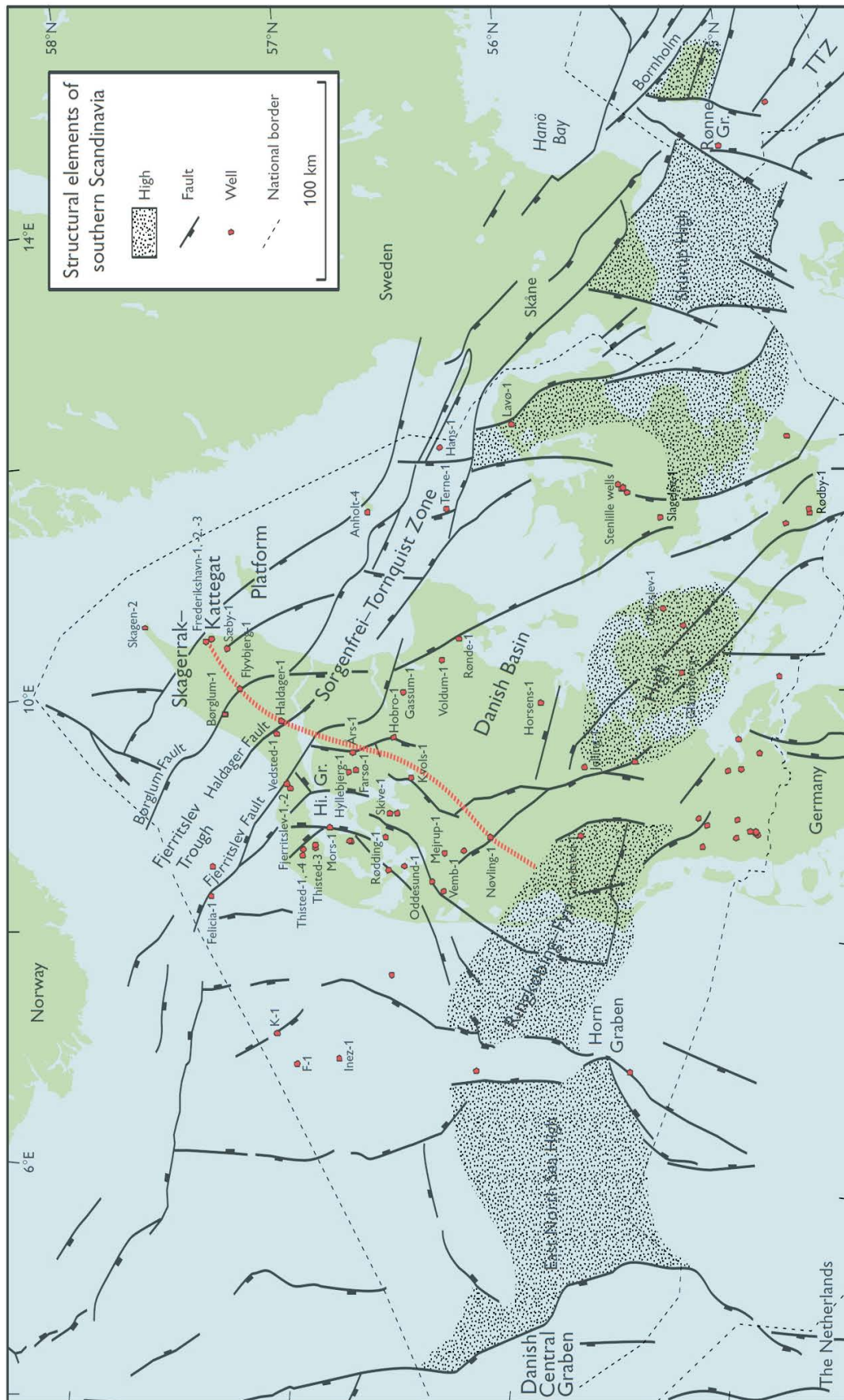




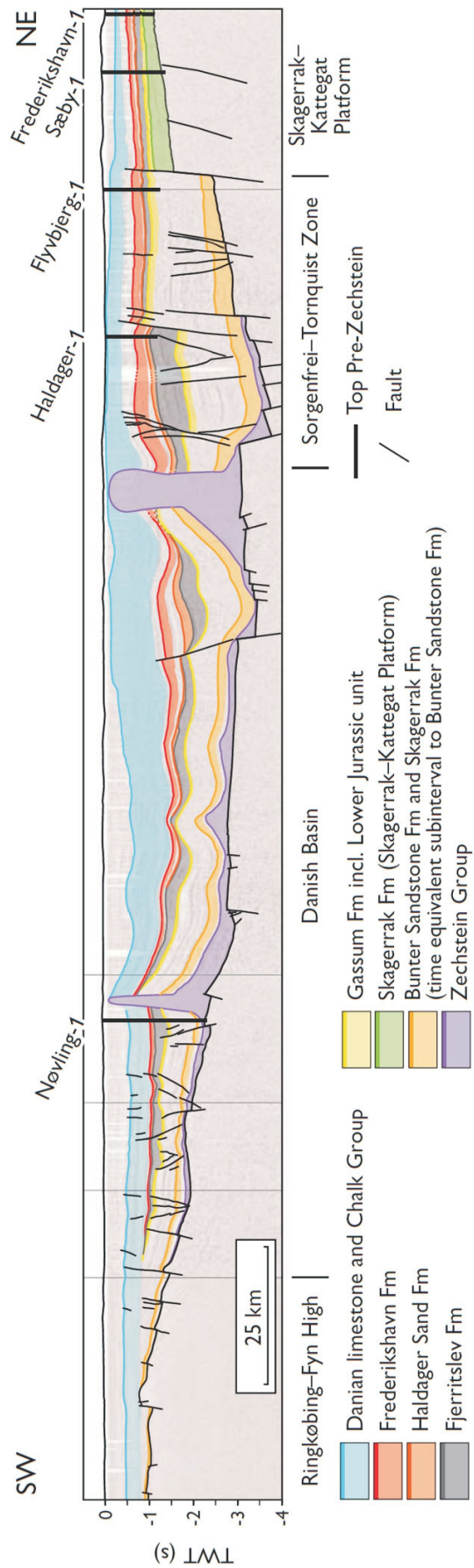
**Figure 6.** A realization of the Miocene succession in south-western Denmark: 3D-view of one of the final realizations: (a) All voxels, (b) The associated fence view. Vertical exaggeration 10x. Thickness of the Miocene succession is in the order of 100 to 200 m. From Høyer et al. (2017).



**Figure 7.** Oblique view of a geological 3D model of Kilen, Eastern North Greenland. Coloured polylines mapped from oblique photogrammetry are shown on a semi-transparent black and white aerial photo draped on a DEM. The various colours refer to different geological units and the bright red lines are faults. The blue undulating surface is a folded Lower Cretaceous marker-bed modelled in 3D based on the 3D polylines and structural measurements. View is towards the north and the distance from the foreground to the background of the image is 20 km. From Svennevig (2016).



**Figure 8.** Structural elements of southern Scandinavia. Well locations and principal structural units. The red line indicates the approximate location of the cross-section in Figure 9. From Nielsen (2003).



**Figure 9.** A SW-NE cross section through the Danish Basin and the Fennoscandian Border Zone. For location, see Figure 8. TWT: two-way travel time. From Vosgerau et al. (2016).

The main part of Greenland is covered by an up to 3 km thick ice sheet (the inland ice) with a relatively narrow ice-free zone along the coast. To the west and the southern part of the east coast, Precambrian basement complexes are found, whereas along the northern part of the east coast, the remains of a Caledonian mountain range and a thick sequence of Palaeozoic and Mesozoic sediments are present. In the northernmost part, a fold belt of the Ellesmerian Orogeny deformed a late Proterozoic to Silurian sedimentary basin. Centrally, both to the west and to the east a several kilometers thick sequence of Tertiary plateau basalt rests on Tertiary and Cretaceous sediments. These plateau basalts belong to the same North Atlantic Tertiary basalt province as found on the Faroe Islands (e.g., Esher and Pulvertaft 1995, Henriksen 2005)

## Data Sources

As mentioned earlier, GEUS is a national survey and data repository and therefore has the obligation to host and maintain a range of databases for data of national interest (Hansen and Pjetursson 2011). These databases constitute the backbone of GEUS's work with geological interpretations and models.

The national borehole database, JUPITER, contains borehole information dating back more than 100 years. This database contains information on just less than 300,000 boreholes, corresponding to an average of about 7 boreholes per km<sup>2</sup>. However, this data density is not enough for detailed geological mapping and therefore other types of data are needed – especially geophysical data. The databases GERDA (Figure 10) and MARTA contains measured data as well as geophysical interpretations for mostly shallow on- and offshore data (e.g., Møller et al. 2009). Other databases host data from oil and gas exploration in the form of reports and data from released 3D surveys and deep explo-

ration and appraisal wells. Apart from confidential data, all other data in the databases are publicly accessible either free or at a specified fee.

The data covering the shallow part of the subsurface originates from investigations for instance at waterworks and in relation to hydrogeological mapping projects performed by consultants and authorities. Legislation in Denmark requires that all data collected in connection with groundwater investigations be sent to GEUS.

In Greenland, as mentioned above, 3D data is mostly gathered in the form of oblique photogrammetry on a local scale for specific projects. Locally, and in some cases regionally, geophysical datasets are available.

## 3D Modelling Approach

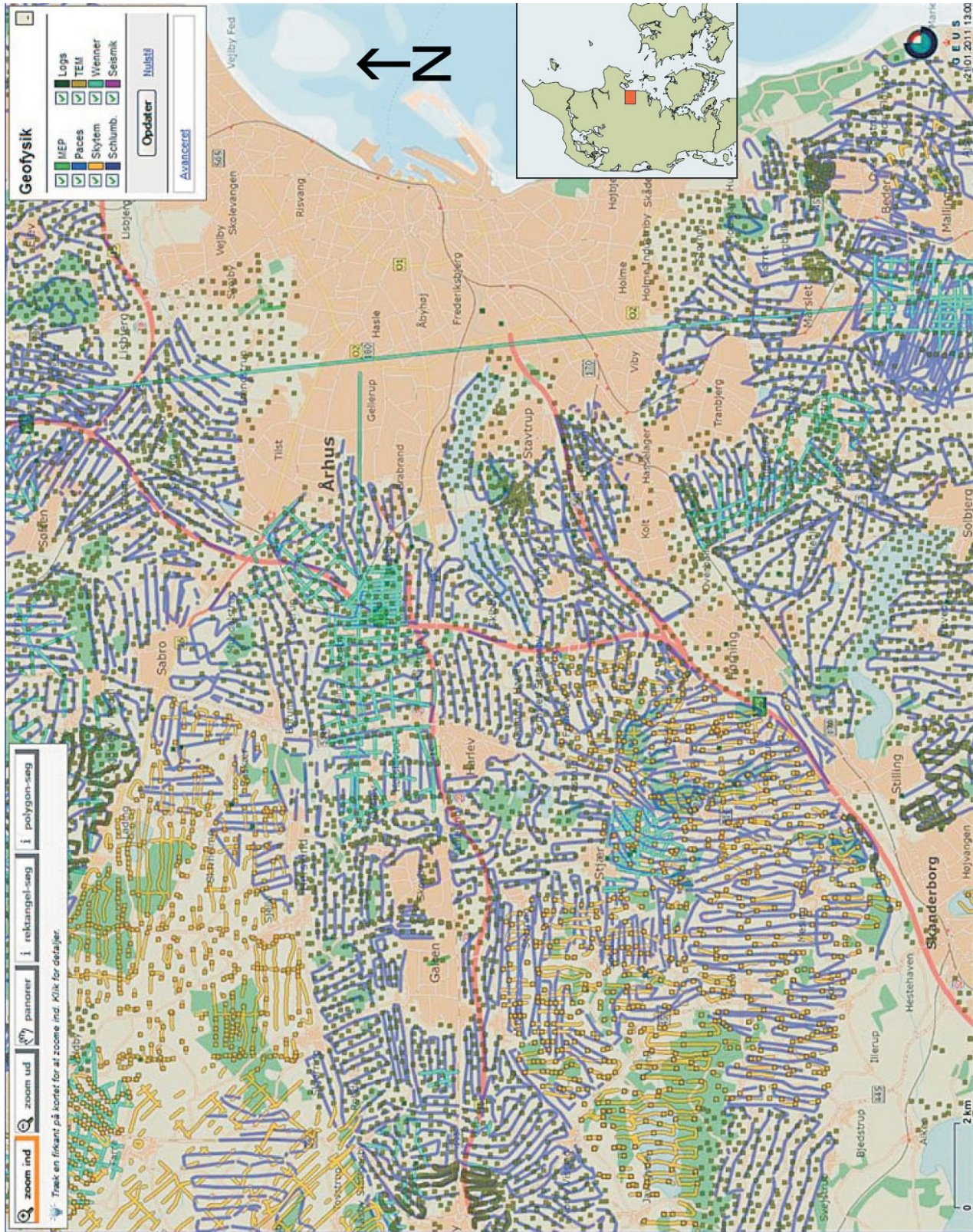
At GEUS, there are different mapping and modelling approaches that are used depending on the area and specific purpose of the model. Some models are supposed to give rough overviews of the geology, while other models need to be highly detailed. Therefore, defining model scale and model detail is important during the initial phases of the mapping and modelling project. An important part of this process is reflections about the capability of the available data to resolve the geology to the required level of detail.

The choice between explicit and implicit modelling depends to a large degree on the end-users needs and in certain cases a combined approach is chosen. In the Danish area, a layer-cake model approach often is used because these models can reflect the overall geological structure of a layered subsurface to a detail that is sufficient in most cases. However, very complex geological successions cannot be built properly using a layer models with interpolated layer boundaries. Therefore, in some cases voxel-modelling and geostatistical methods are used – sometimes with a com-

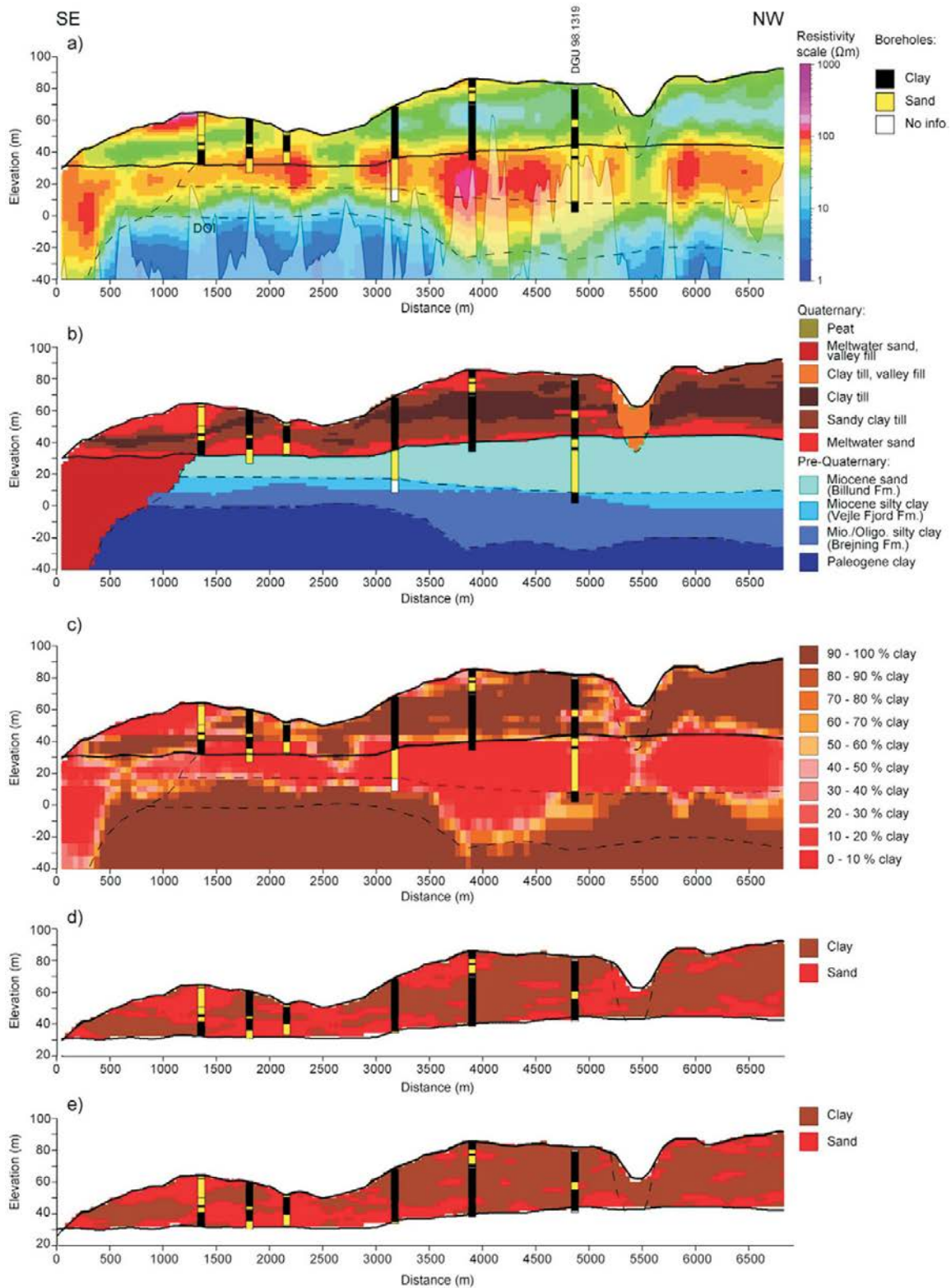
bined voxel/layer approach. When high detail is needed, modellers seek to intensify the mapping for instance by making the data coverage denser or by using new types of data in selected areas. For example, traditional layer modelling has been used in a local model at Odense, where the general purpose was to provide detailed input for groundwater modelling to be used for assessments of groundwater flow and contaminant transport (Sandersen et al. 2018b). Although the sedimentary succession was rather complex, a layer modelling approach was chosen. In this case, highly specialized data in specific local areas paved the way for the construction of a geological model containing new and more detailed geological information.

A traditional layer model was also constructed at the Norsminde site (Høyer et al. 2015a), but for this project, three different model approaches were chosen for comparison (Figure 11). In the study, a manually constructed layer-cake model was evaluated against two automated modelling approaches. The automatic methods were “clay fraction modelling”, where borehole and AEM resistivity models were integrated through inversion (Foged et al. 2014) and a stochastic approach based on transition probability indicator statistics. The models possessed different strengths and weaknesses, and it was clear that the purpose of the models should be taken into careful consideration when choosing the modelling approach.

The layer approach and the voxel approach can be combined in models where parts of the model area is highly complex and others are not. For example, this has been done in the southwestern part of Denmark, where voxel modelling of glaciotectonically deformed parts of the model area was combined with traditional layer-modelling (Jørgensen et al. 2015). Based on the conceptual model of this study, Multiple Point Statistic (MPS) simulations were per-



**Figure 10.** The GERDA database: A close-up of an area west of Aarhus showing data coverage of different geophysical data types. From Hansen and Pjetursson (2011).



**Figure 11.** The Norsminde case: A NW-SE cross-section example shown with resistivity grid and model results. Boreholes are shown as vertical rods. The bottom of the Quaternary is shown as a thick line in all the sections. In a-c the bottom of the valleys, the bottom of the Billund Sand and the Top Palaeogene are marked with dashed lines. a) Resistivity grid. The colours are faded below the gridded DOI (depth of investigation). b) The Manual Cognitive Geological model results from which the dashed boundaries are derived. c) Result of the Clay Fraction modelling. d-e) Two of the TProGS simulations. The TProGS simulations are only conducted for the thick glacial deposits. From Høyer et al. (2015a).

formed on the deep Miocene succession (Høyer et al. 2017; see Figure 6). The project presented a practical workflow for building training images and a means to effectively handle different types of input information for large-scale geostatistical modelling. MPS modelling has been studied by Barfod et al. (2018a, b) using the Kasted dataset and the Kasted voxel model (Figure 5) as training image simulating hydrostratigraphic models. In Barfod et al. (2018b) a number of different modelling setups were tested to study the influence on the uncertainty of the hydrostratigraphic model ensembles.

For Greenland, 3D models have mainly been produced with TIN-surfaces representing geological boundaries and faults. This vector-based approach is suitable for the raw data of 3D polylines digitised in oblique stereo photos (Svennevig and Guarnieri 2012, Sørensen 2012, Svennevig et al. 2015) and for the structural complexity encountered in Greenland (e.g., Svennevig et al. 2016, 2017).

## Clients

GEUS provides geological models to a wide range of clients – both private and non-private. The clients/stakeholders include public authorities (governmental, national, regional, municipalities), private and public research funds, consultancy companies, oil and gas companies, developers of geothermal projects, water utility companies etc.

GEUS generally encourages clients to participate actively during the mapping and modelling projects. Based on experience, this is the best way to secure that the client is kept continually informed about the modelling progress and the decisions that are made. Using this approach, the client becomes more closely connected to the end product. The geological models of today should be more dynamic compared to models constructed just a few years ago and the value of a

model today can be measured in its ability to be continuously updated with new data and knowledge. However, this requires active maintenance and update of databases as well as models. The client should realize that the model most likely is not a one-off, but an active part of their future business that requires continual attention and funding.

## Recent Jurisdictional-Scale Case Study Showcasing Application of 3D Models

An example of a 3D geological model that has had an immediate public interest is the Kasted model (Høyer et al. 2015b). A 3D geological model of an area outside the city of Aarhus was constructed based on borehole data in combination with a spatially dense AEM survey. A complex network of buried tunnel valleys characterizes the area and the model was made as a combined layer and voxel model in order to map both the overall structures as well as the lithological variations in the valleys (see Figure 5). The model was subsequently used as input for groundwater modelling (Barfod et al. 2018a, Vilhelmsen et al. 2018). The results of the geological modelling was of high interest for the waterworks in the municipality of Aarhus because the delineation of the complex valley-system could point to new and hitherto unrecognized groundwater resources. Further work to point out new well-fields has been initiated based on the 3D model and the dense geological and geophysical data in the area.

## Current Challenges

As mentioned, GEUS is in the process of developing a national 3D geological model for Denmark (Jørgensen et al. 2013, Sandersen et al. 2015, 2016). Building a national 3D model is a large project that requires careful planning and organization. The work has been initiated, but

with very little progress until the necessary funding is in place.

## Lessons Learned

Based on our 3D modelling activities in recent years, a few of the lessons learned in the process are:

- The planning of a 3D mapping and modelling project should focus on the end-product: Which questions are the model supposed to answer, which types of data, and which type of model approach is needed to reach that goal?
- There is not always a good match between what the end-users and stakeholders think can be modelled and what actually can be modelled based on the available data. Most often we do not have data of the right type or the right amount to obtain the desired model detail
- 3D geological modelling today is a complex task where the best results come from tight collaboration between modellers and other groups of earth scientists
- Too many geological models from a not-so-distant past cannot be re-used because of too sparse documentation and lack of maintenance. Consequently, geological modelling often has to be done all over again in the same areas. We should all be aware that 3D geological mapping and modelling is an ongoing and dynamic process and thus strive to keep models alive and readily updateable. Static models should be a thing of the past and we must ensure that this message is properly conveyed to stakeholders and end-users
- The demands for geological 3D models in Denmark and Greenland are very different and so are the approaches, tools, and workflows.

## Next Steps

The next steps will focus on:



- Development of a strong business case for establishing adequate funding for the National 3D model
- Continued work on 3D geological modelling in research and consultancy projects with a focus on development of new methods and approaches
- Increasing the awareness among clients and end-users on the importance of keeping 3D geological models dynamic and up-to-date

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# Chapter 12: Geological Survey of Finland: Steps from Seamless Mapping Towards a National Geological 3D-Framework

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## Introduction

The Geological Survey of Finland (GTK) has systematically mapped the geology and Earth resources of Finland over the last 100 years. Regional geology programs are typically long-term and their development is more of a stepwise evolution than revolutionary changes driven by new technologies. From the 1980s all of the field observations have been stored in a GTK database, and since the 1990s, the GIS approach showed the way to fully digital mapping processes. The map sheet based approach was replaced in 2005 by a seamless bedrock map database, which was recently developed further towards a system of nationwide thematic layers compatible with the (IUGS-CGI-GeoSciML) standards.

The surficial geology mapping process was completely renewed after the emergence of LiDAR imagery. The Quaternary mapping program was replaced by modern glacial terrain mapping that was conceptually influenced by glacial dynamics of the Fennoscandian ice sheet. The new mapping process and production of thematic Quaternary maps (Putkinen et al., 2017) is complemented by modelling (2.5D and 3D) of the subsurface asso-

ciated with groundwater (Putkinen et al., 2014) and urban geological research (Ojala et al., 2007; Ojala et al., 2018).

GTK has a long tradition of geophysical modelling and more than 20 years of experience with ore deposit scale 3D-modelling. Belt scale bedrock modelling has been tested in several locations (e.g., Niiranen et al., 2014; Laine et al., 2015). The Onkalo Project (Bedrock Repository for Nuclear Waste) has been a test bench for Engineering Geology 3D applications.

The 3D-modelling and -mapping has emerged with developing technologies, and 3D is now gradually becoming the mainstream in depiction and conceptualization of geology. As a logical step forward, the GTK in 2017 started preparation for a National Geological 3D-framework of Finland.

## Organizational Structure and Business Model

GTK is a government agency and geoscience research center operating under the Ministry of Economic Affairs and Employment. Its activities are aligned with national priorities in research, innovation, and energy policy areas, and there is an active role in the mineral policies of Finland and

the EU. GTK core activities are defined as follows:

- Survey and research of Earth's resources and their sustainable use
- Management and delivery of national geoscience data
- Provision of geoscience information for society and the business sector
- Promotion of regional development
- Specialist services for community and commercial customers
- Active collaboration in international projects

GTK is currently operated by a combination of research processes (information management) and projects (operative activities) via 14 core competencies within business units. Three of the business units ('Regional Geodata and Interpretation', 'Corporate Geodata Management' and 'Digital Products and Services') have a basic role in compilation, management and delivery of the GTK corporate geoinformation.

Like many European GSO's, GTK has been encouraged to increase its customer orientation and income from contracted research. Currently GTK earns about one third of its annual turnover (c. €50 million) from exter-

nal revenues. The volume of regional mapping activities has considerably shrunk during the last ten years for various reasons. Nevertheless, the extensive GTK databases combined with modern information infrastructure still provide a good work environment for regional interpretation supported by targeted field checking. The systematic development of the GTK 3D mapping processes and work flows is seen as one major challenge in the coming years.

## Overview of 3D Modelling Activities

GTK during the last ten of years has developed a vision and a national approach for production, storage, and services for all interpreted geological data (e.g., maps and models). The 2D realization is the seamless map database. The nationwide thematic maps ‘Bedrock Units’, ‘Metamorphic Domains’ and ‘Thickness of superficial deposits’ are completed, and the themes ‘Structural Geology’, ‘Tectonostratigraphic Units’, ‘Metallogeny’ and ‘Glacial terrains’ are in compilation. The unit-based map themes are linked to a non-spatial stratigraphic database (Finstrati), which will further be linked to primary references (scientific publications and reports).

The overall objectives for the National Geological Framework of Finland (NGFF) cover all aspects of GTK mission. Basically a modern information system for all corporate data (primary and interpreted 2D/3D) with a well-organized and structured database is a major asset for the long-term relevance of GTK as a science based agency. The solid data framework increases both efficiency of processes and quality of the end-products in all activities (contracted projects/customer solutions, GTK mapping processes, and science).

From that point of view the 3D-framework - an extension and essential part of the NGFF - shall be scientifically

solid, harmonized with the map database, and capable to accommodate differently scaled models. The following requirements have been identified: (1) the conceptual data models must be nationally relevant, (2) the framework must be capable to serve various research themes (e.g., tectonic modelling, mineral systems modelling, and surficial and engineering-geological modelling) with sufficient spatial resolution, (3) the nationwide realizations (models) must act as an integrated basis for various types of geological interpretation, and (4) the framework must guide novel ideas and support future research.

The current activities and the plans for the coming years are grouped as follows: (1) NGFF, (2) Bedrock geology, (3) Quaternary geology, and (4) Engineering geology. For clarity, the following sections below are structured accordingly. The regional geological setting and rationale for the division is discussed in the separate section below.

### NGFF

#### 2018 (-2020) Activities

- NGFF data architecture with three master data domains: Spatial (2D and 3D) – Finstrati unit database – Primary references
- NGFF Data Models and Model Feature Catalogs (in collaboration with several projects)
- Vocabularies and Stratigraphic Lexicons (links to GeoSciML vocabularies; National vocabularies; Finstrati extensions)
- NGFF technology architecture (including 3D software; 3D database solutions)

### Bedrock Geology

#### 2018 (-2020) Activities

- Crustal scale bedrock 3D modelling (ver. 1.0 / 2019; depth of Moho, tectonic province boundaries and crustal scale structures)
- Belt scale 3D modelling (geological models / mineral system models)

of bedrock; the generic GTK approach (2019; definitions, work flows, testing); two case-study projects ongoing

- Ore deposit-scale modelling (mostly contracted work)
- GECCO project (funded by the Academy of Finland) combines expertise in high performance computing and geomodelling. The aim is to analyze the sources of the uncertainties and the tools to manage and visualize these using stochastic geophysical inversion.
- Testing of different scale (nationwide-belt scale-ore deposit scale) models within the NGFF data model

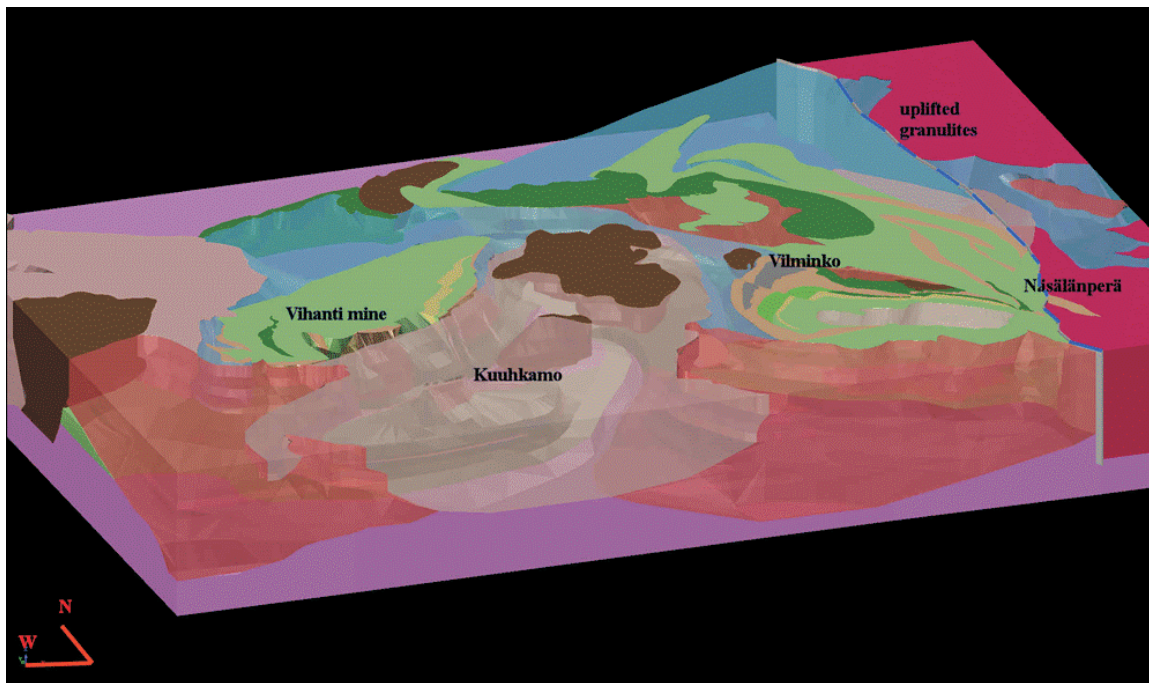
Examples of existing models are presented in Figures 1 and 2. More bedrock models are presented in Niiranen et al. (2014) and Aatos (2016).

### Quaternary Geology

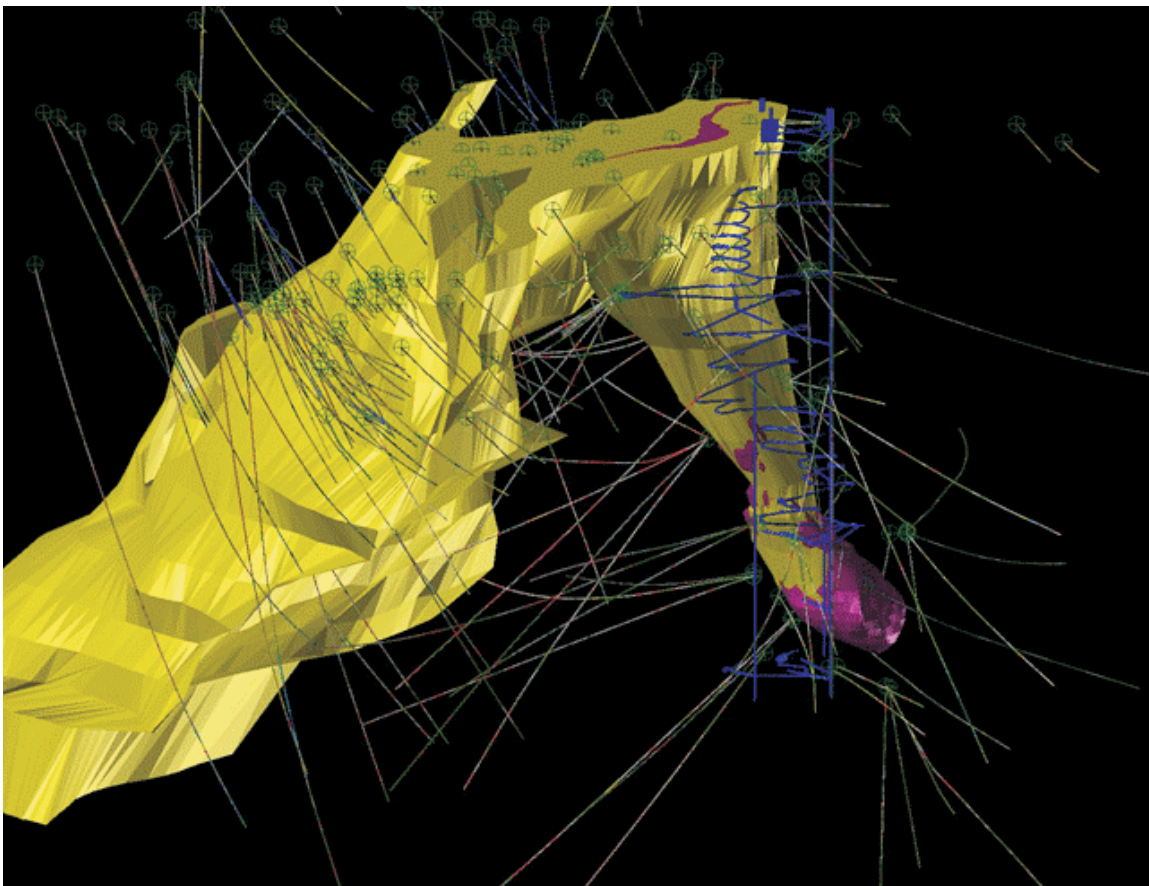
In the following years the main focus will be (1) use of the new unit-based surficial geology data model to 3D modelling and (2) improved coherence of the local (e.g., groundwater) and more regional models.

#### 2018 (-2020) Activities

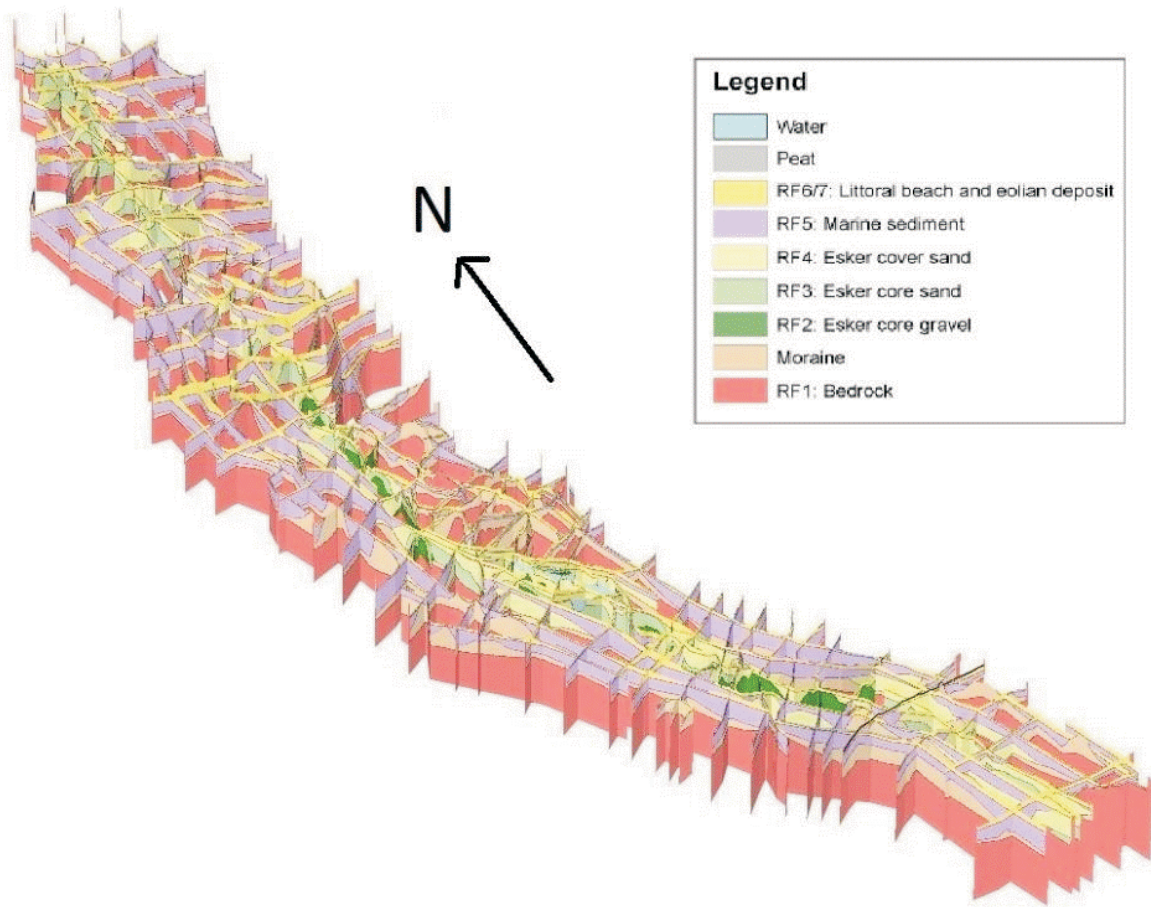
- Several 2.5D cross section-based / 3D block esker aquifer models per year (Figure 3).
- Definition and testing of a nationwide map-unit based system (Finstrati) for superficial deposits and their application to thematic 3D models.
- Pilot models of nationwide 3D compilations (e.g., overburden thickness, glacial meltstream deposits, major till beds and peat deposits).
- A 3D database for hydrogeology projects will be connected to the GTK’s Internet user interface to present real-time groundwater table viewing in geological context. (GTK-BGS Groundhog Desktop and Web system development collaboration)



**Figure 1.** Semiregional 3D model (30 km x 24 km x 10 km) from Vihanti mine district (reddish colors: diverse granitoids, dark brown: gabbro, pale green: intermediate metavolcanics, green: mafic metavolcanics; for details see the reference: Promine project; Laine et al., 2015).



**Figure 2.** Mine scale 3D model from Pyhäsalmi mine. Mine shaft (blue frame) is 1430 m deep. Model viewing direction from south (yellow: altered felsic metavolcanics, purple: massive sulfide ore; for details see the reference: Promine project, Laine et al., 2015).



**Figure 3.** Typical fence-diagram used in esker models. This is an example from Karhinkangas esker (model length is approx. 12 km), Middle Ostrobothnia, Finland (Putkinen et al., 2014).

- Search and definition of local and regionally significant unconformities for allostratigraphic subdivision of the late Pleistocene and Holocene strata in the Finnish sea areas and farther in the Baltic Sea.

### **Engineering Geology**

Engineering-geological modelling builds upon 2D and 3D models of superficial deposits, sedimentological logs, their geotechnical properties and drill holes (e.g., Ojala, 2007; Ojala et al., 2017).

#### **2018 (-2020) Activities**

- 3D modelling of the spatial distribution and thickness of fine-grained deposits in the Helsinki capital region (Geo model).
- Modelling of surface and bottom topography of fine-grained sediments to characterize surface relief types and to classify different sedi-

mentary environments (basin model)

- Regional distribution of different types of fine-grained sediments, including sulphide clay, and integrated geological 3D models of sediment showing their engineering properties (sediment model) (Figure 4).

Fractures and especially the bedrock weakness zones have been mapped in 2D for engineering geological applications. The next steps include:

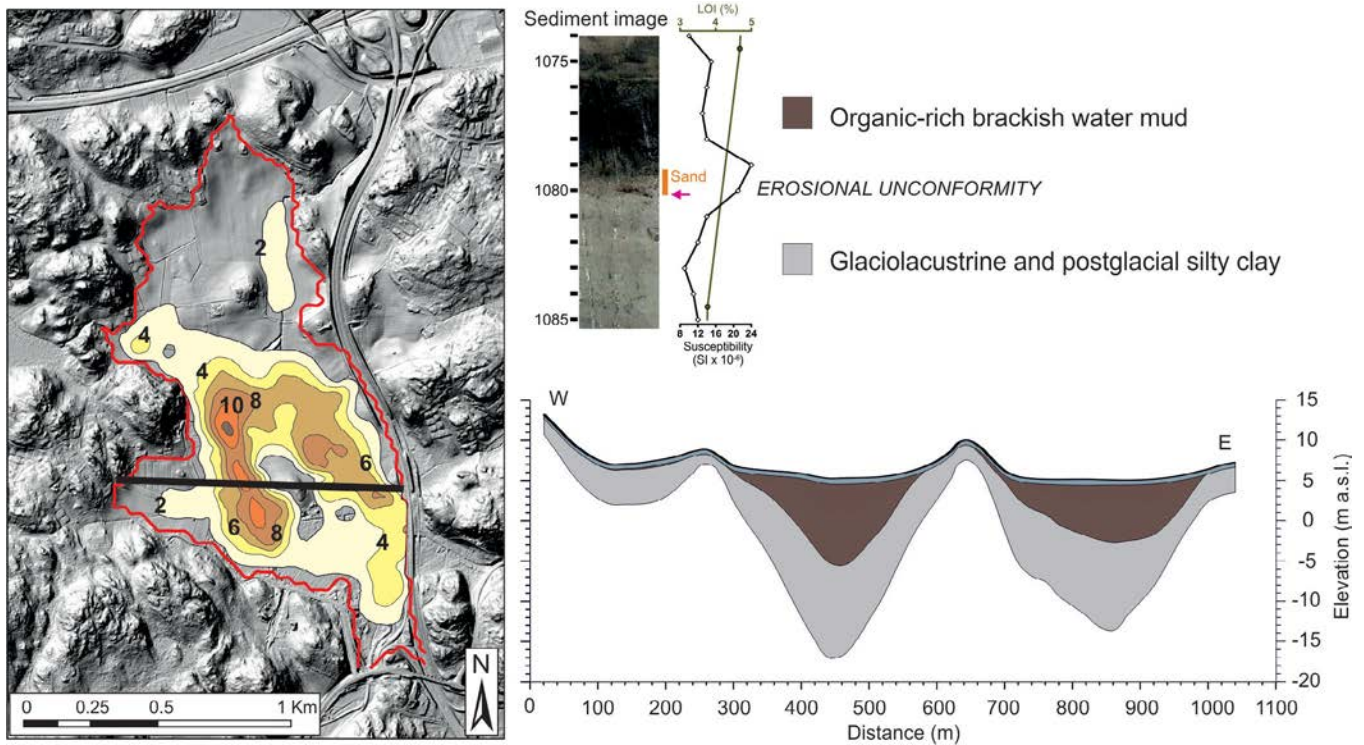
- The harmonization of regional data models (structural geology) and applied data models (bedrock weakness zones, fractures and jointing).
- 3D modelling of brittle structures has been used (e.g., metro tunnels; see Figure 5); and the applicability of the mapping data in modelling

will be tested further in various localities.

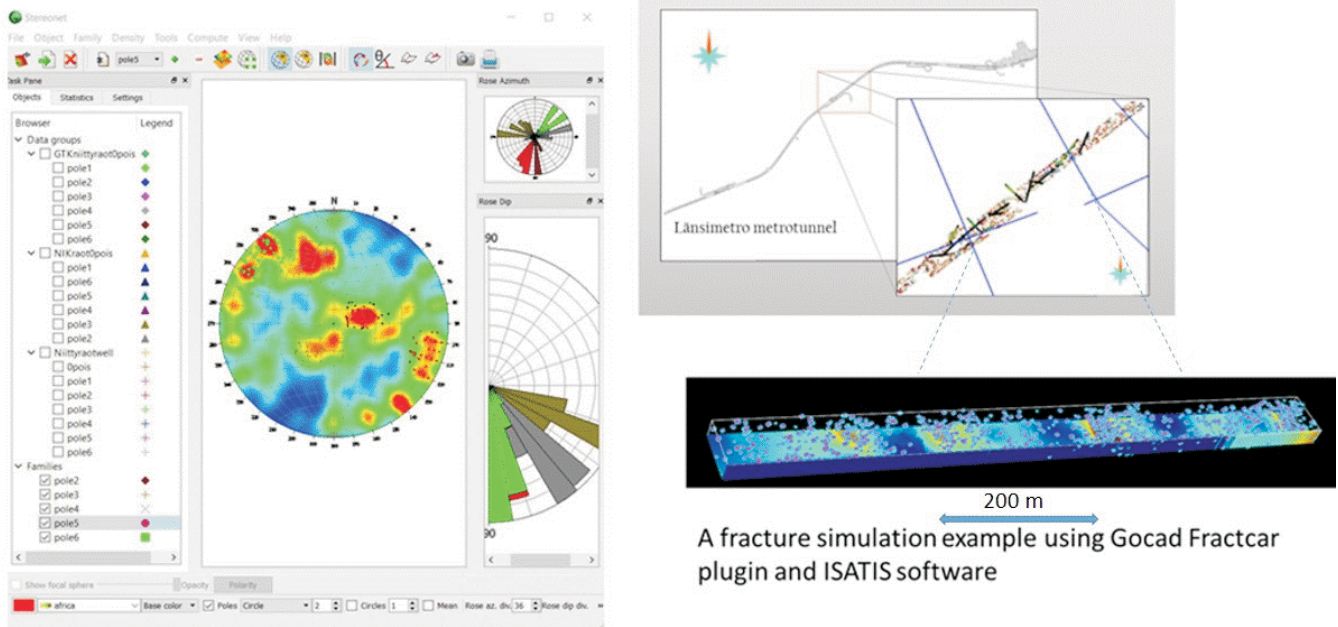
- The contracted modelling work for the Bedrock Repository for Nuclear Waste and other nuclear energy projects will continue.

### **Resources Allocated to 3D Modelling Activities**

The number of staff and yearly budget allocated to 3D modelling activities within GTK is not easy to provide. Only a minor part of GTK experts are extensively engaged in 3D work flows. The activities are embedded within project work packages (both GTK funded and contracted), and although part of the work is not modelling, it still can be considered dedicated to development of the GTK information infrastructure or work flows for 3D modelling.



**Figure 4.** In the southern coast of Finland, the fine-grained sediments are roughly subdivided into two parts: the underlying glaciolacustrine and postglacial silty clay and the overlying organic-rich brackish water mud with a poor bearing capacity and higher abundance of sulphide minerals that form sulphuric acid upon oxidation. The distribution and thickness of these two units are modelled in the Suurpelto area (Espoo) with darker brown indicating the thicker (up to 12 m) and pale yellow indicated more shallow (2 m) thickness of the organic-rich brackish water mud (Ojala et al., 2007; Ojala et al., 2018).



**Figure 5.** Statistical analysis of Niittykumpu fracture orientations, 3D visualization of the Niittykumpu metro tunnel fracture data with weakness zones (blue), and fracture simulation of one fracture set showing fracture density (blue for sparse and yellow for dense fracturing) in the background. The used software were Emerson GOCAD with Fractcar plugin made by RING consortium and ISATIS (Geovariences).

For 2018 the amount of total GTK man-years was 430–450. The 3D-modelling related project work all together is estimated at 20–35 man-years, and the hands-on modelling (production) may be less than half of that estimate. GTK aims to increase substantially both the number of participating staff members and the total volume of 3D-modelling work.

## Overview of Regional Geological Setting

Finland is geologically part of the Fennoscandian Shield with Precambrian crystalline bedrock covered by thin glacial deposits of Quaternary age. The distinctly twofold characteristics of geology and the low lateral continuity of both Precambrian and Quaternary geological units – for different reasons – is directly reflected to the mapping concepts and to the research tradition in Finland.

The medium to high grade metamorphic Archean to Paleoproterozoic rocks represent a crustal section of ancient orogenic belts with complex folding accompanied by migmatites, various intrusive phases, extensive shear zones, and faults. As an implication, the original geological successions are often difficult to connect in a regional scale. This has been a major challenge for bedrock map unit definitions (application of the ‘mappable unit’ concept). Therefore, a strong tradition of 2D-mapping based on lithological division (rock types) has dominated the mapping process until recently. For the same reason, the portrayal of cross sections have not been a standard requirement of the printed maps like in most countries worldwide. The geometrical complexity of the Precambrian crystalline bedrock of Finland needs to be carefully considered when developing 3D-mapping methodologies tailored for the needs of GTK.

The Quaternary superficial deposits cover the variable bedrock topography. These sediments were deposited

mainly during the last glaciation or thereafter as a result various glacial and postglacial processes. The deposits are composed of different types of moraines, that are partially superimposed by glaciofluvial deposits (e.g., eskers, deltas, ice marginal complexes), and fine-grained silt, clay, gyttja, and peat that were formed during the thousands of years that followed.

The composition, structure, and occurrence of till vary spatially due to differences in topography, subglacial deformable material and the distribution of Late Weichselian ice streams. Subglacial tills are often covered by loose till (hummocky moraine) accumulations on melting ice margins and in fracture zones. The locations of subglacial drainage systems are composed of washed and highly sorted gravel, sand and silt, and often characterized by the thickest accumulations of superficial deposits in Finland. The Salpausselkä I, II and III ice marginal complexes represent this well. Fine-grained silt and clay sediments represent glaciolacustrine and lacustrine sedimentary environments and were deposited on the bottom of Baltic Sea basin and isolated lakes from suspended material. Clay deposits mostly appear below the highest shoreline and especially in the coastal areas.

## Data Sources

The major data source for regional scale models is the GTK corporate database. All of the GTK corporate data is public information; mostly licensed (priced or free-of-charge) and partly open data (with unrestricted rights of re-use). In addition, both the land survey data (including DEM and LiDAR) and the environmental (EPA) data are delivered by open license in Finland. With increasing resolution (e.g., ore deposit modelling, engineering geology, and aquifer modelling) the data provided by the client or collaborator becomes more significant.

## Bedrock Geology

- Crustal scale 3D-model of Finland: GTK 2D map database; airborne geophysical data, seismic sections and their interpretations, gravity, magnetic and electromagnetic inversion models; tectonic evolution models
- Belt scale 3D modelling: GTK 2D map database, airborne and ground geophysical data; structural interpretations, mineral exploration data (both by GTK and mining companies), regional structural models
- Ore deposit-scale modelling: mostly exploration/mining data provided by the client)

## Quaternary Geology

- Regional modelling: GTK 2D map database, LiDAR DEM, basin interpretations, airborne geophysical data
- Applied modelling: LiDAR DEM, ground geophysical data (gravity, GPR, refraction/reflection seismic, ERT), borehole and excavation pits profiles

An increasing proportion of contracted and jointly funded research projects underline the importance of corporate data policy. Confidentiality issues are not normally complicated, but good practices are essential both in project work (contracts and agreements with clear definitions of IPR) and in information management (data classification, licensing).

Clients are increasingly interested in shared information infrastructures and/or in GTK’s role in data archiving. Before committing to such sharing, there needs to be a long-term maintenance cost considered on a case-by-case basis, and done so according to the objectives of the GTK data policy.

## 3D Modelling Approach

Each specific geologic application area (mineral exploration, groundwa-



ter, engineering etc.) have different customer needs, modelling processes, and end-products. Consequently, they need to be described and discussed separately in terms of 3D methodologies and modelling workflows. In this section, concise information on the current GTK approaches are summarized.

### **Bedrock Geology Modelling**

The 3D bedrock modelling process depends on the scale and purpose of the study. The regional scale models are based on the geological interpretation that is often constrained by sparse data. These conceptual 3D models largely build on the present understanding of the subsurface geology. The process typically combines information of the seamless digital map database (DigiKP) with vertical section compilations. In the forward modelling the explicit model is tested against seismic sections and other geophysical data. In mining sites, dense drilling often provides the possibility for more reliable models. Even then, the structures between drill holes can be drawn in many different ways depending on geological interpretations.

- Regional 3D geological models are built using the explicit approach using GOCAD and Surpac software. The GOCAD examples include the 3D geological model of Central Lapland (Niiranen et al. 2014) and Outokumpu assemblage (Saalmann and Laine, 2014). Surpac software was used to build the Pyhäsalmi-Vihanti area by Jouni Luukas (Laine et al., 2015).
- The implicit method using Leapfrog, Geomodeller, or GOCAD software is applied for dense data sets in order to define lithological boundaries or orebodies (based on the geochemical cut offs). It is also used to improve and update explicit 3D geological models.
- Seismic sections and geophysical inversion are used to build geological 3D models. 3D geophysical inversion is done mainly by

ModelVision and UBC code. Seismic sections are interpreted and visualized using GOCAD.

- Geostatistical 3D models are done using ISATIS and Surpac software. These are needed for ore evaluation and uncertainty studies. The resulting 3D models are voxels, in which grid cells are populated by lithologies, rock properties, and in part by probability distributions instead of one single property or rock type.

### **Surficial (Quaternary) Geology Modelling**

3D modelling of Quaternary deposits differs from the Precambrian formations because in most cases, the stratigraphy is nearly horizontal, has a patchy appearance, and the surficial sedimentary cover is often rather thin, typically 1-50 m with an average thickness is less than 5 m. The variable characteristics and clear discontinuities between sedimentary units enhance the 3D modelling. The unconformities are particularly useful in offshore areas, where the late Pleistocene and Holocene strata can be subdivided into several allostratigraphic units (Virtasalo et al., 2014), and the major unconformities can be traced into the Baltic Sea basin-wide in marine seismic profiles (Virtasalo et al., 2016). Combined with 2D maps and datasets of surficial deposits, differences in sediment types (and genesis) and unconformities also allow a utilization of explicit conceptual 3D characteristics for geological subsurface modelling. Typical subsurface 3D modelling projects at GTK are related to hydrogeology, geoenergy, mine and industrial environments, offshore infrastructure and underground construction and land use planning.

- 3D modelling projects typically utilize ground penetrating radar, offshore acoustic-seismic profiling and reflection seismic data for determination of sedimentary unit boundaries that will be digitized, and then cross sections can be

constructed. Sediment coring and terrestrial borehole data guides interpretations of sedimentary units. The constructed models are typically explicit and created using Groundhog Desktop, ArcGIS, and GOCAD. In rare cases in groundwater flow modelling projects, GMS software implicit algorithms are utilized.

- Marine seismic profiles and side scan sonar images are interpreted using Meridata Data Processing Software, and visualized using Golden Software Surfer and ArcGIS. Multibeam data are processed with Hypac and visualized with Fledermaus software.

### **Engineering Geology Applications**

As population shifts from rural to urban, cities are expanding and becoming more densely populated. Therefore, the need for engineering-geological 2-3D models has increased. GTK contributes to be involved with land-use and underground planning and construction with 3D model applications that are based on geological and geophysical information. The bedrock 3D models are typically designed for underground infrastructure (e.g., tunneling and other subsurface constructions) and geoenergy potential, whereas studies of superficial deposits concentrate in areas with unconsolidated sediments (clay-silt) across the coastline. GTK's 3D modelling in the urban environment is targeted to provide information about geological conditions and processes to anticipate ground behavior and make realistic assumptions regarding material properties.

The more data that is available for development of 3D geological models, the more the models become data based, and even the implicit approach to building potential surfaces can be applied. Implicit approach can also be used to update 3D models based on sections and drill core data, as it is

case in the Onkalo nuclear waste site. In addition to surface models, also solid and voxel models are built using rectangular unstructured grids. These are important for representing both rock properties and chemical compositions.

- The implicit method (e.g., Leapfrog, Geomodeller or GOCAD software) is applied for dense data sets. Explicit Quaternary geological conceptual modelling is based on Groundhog desktop operations.
- Recent developments in 3D modelling include 3D models built using drone photographs and X-ray tomography of rock samples.

In many practical applications, such as in nuclear waste site investigations, bedrock groundwater modelling or rock engineering, it is important to estimate rock fracturing in 3D. Connected rock fractures act as water conduits and, in general, fracturing affects the rock's mechanical properties. A special type of 3D models are related to fracture or discontinuity models (DFN) derived from fracture property statistics using Monte Carlo simulations. Geological and stochastic methods are applied in fracture network simulations.

- Presently used software for stochastic fracture simulation is Fractcar plugin for GOCAD developed by RING consortium. In addition, own tools are developed. Fracture networks will be used in geomechanical modelling (Irazu FEMDEM).

### **Generic Applications**

Visualization and, finally the 3D model storage for re-use, are the final steps of a managed modelling process. The option for re-use is seen as a strategic requirement both for the modelling software and for the 3D database solution. Appropriate metadata with a description of the modelling process will be one key factor in evaluating the reliability of the models.

- 3D visualization is done using 3D modelling software and their viewers, ArcScene and Paraview.
- The 3D storage / database is technically not resolved; and both commercial and in-house options are actively studied.

### **Clients**

Considering the fast development of technologies and customer expectations, the definition of precise, use-case based requirements for GTK 3D mapping activities and for the National Geological 3D framework is a demanding task. Therefore GTK has selected an approach emphasizing the easy re-use of the corporate data (2D and 3D), standards (for interoperability) and data access. This information infrastructure objective must be aligned with real-world project needs (increased efficiency), the customer needs, and the overall societal impact of data services.

The clients and stakeholders are all different and represent various business areas. Mineral industry (mineral exploration, mining) still is the most important stakeholder for GTK and much of the modelling has been (geophysical modelling, ore deposit modelling) and will be (belt scale geological modelling for mineral systems modelling) developed accordingly. Groundwater projects collaborate with municipalities and environmental agencies. Urban geology and engineering geology are of increasing importance in GTK strategies and modelling partnerships.

### **Current Challenges**

The identified challenges are severe when applying new technologies and developing basic work processes at the same time.

- Software architecture – affordable – compliant for all application areas from crustal modelling to engineering geology;
- Allocation of resources (especially key experts) to long term objec-

tives (like NGFF) due to competition by contracted projects with high priority

- Web-based 3D visualization solutions for professionals and the general public.

### **Lessons Learned**

The transition from 2D mapping to 3D mapping is a pervasive process for a GSO. Steady support from strategy level planning, consistent long-term objectives, and involvement of key experts are essential - otherwise the results are achieved too slowly compared to the rate of the technological change.

The conflicting priorities of long-term objectives (requirements of a robust, versatile corporate data; e.g., conceptual data models, vocabularies, architectures) and short-term project needs (e.g., a contracted case model tailored for customer needs) cannot be avoided in a business model with multiple funding sources. Realistic balancing just needs to be done even when it causes some frustration or temporary anomalies to the planned long-term objectives.

### **Next Steps**

- Consolidation of the GTK 3D strategy and strict prioritization of 3D key objectives and results to 2020.
- Identification of domestic and international key partners in various branches of 3D mapping and modelling, including:
  - 3D framework and reference system
  - Modelling and visualization technologies
  - 3D-databasing
  - Benchmarking of processes and products:
    - Crustal scale modelling
    - Belt scale bedrock modelling (combination of geological models and mineral system models)

- Regional scale glacial deposits modelling
- Urban geology modelling

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# Chapter 13: Examples of Computational 3D Modelling at the German Federal Institute for Geosciences and Natural Resources

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## Introduction

The Federal Institute for Geosciences and Natural Resources (BGR) is the geological Survey of Germany. The geoscientific center of excellence is embedded within the federal government and part of its scientific and technical infrastructure. As a federal institute, accountable to the Federal Ministry for Economic Affairs and Energy, BGR is obligated to provide neutral and independent advice and information related to geoscience and natural resources including energy resources, mineral resources, groundwater, soil, deep subsurface use, geological disposal of radioactive waste, and geohazard assessment. Further tasks assigned to BGR emphasize on international cooperations, geoscientific information, as well as obligations related to the international nuclear weapons test ban.

Due to the federal structure of Germany, the State Geologic Surveys (SGD) themselves are responsible for their respective territory. Therefore, in regards to German 3D models, BGR focusses either on large overviews or on small customized scales addressing specific scientific questions. In the following, some of the modelling activities ongoing in the different departments will be presented, however,

they can only be considered as a small insight. Furthermore, the scope of this text lies on BGR's different aims, approaches, and methods related to 3D modelling, and not on the scientific outcomes as the latter are documented in technical reports, published in journals, and presented at national and international conferences.

## Organizational Structure and Business Model

BGR is divided into five departments. Figure 1 provides an overview of the internal structure. Departments 1 to 4 contribute to the vast number of 3D modelling. However, only a small selection of the diverse field can be presented in this text, it is given without any claim to completeness. The examples are provided by three departments highlighted in red, refer Figure 1.

In general, BGR is directly financed by the German Federal Ministry for Economic Affairs and Energy. However, numerous projects are completed in cooperation with partners, hence, co-funding is provided in some cases by e.g. the European Union, national and international research funding agencies or, to a lesser degree, industrial partners. Most of the 3D modelling described in this text, is performed by Department 3

“Underground Space for Storage and Economic Use”, with additional contributions from Department 1 “Energy Resources” and Department 2 “Groundwater and Soil Science”.

## Overview of 3D Modelling Activities

As stated above, several departments in BGR are actively involved in static or dynamic 3D modelling or both (Figure 1). Department 1 “Energy Resources, Mineral Resources” focusses on 3D petroleum system modelling, whereas the main objective of Department 2 “Groundwater and Soil Science” is building 3D hydrogeological models. Department 3 “Underground Space for Storage and Economic Use” builds 3D structural models at different scales, parameterized 3D models, and models of dynamic processes. The spatial extent of these models vary from small reservoirs or sites to large basin-scale models. Out of the diverse field of 3D modelling, this text focusses on a few 3D modelling projects situated in Northern Germany. An overview of their location and spatial extent is given with the respective model borders shown in Figure 2.

At present, the 3D modelling project with the largest spatial coverage is the “Subsurface Potentials for Storage



**Organisational Chart of the  
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German Mineral Resources Agency (DERA) / Berlin Office:  
Address: Wilhelmstr. 25-30, 13593 Berlin  
Telephone: 030 36993-0 or extension  
Telefax: 030 36993-100  
Internet: <http://www.bgr.bund.de>  
Email: [Poststelle@bgr.de](mailto:Poststelle@bgr.de)

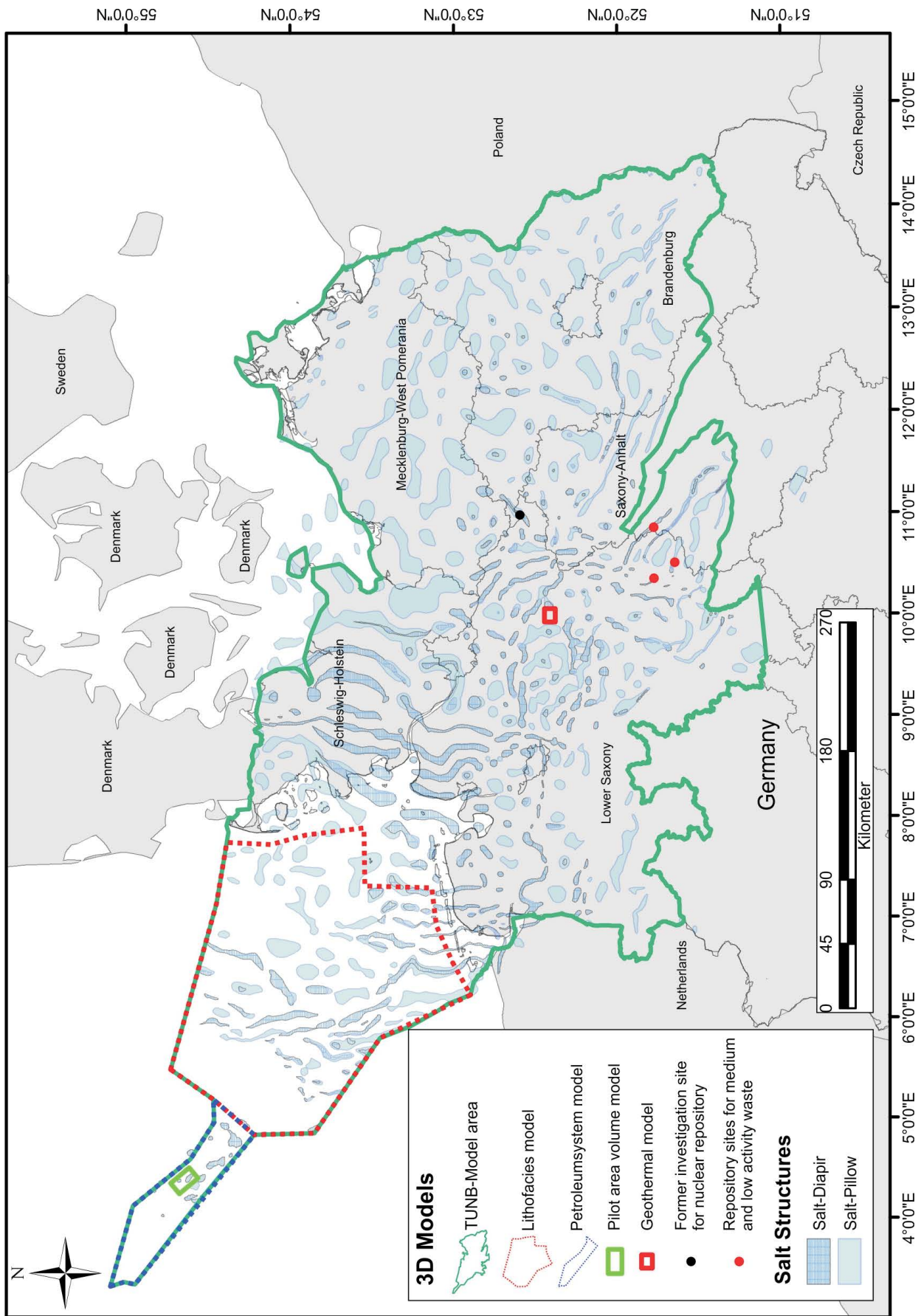
Last update: 01<sup>st</sup> of August, 2018

<b>Presidential Staff, Public Relations</b> C. Blume <sup>3)</sup> Public Relations Officer: A. Beuge	<b>President</b> Prof. Dr. R. Watzel	<b>Internal Auditing</b> Contact	2835 2679	2101	2235	K. Kruse K. Harder M. Zaepke A. Schenk D. Reinert Dr. H. Höper <sup>2)</sup>
<b>Vice President</b> Dr. V. Steinbach	<b>Department 1 Energy Resources, Mineral Resources</b> Dr. V. Steinbach Deputy: Dr. H. Wilken Department Controlling Dr. I. Heyde	<b>EU Due Diligence Obligations in Mineral Supply Chains</b> Contact	2352	3794	2442	3036 2234 2403 3688 2248 3265

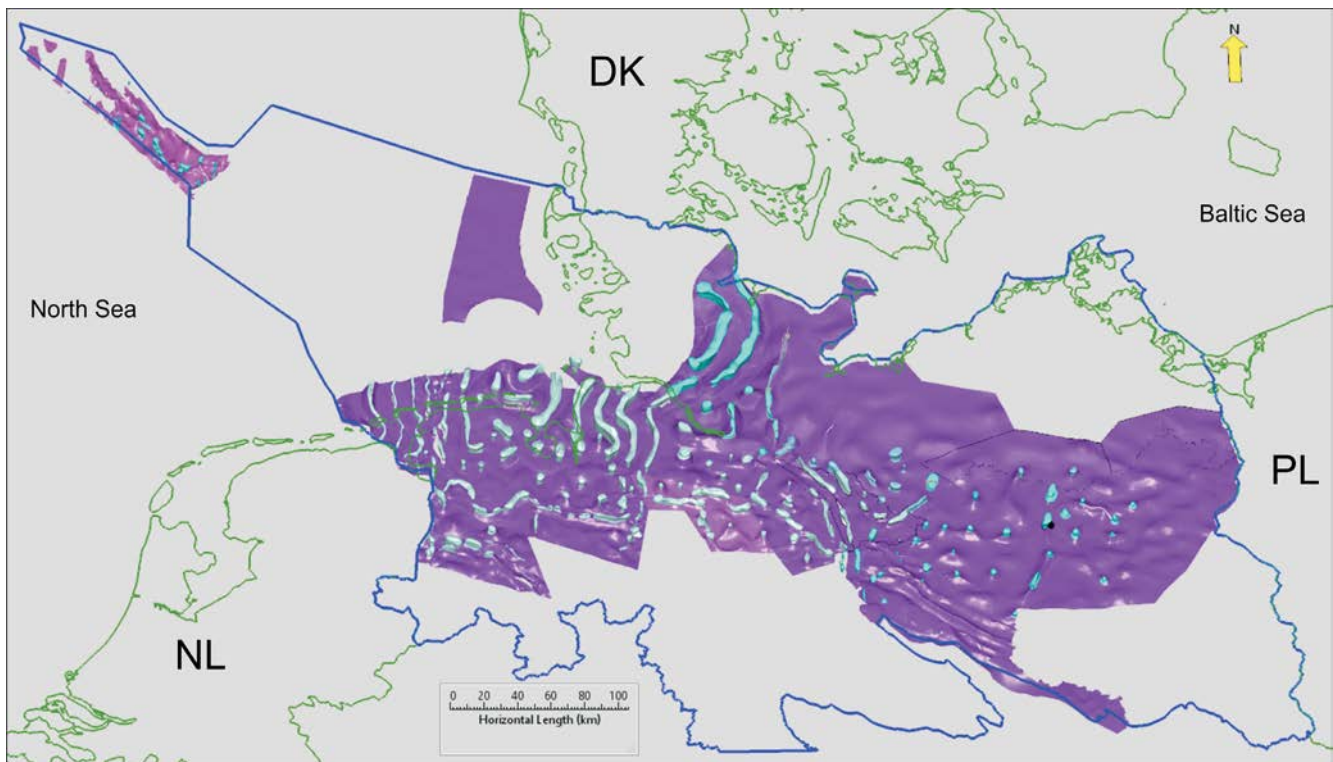
<b>Department Z 1) Central Affairs</b> B. Zober Deputy: C. Jahn Department Controlling A.-C. Woodyard	<b>Department 2 Groundwater and Soil Science</b> Prof. Dr. T. Himmelsbach Deputy: N. N. Department Controlling Dr. R. Bäumlé	<b>Department 3 Underground Space for Storage and Economic Use</b> G. Enste <sup>3)</sup> Deputy: N. N. Department Controlling H.-D. Bähre	<b>Department 4 Geoscientific Information, International Cooperation</b> N. N. Deputy: Dr. C. Bönнемann Department Controlling C. Wosniok
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<b>Section Z.3 Organisation, Central Controlling</b> G. Lopez Wismer	<b>Sub-Department 2.3 Groundwater Resources - Quality and Dynamics</b> N. N. Deputy: Dr. G. Houben	<b>Sub-Department 3.3 Rock Characterisation for Storage and Final Disposal</b> Dr. J. Lippmann-Pipke Deputy: N. N.	<b>Sub-Department 4.3 Central Seismological Observatory, Nuclear Test Ban</b> Dr. C. Bönнемann Deputy: Dr. L. Ceranna
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<sup>3)</sup> Permanent post at LBEG  
<sup>4)</sup> entrusted with management of affairs

**Figure 1.** BGR's organizational chart. The presented 3D modelling is embedded in the three departments highlighted in red, the eight 3D modelling cases shown exemplarily are provided by the sub-departments highlighted in blue.



**Figure 2.** Overview map of the presented 3D models and their locations. As the subsurface of Northern Germany is dominated by salt structures, locations of the salt structures after Reinhold et al. (2008) are included in the map for a better orientation. In addition, the borders of the federal states of Schleswig-Holstein, Mecklenburg-West Pomerania, Brandenburg, Saxony-Anhalt, Lower Saxony, the German North Sea, and coast lines are indicated as gray lines.



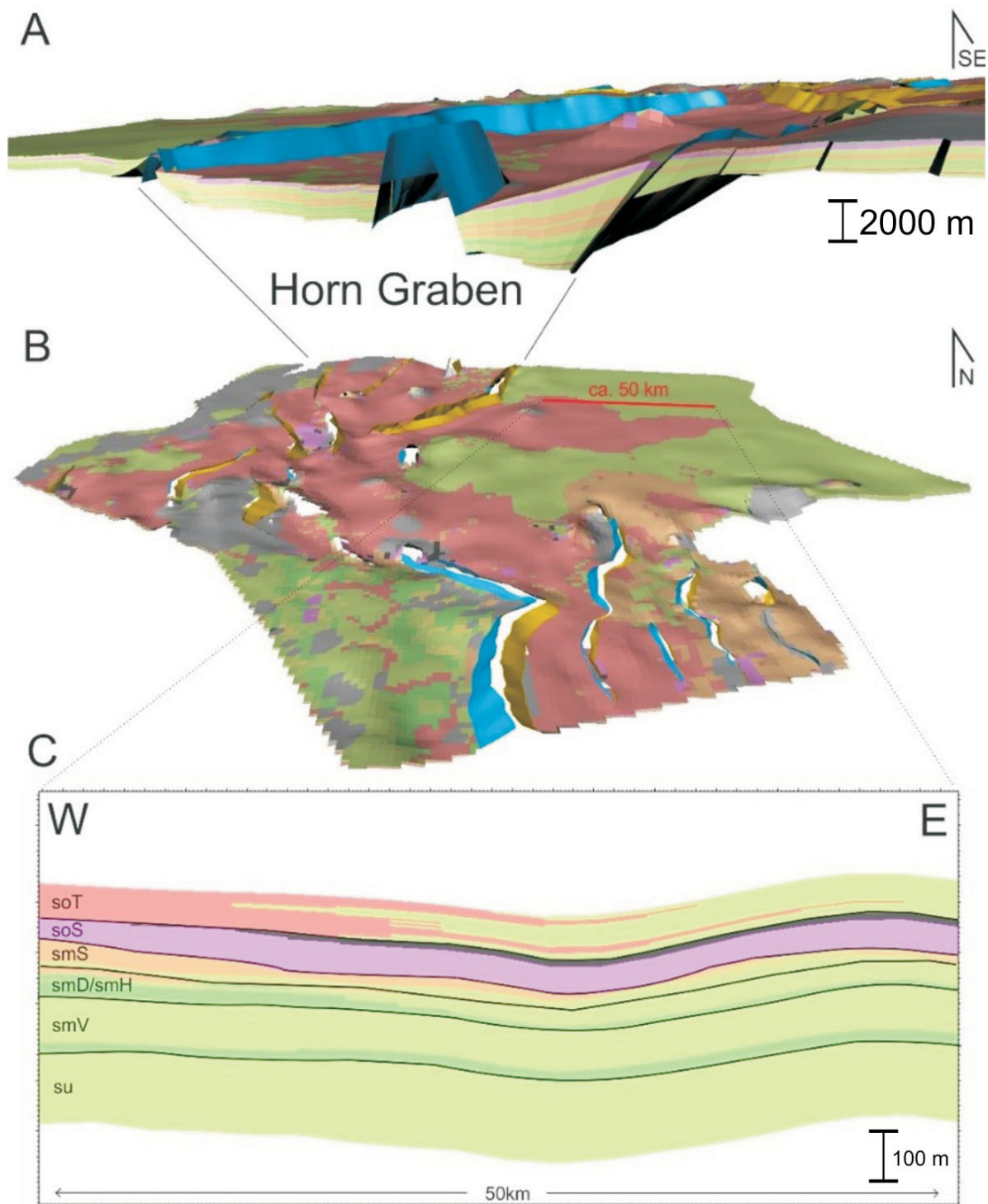
**Figure 3.** Most recent state (March 2019) of the 3D model using Emerson’s software GOCAD, almost half of the model is already completed. The color code is as follows, external border of the final model (dark blue), modelled horizon “Base Triassic” (purple), salt structures (turquoise), faults (either black, gray, or dark blue), coastlines and border between states (green). At the time of the editorial deadline, the model covers an area of 76,500 km<sup>2</sup> (equivalent to 46 % of the final model), so far 169 salt structures and approximately 2,600 faults could be integrated. The model is slightly tilted towards the south to increase the visibility of the salt structures.

and Economic Use in the North German Basin” (TUNB). Here, the main objective is to develop a consistent and harmonized structural model with 16 base horizons starting from the Permian “Zechstein” up to the surface. In addition to these base horizons, important faults and salt structures are incorporated in the model. The TUNB project (Figure 2), which started in 2014, is a collaboration between BGR and the State Geologic Surveys (SGD) of the northern German federal states. While every SGD is responsible for its own territory, BGR accounts for modelling the offshore area (exclusive economic zone – EEZ) of the German North Sea. The harmonized final model will integrate all of these submodels, covering an area of about 170,000 km<sup>2</sup>, which extends from the westernmost part of the German North Sea to the border between Germany and Poland in the East (Figure 3). An important charac-

teristic of the modelling area is the existence of large and complex salt structures. These structures can extend up to several thousand meters in the vertical direction and tens of kilometers in the horizontal direction. Due to the relative large size of this model, the model is being built in multiple pieces. Hence, every SGD is working on its own area, dividing the entire model in six sub-models. Furthermore, each of these SGD areas have been divided further into several tiles, which were modelled separately and harmonized along their common borders. The current state of the TUNB model is illustrated in Figure 3.

Within the border of the TUNB project, some other, more detailed 3D models were developed in order to address various scientific questions. The first one presented here is a lithofacies model of the Triassic subunit “Buntsandstein” located in the central part of the German North Sea (Fig-

ure 2). The model is based on a 21 wells, a dense network of 2D seismic lines (Figure 15), and a pre-existing structural 3D model ([www.gpdn.de](http://www.gpdn.de)). The entire model covers an area of approximately 20,000 km<sup>2</sup> and served as a basis from which a volume model was derived, consisting of 6 stratigraphic horizons, divided into 20 layers each. This volume model contains slightly over 5 million rectangular grid cells, each measuring 1 km<sup>2</sup> with a varying thickness between 5 m and 80 m. The subsequent parametrization of the model was completed by extrapolating the lithological information of the 21 wells using the Sequential Indicator Simulation (SIS) within the Petrel software by Schlumberger. The result was the first regional scale 3D lithofacies property model for the Buntsandstein in the central German North Sea (Wolf et al., 2015) providing spatial distribution of the different lithologies (Figure 4).



**Figure 4.** Parametrized lithofacies 3D model of the Lower Triassic Buntsandstein in the central German North Sea, modified after Wolf et al. (2015). The top of the model is located in an average depth of 2000 m and the deepest parts of the model are (in the Horn Graben) at a depth of approx. 8000 m. The different lithologies are color coded: mudstones to coarse grained sandstones (red to dark green), salt (pink), anhydrites (black), unassigned areas (gray). Part A shows the generalized structure and lithological filling of the Horn Graben in the north part of the model. Part B features an overview of the whole study area. Part C illustrates a cross section featuring prominent fining upward cycles of the Middle Buntsandstein and subsequent barrier formations. The Buntsandstein is stratigraphically abbreviated by “s” and divided into 3 subunits: “su” (Lower Buntsandstein), “sm” (Middle Buntsandstein) and “so” (Upper Buntsandstein). The third letter of the names on the left represent the respective formation, i.e. “smV” (Volpriehausen fm), “smD” (Detfurth fm), “smH” (Hardegsen fm), “smS” (Solling fm), “soS” (Roet-Salt), “soT” (Roet clay).



A second, smaller lithological model was developed within the geothermal project “Horstberg” for a deep geothermal test site in Lower Saxony (Figure 2), again using Petrel. The base for this project was a 3D seismic cube in addition to three wells providing information on lithology. The model area extends approximately 10 km x 6 km laterally, and extends from the ground surface to a depth of 4.5 km at the base of the Permian “Zechstein”. A detailed seismic interpretation allowed the implementation of a complex fault system in combination with the most prominent horizons (Figure 5).

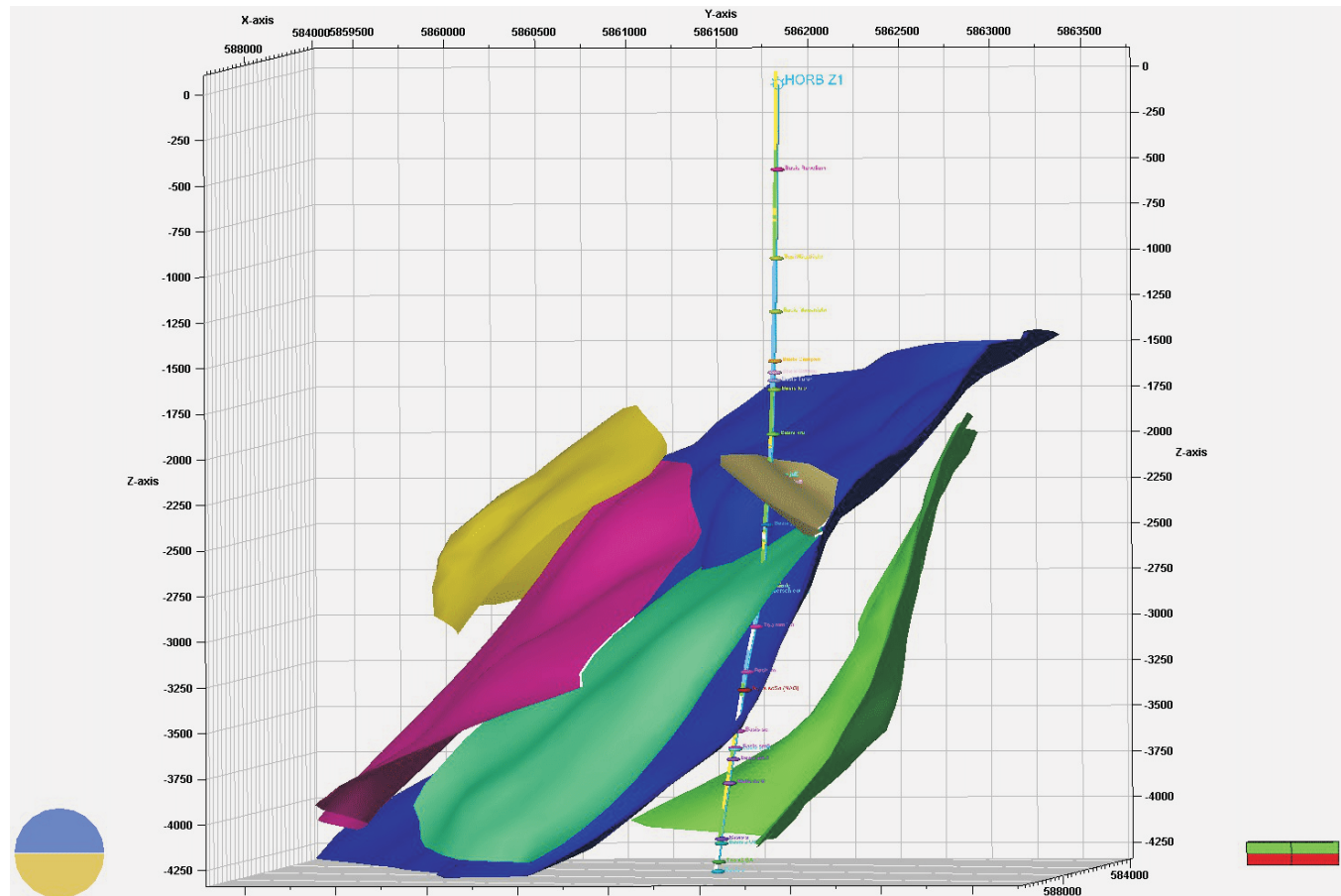
Based on the time-depth conversion of the interpretation, a volume model was created consisting of 15 horizons. The main target formations for the

geothermal test site were divided into 15 to 20 layers each, while the other formations were divided into 5 layers each, adding to a total of 128 layers featuring variable thicknesses. Within each of these layers, grid-cells with a size of 15 m x 15 m were defined. Using the stochastic extrapolation (SIS by Schlumberger) and constrained by calculated and defined probabilities of the respective lithology in each layer, the cells were populated with the lithological information from the wells. The final model is shown in Figure 6.

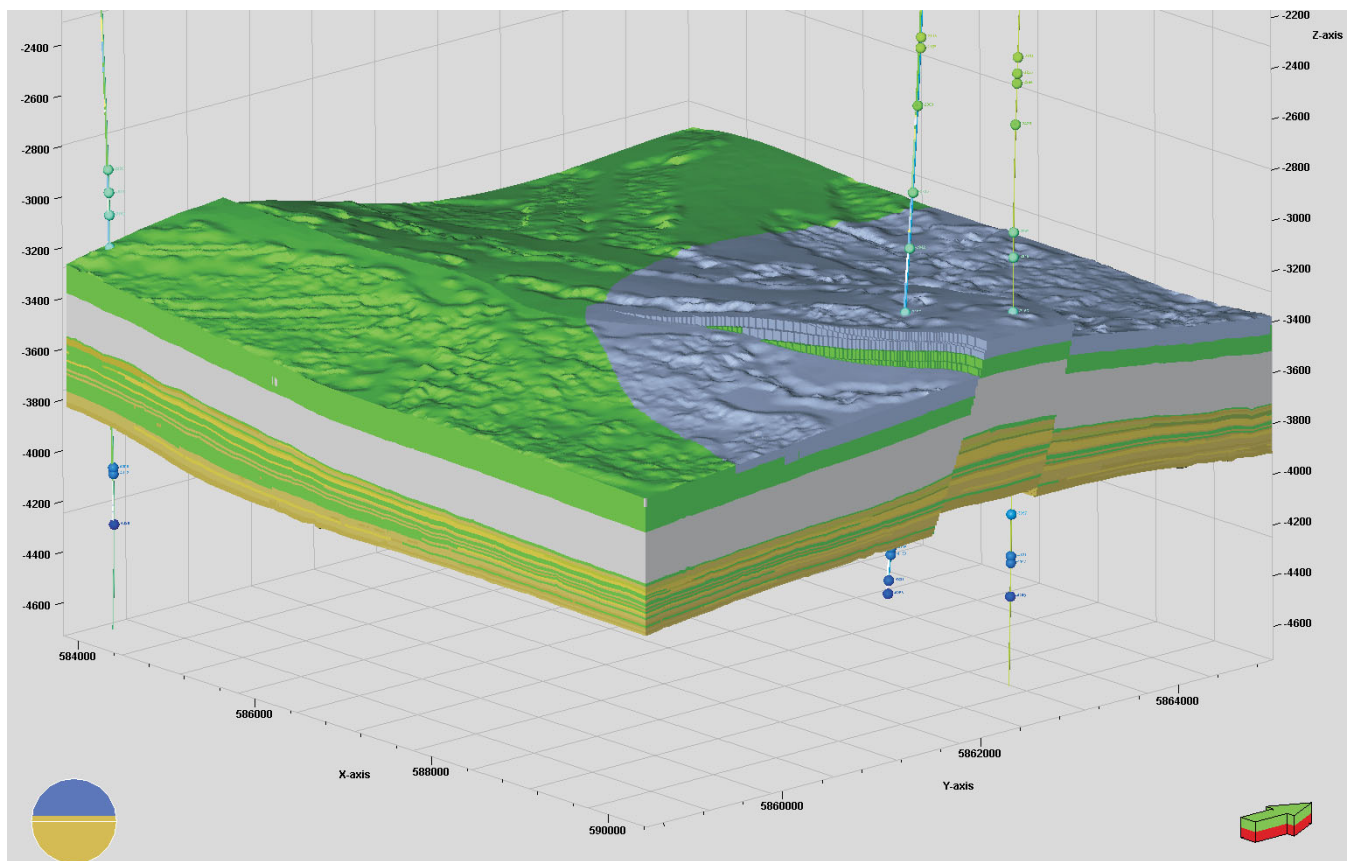
The third model within the TUNB framework is a modelling study of a 3D basin and petroleum system covering the NW German North Sea, referred to as the Entenschnabel (Figure 2). The aim of this research was

the reconstruction of the thermal history, maturity, and petroleum generation of three potential source rocks, i.e. the Namurian-Viséan coals, the Lower Jurassic Posidonia, and the Upper Jurassic Hot Shales. The study was realized using the software package PetroMod by Schlumberger. The development of the geological model is based on a detailed 3D model (Figure 7), recently compiled maps, and structural information of the Entenschnabel obtained in the GPDN project (Arfai et al. 2014). The whole model, as well as a cross-section through the model is shown in Figure 8.

All information is available online at [www.gpdn.de](http://www.gpdn.de), including thickness and depth maps of relevant stratigraphic seismic horizons as well as



**Figure 5.** Fault model of the geothermal site “Horstberg” with the geothermal well in its center. For this application, the complex fault zone in the middle of the model could be simplified to two normal faults (brownish-grey and yellow) and for elements representing the inverted normal fault of a former halfgraben and thrust faults (green, blue, pink, and turquoise); view from the East.

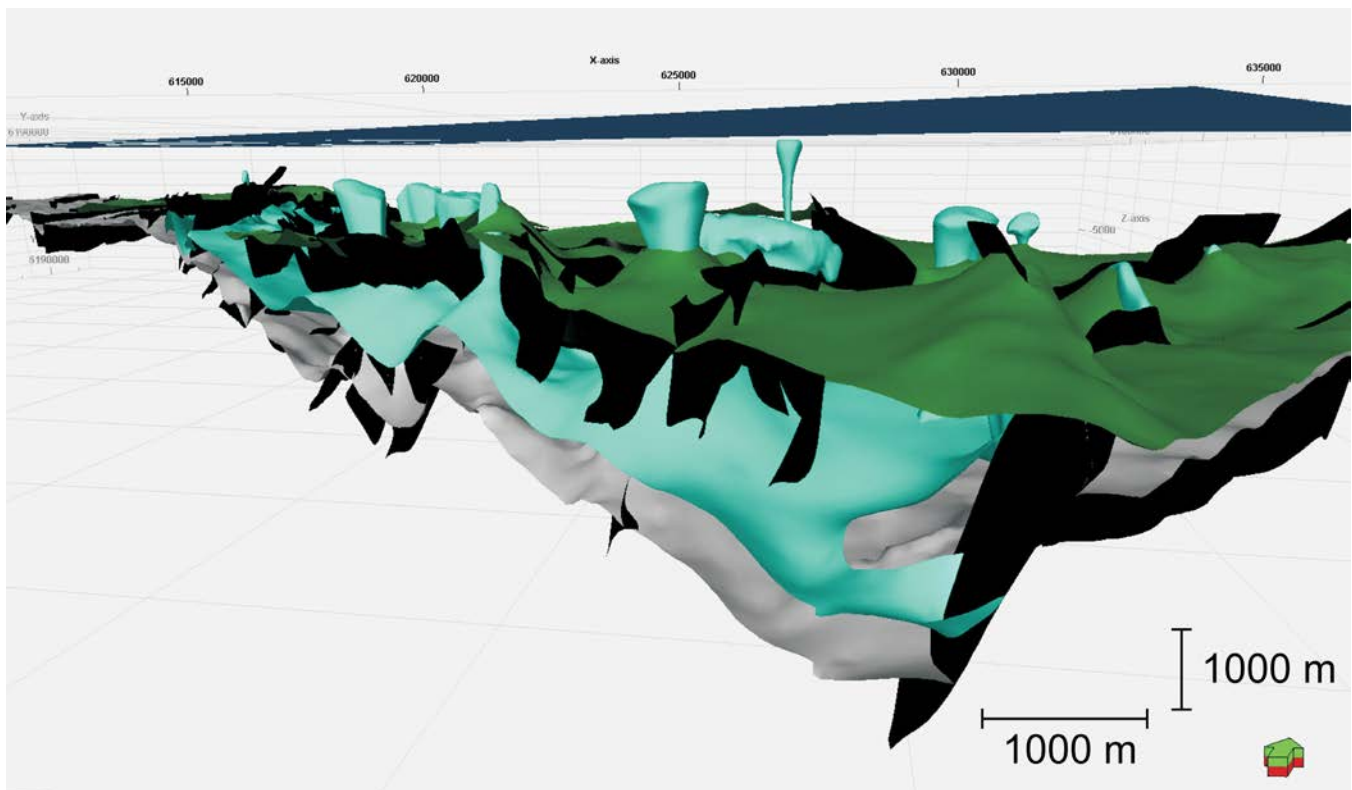


**Figure 6.** Lithology-Model for the Lower Triassic “Buntsandstein” at the deep geothermal site “Horstberg”. The model shows the lithology from the base of the Middle Triassic “Muschelkalk” to the base of the Triassic. Brown to yellow colors represent clastic material (the darker, the coarser), green colors represent claystone, white stands for rock salt, and blue represents anhydrite. The fault-system is not displayed, but visible in the offset of the layers; view from the South-East, vertical exaggeration: 2x.

locations of faults and salt structures. Petrophysical values and facies information from wells are assigned to the different geological layers in the 3D model. The latter is further optimized with temperature and maturity data obtained from wells and literature. A time span from the Late Palaeozoic to the present is covered by the model including three erosional phases related to large-scale tectonic events, which had a significant effect on the region of interest: the Saalian (Late Carboniferous to Early Permian), the Late Cimmerian (Late Jurassic to Early Cretaceous), and a Late Cretaceous to Paleogene structural inversion. Additionally, halotectonic activity through time expressed as diapirs and pillows in the area of interest is considered within the 3D model (Arfai and Lutz 2018).

In addition to the demands of building large complex regional models and limited input data, there are also methodological challenges that BGR is facing. While the 3D model of the entire North German Basin is built as a triangular surface based structural model, using SKUA-GOCAD, it is intended to construct volumetric (cell based) models of several pilot regions in a later phase of the project. Ideally, these cell based models should retain the original structural complexity (i.e. no simplification) while being suitable for the use of numerical simulators. For structurally complex regions with faults and unconformities, this can only be done using tetrahedral grids that are constructed from a topologically clean and watertight triangular boundary representation. Obtaining this representation is labour-

intensive and the methods that are currently the state of the art were mainly developed with the requirements of the exploration industry in mind (e.g. for 3D models of reservoir size) but are still a matter of active research for complex regions and on a basin scale. For this reason, BGR is working on developing and applying the necessary workflows for constructing cell-based volumetric models (Figure 9) needed as input for dynamic simulation (Zehner et al. 2015; Zehner et al. 2016). We are intending to publish this model on the web upon completion. Hence, BGR is (a) evaluating different visualization options for 3D models and (b) investigating how uncertainty could be treated and visualized, such as the European funded GeoERA project ([www.geoera.eu](http://www.geoera.eu)).



**Figure 7.** Model of the Entenschnabel in the German North Sea displaying salt structures and the top of the Permian Zechstein (bright blue), the base of the Zechstein (grey), the base of the Cretaceous (green), and the seafloor (dark blue). Fault structures are shown in black. For better visibility faults on top of the salt structures are omitted in the figure; view from the south. The model was developed in the GPDN project (active time frame from 2009 to 2013, [www.gpdn.de](http://www.gpdn.de)) with the software GOCAD, here displayed using the software Petrel.

Our first approach of visualizing less constrained areas in models is to use marker “Regions” in GOCAD. Poorly constrained areas (e.g. those around salt structures) are interpreted in the seismic section and subsequently modelled as separate bodies (Figure 10). Afterwards, these bodies are intersected with the final structural model and the parts of the model within these uncertainty bodies are marked by a region (Rebscher and Steuer 2018).

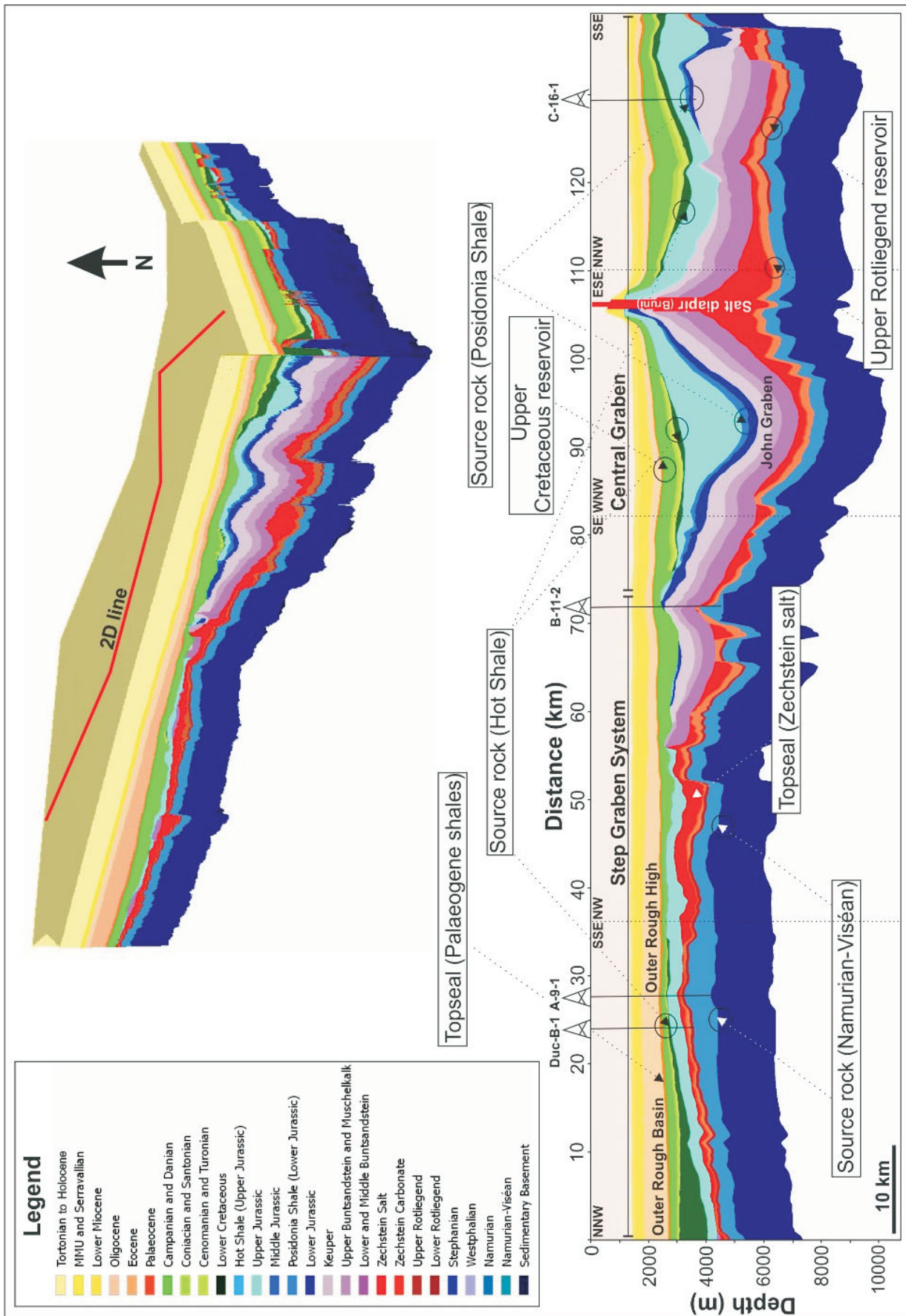
Partly based on the structural models described above, and partly on similar or generic models, BGR performs also a vast number of dynamic 3D modelling. Depending on the geoscientific topics and the relevant coupled processes, thermal, hydraulic, mechanical, and chemical (THMC) modelling is performed in several departments, applying different software

packages (refer to the section on 3D Modelling Approach).

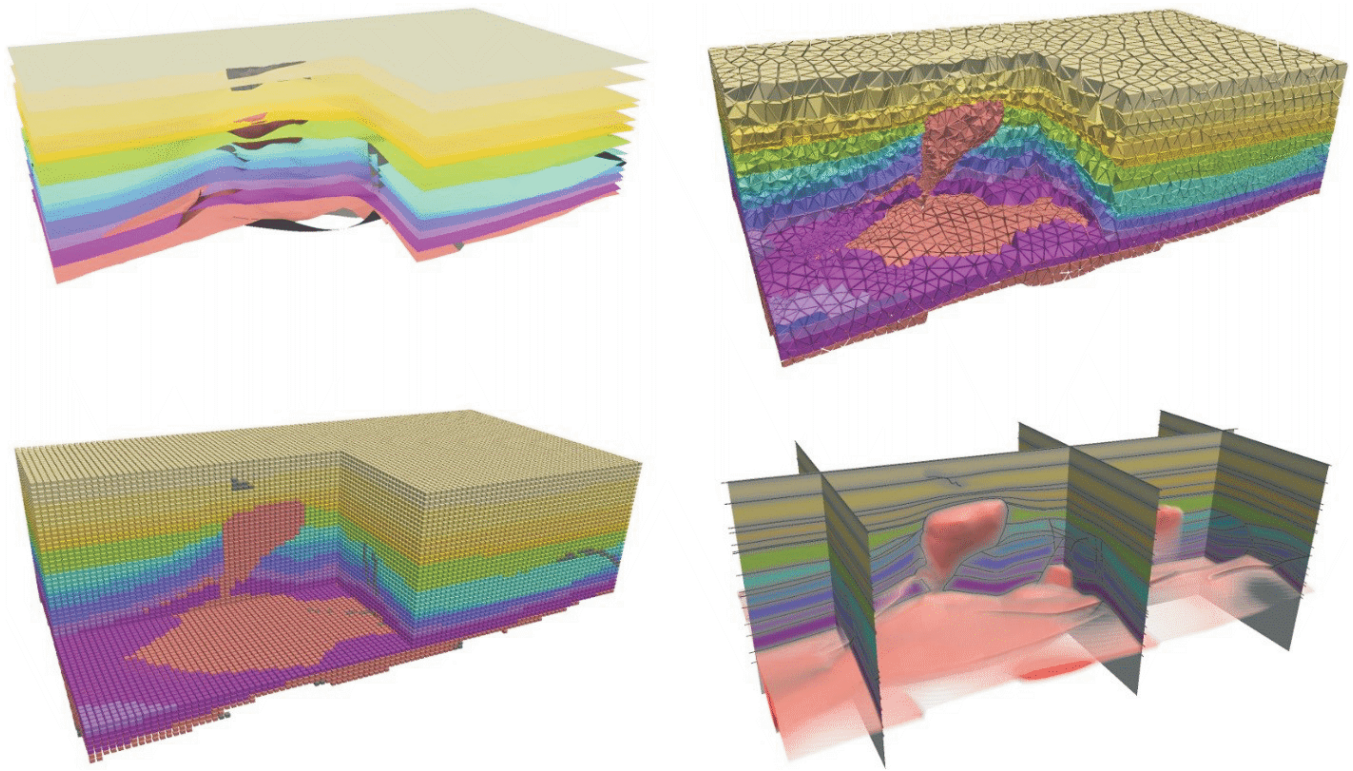
The first out of two 3D dynamic modelling cases presented in this text, is part of the geothermal project “Horstberg” (Figure 2). It is realized using the software package COMSOL Multiphysics. Parts of the lithology model presented above define the underlying mesh for the dynamic 3D model simulating the behavior of a hydraulic fracture during different operating conditions (Hassanzadegan and Tischner 2018). A determining factor in this THM model is the stress field in the vicinity of the borehole and the fracture. In general, the stress field in Northern Germany varies significantly in regions above the decoupling “Zechstein” salt layer (Littke et al. 2008). As the stress regime strongly influences the behaviour of a producing hydrofracture during operation, with the use of a detailed struc-

tural geologic model, the knowledge of the local stress field around the well enables realistic dynamic modelling of the relevant processes, i.e. the influence of production and injection of fluids on fractures can be investigated in a high level of detail.

Figure 11 shows the 3D model including an artificial hydrofracture in the middle Lower Triassic Detfurth formation, connecting the overlying middle Lower Triassic Solling formation. However, because the geometric characteristics of the fracture are not exactly known, the coin-shaped fracture has to be modelled based on the hydromechanic response, calculated by the Barton-Bandis model (Bandis et al. 1983). Hence, the fracture dimensions calculated accordingly are 140 m in height (i.e. the distance between the Detfurth- and Solling sandstones) with a lateral radius of about 500 m.



**Figure 8.** NW to SE-trending 2D cross-section through the 3D model. The cross-section shows the three source rocks and the possible reservoirs and seals: the 27 stratigraphic layers covering a time interval from the Devonian to the present are identifiable by different colors (Arfai and Lutz 2018).



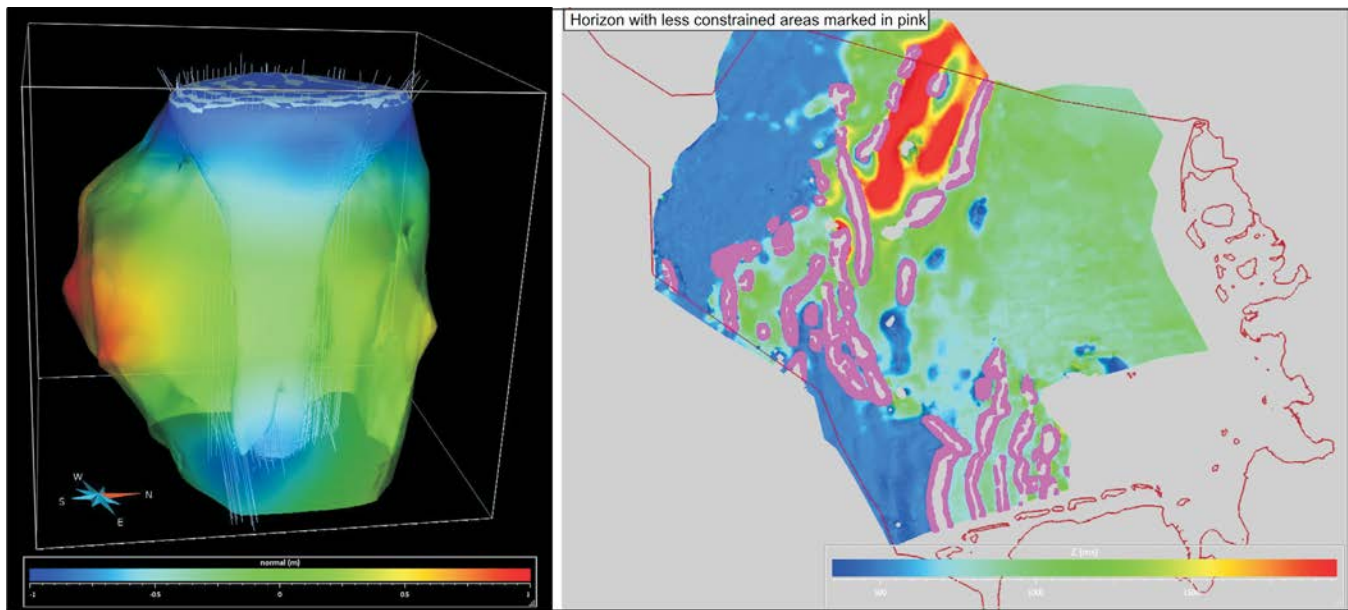
**Figure 9.** Four different representations of the 10 km times 20 km large pilot region in the Entenschnabel in the German North Sea Sector, using either chair cuts or sections for improving visibility of the structure. Top left: representation of the stratigraphic interfaces and faults as triangular surfaces – this type of representation will be constructed for the whole North German Basin. Top right: tetrahedral representation, suitable for finite element simulation. The tetrahedrons stand for the different units while the stratigraphic interfaces and faults are contained implicitly as they are implemented as connected sets of the faces of the tetrahedrons. Bottom left: A rastered (voxel based) version of the model that correspond to the tetrahedral model could be used for finite difference simulation. Bottom right: visualization of the model also showing the uncertainty in the knowledge to which unit a certain point actually belongs. With increasing uncertainty, the color which indicates the different units is faded into gray on the sections and into translucency in the volume. As the uncertainty has not been estimated for the original model, it has been created artificially for presenting and discussing visualization methods.

The second example of 3D dynamic modelling is embedded in BGR’s technical cooperation. In addition to the modelling endeavors within the German border, a different important field belongs to BGR’s portfolio of obligations to work with other countries and provide support when requested. Included herein are various technical cooperations cultivated with developing countries worldwide focussing on hydrogeological issues. These projects, concerning groundwater management and groundwater exploration, require structural, hydrogeological, and numerical models, as well as capacity building for groundwater management purposes. It is steadily becoming a more and more established practice to use 3D models for re-evaluating the available hydro-

geological data, improve and combine data (boreholes, maps, topography, historic cross sections, geophysics, etc.) to understand and to visualize complex groundwater systems, and to provide tools representing complex hydrogeological issues to political stakeholders in the partner countries. A key objective of the modelling program is to use easy to use and affordable software, e.g. the GMS modelling environment (Wu et al. 2003). A favorite software to use is the GSI3D/SubsurfaceViewer (Kessler et al. 2009) or, for capacity development in 3D understanding of hydrogeology, the BGS Groundhog software (Wood et al. 2015). Partner countries with ongoing or accomplished projects are Namibia, Vietnam, Bangladesh, Jordan, and Niger. In Jordan,

for example, the so called “structure contour maps” from 1995 (Margane 1995), the major hydrogeological working basis in Jordan, were re-worked recently (Brückner 2018). In addition, a close up model was compiled of the important groundwater catchment of Wadi al Arab wellfield at the Jordan Valley Graben shoulder (Figure 12).

The sub-department “Geological-geotechnical Exploration” is responsible for developing 3D geological models within the framework of research projects as well as national projects on radioactive waste disposal. The objectives of these models are to identify damage on the surface due to mining activities (Dresbach et al. 2008, Behlau et al. 2012) or specific issues on the construction of cav-



**Figure 10.** Examples for the visualisation of uncertainties around interpreted salt structures. Left: 3D model of a salt structure in the German North Sea. The salt structure (blue) is surrounded by a semi-transparent envelope indicating the seismically less constrained area. The color code on this envelope refers to the distance between the envelope and the interpreted salt body. Right: Modelled horizon for the base of the Upper Buntsandstein. Regions (pink) are obtained by intersecting the horizon with the uncertainty envelope around the salt structure. These regions indicate areas where the depth and structure of the horizon are less constrained by seismic data. The depth of the horizon is indicated by the color code.

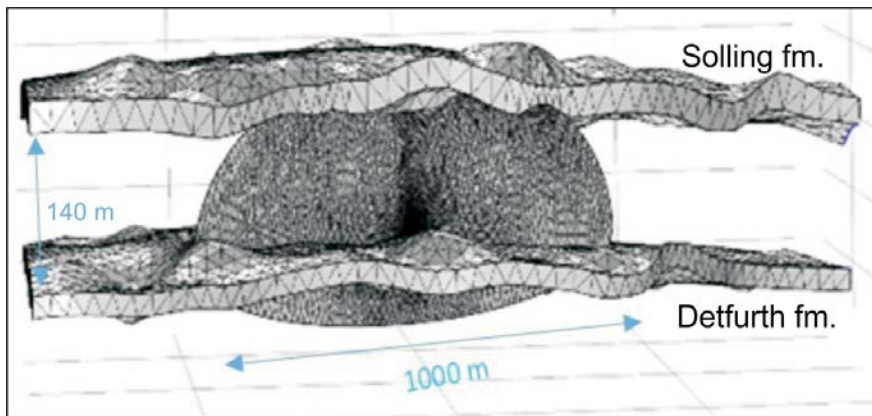
erns in salt (e.g. InSpEE/InSpEE DS; Zander-Schiebenhöfer et al. 2015). These projects refer either to site-specific or regional problems covering large areas (Pollok et al. 2016; Onneken et al. 2018). These 3D geological models are used to support radioactive waste management. These research projects support generic studies that mostly deal with the integrity of waste disposal systems in different host rock such as claystone

(Jobmann 2016), crystalline rocks, and salt (Bollingerfehr 2018; Jobmann et al. 2017; Ziefle et al. 2018; Heusermann et al. 2017).

These 3D geological models provide important input data for the project partners, which are developed in respect to the specific needs of the users regarding extension, complexity (geological resolution of structures and strata), and parameterization of

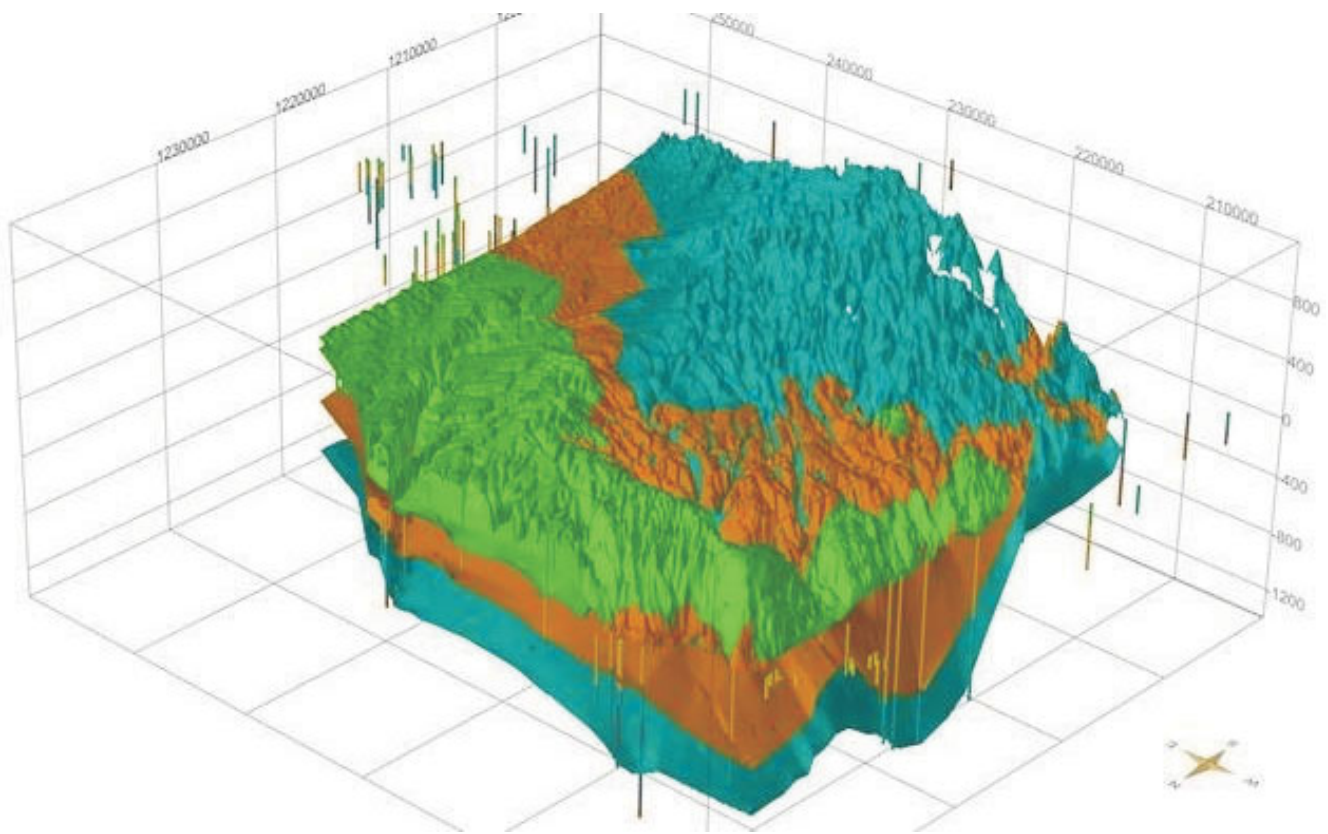
the models. Thus, the modelers and the end users of the models often interact with one another throughout the entire duration of the projects. The geological models generated within the research projects mentioned within this paper are generally derived from existing data. Only in rare occasions, exploration is carried out by BGR or project partners to obtain new data sets for model completion.

Besides being involved in research projects, the sub-department “Geological – geotechnical Exploration” develops 3D geological models for national projects on final disposal of radioactive waste. The 3D geological models are used to support radioactive waste disposal projects within different stages of their life cycle. These stages are site selection (Gorleben, exploration is terminated), construction (Konrad), closure (Morsleben), and waste retrieval (Asse) (Figure 2).



**Figure 11.** Numerical model of a hydraulic fracture (center of the diagram) in the middle Lower Triassic Buntsandstein. The fracture is modelled as an elliptical, vertical 3D structure, connecting the sandstone horizons of the two formations Detfurth (smD, bottom layer) and Solling (smS, top layer), refer (Hassanzadegan et al., 2018).

The types of data used for building 3D geological models are mostly information from boreholes (cores and loggings), geophysical overview



**Figure 12.** 3D model on borehole logs, historic cross sections, and geological maps for the Wadi al Arab wellfield in the north Jordan. The major aquifer (blue) crops out in the south but dips deeply down in the north-west towards the Jordan Graben. There it is covered by a confining unit (brown). The view on the model is south-east.

methods like seismic surveys, ground penetrating radar or resistivity measurements, chemical analysis, petrological investigations, and geomechanical tests. BGR is involved as much as possible in the surveys and generally carries out most of the evaluation of the data. This allows for intensive exchange of expertise between the people involved, which is beneficial as these projects typically span decades.

The 3D geological models built to support the radioactive waste disposal projects serve many different purposes. Mostly these geological models provide basic data for numerical models aiming at calculations on the integrity of a repository system targeting temperature criteria, fluid pressure criteria, dilatancy criteria, and advection criteria. As all the data utilized for the construction of a particular model is captured at different

times or states of exploration respectively, the models serve as kind of knowledge repository. These geological models are also used for planning and exploration. The applied software solution is based on CAD so the geological models can easily be used as a tool for planning openings in a mine.

The models are completed with the software openGeo (Kloke et al. 2018). This is a program designed especially for 3D modelling of complex geological structures. As opposed to modelling software working on the basis of interpolation, openGeo horizon creation relies on lines instead of points. In this way the user directly steers the horizon definition, since openGeo does not generate new data points off the construction lines. If, for example, contour lines are being used for model generation, the creation process is similar to the editing of a geological map. openGeo uses

relational databases for data storage and utilizes a CAD software for data visualization. This approach allows a combination of graphic/engineering design capabilities of a CAD software with query and search capabilities of a database engine. This applies to borehole data as well as geophysical data, e.g. from seismic, geo-electric, or helicopter electromagnetic surveys. The software especially supports the visualization and interpretation of underground geophysical surveys, for example ground penetrating radar data that needs to be analyzed in three dimensions. The full compatibility to all drawings created with the CAD-software is a valuable advantage. Thus, openGeo offers the possibility to directly integrate mine surveying documents like mine layout plans and mine workings for further use. The models created with openGeo are hollow bodies that share one single boundary surface at their contact. Fig-

ure 13 provides an example of a 3D geological model constructed with openGeo representing relevant elements of a salt structure in combination with mine openings.

### Resources Allocated to 3D Modelling Activities

Information on this topic is currently not available.

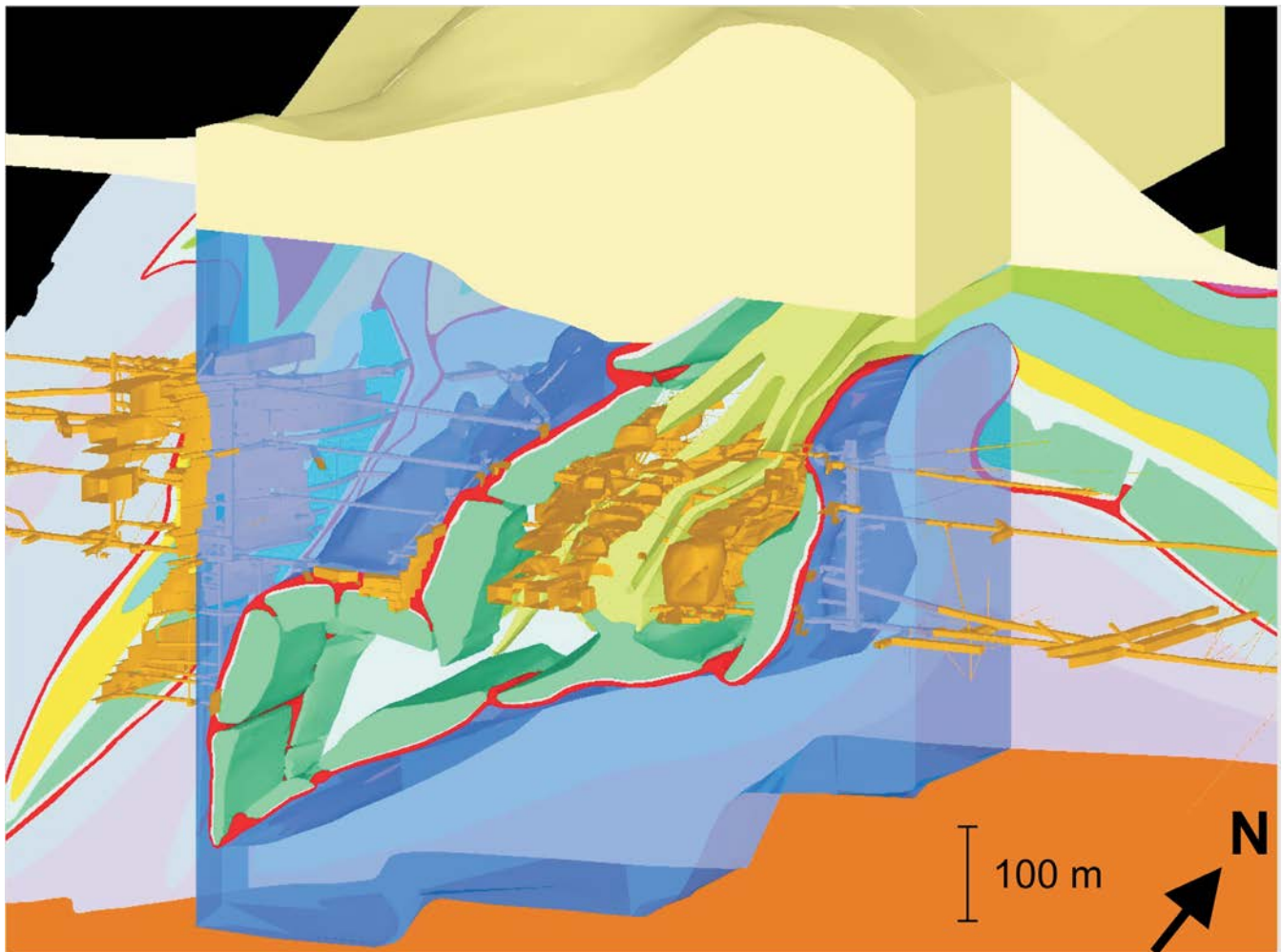
### Overview of Regional Geological Setting

The geological setting of Germany is quite complex and highly variable. It ranges from an active orogenic belt (Alps) in the south to old Variscian

orogenic belts and Pre-Cambrian to Cambrian rocks in the center to a large Permian to Cenozoic basin in the northern part with a Variscian to Caledonian age basement. A Cenozoic rift (Upper Rhein Graben) and several other basins, as well as Tertiary and Quaternary volcanism (e.g. Eifel area) contribute to the wide range of geological settings (Henningsen and Katzung 2006; Meschede 2015).

Since most of the recent 3D modelling done at the BGR is located within the North German Basin (NGB), the focus in this section lies on the regional geological setting of this area. The NGB is part of the Central Euro-

pean Basin System (CEBS). An overview map of the CEBS at the Upper Permian Zechstein is given in Figure 14. The CEBS is divided into two WNW-ESE striking sedimentary basins, which are named after their location and age Northern and Southern Permian Basin (NPB and SPB). These elongated basins are divided by a system of highs that are recognizable by reduced thicknesses of the Mesozoic sediments, graben structures, unconformities, and different sedimentary facies (Röhling 2013a, b). This basin structure was initiated in the Permo-Carboniferous and the regional subsidence pattern follows this structure until Triassic times (Doornenbal and Stevenson 2010). From the Paleozoic



**Figure 13.** A 3D geological model consisting of geological and mine data. The geological model is part of the input data for geomechanical calculations as a component of a safety assessment study (Fahland et al. 2015). The mining galleries, shafts and excavations are displayed in Orange the different colors correspond to different successions of the Permian “Zechstein” salt unit. View from the east.



till the Cenozoic, the sedimentary facies within the CEBS changed several times between marine and terrestrial conditions, leading to the intercalating deposition of siliciclastics and evaporitic sediments. Especially in the upper Permian “Zechstein”, thick successions of evaporates, with predominantly rock salt, were deposited in the basin center.

These evaporites were mobilized in the Triassic, forming various kinds of salt structures. The complex sedimentary and structural development of the CEBS is described in a regional context by several authors e.g. by Ziegler (1990), McCann (2008a, b), Littke et al (2008), and Doornenbal and Stevenson (2010). During the upper Cretaceous, the tectonic regime changed from extensional to compressional leading in some places to the inversion of older graben structures and reactivation of salt structures.

This led to the partly quite complex internal structure of the basin.

## Data Sources

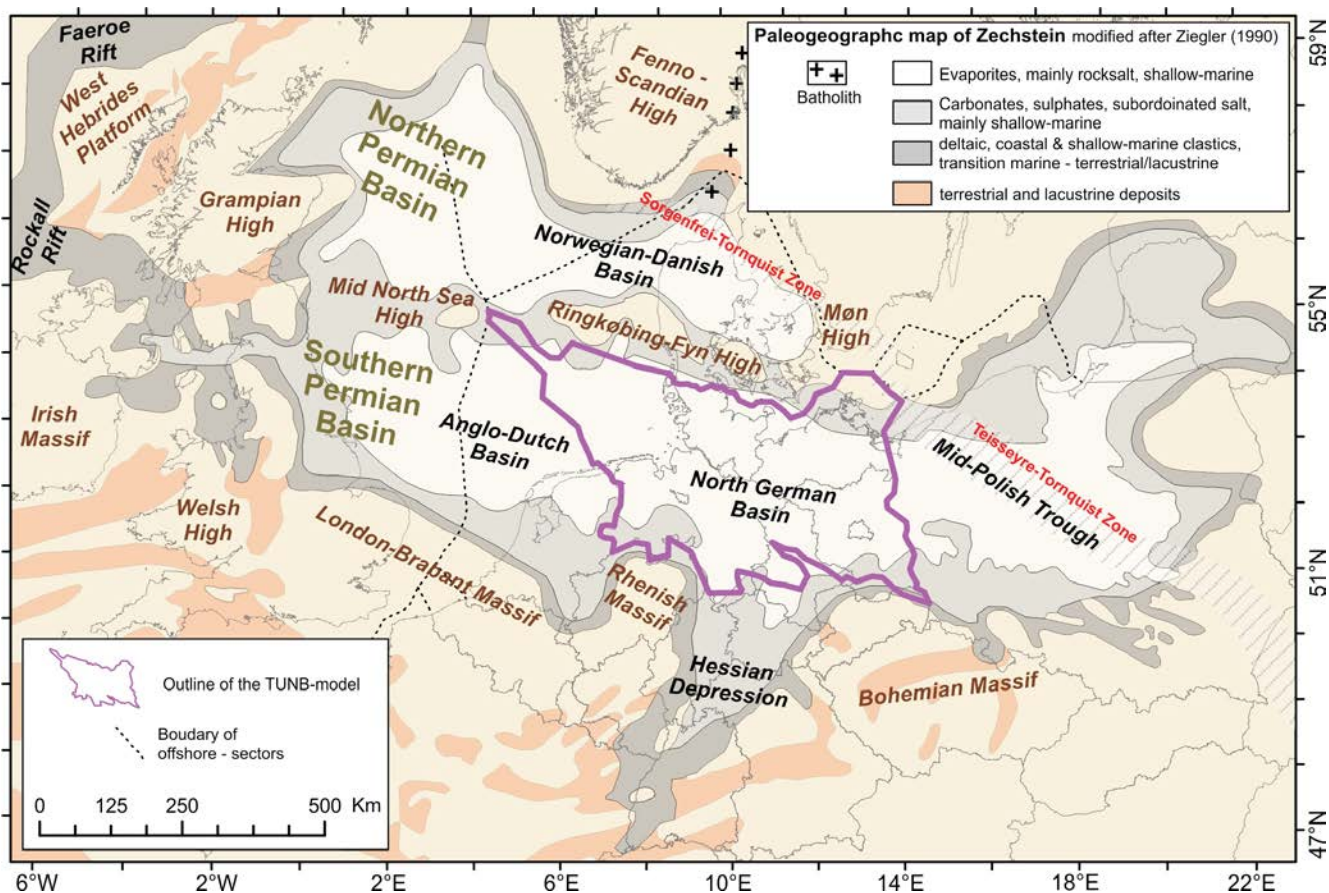
The different modelling projects (within the North German Basin) are based on various data sources (Müller et al. 2016). The models in the German North Sea are primarily based on well and seismic data sets, which are mainly owned by the E&P industry. While the E&P industry are providing the data to the SGD to comply with legal requirements, BGR has to apply for allowance to use the data for every project separately. However, some of the seismic data, especially in the German North Sea, is acquired by BGR itself. The seismic data used to model the German North Sea originates from surveys since the 1960s, hence, the data quality ranges from analog seismic to high-quality 3D seismic (Figure 15). In the North Sea,

we were able to constrain the seismic data by well data from more than 100 wells, which was in this case, provided by the E&P industry (Figure 15).

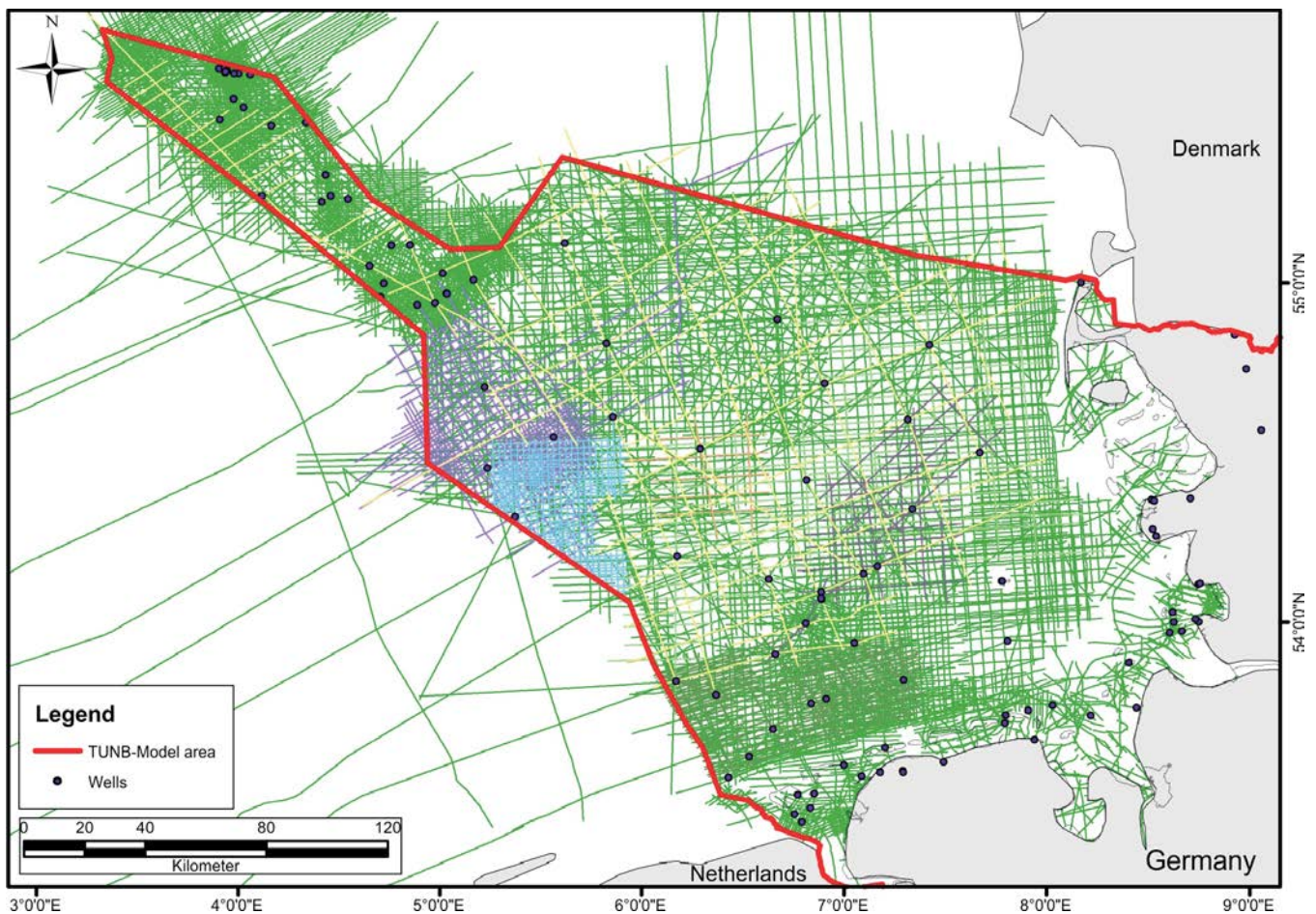
In contrast, 3D modelling projects built in the search for a repository for nuclear waste are based mainly on data (geological and geophysical) that was acquired by BGR. These datasets are located in close proximity to the repository sites (Figure 2). For numerical modelling the data sources are a combination of 3D models, geophysical measurements, and literature data.

## 3D Modelling Approach

BGR uses several software packages for static modelling. The large scale regional models are built using Emerson’s SKUA-GOCAD software (Mallet 1992), using both, implicit and explicit techniques (DSI and Structure



**Figure 14.** Paleogeographic map of the Central European Basin System during the Upper Permian Zechstein. The outline of the model TUNB, the largest model described in this text, is given in purple. Modified after (Müller et al., 2016).



**Figure 15.** Map of the distribution and location of offshore 2D seismic lines (colored lines) and wells (black dots) in the German North Sea that are used to develop the TUNB 3D model in the area of interest. The different colors of the seismic lines refer to different seismic surveys acquired in the last decades. The outline of the German exclusive economic zone (EEZ), and therefore also the outline of the TUNB model in the German EEZ, is given as a red line. The German North Sea is kept in white, on-shore areas in gray.

& Stratigraphy workflow). Schlumberger's Petrel is also applied for studies on a smaller spatial scale (e.g. reservoir size), whereas Midland Valley's Move software is favored for kinematic structural restoration studies or kinematic forward modelling. The detailed 3D static modelling that is carried out for the nuclear waste repositories Asse, Konrad, Gorleben, and Morsleben are completed using the software openGeo, which is implemented as an Extension for AutoDesk's AutoCAD software.

In respect to the quite diverse fields of applications, a large variety of different state-of-the-art software packages are applied for 3D dynamic modelling at BGR on a regular basis. The various THMC programs inte-

grating different thermal, hydraulic, mechanical, and chemical couplings are used to address scientific questions on multiphase, nonisothermal reactive flow and transport in the subsurface and the corresponding mechanical behavior. In addition, some of them are used for inverse modelling. The applied programs are based on the finite element method (FEM) as well as the finite difference method (FDM), running on different platforms. This list includes programs under proprietary licence and within the public domain, as well as some codes that have been developed by BGR for specific needs, e.g. the software JIFE (Java Application for Interactive Non-linear Finite-Element-Analysis in Multiphysics). While some programs

are commercially available (e.g. TOUGH suite of codes (Jung et al. 2018; Pruess, 2004) and COMSOL Multiphysics), others are part of the scientific open-source project e.g. OpenGeoSys (OpenGeoSys 2018). The codes are applied in quite diverse fields of applications, such as;

- COMSOL Multiphysics (COMSOL 2018) in THM modelling of deep geothermal energy (Hassanzadegan and Tischner 2018);
- FEFLOW (Finite Element subsurface FLOW system), (Diersch 2005) TM modelling of flow dynamics on laboratory scale (Stoeckl and Houben, 2012) and in a Karst environment (Neukum et al. 2014);

- FLOTRAN (Lichtner 2007) THC modelling of mine tailings (Meima et al. 2012);
- GMS MODFLOW, TH modelling in groundwater management (Houben et al. 2014);
- HYDRUS 2D/3D (Šimůnek et al. 2006), TH nonisothermal flow and transport in soil
- JIFE for THMC processes in saliferous systems (Faust et al. 2018);
- OpenGeoSys for THM modelling in combination with experimental data in the context of nuclear waste management (Shao et al. 2018, Ziefle et al 2017);
- PHREEQC (Parkhurst 1995) in THC modelling of reactive flow and transport of impure CO<sub>2</sub> in Carbon Capture and Storage (Waldmann and Rütters 2016);
- TOUGH2 (Pruess, 2004) and TOUGH3 (Pau et al. 2016) TH modelling of a Carbon Capture and Storage (CCS) case study (Rebscher et al. 2006);
- TOUGHREACT (Xu et al. 2014) in THC modelling of reactive flow and transport of impure CO<sub>2</sub> in CCS (Rebscher et al. 2015).

Contributing to international efforts to ensure the validation of codes and modelling approaches, BGR is taking an active role in benchmark initiatives e.g. ANSICHT (Maßmann et al. 2013), Benchmarking Initiative Series e.g. Kolditz et al. (2016), Lux and Rutenberg (2017).

## Clients

The main financial sources for the research projects are funding programs of the Federal Ministry for Economic Affairs and Energy, the Federal Ministry of Education and Research, as well as the Federal Ministry for Economic Cooperation and Development. In some projects, which are completed in collaboration with external partners, other clients include the European Union, industrial partners, and universities.

## Recent Jurisdictional-Scale Case Study Showcasing Application of 3D Models

The DIN Standards Committee Building and Civil Engineering (NABau) opted for a revision of the map for the geologic subsurface classes. The subsurface in Germany was divided into three classes (“R”, “T”, “S”; Figure 16), according to its response to seismic shear waves. These subsurface classes are associated with the seismic activity and lead to different specifications for buildings and structures. The new map will be based on a 3D model of the Quaternary and Tertiary with a resolution of 1 km x 1 km. The State Geologic Surveys will provide the data and BGR will develop a consistent and harmonized 3D model using GOCAD. The outcome of this ongoing effort will be a model showing the thicknesses of the Quaternary and Tertiary at a horizontal resolution of 1 km x 1 km. The thickness will subsequently be translated into the classes “S” or “T”, everything else will be considered to be class “R”. The resulting map for these classes will be similar to the map shown in Figure 16. It will serve as a base for the definition of new standards by the NABau committee.

## Current Challenges

In general, a major challenge for BGR is the accessibility of data needed to develop a 3D model. For many tasks, the proprietary rights of the relevant data are owned by the industry, as is the case for the 3D model of the German North Sea. However, there is no legal requirement for the E&P industry to make their data available to the public. Therefore, a lot of time and effort has to be invested before modelling can start (e.g. finding out which company is the current owner of the relevant data or to obtain permission to use or show the data either for published or unpublished work).

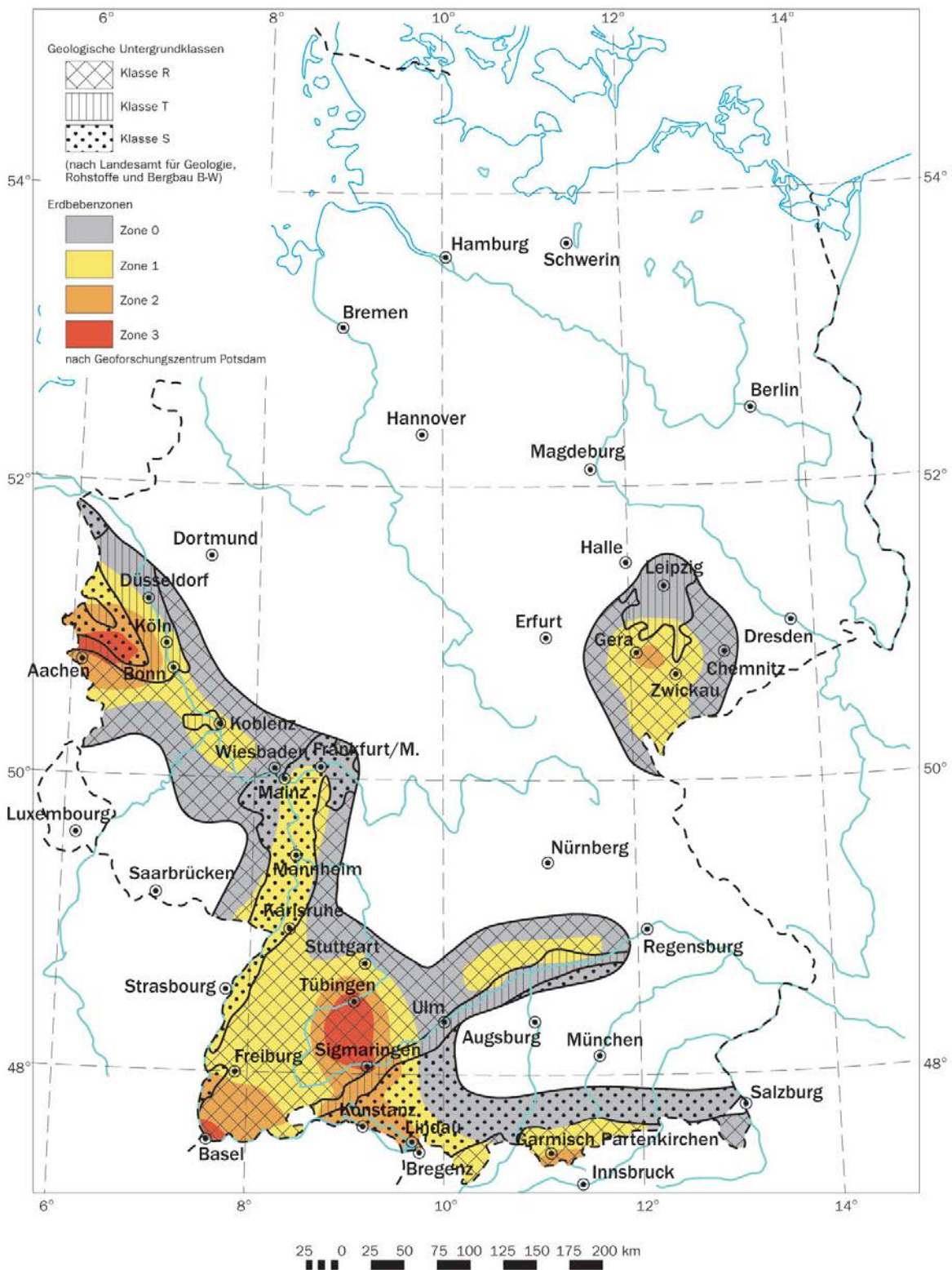
With respect to the purpose of individual projects in the field of radioactive waste disposal, the requirements and challenges of modelling vary. In contrast to research projects with a relatively short duration and a more or less static database, the most challenging issue in projects related to the disposal of radioactive waste is that the database is constantly growing and changing over long periods of time (decades), and keeping the models updated with the continuous influx of new data is a challenge. This requires a precise tracking of the versions as well as the input data for each model. Special requirements on the documentation within the licensing procedures need to be fulfilled according to the atomic energy act in combination with the mining law and subordinate regulations. Thus, the 3D geological models also function as a repository for the data used during the evolution of the project through time.

## Lessons Learned

The past few years have shown an increasing demand for geological 3D models, affecting different departments within BGR. It is essential to leverage 3D models to support projects within many thematic fields throughout BGR by combining thematic expertise with modelling skills. It is also essential for the modeller to have a sound knowledge of the topic and a willingness to continuously exchange knowledge with other national and international modelling groups. Another important task is to find new ways to communicate 3D models to the public, because many of our models are difficult to interpret by a non-professional, and only very few people have access to the professional and often expensive software required to visualize 3D models.

## Next Steps

After finalizing the model of the whole North German Basin (TUNB-Model), the intention is to develop follow-up projects in collaboration



**Figure 16.** Simplified (low resolution) map of the seismic hazard zones and geologic subsurface classes ([www.zapf-daigfuss.de](http://www.zapf-daigfuss.de)). The classes are as follows: “R” for bedrock or consolidated rock (shear wave velocity >800 m/s), “T” for shallow sedimentary basins and transition zones (up to 100 m loose sediments, mostly Quaternary, overlying class “R”), and “S” for deep sedimentary basins (more than 100 m of loose sediments, Quaternary, or more than 500 m thick Tertiary sediments overlying class “R”). The shading indicates the different classes. The coloring represents the seismic hazard zone with red representing the highest hazard ranging from zone 0 (no hazard) to zone 3 (high seismic hazard) (DIN EN 1998-1). The outline of the shaded area corresponds with the outline of the 3D model.



**Figure 17.** Rollercoaster ride around a salt structure in the German North Sea realized in Minecraft®. The solid grayish body in the background on the right represents the salt structure; geologic base horizons are realized in colored glass (yellow: Quaternary, orange: Tertiary). The vertical line in the background symbolizes an exploration well. The model is also available in VR.

with the State Geologic Surveys (SGD). Many SGDs are already working on 3D models of the main sedimentary basins, which often also cross the border between the federal states, e.g. the model of the Upper Rhine Graben within the GeORG project (Zumsprekel 2011), or the model of the pre-alpine Molasse-Basin of GEOMOL project (Diepolder and Pamer 2014). In the future, these models should be expanded, harmonized, and connected with other models, as one of the important long term aims of BGR is to create a nationwide 3D model of Germany. Comprehensive parametrisation of 3D volume models will play an increasing role in BGR's modelling endeavors. Another field of interest, is how to communicate the complexity of the subsurface to the public. Here some research is done in collaboration with our colleagues from the British Geological

Survey to convert 3D models into Minecraft worlds (Figure 17) to provide easy and engaging access into the world of 3D modelling for the interested public.

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# Chapter 14: Illinois State Geological Survey: Three-Dimensional Geological Mapping and Modelling in Illinois, USA

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## Introduction

The Illinois State Geological Survey (ISGS) has engaged in three-dimensional (3D) geological mapping and modelling since the mid 1970s (Bogner, Cartwright, and Kempton 1976). It grew from the need for subsurface information in complex glacial terrain, particularly in the heavily populated Chicago metropolitan region. Importantly, the influence of local funding partners, typically counties, determined the mapping areas, and to some extent the type or style of map product. A more detailed understanding of the subsurface was needed to (1) support resource-based land-use planning by decision makers, and (2) directly balance the delicate relationships between groundwater and mineral resource extraction, waste disposal, and engineering/construction considerations with environmental concerns (Frye 1967).

To initially address the above issues, “stack-unit maps” were developed showing the succession, thickness, and extent of deposits of the upper 6, 15, or 30 meters, (e.g., Kempton, Bogner, and Cartwright 1977; Berg, Kempton, and Stecyk 1984), and later the entire glacial succession and this was supplemented by targeted derivative maps (e.g., geologic conditions for surface spreading of wastes). The late 1980s experienced the advent of systematic computer mapping (Krumm et al. 1989) that completely

changed the ISGS’ institutional geological mapping approach through the integration of GIS with surface and volume modelling. Krumm et al. (1992) and Riggs et al. (1993) report on some of the earliest 3D models of surficial deposits. From the mid 1990s to the present, the ISGS has undertaken a lithostratigraphic approach to 3D geological mapping and modelling, with a focus on the Chicago metropolitan area counties (e.g., Dey, Davis, and Curry 2007). Changes in technology, both hard and soft, have migrated the process of digital mapping from those specifically trained in technology to those trained in thinking about geology. A more detailed discussion of the 3D mapping and modelling history at the ISGS can be found in Berg and Leetaru (2011).

## Organizational Structure and Business Model

The ISGS initially was founded in the 1850s, but it was not until 1905 that it became continuously operational with dedicated State funding. For more than 100 years, the ISGS was a division within various Illinois State government agencies, lastly being part of the Illinois Department of Natural Resources. In 2008, the State Scientific Surveys, which in addition to the ISGS presently include the Illinois State Water Survey, Illinois Natural History Survey, Illinois State Archeological Survey, and Illinois Sustainable Technology Center, were trans-

ferred to the University of Illinois by state legislative act. The Surveys employ about 1000 scientific and support staff and are administratively organized under what is now called the Prairie Research Institute housed on campus at the University of Illinois at Urbana-Champaign and at a number of field offices throughout the state.

The ISGS, in FY2018, had a State appropriation of ~\$4.3M, and contractual expenditures of >\$14.8M. It has ~170 scientific and support staff that are divided into nine discipline focused sections - Applied Research Laboratory, Coal Bedrock Geology and Industrial Minerals, Environmental Site Assessments, Geochemistry, Geoscience Information Stewardship, Hydrogeology and Geophysics, Petroleum Geology, Quaternary and Engineering Geology, and Wetlands Geology. The Applied Research Laboratory, Coal Bedrock Geology and Industrial Minerals, and Petroleum Geology sections are within the ISGS’ Energy and Minerals group, where considerable effort is focused on managing large U.S. Department of Energy contracts. Three-dimensional geological mapping and modelling of surficial deposits is conducted in the Quaternary and Engineering Geology Section and the Hydrogeology and Geophysics Section, with cartographic and database support from the Geoscience Information Stewardship Section. Bedrock mapping primarily is conducted in the



Coal Bedrock Geology and Industrial Minerals Section, as well as the Petroleum Geology Section, the latter of which has focus on hydrocarbon and carbon sequestration reservoir modeling.

The ISGS' 3D geological mapping and modelling program clearly reflects the overall mission of the institution, dictated by Public Law: *"to provide the citizens and institutions of Illinois with earth science research and information that are accurate, objective, and relevant to our State's environmental quality, economic prosperity, and public safety"*, and its concurrent long-range vision of *"...upholding the highest standards for scientific research, service to our constituents, and professionalism in all our activities"*. The concepts of both engineering geology, that emerged in the 1940s, and environmental geology, that emerged in the 1960s, were first conceived by ISGS geologists driven by the need to address critical societal issues with relevant, accurate, detailed, unbiased, and timely geological information. It is within this context that our current 3D mapping and modelling efforts have evolved and are presently focused. The three case study examples below "tackle" the deciphering of the very complex glacial deposits of northeastern Illinois in three of Illinois' "collar" counties surrounding Chicago, all of which are experiencing rapidly increasing urbanization. It is here where critical decisions regarding water and land use, as well as aggregate extraction, are needed, but answers to planning scenarios are complicated by the desire for ecosystem health, open-space scenarios, and groundwater recharge optimization. Importantly, these issues cross urban, suburban, and rural areas that are ruled, taxed, and managed by more than 1000 county and local non-county (e.g., township, town, city) governmental jurisdictions.

## Overview of 3D Modelling Activities

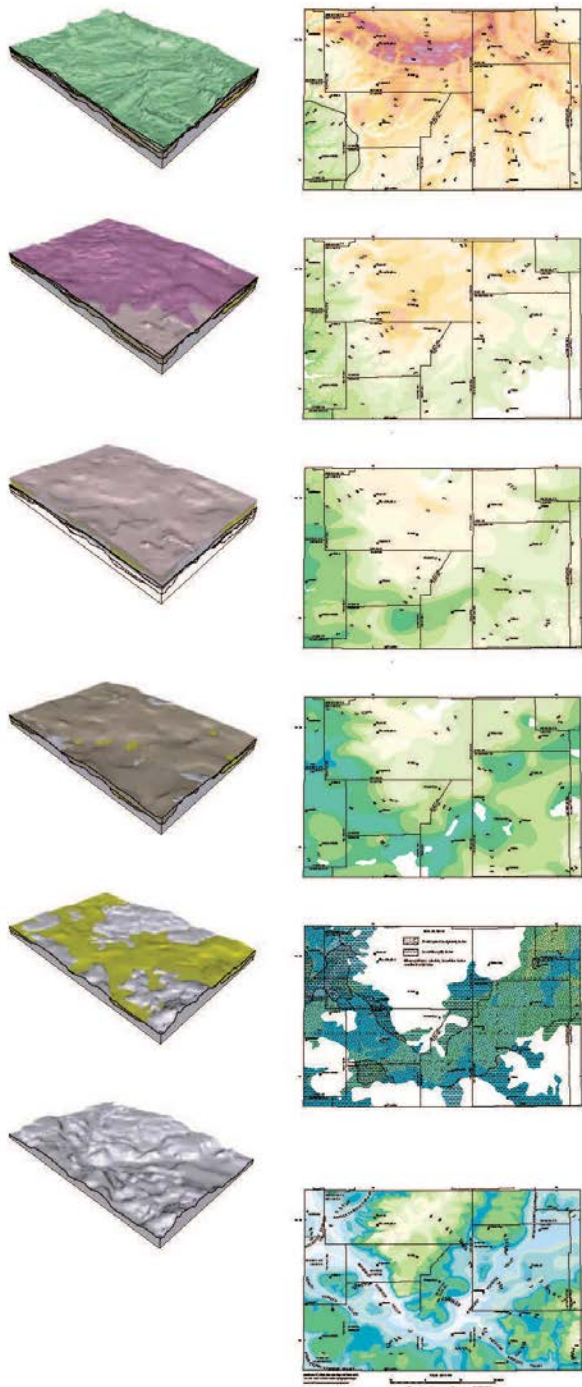
Three-dimensional geological modeling in Illinois primarily has focused on Quaternary glacial and postglacial sediments. These very complex sediments, deposited in various environments, during different times, and with varying degrees of erosion, provide major groundwater and aggregate resources, host waste disposal sites, underpin ecosystems, and provide support and environmental conditions for infrastructure. Very detailed mapping and modelling is required because land-and water-use planning and policy decisions are based on the maps and models.

Since the early 1990s, 3D geological modelling of surficial deposits has focused on three regions – east-central Illinois and the Mahomet aquifer, middle Illinois River valley, and the northeastern Illinois Chicago metropolitan region.

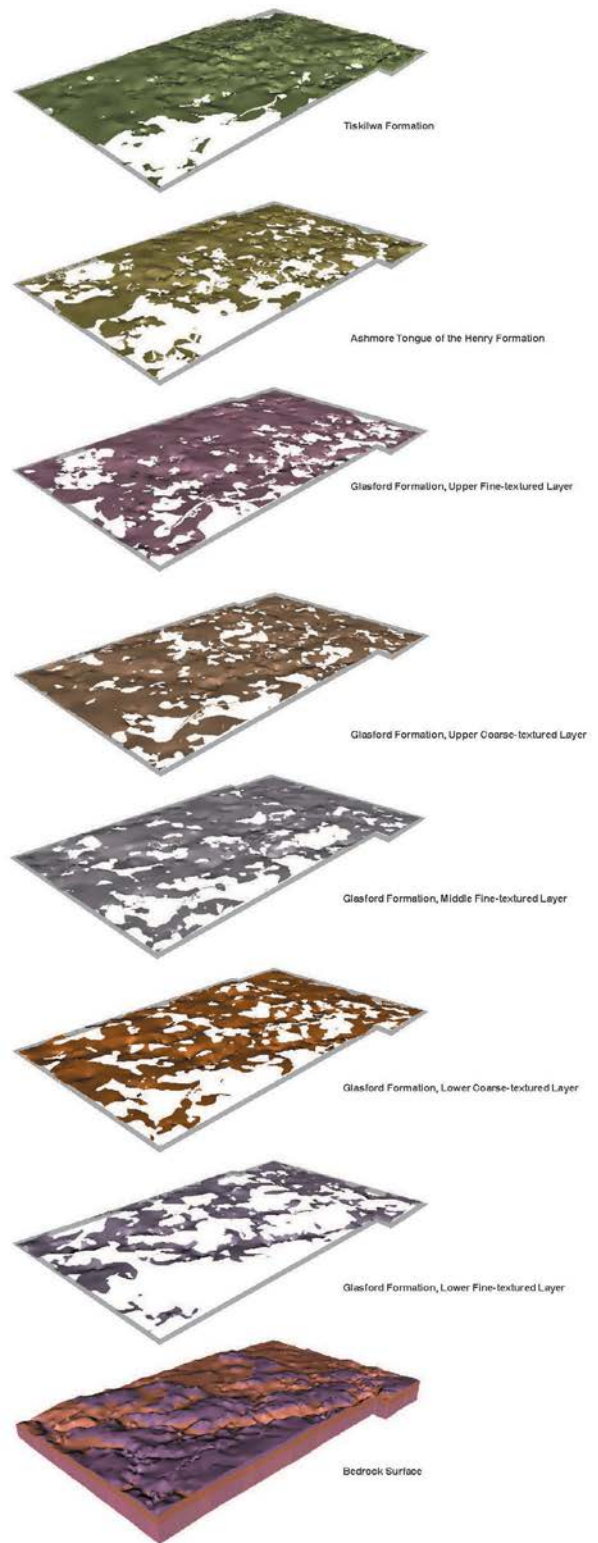
- **1990s** - The first published regional geologic model of any surficial deposit was done in the early and mid 1990s and published in 1999 by Soller et al. It portrays the Quaternary geology in a 15-county region that overlies the Mahomet Bedrock Valley in east-central Illinois. Three atlas sheets offer multiple 3D perspectives of the bedrock valley that contains a thick sand and gravel, known as the Mahomet aquifer (Figure 1). This regional aquifer is now designated by the U.S. Environmental Protection Agency as a Sole Source Aquifer. Also in the early 1990s, the ISGS' County Assistance Program with funding by the Illinois Department of Energy and Natural Resources, used interactive volume modelling to produce 3D models for the north-central portion of Lake County, north of Chicago (e.g., Riggs et al. 1993) and southern Will County, south of Chicago (e.g., Abert et al. 1993). Maps, models, and other products included surface and bedrock to-

pography, thickness of Quaternary deposits, cumulative sand and gravel thickness, sand thicknesses at various depth slices, and cross-sectional views and geologic interpretations from the 3D models.

- **2000s** - There was a partial geologic model developed for all or parts of five counties – Bureau, Marshall, Putnam, Peoria, and Woodford - along the middle Illinois River valley in central-northern Illinois (Berg et al. 2002). Products include maps for surficial geology, bedrock topography, drift thickness, elevation and thickness of a deep glacial aquifer, and aquifer sensitivity. There was significant funding provided by the Illinois Department of Transportation, as this effort was developed as part of a transportation planning endeavor. Also during this decade, the Great Lakes Geologic Mapping Coalition (GLGMC) was formed specifically to address a national shortfall in funding for 3D geologic mapping within the nation's central economic hub.
- **2010s** - The first comprehensive county-wide 3D model in northeastern Illinois was completed for Kane County west of Chicago (Abert et al. 2007) (Figure 2). Significant county funds supplemented the effort as there was concern regarding population growth and competing water resource needs among their more than 30 municipalities. This modelling resulted in maps of LiDAR derived surface topography, bedrock geology, major Quaternary aquifers, aquifer sensitivity, and numerous geologic cross sections. This was followed by 3D hydrogeological mapping for Kendall County, west of Chicago (Figure 3) that has not been published (Keefer et al. 2013). The most recent 3D modelling by the ISGS of surficial sediments, center on three counties within the Chicago metropolitan region – Lake County north of Chicago, McHenry County north-



**Figure 1.** Examples of 3D maps and models of Quaternary sediments in the Mahomet Bedrock Valley in east-central Illinois (Soller et al. 1999). Maps are ~145 km east-west and 80 km north-south. The maximum model depth is >140 m, but the valley thalweg generally has between 100-120 m of sediment. Quaternary deposits are diamicton and sand and gravel. Green are primarily Wisconsin Episode diamictons. Purple are Illinois Episode diamictons. Brown and gold are pre-Illinois Episode diamictons and sand and gravel (Mahomet aquifer) respectively. The gray surface is bedrock topography. Copyright © 1999 University of Illinois Board of Trustees. Used by permission of the Illinois State Geological Survey.



**Figure 2.** Example of a portion of the 3D model for Kane County, Illinois showing the bedrock surface at the bottom and successive layers of Quaternary sediments above. North is to the upper right and the southern border of the county is ~19 km wide. The total model thickness is ~100 m. (Abert et al. 2007). Copyright © 2007 University of Illinois Board of Trustees. Used by permission of the Illinois State Geological Survey.

west of Chicago, and Will County south and southwest of Chicago (Figure 3). These three geologic modelling activities are the subject of our case studies, described in detail below.

There has not been an ongoing institutional effort for 3D modelling of the bedrock in Illinois due to staffing constraints and contractual obligations. However, specific projects have resulted in two modelling efforts – Cook County (Chicago region) and the central Illinois CO<sub>2</sub> sequestration project.

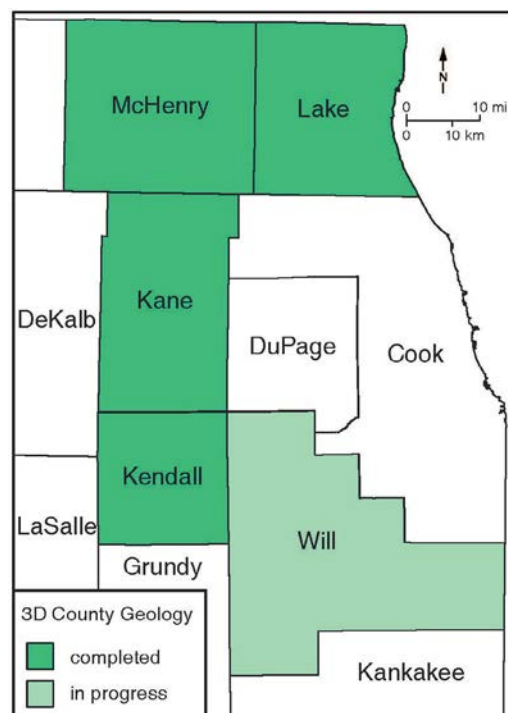
- Leetaru, Sargent, and Kolata (2004) produced a geologic atlas of Cook County to address the quality, quantity, distribution, and accessibility of bedrock groundwater resources, underground construction conditions, and mineral resource assessment and management. The atlas portrays the thickness, distribution, lithologic character, and structure of major bedrock units from the Paleozoic rocks immediately beneath the Quaternary sediments down to the top of the Precambrian crystalline basement. Formation tops were determined from approximately 5,900 drillhole records.
- Greenberg et al. (2017) report that 3D geologic modelling was central to the success of a U.S. Department of Energy-funded carbon sequestration project in central Illinois. It is here that the safety, effectiveness, and efficiency of deep storage of CO<sub>2</sub> in a deep saline reservoir >2000 m below land surface was proven. Through use of extensive geophysical site characterization efforts, a 3D geological model was developed and systematically updated as new geological and geophysical data became available. The model included data from drilling ~45 m into the Precambrian.

In addition to the above, a statewide compilation of bedrock topography and structure contour maps of se-

lected bedrock units, including the Precambrian basement (e.g., Marshak, Larson, and Abert 2016), are available and serve as building blocks for the eventual construction of a statewide 3D model of Illinois' bedrock.

### Resources Allocated to 3D Modelling Activities

There is no consistent revenue stream that provides for the needed staffing and other resources for a systematic statewide 3D modelling effort that can be accomplished within a reasonable time frame. Resource allocation is driven by federal funding priorities, supplemented by occasional local support, and typically on a contractual basis. State funding support typically consists of existing ISGS personnel under the University of Illinois State Scientific Surveys Act (110 Illinois Compiled Statutes (ILCS) 425/20 (7)) and is prioritized or redirected for contract match requirements. Required staffing needs are defined by project objectives. Most federal or local support is insufficient for supporting salaries of staff required for geologic mapping, as well as geoscience sub-discipline and technological computing expertise. On occasion, real cash resources support infrastructure (e.g., technology) or field data acquisition (e.g., drilling). Financial sustainability is dependent on project-by-project financial resource availability. Therefore, long-term planning is hampered by an uncertain funding outlook. The current ISGS larger business model supports a pool of geologists with geologic mapping and modelling expertise so that from time to time, a few staff from the pool may focus on a 3D geologic mapping and modelling activity within a project-defined geographic extent.



**Figure 3.** Counties in northeastern Illinois where 3D modelling of geology has been done.

Despite the above constraints, the ISGS' mapping and modelling program has benefitted by continuous funding since 1993 (average award of \$168,293 per year) from the U.S. Geological Survey's STATEMAP component of the National Cooperative Geologic Mapping Program that supports traditional 2D geological mapping. However, it was recognized in the late 1990s that additional funds were needed for "subsurface mapping" at a detailed scale usable by local jurisdictions for land- and water-use planning, as well as a more multi-agency and multi-jurisdictional mapping approach. This was particularly the case in complex glacial settings where considerable exploratory drilling and geophysics were required. In response, what is now called the Great Lakes Geologic Mapping Coalition (GLGMC) was formed in 1997 to supplement STATEMAP-driven surficial geologic mapping (Berg et al. 1999).

The GLGMC now comprises State Geological Surveys from all eight Great Lakes states as well as the On-

tario Provincial Geological Survey, the latter of which does not receive any U.S. State or Federal funding under the described programs. According to Berg et al. (2016), “*The strategy involved establishing a mapping coalition of geological surveys that would seek federal funds, pool physical and personnel resources, and share mapping expertise to characterize the thick cover of glacial sediments and shallow bedrock in three dimensions, particularly in areas of greatest societal need...leaders felt that the combined resources of multiple agencies, in concert with increased targeted federal funding for the coalition, would allow 3-D geological mapping to be conducted in a cost-efficient and cost-effective manner*”.

The GLGMC, a Congressionally mandated activity, has supported 3D modelling at a funding level for the ISGS of ~\$100,000 per year since 2000. Overhead (indirect) costs reduce this amount to about \$85,000 for spendable (direct) project funds. This annual amount is sufficient to fund

one data-entry staff person (\$45,000, including fringe benefits) and support of one field geologist’s expenses for drilling, analytical tests, supplies, travel, and other non-salary costs. Because of the cost of drilling, a county-scale project typically has a minimum timeline of five years just to acquire the adequate 3D geological information at this funding level.

At the ISGS, it has been a specific strategy to increase project efficiency by applying funding from several programs with separate contract deliverables to a geographic area. Therefore, STATEMAP funded work occurs in the same geographic areas as GLGMC projects, as does the addition from time-to-time of county or other funds (Table 1). It is essential that accounting practices verify the proper asset allocation, and the project design has to accommodate different funding cycles, non-duplication of effort, and the clear separation of contract deliverables (e.g., 2D surficial geologic maps vs. 3D subsurface maps and models). This approach significantly strengthens

project proposals as reviewers recognize the benefits of multiple funding sources to address specific issues.

There are 35 scientific and support staff involved with the ISGS geological mapping program – 23 with expertise in surficial sediments and 12 with expertise primarily in Paleozoic bedrock geology. However, only four have the expertise in full 3D mapping or modelling (not including petroleum reservoir modelling). Table 1 shows the funding associated with geological modelling of surficial deposits in Illinois from 2000 to 2018 with 54% derived from State appropriations in the form of salaries, 31% from Federal sources (USGS’ STATEMAP and Great Lakes Geologic Mapping Coalition), 9% from county funds, and 6% from the Illinois Department of Transportation (IDOT).

## Overview of Regional Geological Setting

As described in Berg et al. (2011), 3D geological mapping and modelling currently is focused on describing the

**Table 1.** Geological modelling of surficial deposits 2000-2018, showing percent allocations from funding sources.

Project Area	Dates	Major Issue	County Funds	Federal Funds	IDOT Funds	ISGS Funds	TOTAL Funds
Kane County	2002-2007	Sustainable water supply planning	\$555,880 37%	\$470,000 32%		\$470,000 31%	\$1,495,880
Lake County	2000-2014	Water resource planning	\$180,000 4%	\$1,600,000 34%		\$2,900,000 62%	\$4,680,000
McHenry County	2008-2013	Water resource management	\$175,000 13%	\$360,000 26%		\$848,240 61%	\$1,383,240
Will County	2013-2018	Sustainable economic development		\$560,427 47%	\$63,000 5%	\$564,250 48%	\$1,187,677
Middle Illinois valley	2001-2014	Transportation planning			\$547,492 52%	\$500,000 48%	\$1,047,492
		<b>TOTALS</b>	<b>\$910,880</b> 9%	<b>\$2,990,427</b> 31%	<b>\$610,492</b> 6%	<b>\$5,282,490</b> 54%	<b>\$9,794,289</b>

distribution and character of Quaternary glacial and postglacial deposits (Figure 10-1 in Berg et al. 2011), which are as thick as 150 m and overlie a bedrock surface with a shape and depth that varies greatly across the state. Most Quaternary deposits in Illinois are glacial deposits (poorly sorted deposits, typically rich in clay and silt) or sorted glaciofluvial or glaciolacustrine deposits. Glaciofluvial and glaciolacustrine sand and gravel can form important aquifers and those typically are identified on drillers' records. Correlation and mapping of diamictos is challenging because many of the diamictos are similar in color, texture, and mineralogy. Occurrence of glacial sand and gravel beds can therefore serve as important bounding units. Glaciofluvial beds could be under represented as they can occur as multiple, thin deposits and not reported on drillers' records. The Lake Michigan (one of the Great Lakes) basin extends into areas that are now terrestrial, but that are underlain by thick glaciolacustrine sequences. In these areas, diamicton stratigraphy is regionally absent and therefore requiring geologic mapping to be based on sequence stratigraphy with mapping units defined by bounding surfaces or marker beds, rather than lithologic properties of mapping units.

## Data Sources

ISGS data sources, typical of any geologic mapping and modelling endeavor, include:

- 1) Thousands of descriptive geologic records, each usually represented as a point location.
- 2) Geophysical data represented as a point location (e.g., borehole geophysics) or cross sectional profile (e.g., seismic refraction or reflection) and typically interpreted or displayed in raster format.
- 3) Existing geologic maps or other natural resource thematic maps, such as USDA-NRCS Soil Survey

information, in vector and raster format.

- 4) Photographic or remote sensing imagery acquired by plane, helicopter, or satellite in raster format.
- 5) Digital elevation data, preferably obtained by LiDAR method, in vector (e.g., point cloud, digital line graph) and raster format (e.g., interpolated digital elevation model, digital surface model).

Descriptive geologic records and logs include:

- 1) Archived outcrop or landscape geologic field notes and photographs.
- 2) Well and boring records related to water, oil, natural gas, coal, injection, geotechnical, infrastructure site design, waste disposal, and exploratory test drilling.

The need to access, use, and/or retain confidential records is infrequent, but not uncommon. Protocols are in place to store and manage access to confidential records. State mandate requires the ISGS to steward some types of records (e.g., state repository for drill-hole samples - 225 ILCS 730/2). Other data (digital and paper) are acquired and archived through cooperative relationships or tradition. Extensive effort is undertaken to ensure that data meet scientific mapping requirements, although the value or quality of any particular dataset, data type, or even individual data record can be evaluated by both subjective and objective standards. Factors include overall data quantity and quality, as well as the geologic problem to be solved, the background and experience of the project geologist, and the ability to acquire primary geologic data such as core or samples from stratigraphic test holes.

During the last 15 years, one staff person supported by external funds has been fully dedicated to data entry, locality verification, and location confidence quality control of water-well and engineering borehole record information. This process typically

takes that single staff member three or more years to fully review the 10s of 1000s of all subsurface data for a county-scale project.

## 3D Modelling Approach

As described above, geological modelling has been ongoing at the ISGS since the early-mid 1990s, and numerous approaches have been undertaken with several different software packages. However, this article focuses on the ISGS' most recent 3D geological modelling endeavors in northeastern Illinois, and even now three different technological approaches to 3D modelling were implemented for the three counties of Lake, McHenry, and Will (Figure 3). Each method was determined by the project geologist based on a variety of circumstances. Each case considered the client's technological expertise and software use, software training requirements, internal computing support, formats of existing datasets, availability of particular proprietary software applications, and previous software use experience. The ISGS defines models as being constructed from representations of 2D surfaces that are essentially geologic structure contour maps, in the traditional sense, done by traditional analytical practice, but using digital tools.

In the Lake County case study, the ISGS modeller (author Brown) joined the project at the end, and needed to rely on existing technological expertise to finish contract deliverables that were overdue. Although the client used ESRI software products, the use of the geologic map layers in the 3D software environment or visualizing the maps in the appropriate stratigraphic order in the traditional 2D GIS view, required an understanding of the stratigraphic assembly. A "cookbook" was required to specify the layer order, and text described what could otherwise be seen in a true 3D model. In the McHenry County case study (author Thomason), software was used that had the promise of

a viewer or user plug-in that would enable very little user training to achieve an interactive 3D viewing experience. For Will County (author Caron), the ISGS is currently collaborating with the county for a 3D viewer on their website. In all cases, text based records describing subsurface geology were processed through a data dictionary so that descriptive terminology was standardized following the method described by Brown (2013). Specifics of these three geological modelling approaches are found in the below section on Recent Jurisdictional-Scale Case Studies Showcasing Application of 3D Models.

## Clients

The ISGS' county-based projects have established a strong awareness of the broader resources that a state geological survey offers to solve natural resource issues. The Lake County project began without a specific client or end user in mind, but as a result of marketing the yet-to-be-complete product, it became a referenced source of information in a county planning document (Lake County Illinois 2004). Expectations for use were established before any practical analysis of the ability to map or reveal subsurface features. While a number of different county agencies had interest based on their mandated functions, use by the health department gained traction for water quality issues related to private, single-parcel land ownership. Before the completion of the mapping, a major regional effort related to withdrawal of Lake Michigan surface water for public water supply at a proposed cost of more than \$200 million was a contentious issue for which the yet unfinished work was used to help evaluate the availability of shallow groundwater resources.

The McHenry County 3D model has been a vital tool for local industry, as well as county and state organizations that are addressing acute water and environmental issues and long-term

planning. Different from Lake County, McHenry County includes proportionally more rural area, and therefore different planning and water-use issues. Since model completion in 2013, the ISGS continually has engaged with these constituents. For example, the 3D model was used as a geologic framework when addressing local volatile-organic compound contamination by a local industry. The contamination was impacting domestic supplies and threatening municipal supplies. The Illinois Environmental Protection Agency and private environmental consultants regularly queried the 3D model for geologic insights. Additionally, the ISGS regularly has engaged with county administrators while they develop long-term planning guidelines and statutes, which include water-resource management and environmental protection policies. The ISGS has helped McHenry County use the 3D geologic model to revise/update aquifer contamination-potential maps and discretize countywide planning zones. Part of this continued engagement has been ISGS-led field trips and workshops, which regularly are attended by local elected officials, county leaders, and the public.

## Recent Jurisdictional-Scale Case Studies Showcasing Application of 3D Models

Each of the three county case studies are compared below. The workflows to build 3D geologic models for the three cases were an iterative process of visualization, interpretation, and model construction. The reliability of the resultant 3D geologic maps and models is a function of the spatial distribution and density of data, quality of data, density of interpreted cross sections (for workflows where cross section construction is part of the interpretative process, rather than a derived product from the model), and the inherent complexity within and between geological units. Thus, the

3D models likely are most accurate where geologic test boring and geophysical data acquisition occurred, especially when the data derived from these methods are coupled with high-quality, high-density water-well and other records sourced from other entities, such as water-well drilling companies. The 3D models may be less accurate in geographic extent and interpreted thickness in areas of low data density or poor quality data. Accuracy also depends on the level of geologic complexity in any given area, and whether or not complexity or heterogeneity was described on any records at all, and importantly, the overall experience of the geologists involved with mapping and modelling.

### Lake County

For the Lake County project, more than 30% of all water-well and engineering bore-hole records (15,000 of 39,000) were excluded because of the inability to meet a location verification threshold determined by the project geologist. In addition, 200 stratigraphic test holes (7,300 m of sediment), 400 bore-hole geophysical logs, and 35 km of 2D geophysical transect data were acquired.

Traditional geologic mapping was accomplished primarily with ESRI ArcGIS software modules and tools, as well as Adobe Illustrator with the AVENZA MAPublisher plug-in as described by Brown (2013). Structure contour maps in raster format were created for 18 subsurface geologic units. The surface interpolation included interpreted point data and hand drawn, but digitally created, structure contour lines that controlled the shape of computational driven mapping. The raster surface interpolation was achieved using the ESRI Spatial Analyst, Topo to Raster Tool. The entire suite of interpolation Tools available with the Spatial Analyst were tested. None were ideal, and the ones that used more complex geostatistical algorithms were the worst at

deriving a result that was satisfactory to the geologist. The entire workflow process required a high level of technical knowledge of ESRI GIS applications (i.e., scripts and tools), Boolean logic, and raster mathematics specific to the capabilities of the Tools available in the ArcGIS Toolbox. Workflows were invented through trial and error, and driven by user experience. Most likely, the workflow created for this project will not and possibly cannot be reproduced by another user because it was experience driven with considerable customization. The decision to use ESRI GIS as a mapping workflow was influenced by the client's institutional use of, and reliance on, ESRI software applications and the need for easily transferable digital file formats.

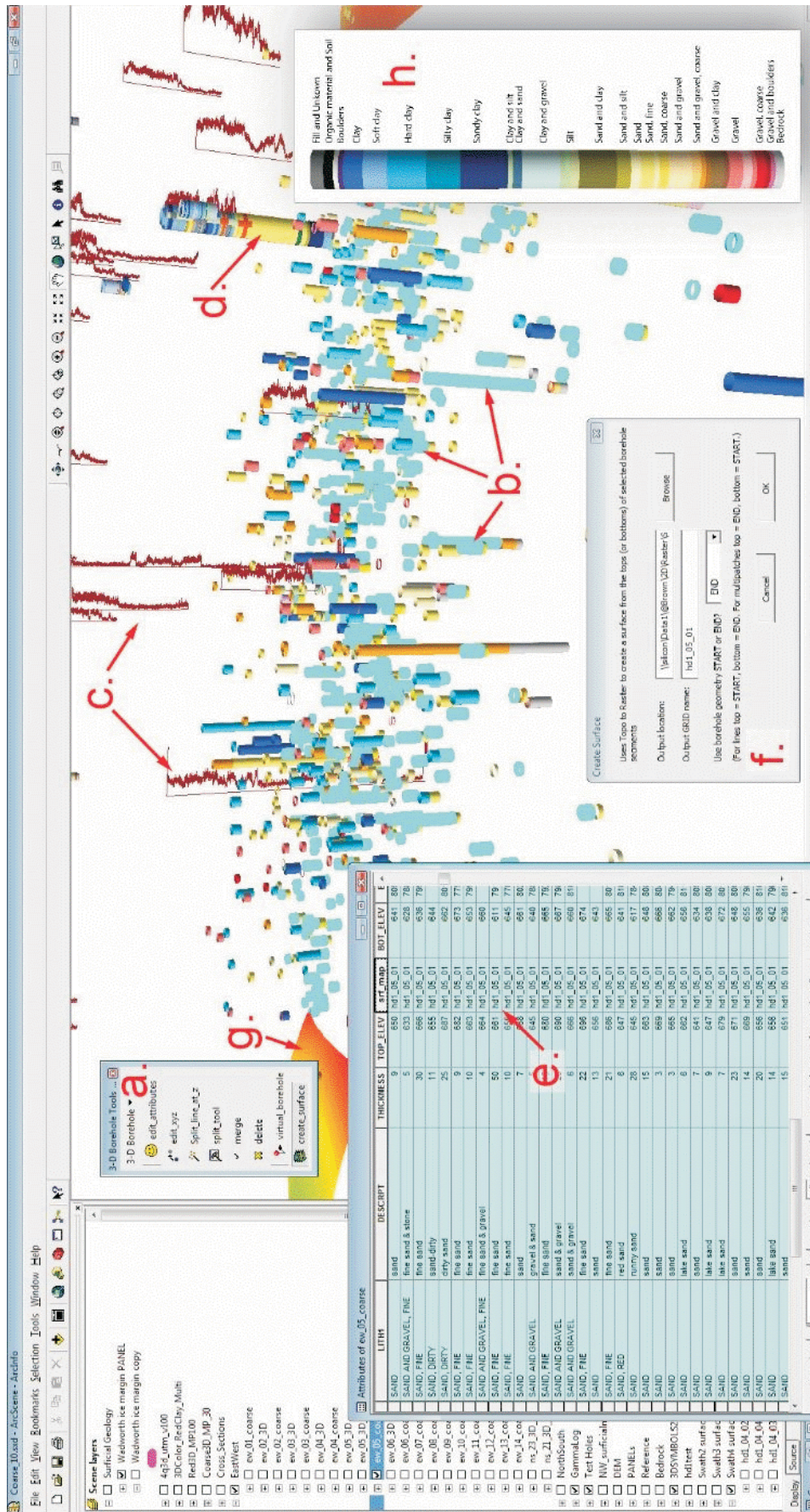
The ISGS has had a long-term reliance on ESRI software applications and delivery of data through continuously evolving Web interfaces and other customer-driven data delivery methods. A key element for using ESRI software components was the development of custom scripts (i.e., 3D Borehole and X-act-section scripts by ISGS staff) for productive geologic classification of subsurface information (the ability to visualize subsurface information in 3D enhanced the ability to understand geologic relationships) in ESRI ArcScene (Figure 4; Carrell 2014; DeMeritt 2012). The AVENZA MAPublisher plug-in for Adobe Illustrator enabled rapid drawing of structure contour lines and other features for depiction in 3D. This was particularly important as some surfaces required 10s of iterations to achieve a desired shape and extent, and the creation of a few structure contour lines as input data in the Topo to Raster Tool provided geologic control not achieved with other interpolation methods. The use of MAPublisher also allowed for the creation of graphically depicted paleo-environment reconstructions, with actual geospatial data, that guided mapping and served as a logic

check, such as the extent of former ice blocks and glacial lakes (Figure 5). The GeoVisionary application that the British Geological Survey (BGS) developed in partnership with Virtualis Ltd., enabled visualization of high resolution aerial imagery blended with LiDAR derived digital elevation models to analyze and understand realistic geometries of glacial depositional features at the land surface. Key to the visualization with this application was reducing exaggeration as low as possible and aligning the software's azimuthal illumination to match the shadow angle and shape depicted on aerial imagery that was acquired at a specific time of day and month of the year (different times and dates result in different shadow angles, shapes, and intensities). This effect accentuated relief derived from LiDAR data and enabled realistic size and shape comparison to subsurface data displayed in ArcScene for local scale features, such as alluvial fans and deltas, in settings of extreme sedimentological variation. Vector format cross sections with X, Y, and Z geospatial reference for 3D use in ArcScene were created directly from the 18 raster format structure contour surfaces with the ArcGIS X-act-section script (Figures 6 and 7).

### **McHenry County**

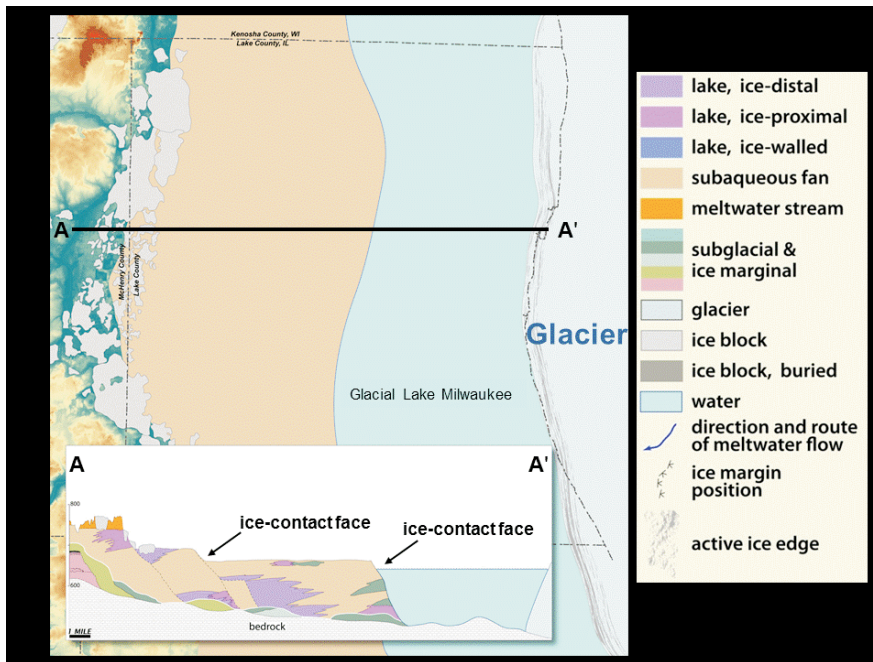
The 3D geologic model of McHenry County was developed using explicit modelling strategies to guide implicit modelling techniques. Initially, 3D visualization of geologic data was integrated with 3D modelling tools that allowed for interactive stratigraphic interpretation, stacked-surface grid production, and editing capabilities in the 3D viewing environment. This was achieved using ESRI ArcGIS and GeoVisionary. Different from the Lake County project, GeoVisionary was used extensively to display high-resolution aerial photographic and elevation datasets in full resolution along with other subsurface geologic data (Figure 8). For example, LiDAR land surface models and color aerial

photography of McHenry County were viewed readily in relation to water-well records, 1D and 2D geophysical profiles, as well as other existing subsurface information represented in raster grid format. More than 22,000 water well records, created as multi-patch shape files with the ArcGIS 3D Borehole script (Carrell 2014), were graphically displayed at the same time in GeoVisionary, which was key to efficient and effective interpretation of the subsurface geology. Subsequently, with GeoVisionary as the primary 3D visualization tool, ArcGIS was used as a data-interpretation tool. Like the Lake County project, the ArcGIS 3DBorehole, script allowed for querying and editing of shapefile attributes in the 3D viewing environment of ArcScene (Figure 4.). It was used to interpret 11,000 stratigraphic water-well records across the county. It also allowed the user to generate on-the-fly 2D raster format structure contour surfaces from selected water-well records as well as 3D shapefiles of downhole geophysical data. Thus the 3DBorehole script was the primary interpretive component of the 3D modelling process. Different from Lake County, the final step in the 3D modelling process used cross-section based modelling within Subsurface Viewer and GSI3D (Mathers et al. 2011), which were developed by INSIGHT Geologische Software-systeme GmbH, and the BGS. These software packages allowed for construction of 3D geologic models primarily from interpreted geological cross sections (Figure 9). Interpretations of borehole stratigraphy and geologic boundaries, most often generated through ArcGIS and GeoVisionary as described above, were incorporated into a dense network of cross-section interpretations. Furthermore, the spatial distribution of geologic units were interpreted and modelled in congruence with the cross-section network. Thus, coupling the lateral extents of geologic units with the cross-section network allowed for

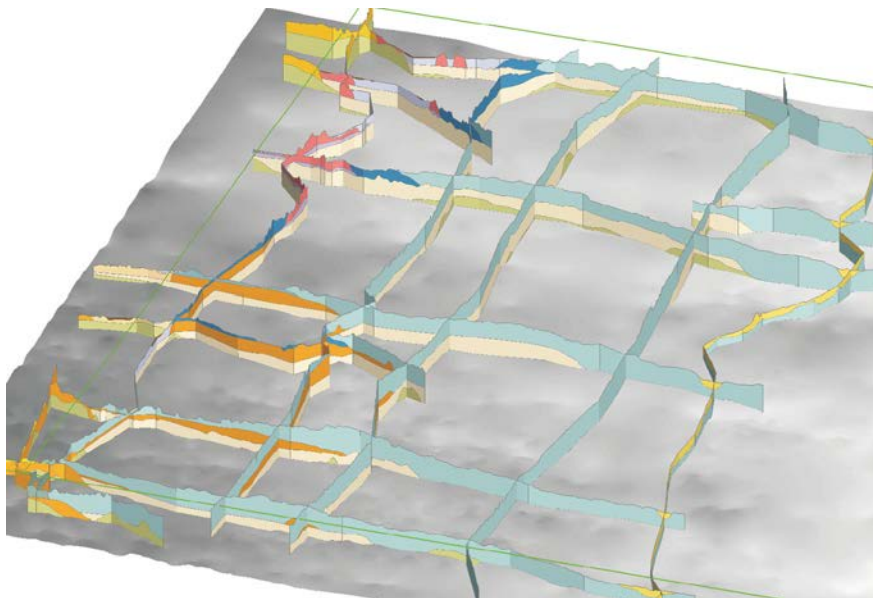


**Figure 4.** Lake County project example. Screen capture of an ArcScene window showing elements of the 3D geologic mapping workflow. **a.)** Custom toolbar with buttons that execute custom scripts; **b.)** selected intervals (highlighted in light blue) of 3D multipatch features that represent lithologic records, and note that only intervals that represent sorted sediment are shown; **c.)** natural gamma-ray log traces; **d.)** exploration test hole shown in larger diameter to highlight better quality information, displayed as a separate dataset; **e.)** selected multipatch features highlighted as attribute table records, interpretation for geologic unit identified in field by red arrow; **f.)** "Create Surface" script executes the TopoRaster geoprocessing tool based on tops or bottoms of selected intervals (user choice); **g.)** raster surface rendered from selection of interpreted record intervals using the "Create Surface" window shown in f.) and **h.)** key to 3D borehole representations, based on standardized terms. From Brown 2013. ©2013 by the Regents of the University of Minnesota.





**Figure 5.** Lake County project example. One of many paleo-environmental illustrations to aid 3D interpretation. Line of cross-section is about 40 km long. North is up.



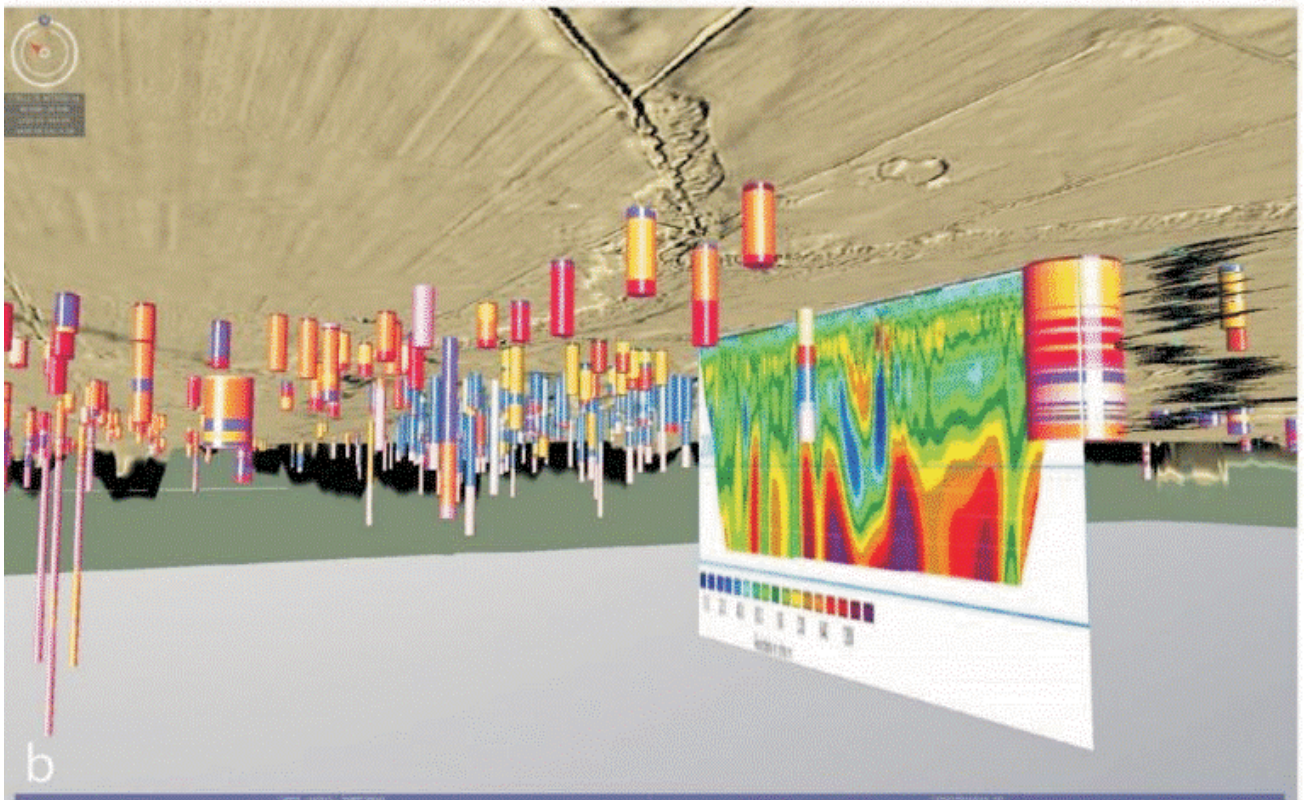
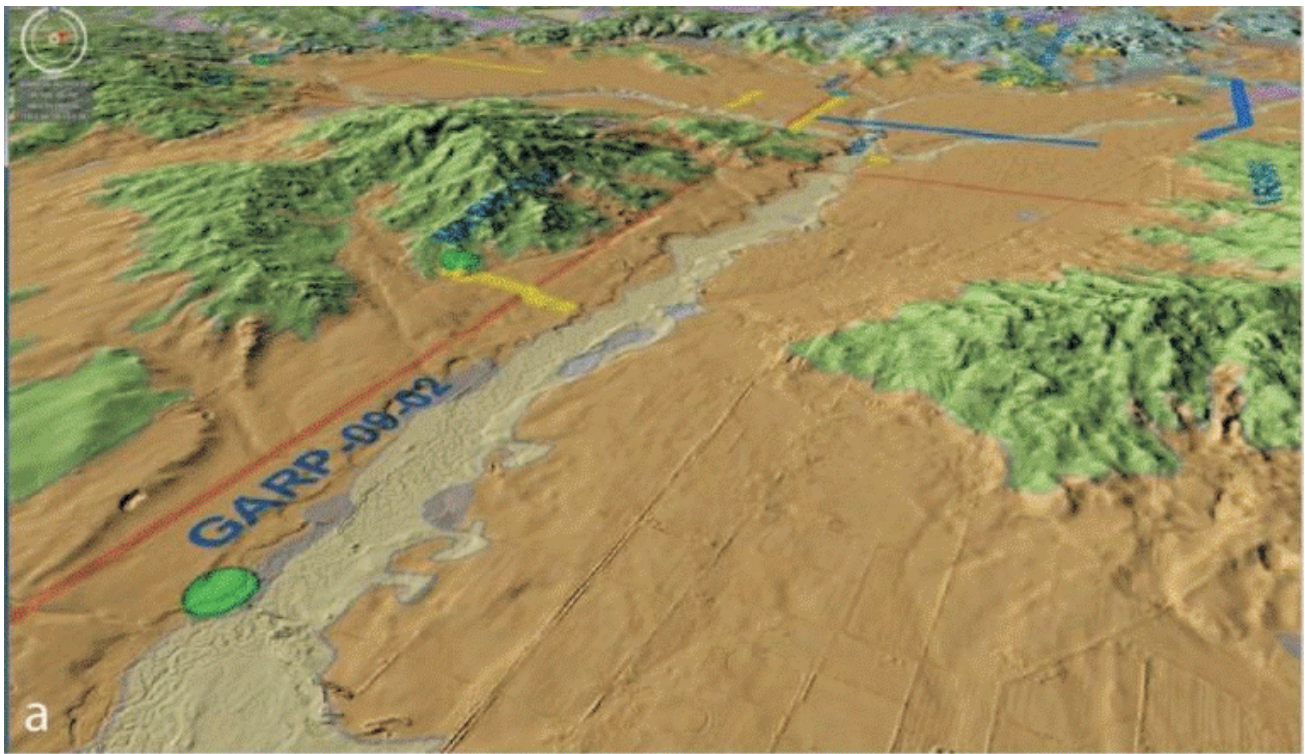
**Figure 6.** Lake County project example. Intersecting cross sections spaced approximately 3.2 km apart and derived from 3D data set produced with an ISGS created ESRI ArcGIS X-acto-section script. Originally developed for assisting the development for cartographic cross sections by accurately depicting land surface and bedrock topography for typical 2D geologic maps, application of the X-acto-section script to create vector polygons from the complete geology stack of raster structure contour surfaces was completely unintended. North is to the upper right.

significant interpretive control of each unit (Figure 10).

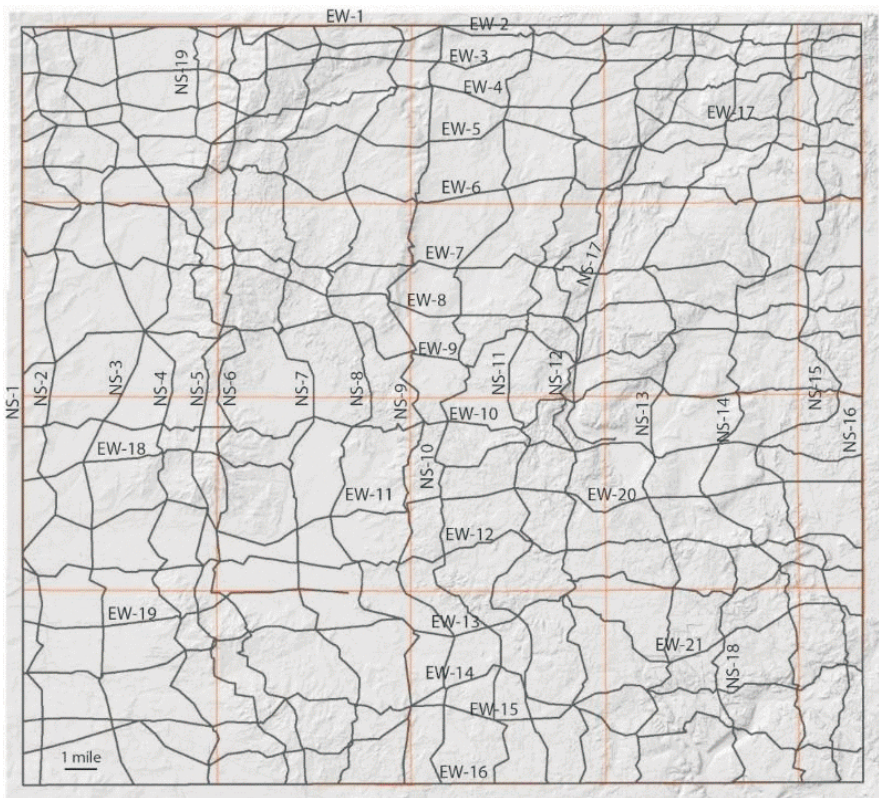
The Subsurface Viewer and GSI3D applications built triangulated irregular network (TIN) surfaces based on digitized node locations along cross sections and node locations along the mapped extents of each geologic unit in the model. Stratigraphic-hierarchical criteria were also included in the modelling protocol, which constrained model results and enforced geologic control. This workflow was parallel to the step in the Lake County project in which digital structure contours were created as input elements in the ArcGIS Topo to Raster surface interpolation process.

The 3D model of McHenry County is comprised of 22 geologic units associated with the unconsolidated, Quaternary glacial deposits. The regional geologic framework of the model is dependent upon 40 key-cross sections (Figure 9). In general, those key-cross sections are oriented north-south and east-west and located approximately 1.5-3 km (1-2 miles) apart. The key-cross sections were interpreted using the highest-quality water-well logs, test-hole data, and geophysical profile data. Secondary-cross sections (total of 70) were interpreted most often along topographic valley edges and valley bottoms to further delineate the boundaries and geometries of individual units (e.g., uppermost glaciofluvial and modern stream deposits). The secondary cross sections were critical to increase the quality and confidence of the 3D model between key cross sections and to improve the modelled contacts between units near land surface. The secondary cross sections also helped, in part, to control geologic boundaries in areas with very thin, shallow geologic units and in areas of high topographic relief. Different from Lake County, the cross-section building process was a step in making the model, whereas for Lake County, cross sections were an output after the model was created.

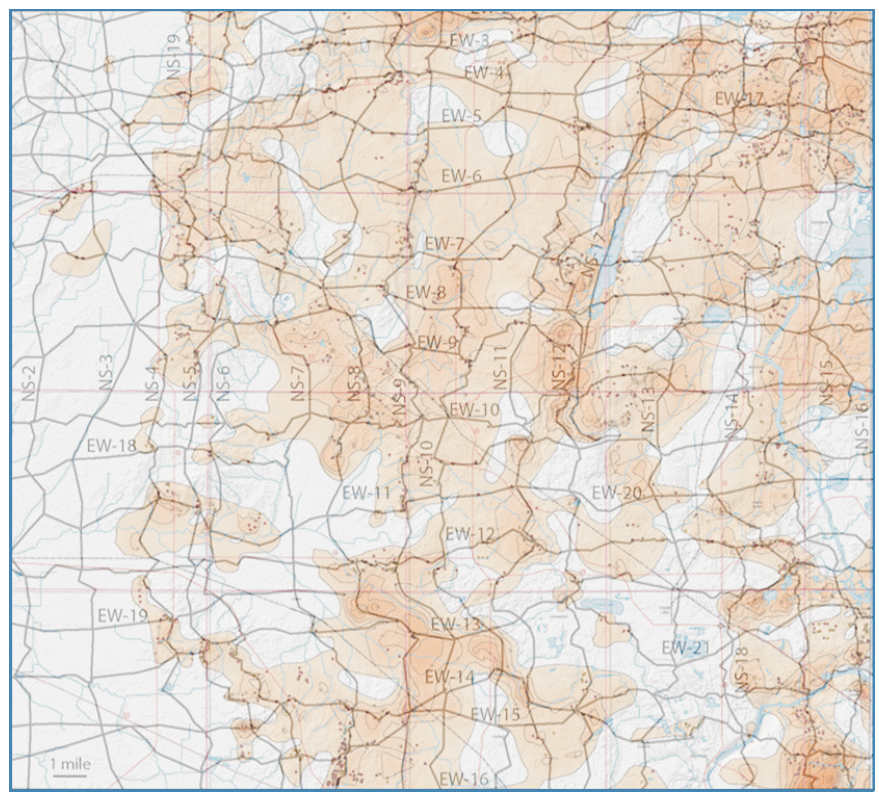




**Figure 8.** Three-dimensional visualization of (a) land-surface elevation model and (b) subsurface data in Geovisionary. In (a), the geologic map of McHenry County is overlain on the land-surface elevation model. In (b), ESRI shapefiles of lithologic descriptions of water-well logs and test holes are color-coded and viewed with 2D geophysical profile data in Geovisionary.



**Figure 9.** Locations and names of key-cross sections used in the Subsurface Viewer/GSI3D model of McHenry County. County is ~42 km wide. North is up.



**Figure 10.** Distribution of a modelled geologic unit (orange) relative to the key cross section network in McHenry County. County is ~42 km wide. North is up.

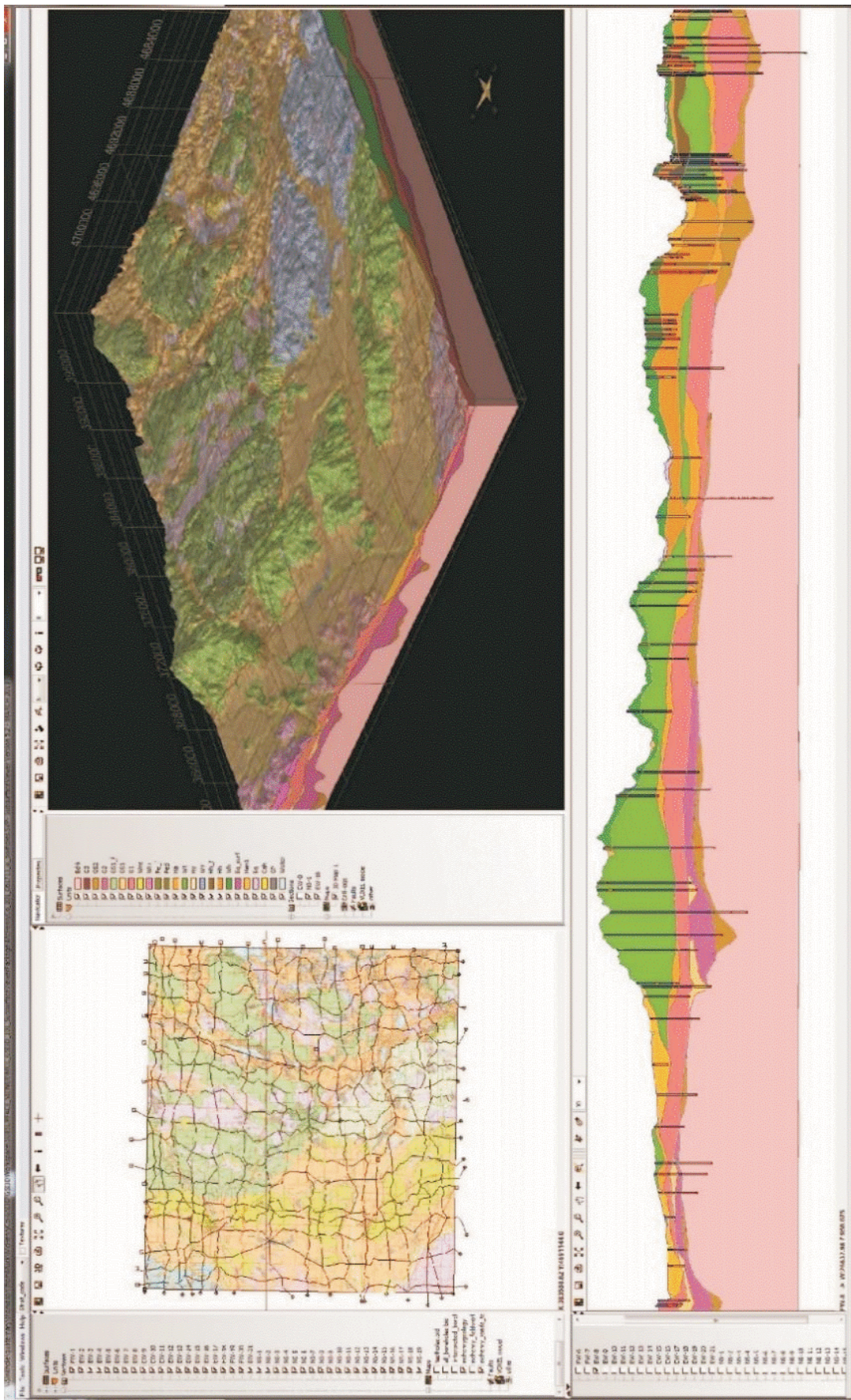
The McHenry modelling workflow was aimed at reducing uncertainty and optimizing modelled resolution by integrating the highest quality and density of geologic data and extrapolating their interpretations into a network of cross sections at a scale relative to the understanding of geologic complexity.

A primary goal was to develop an interactive, digital product to query and visualize the 3D geologic model data with an interface that the user or client could download and use.

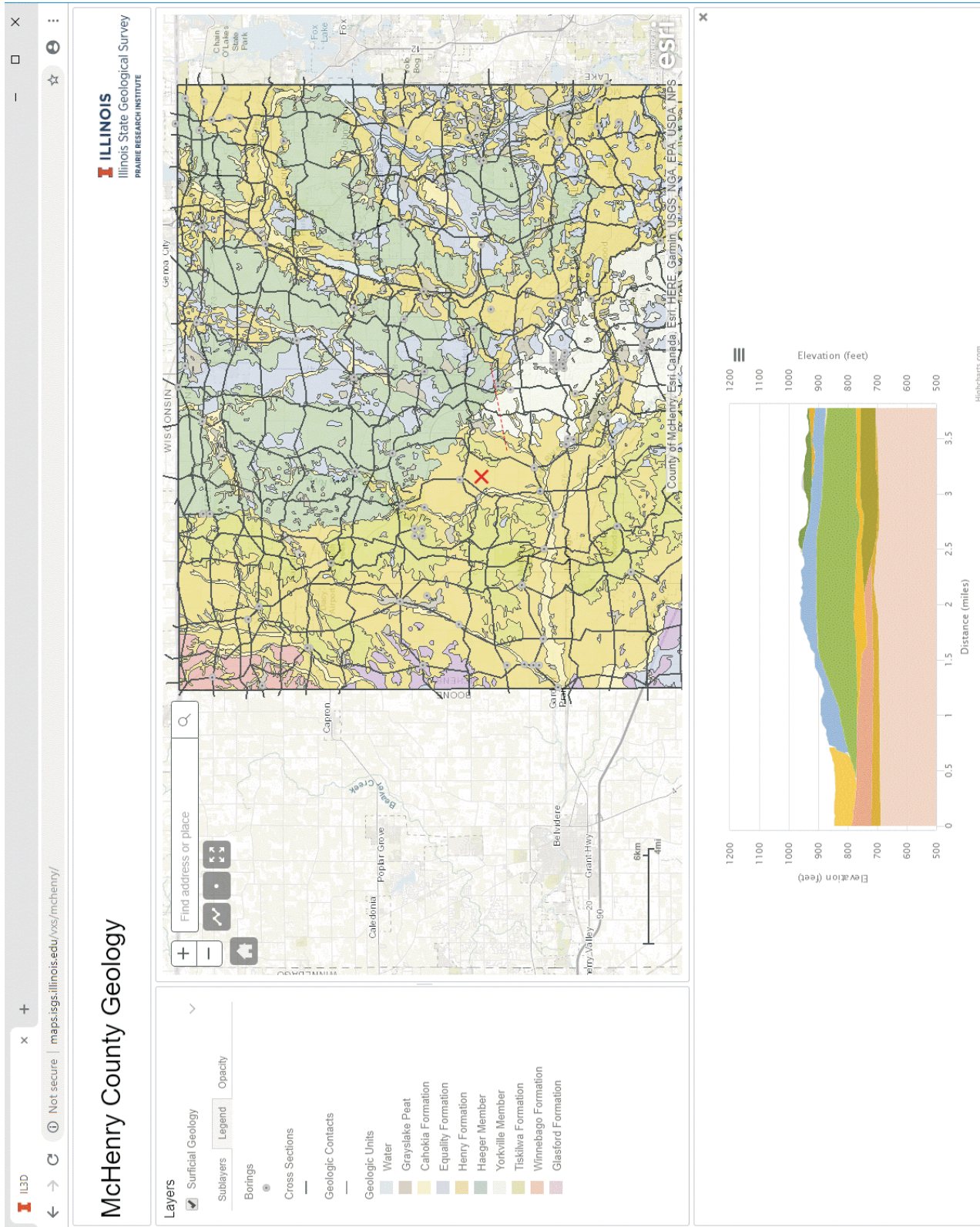
INSIGHT GmbH offers a free model-viewer software version of Subsurface Viewer, which allows a user to view and manipulate exported and encrypted Subsurface Viewer/GSI3D geologic models. The graphic-user interface in Subsurface Viewer includes map-view, 3D-view, and section-view windows (Figure 11). It also includes a borehole viewer to show the geology of selected water-well or test-hole data, or the interpreted geology at any user-defined point location or cross section within the 3D geologic model. Similarly, the ISGS has developed an open-source web viewer called IL3D (<http://maps.isgs.illinois.edu/vxs/mchenry>), which queries data from the McHenry County model to generate interpreted stratigraphic boreholes and cross sections at any location within the model domain (Figure 12). The data for Lake County and Will County are also loaded into IL3D and available in a somewhat seamless fashion to users. Therefore, despite any differences in the mapping and modelling approaches, the final products can be merged into an institutional data structure that is manageable and deliverable in a consistent and reliable manner.

**Will County**

Similar to Lake and McHenry Counties, a database was developed consisting of ISGS test holes and archival water-well descriptive logs from ISGS holdings and from private



**Figure 11.** Graphical user interface of the Subsurface Viewer/GSI3D and the McHenry County 3D model showing the cross section network, block diagram, and selected cross section. On the block diagram, north is to the upper left. The county is ~42 km wide.



**Figure 12.** IL3D web viewer interface for the McHenry County 3D model. The same application applies to the Lake and Will County datasets, creating a unified delivery protocol for all 3D geologic maps and models.

firms. Data representing ~29,000 boreholes were reviewed and compiled, assigned accurate geospatial coordinates, and given elevation values derived from the best available elevation datasets. Earth electrical resistivity (EER) profiles totaling 14 km were acquired along 8 lines, and mostly across an expansive moraine, known as the Valparaiso Morainic System. Siting resistivity targets was difficult because of an extensive subsurface oil pipeline network and the adverse impact of that subsurface infrastructure on geophysical data. The subsurface data also included information from 105 stratigraphic test holes (drilled by the ISGS). Drilling methods included hydraulic push (representing 660 m of core at 70 locations) and continuous wireline coring (representing 1,200 m of core at 35 locations). Holes drilled by the wireline method typically reached bedrock and were also logged by the natural gamma-ray borehole geophysical technique.

The 3D geologic modelling for Will County relied on lithological information from subsurface data, as described above, used in tandem with data from more than 100 field outcrops. Different from Lake and McHenry Counties, Will County's geomorphology provided a greater distribution of outcrops which was key for solving particular stratigraphic problems. Also, different from the Lake and McHenry County projects, GeoScene3D software was used to define the thickness and stratigraphic distribution of Quaternary deposits and it enabled strict coherence between the surface distribution of the various deposits (deduced from geologic maps) and borehole stratigraphy (Figure 13). This software application provided the ability to create the first 3D voxel model at the ISGS. During the basic geological interpretation for the model building, a structure contour map of the lowermost sand and gravel unit (typically within a bedrock valley) was first evaluated

and placed stratigraphically above the bedrock topographic surface, and then correlated (if possible) to other parts of the county. This was followed by successive construction of structure contour surfaces representing successively younger geologic units. Consequently, structure contour maps were created for 16 subsurface geologic units, and then based on the structure contour maps, 65 cross sections were built across the county from known data points. The cross sections and geological map contacts were used as the primary expert knowledge constraints (Figure 14).

Differences in lithological information from boreholes were used to place interpretation points. These points were used to create raster grids using the kriging interpolation method to obtain the base of each unit (in contrast, the top of each unit was mapped in the Lake County project, and bases were calculated after the mapping was completed). Since building surfaces separately does not ensure that they are consistently in the correct stratigraphic order (in other words ensuring that lower surfaces do not "pop out" above upper surfaces) in areas between cross sections, increased mesh density and minimum thickness constraints were applied locally to remove most crossovers which were frequent where units were thin, especially if the variability of the top elevation of a unit was larger than its thickness. During this trimming exercise, the surfaces of older valleys were cut by younger valleys. The remaining crossovers were removed manually by adjusting grid nodes. Special attention was also given to reliable boreholes that did not reach bedrock in order to respect minimum thickness constraints using interactive tools. Thus, crossovers and other thickness problems were corrected locally depending on the specific problem instead of taking a reference surface, calculating its thickness, and then adjusting all of the others to fit that layer. Therefore,

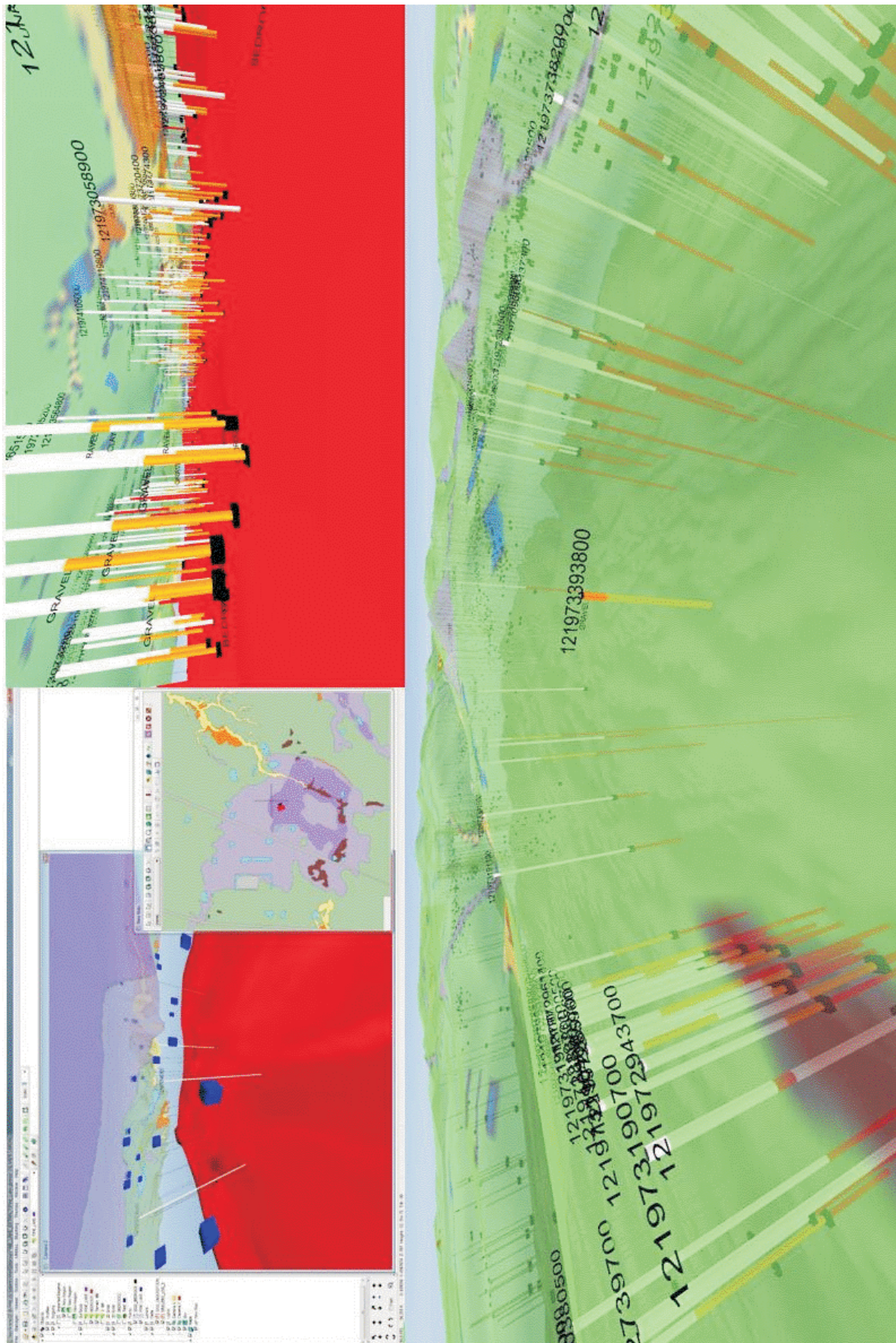
surfaces are not regionally modified on the basis of a reference layer, as opposed to what is often done in multi-layered modelling using standard GIS tools.

The completed 3D voxel model covers the entire study area with a grid discretization of 50 m laterally and 5 m vertically. These dimensions were chosen to achieve a proper resolution of the mapped buried bedrock valley structures. The voxel modelling was performed using a manual approach, where geological units were interpreted without any automated routines. This was done by using a set of specific tools in GeoScene3D, where it was possible to select and populate the voxels in different ways (Jørgensen et al. 2013). GeoScene3D tools subsequently were used that enabled the selection of voxels within volumes delineated by the interpolated raster surfaces, and where voxels were selected within digitized polygons on cross-sections. Using these tools, major volumetric bodies were populated by picking groups of voxels that were constrained by the initially modelled surfaces. Minor geologic bodies were manually digitized. Importantly, the ability to create smaller geologic bodies as voxels within the larger mapped units provided a means to demonstrate variability within mapped units. This is an aspect of geologic modelling that was not accommodated in the Lake and McHenry County examples. In those cases, internal unit variation could only be described in text, not visually, unless subsequently displayed graphically as additional content in cross sections.

## Current Challenges

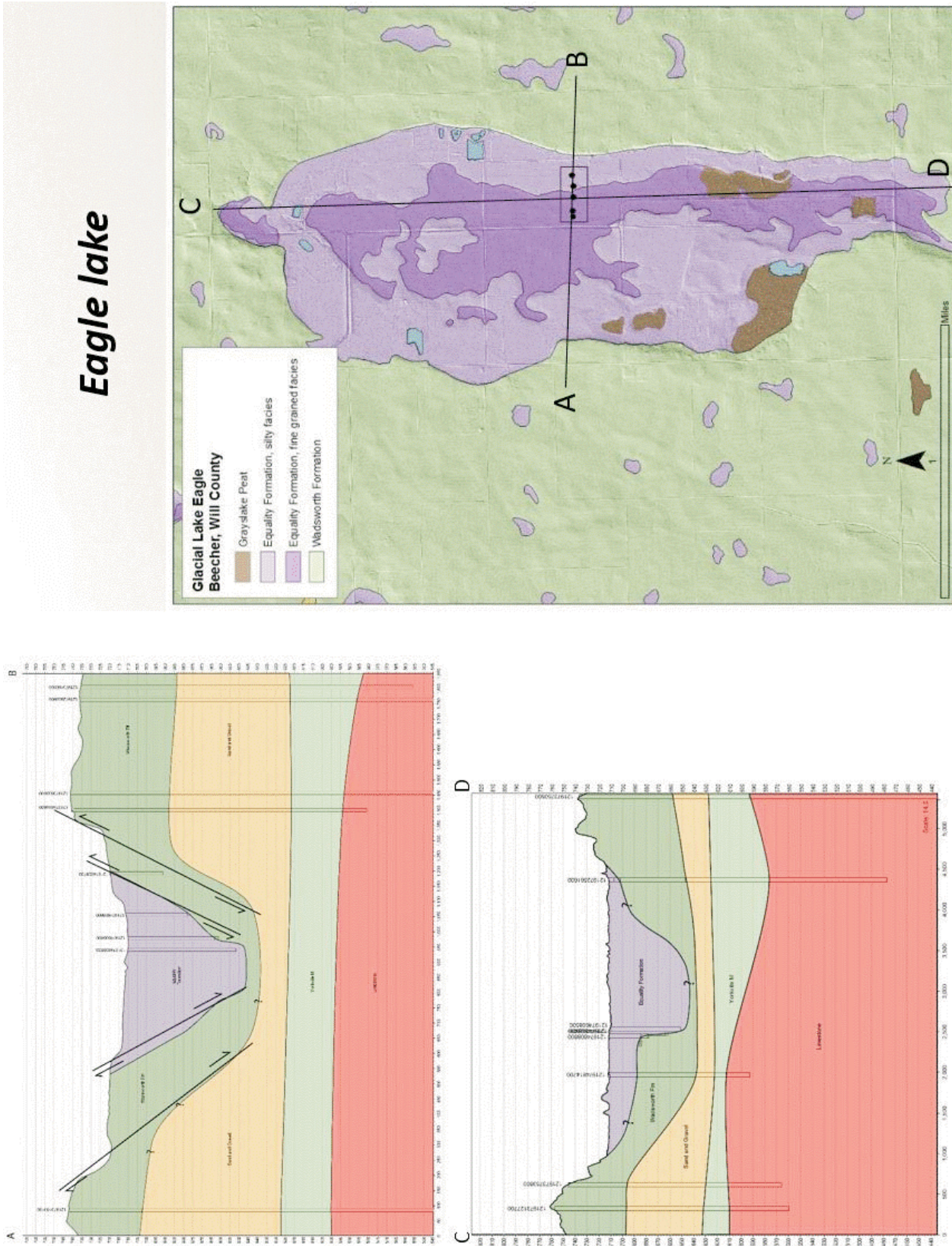
### 1. Funding

The long standing challenge is the low funding level for geological mapping and modelling. The inability of the United States to fund this effort at the levels required to understand the country's natural resources will likely



**Figure 13.** Graphical user interface of GeoScene 3D and a portion of the Will County 3D model showing boreholes and surfaces. The red surface is bedrock, green is Quaternary sediments, and purple is lacustrine sediments. The below image is ~4.8 km east-west, and all images are looking north.





**Figure 14.** Surficial geology of the Eagle Lake area located in Will County and selected cross sections from Geoscene 3D. On the map and cross sections, orange is bedrock, green is diamictons, yellow is sand and gravel, and purple is lacustrine sediments. Cross-section AB is 2.25 km long and cross-section CD is 4.54 km long.

result in an economic disadvantage, as globalization continues to increase competition for resources between nations. Possible redistribution of populations and shifting agricultural production resulting from climate change will require more robust knowledge of groundwater resources and the defining of geologic units that contain the water. The lack of adequate 3D geologic models to respond to these potential national challenges could be devastating (Reidmiller et al. 2018).

The lack of adequate federal and state funding to minimally support one or two concurrent 3D geologic mapping projects in Illinois that construct products within a 3-year or less time frame means that progress will be slow. However, technological developments, and particularly airborne geophysics, have proven that the up-front cost is worth the investment. Every 3D mapping project should require this so that complete high-resolution low altitude geophysical surveys are conducted to supplement traditional methods of subsurface data acquisition, as has been done routinely in Denmark (Thomsen 2011). As of this writing, there appears to be an effort through the Illinois General Assembly for legislation that would fund 3D mapping of the area underlain by the Mahomet aquifer in east-central Illinois for approximately \$20 million. This would be the first fully funded, state supported, 3D geologic mapping project in Illinois using all available exploration techniques including high resolution helicopter borne time-domain electro-magnetic geophysics (Brown et al. 2018).

## **2. Technology Platforms**

Technology changes, and typically does so with outcomes that improve productivity. A review of every type of 3D modelling or mapping project at the ISGS shows that each used a uniquely different technological workflow. No two were exactly alike in the use of software and development of digital products. A challenge

remains with implementing a consistent software workflow that withstands time and also is financially sustainable. The ISGS followed the lead of the BGS with investment in the same software and similar computing infrastructure, and joined the 5-year GSI3D Research Consortium managed by the BGS under license from INSIGHT GmbH. With demise of the license agreement, and dissolution of the Consortium, the outlook for continued software support and the promise of a solution for client/customer user interface, no longer appeared as a viable strategic direction.

## **Lessons Learned**

### **1. User-Client Technological Expertise**

The Lake County project included a group of very advanced county level GIS managers and users. Even after onsite demonstrations, clear communication regarding 3D models, and how 2D information could be visualized or used for analysis in ESRI applications, the county customer revealed on the day of product delivery that they did not use the 3D component of ArcGIS, ArcScene. In addition, they had no other software that could accommodate 3D visualization. A clear gap exists in the ability for most government clients or customers to use any 3D software application, nor can we expect them to do so.

In McHenry County, awareness and utility of the 3D geologic model has been challenging because of county administrative turnover. New administrative staff have been largely unfamiliar with the project and had to be re-educated about the 3D model and re-convinced of its value and utility. Similarly, new locally-elected officials often have been unaware of the model and its benefits. Consistent communication and follow-up meetings by ISGS scientists and county decision makers is absolutely necessary for forward progress by a dy-

namically changing constituency. Furthermore, consistent communication and productive 3D model applications are particularly successful within counties that employ professional positions that are charged with meeting natural-resource planning objectives.

For Will County, geological modeling is scheduled for completion by the end of 2019. Therefore, time has not elapsed to provide any lessons learned.

### **2. User-Client Needs vs. Jurisdictional Constraints**

Ask any public employee responsible for delivery of services related to natural resources, enforcement of public ordinances or laws, or involved in public education, regarding their needs and they will respond “yes” to every possible mapping or modelling product that can be created. They will do so without analysis of existing jurisdictional constraints, actual actionable ordinances or laws, and realistic analysis of their own day-to-day, month-to-month, and year-to-year workflow, defined work protocols, and bureaucratic hurdles. Unless the use of geologic information is imbedded in a required workflow for public employees, most likely the information will not be used as intended by the geological community.

### **3. Map Product Convergence**

Despite the different technological approaches used to make 3D geologic maps and models described in the case studies, the robust technology infrastructure at the ISGS has allowed geologists to produce digital geologic map data that can be ingested into web delivery services. Instead of packaged viewers, the promise to show it all, and imposed software learning requirements on the user, simple tools that allow users to select a line of profile that creates a user defined cross section from continuous structure contour surface data, appears to have great appeal by clients.

The ISGS concept of 3D and the user's concept of 3D may be very different considering the client's exposure to IMAX movies, video gaming, and other consumer oriented products. Thus, expectations on what the client receives could be much different from what the client expects to be delivered. Depictions of the 3D stack of maps has a useful, perhaps dramatic, effect of showing the complexity of geologic relationships, but is quite useless for problem solving. We have found, through one-on-one trial with clients/users, that most users understand the simple concept of cross sections. The concept is reinforced when the user can create his or her own cross section from the 3D data. The delivery of data as shown in Figure 12 both achieves the goal of providing 3D information, and an institutional data management solution by providing a single point of delivery. New data can be added at any time, and it appears to be seamless. Perhaps most importantly, there is no vendor created obsolescence through proprietary reliance and the continued financial investment for technology that serves a single purpose.

## Next Steps

The future of 3D geological modeling at the ISGS is to:

- 1) Complete geological modelling for Will County in 2019, and transition to the northeast to Cook County, which includes urban mapping and modelling of the city of Chicago.
- 2) Complete nearshore modelling of bottom sediments along Lake Michigan's Illinois shoreline to be integrated into the Cook and Lake County geological models.
- 3) Expand the Will County modelling southward to Kankakee County where groundwater and aggregate extraction are issues.
- 4) Update the 2007 Kane County geological model (Dey, Davis, and Curry 2007).

- 5) Begin 3D geological modelling northwest of Chicago in Boone County, where glacial sediments are complex and deep glacial aquifers require improved delineation.
- 6) Begin 3D geological modelling in DuPage County, west of Chicago, where infrastructure issues prevail.
- 7) Update and complete the unpublished Kendall County geological model (Keefer et al. 2013).
- 8) Construct a 3D geological model of the state (perhaps at 1:500,000 scale).

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# Chapter 15: 3D Geological Modelling at the Geological Survey of Italy (Servizio Geologico d'Italia): an Overview

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D'Ambrogi, C. 2019. 3D geological modelling at the Geological Survey of Italy (Servizio Geologico d'Italia): an overview; Chapter 15 in 2019 Synopsis of Current Three-Dimensional Geological Mapping and Modelling in Geological Survey Organizations, K.E. MacCormack, R.C. Berg, H. Kessler, H.A.J. Russell, and L.H. Thorleifson (ed.), Alberta Energy Regulator / Alberta Geological Survey, AER/AGS Special Report 112, p. 159–170.

## Introduction

Since 2000 geological 3D modelling is part of the institutional mandate of the Servizio Geologico d'Italia (SGI). In a country characterized by high geological complexity, natural hazards (e.g., earthquake, volcanic activity) and increasing demand of natural resources, several 3D models have been produced to answer the need for a better knowledge of subsurface geology. These activities have been carried out in the framework of national and European projects. The SGI has also devoted significant efforts to the design of specific workflows both for the 3D model building stage and the following analysis and applications.

Despite the important progress, several aspects remain unresolved: the poor use of 3D geological models by a large number of stakeholders, probably related to the dissemination format of 3D models; and the extension to the entire Italian territory of a “bedrock and Quaternary 3D model” thus providing a framework for detailed local 3D geological models.

## Organizational Structure and Business Model

The Servizio Geologico d'Italia (SGI) is the national geological survey for Italy; it was established in 1873 and since 2008 it became a Department of the larger Italian Institute for Environmental Protection and Research (ISPRA). Its institutional mandate has progressively expanded coupling geological and geothematic mapping with

technical-scientific support to local, regional and national authorities in several fields of the geosciences (e.g., natural hazards, hydrogeology, monitoring of soil and subsoil conditions, geophysics). In case of emergencies (e.g., earthquakes, landslides, floods) the SGI acts as an operational arm of the Italian Civil Protection Service and also provides scientific and technical support in seismic microzonation studies. Its production at various scales of geologic and geothematic national coverages (from 1:1,000,000 to 1:50,000), and relevant database, provides a complete collection of geological information of the Italian territory. Since 2000 SGI has embraced 3D geological modelling to implement analysis and visualization of geoscience data; this activity is supported mainly by European (EU) funds to research and applied sciences, or realized for national research projects.

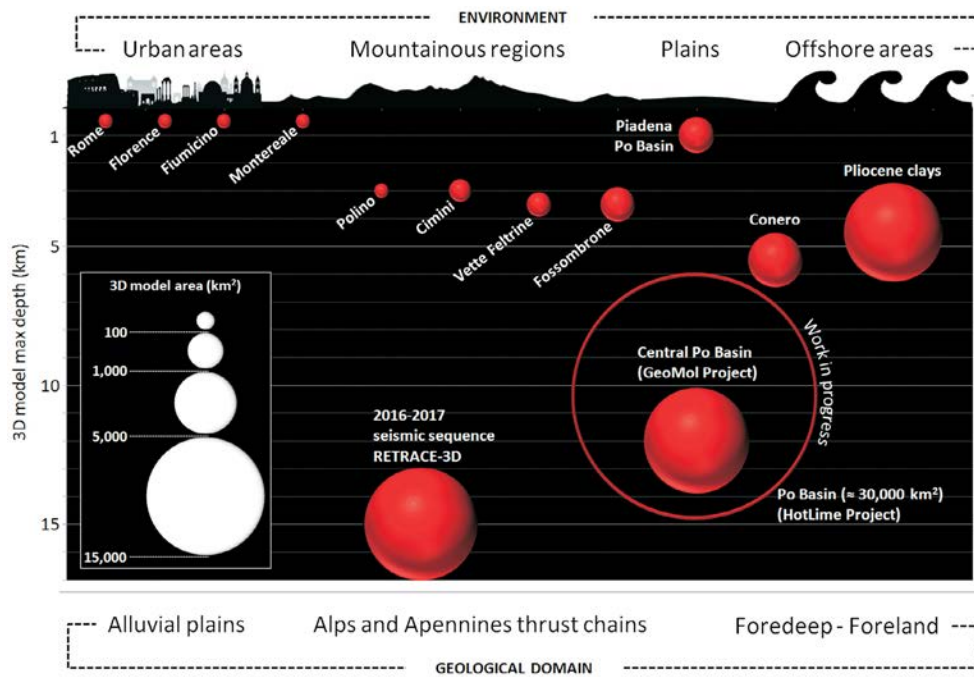
The SGI maintains a staff of 140 people, composed by 120 technical and 20 administrative units. The annual budget is about 1 million Euros; more than the 50% of the budget derives from European or national project-related funding.

In February 2019 a “Work Group on 3D geological modelling” has been established based on the cooperation between SGI and 8 regional GSOs, with the main aims to exchange knowledge, workflows, and tools, and to define national standards for production, exchange, and dissemination.

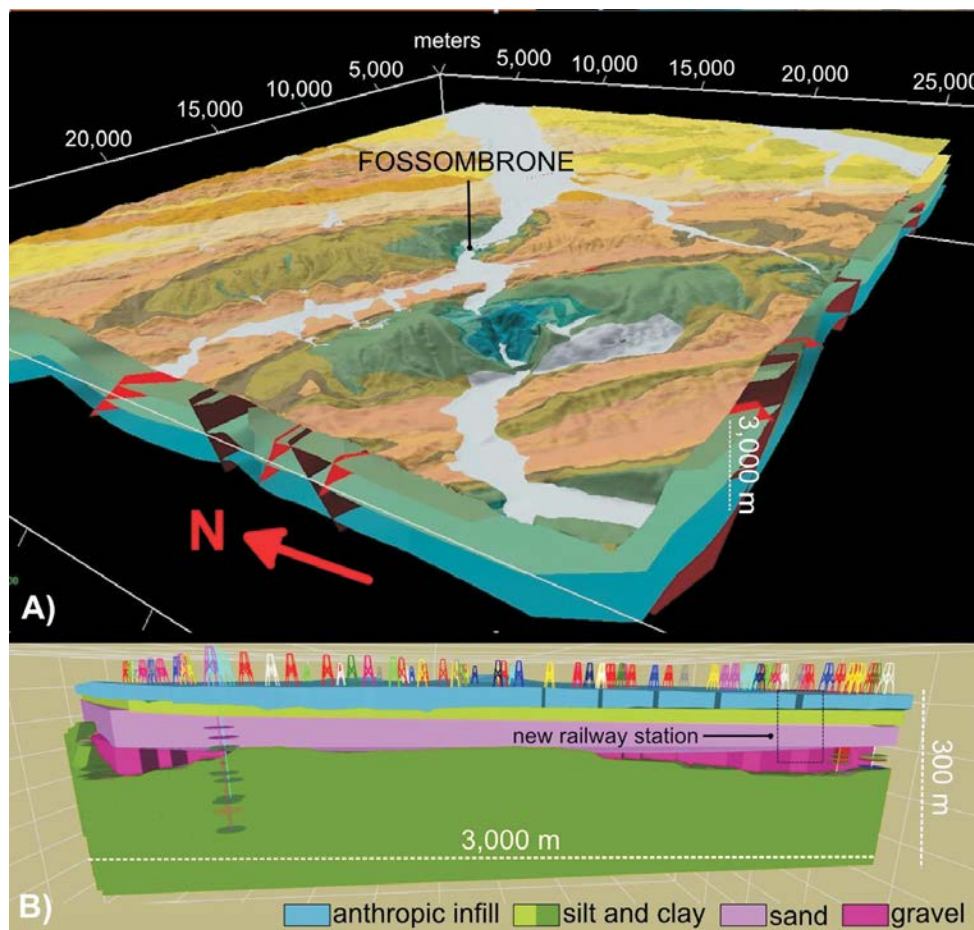
## Overview of 3D Modelling Activities

The geological 3D modelling activities carried out by SGI have as a main goal the maximization of the geological information through the integration of surface and subsurface data derived mainly from SGI national geological databases, to support applicative uses or tectonostratigraphic analyses. Several 3D geological models, from local to nation-wide coverage, have been built to describe various geological domains, from fold-and-thrust mountain belts to plain areas (Figure 1); they are part of “GeoIT3D - 3D modelling and visualization of geological data” institutional framework.

Initially, 3D models built by SGI were related to the National 1:50,000 scale Geological Mapping Project (CARG Project). The idea was to pair the geological mapping with a 3D model of the geological complexity in the subsurface. These 3D models, covering the area of a single Geological Sheet at 1:50,000 scale (~600 km<sup>2</sup>), were mainly based on field data (e.g. stratigraphic boundaries, attitudes, tectonics), geological cross-sections, and borehole stratigraphies obtained from the CARG Project database (1:25,000 scale), integrated with seismic reflection profiles, if available. The quality of the resulting 3D models demonstrated the full applicability of SGI public geological databases to obtain comprehensive and coherent 3D models in different geological domains such as the Apennines thrust belt (Fossombrone Sheet, Figure 2A)



**Figure 1.** 3D geological models produced by SGI in the frame of “GeoIT3D - 3D modeling and visualization of geological data”, supported by EU or national funds. See Figure 3 for the location of each model.



**Figure 2.** **A)** 3D geological model of the Geological Sheet Fossombrone; **B)** 3D geological model of the urban area of Florence, view from north. See Figure 3 for the location.

(De Donatis et al. 2002 and D'Ambrogi et al. 2004) or alluvial-coastal areas (Fiumicino Sheet, see Figure 3 for the location).

Following this experience, the SGI 3D modelling activities have been expanded in two domains. Firstly to specific projects dealing with applicative purposes (e.g. tunneling, hydrogeology, geothermal studies), urban geology, basin analysis, and seismotectonic studies. Secondly to long-term activity devoted to the production of a 3D framework for the entire Italian territory.

Small and shallow 3D models of the urban areas of Rome and Florence (1 and 2 in Figure 3) were almost exclusively realized based on borehole stratigraphies, with some additional data derived from surface geology. These models investigated to a few hundred meters depth the subsurface, giving a well-constrained description of the geometrical relationship of the units within alluvial sediments (e.g., Florence area), or thickness of anthropic infill (e.g., Rome), and underlying volcanic units. The 3D model of the Florence urban area (Figure 2B) was realized in the framework of the Environmental Observatory, defined by the Italian Ministry of Environment, for a new underground railway station. It allowed the calculation of the volume of coarse alluvial sediments intercepted by the underground excavation and supported relevant decisions on the disposal of the excavated material, including its potential recycle as natural aggregate for concrete.

In the Alps and Apennines, small regions covering a few hundred km<sup>2</sup> have been modelled, in collaboration with universities, as part of scientific projects for paleogeographic and structural analyses: i) the evolution of a Jurassic Pelagic Carbonate Platform (Polino area, 4 in Figure 3), ii) the shortening of a sector of Southern Alps (Vette Feltrine - 6 in Figure 3; D'Ambrogi and Doglioni 2008), iii) the evolution of thrust-related

anticlines, with quantitative evaluation of uplift rates and Plio-Pleistocene sedimentary infill (Piadena - Po Basin, 8 in Figure 3; Maesano and D'Ambrogi 2016), iv) the Quaternary basin infill history of a tectonically controlled intermontane basin (Montereale, 3 in Figure 3; Chiarini et al. 2014).

Geological 3D models of larger areas (1,500 - 15,000 km<sup>2</sup>) have been completed as part of European funded projects for resources assessment or national research programs supporting quantitative analysis of faults activity related to seismogenic potential evaluation (Central Po Basin, 8 in Figure 3; Maesano et al. 2015, Maesano and D'Ambrogi 2016; Conero, 9 in Figure 3; Maesano et al. 2013). These 3D geological models extend to a depth of up to ≈20 km by integrating seismic reflection profiles, deep wells for hydrocarbon and geothermal exploration, and other data (e.g., instrumental seismicity, gravity and magnetic anomalies, heat flow).

The 3D geological model of the central Po Basin (Figure 4), produced in the frame of the European funded project GeoMol "*Assessing subsurface potential of the Alpine Foreland Basins for sustainable planning and use of natural resources*", covers an area of 5,700 km<sup>2</sup> and reaches a depth of 12 km (GeoMol Team 2015; ISPRA 2015). This model will be extended to the entire Po Basin, a plains area of more than 30,000 km<sup>2</sup>, in the upcoming HotLime - GeoERA Project (*Mapping and Assessment of Geothermal Plays in Deep Carbonate Rocks – Cross-domain Implications and Impacts*) (12 in Figure 3).

Since 2009 the SGI 3D models production has focused on active tectonics and seismogenic faults; the areas hit by the most recent seismic events were modelled with special attention to the geometry and relationship between faults. A further step will be the collection of geometrical data derived from the existing 3D models as

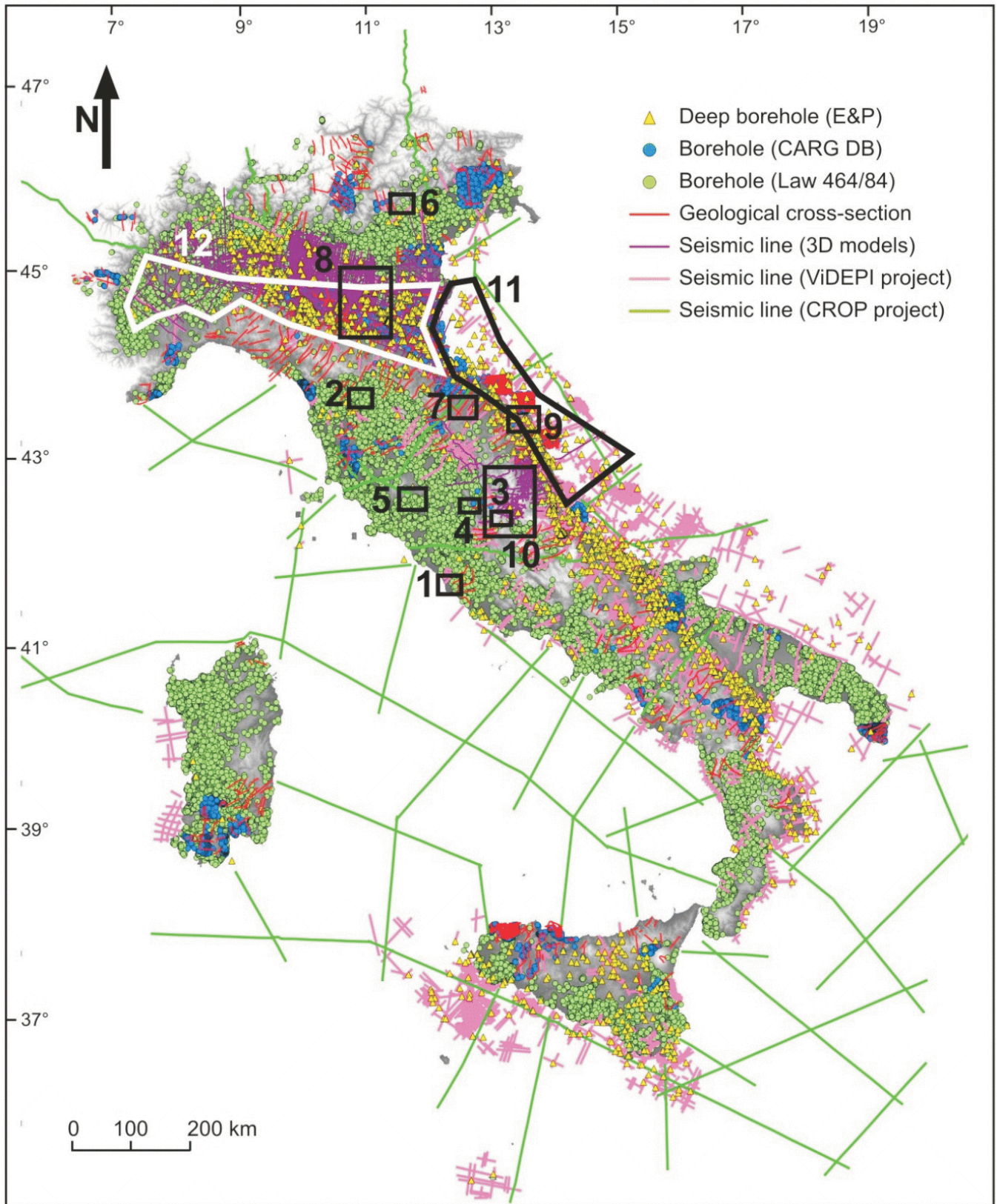
the contribution to the European Fault Database that will be realized in the HIKE - GeoERA Project (*Hazard and Impact Knowledge for Europe*).

Currently, the National Civil Protection Department supports the collaboration between SGI and other research institutes for producing the 3D crustal model of the area hit by 2016/2017 Central Italy seismic sequence (max Mw 6.5, and four events of Mw >5.0). This 3D model will be realized in the project RETRACE-3D "Central Italy Earthquakes Integrated Crustal Model" ([www.retrace3d.it](http://www.retrace3d.it)), that has also the support of private oil companies (ENI and TOTAL), that kindly provided the seismic reflection profiles of a large area (>5,000 km<sup>2</sup>, 10 in Figure 3).

The next long-term step will be the building of an Italian Bedrock and Quaternary 3D model, through the full integration of the data stored in SGI databases and local 3D models, with data from external sources (Figure 5). A preliminary harmonization phase of basic datasets is ongoing and will hopefully be implemented by the collaboration with regional geological survey organizations and other research institutes. This long-term challenging activity started in 2010 (D'Ambrogi et al. 2010) with a first 3D visualization of the crustal and sub-crustal structure of Italy, including main seismogenic sources, seismicity distribution, Moho discontinuity, and lithosphere-asthenosphere system.

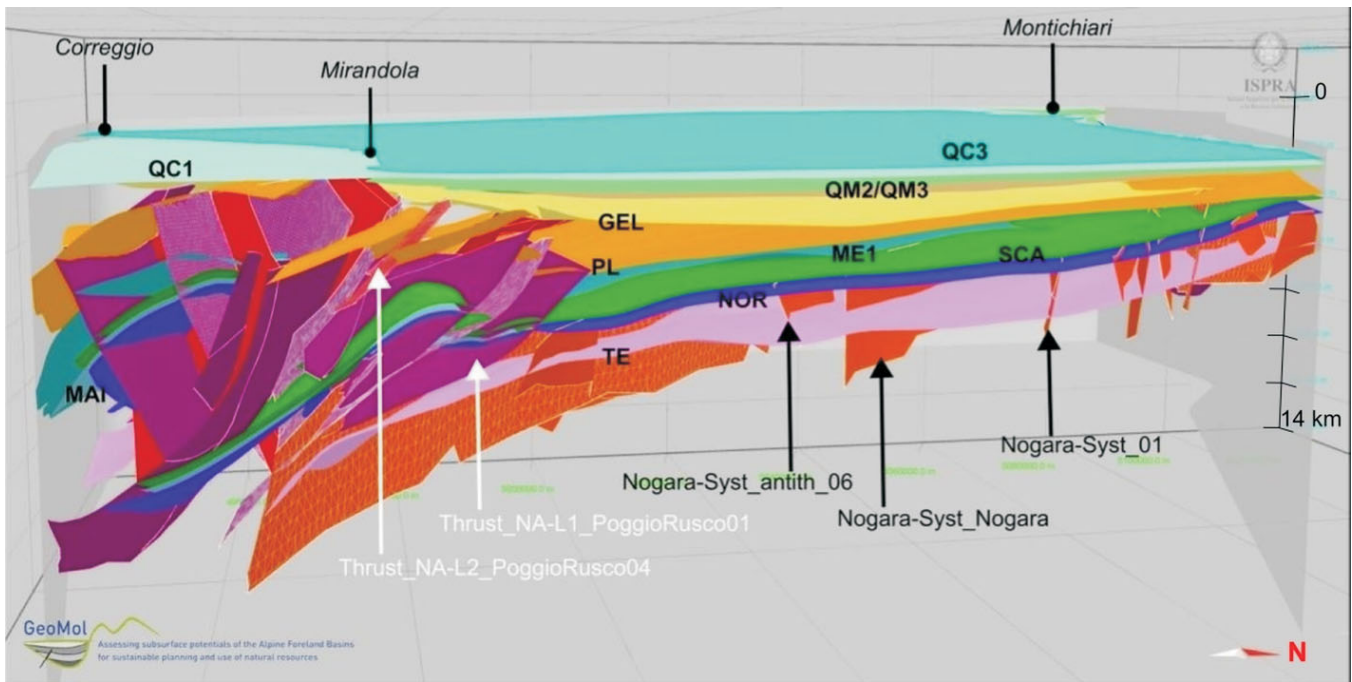
## Resources Allocated to 3D Modelling Activities

The annual resources allocated to 3D modelling activities at SGI vary significantly from year to year as they derive mainly from the participation to nationally-, European-funded research and applied-science projects. These project-related resources clearly constrain the 3D modelling activities either for choosing the areas to be investigated or for selecting the

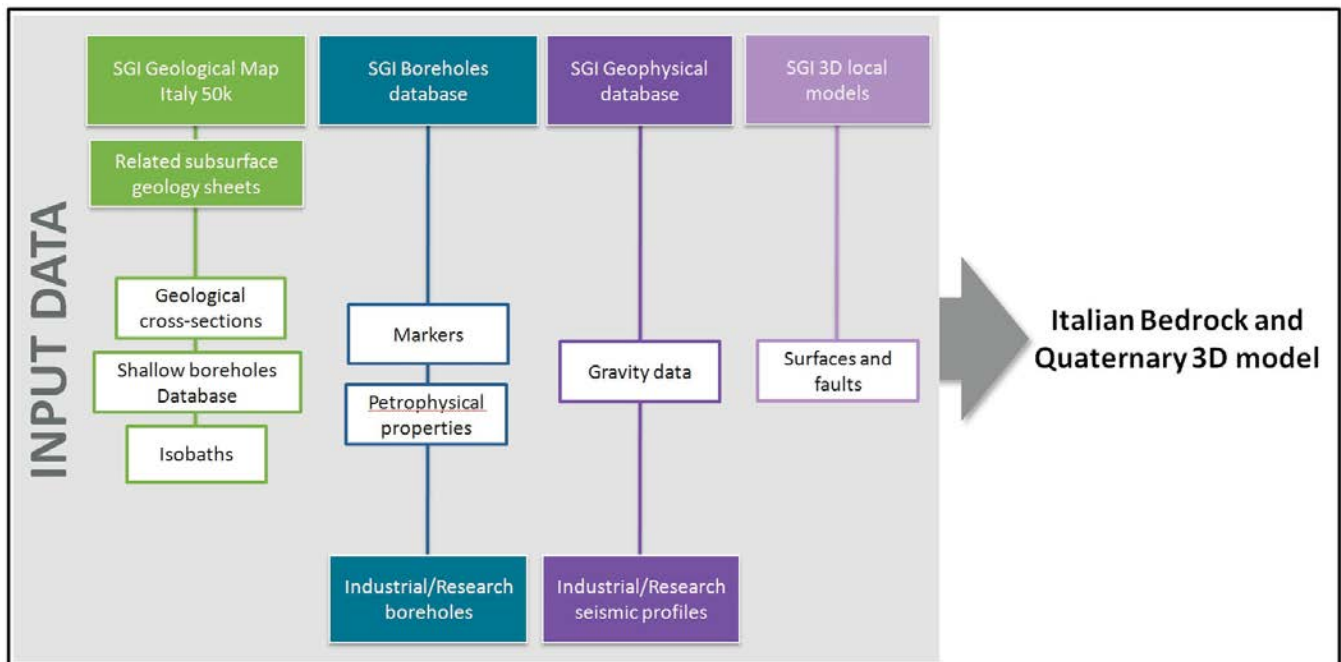


**Figure 3.** Distribution of main geological data publicly available. Purple lines indicate seismic lines used for 3D model construction available under a confidentiality agreement. Black polygons indicate the areas covered by 3D models, in white those under construction. 1. Rome and Fiumicino, 2. Florence, 3. Montereale, 4. Polino, 5. Cimini, 6. Vette Feltrine, 7. Fossombrone, 8. Po Basin: GeoMol Project and Piadena, 9. Conero, 10. RETRACE-3D Project area, 11. Pliocene clays, 12. Po Basin: HotLime Project area.





**Figure 4.** 3D geological model of the central Po Basin (GeoMol Project). The surfaces marked with black labels represent horizons from Trias (TE) up to Pleistocene (from GEL to QC3). The purple surfaces represent the main thrusts, responsible for the Emilia 2012 seismic event. The orange surfaces represent inherited normal faults in the Mesozoic carbonatic succession. The horizontal grid spacing is 10 x 10 km.



**Figure 5.** Workflow for the realization of the Italian Bedrock and Quaternary 3D model. All the input data will be harmonized following a structural and stratigraphic scheme based on Geological Map of Italy 1:1,000,000 scale (ISPRA 2011).

3D model applications (e.g. wide basins analysis, geothermal resource assessment, seismotectonics).

Only a small amount of resources derives from institutional funds.

The staff involved in the 3D modelling activities changes based on the budget and timeframe of the projects, the type of applications, the size of the modelled areas. They are field ge-

ologists, geomodellers, geophysicists, and GIS experts, generally not full-time involved.

The 3D modelling activities in specific research projects involve also

geoscientists from universities or research institutes, and undergraduate or PhD students that use 3D modeling techniques as part of their theses.

## Overview of Regional Geological Setting

The geology of Italy is the result of a long series of geological events that include: i) the evolution of the passive margin of the Gondwana continent (Precambrian–Ordovician); ii) the opening and closure of the Rheic ocean (Ordovician–Devonian); iii) the Variscan (or Hercynian) orogeny and the following creation of Pangea (Carboniferous–Triassic); iv) the opening of the Tethys ocean and its closure due to Alpine orogeny, that generated both the Alps (Jurassic–Oligocene) and the Apennines - Maghrebic chains (Upper Oligocene–Present); v) the opening of the Liguro-Provençal and Corsica basins (Lower Miocene); and vi) the opening of the Tyrrhenian basin (Late Miocene).

On this basis, the Italian territory ( $\approx 300,000$  km<sup>2</sup> on-land) can be subdivided into seven sectors, from north to south: the Alps, the Po Plain, the Apennines, the Apulia foreland, the Calabrian-Peloritan arc, Sicily (that includes the Maghrebic chain and its Hyblean foreland), and Sardinia (Figure 6). Furthermore, the Italian peninsula is characterized by the presence of active volcanoes (i.e., Campi Flegrei, Vesuvio, Etna, Stromboli, and Vulcano) and has frequent earthquakes.

Sardinia island (SA in Figure 6), in the western Tyrrhenian Sea, has preserved the oldest rocks outcropping in Italy, Precambrian-Carboniferous in age, related to the pre-Variscan orogenic history. In the other parts of Italy the Variscan orogeny has been overprinted by the Alpine orogeny.

The Italian portion of the Alps mountain belt extends from the Gulf of Genova in the west to the boundary with Austria and Slovenia, in the east.

It can be subdivided into two belts, according to the sense of tectonic transport toward the foreland: a Europe-vergent belt (Al-E in Figure 6) and an Africa/Adria-vergent belt (Al-A in Figure 6), named the Southern Alps (Dal Piaz 2010).

The Europe-vergent belt includes units deriving both from European and African continental crusts and Tethyan ocean domain, displaced towards the Molasse foredeep and European foreland. The Africa/Adria-vergent belt consists of units of non-metamorphic, ophiolite-free, African continental crust, developed inside the Alpine hinterland (retro-wedge). The two belts are juxtaposed along the Periadriatic (or Insubric) lineament (IL in Figure 6).

The Po Plain (PP in Figure 6) developed between the Alps and the Apennines. It represents the common foreland of these oppositely verging fold-and-thrust belts. The outer fronts of the Southern Alps, to the north, and Northern Apennines, to the south, are buried below  $>7,000$  m thick pile of Plio-Quaternary marine-to-continental sediments (Fantoni and Franciosi 2010).

The Apennines geographically extend the length of the Italian peninsula, from north to south (AP/APm in Figure 6); this belt is the result of the convergence between the Alpine orogen and the continental crust of the Africa plate (Adria promontory or Adria microplate). The deformations of the Apennines are superimposed on previous compressional events, responsible for the formation of the Alps during the Late Oligocene-Early Miocene counter-clockwise rotation of the Corsica-Sardinia block. The Apennines include units of African continental crust derived from the Mesozoic Tethys ocean.

In the Apennines since the Miocene the eastward migration of compression has been followed and coupled by the contemporaneous activity and

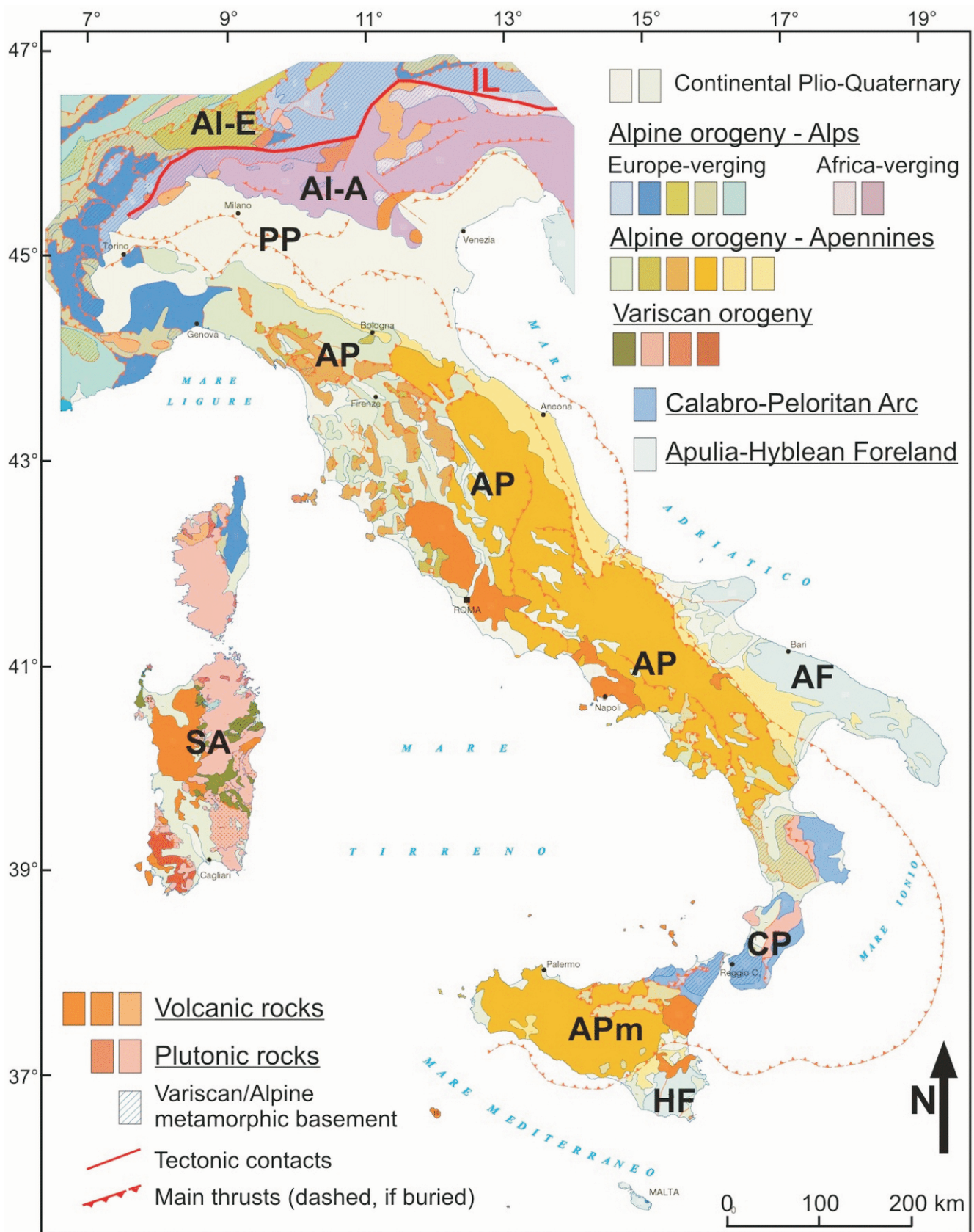
migration of a co-axial extension (in the hinterland), due to the opening of Tyrrhenian basin. The extension has been accompanied and post-dated by magmatic activity.

This tectonic couple (compression - extension) is responsible for the seismic activity that characterizes Italy. Several earthquakes have hit the peninsula in the past ten years, notably connected with either blind or buried thrusts of the Apennines (i.e., 2012 - Emilia Seismic sequence, Mw 5.6 and 5.8) or to the extensional tectonics in the hinterland (i.e., 2009 - L'Aquila, Mw 6.3; 2016/2017 - Central Italy, max Mw 6.5 and four events of Mw  $>5.0$ ).

Toward the south the Apulia forms the still undeformed foreland of the Apennines belt, as Hyblean foreland is for the Maghrebic (Apennines-Maghrebic) chain in Sicily (respectively AF, HF, and APm in Figure 6). Finally, the Calabro-Peloritan arc (CP in Figure 6), interpreted as a fragment of the Alpine chain migrated toward the SE and overlay the Apennines-Maghrebic belt, where some sectors preserve nearly entire segments of Variscan continental crust, unaffected by Alpine metamorphism.

## Data Sources

According to the type of 3D model (shallow or deep, in mountain regions or plain areas), different types of data constitute the main input and constraints. In Italy, geoscience data are generally publicly available through the web Portal of SGI ([www.portalesgi.isprambiente.it](http://www.portalesgi.isprambiente.it)). They usually have national coverage, although their distribution can vary, with poor density in some areas. Most of the datasets owned and managed by SGI comply with the INSPIRE standard established to ensure that the spatial data infrastructures of the Europe Member States are compatible and usable in a Community and transboundary context (Directive



**Figure 6.** Tectonostratigraphic scheme of Italy (modified after ISPRA 2011). Alps Europe-verging (AI-E), Alps Africa-verging (AI-A), Po Plain (PP), Apennines (AP), Apulia foreland (AF), Calabrian-Peloritan arc (CP), Sicily: Maghrebian chain (APm) and Hyblean foreland (HF), Sardinia (SA), Periadriatic (Insubric) lineament (IL).

2007/2/EC of the European Parliament, <https://inspire.ec.europa.eu>).

Geological 3D models in deformed areas (e.g. Fossombrone, Vette Feltrine, Polino) are mainly based on surface data deriving from SGI geological map database (CARG DB) where at least unit boundaries, fault traces with measure points, attitudes, shallow boreholes, and cross-sections give constraints on the position of the geological units and geometrical characteristics of structural elements. Seismic reflection profiles and gravity data are used if available in public databases or accessible under confidentiality agreements (e.g., Piadena). Shallow 3D models in plain or urban areas (e.g., Rome, Florence, Fiumicino, Montereale) are built using the SGI boreholes database and geophysical data specifically acquired (e.g., geoelectric field, MASW - multichannel analysis of surface waves, gravity anomalies).

The production of deeper crustal models (e.g., Po Basin, RETRACE-3D, Conero, Pliocene clays), both in mountain and plain regions or in offshore areas, is based on data, such as seismic reflection profiles, deep wells for hydrocarbon and geothermal exploration, geophysical data, seismicity distribution, coming from national public database or private repositories (on request). Additional inputs are derived from published maps on Moho discontinuity, lithosphere thickness, heat flow, and seismic tomography.

Most of the data needed as input for 3D model production are made publicly available by the SGI through its web Portal (Figure 3):

- geological map database (CARG DB);
- database of subsoil investigations according to the Law 464/84. This national Law establishes the obligation to notify to the SGI all the information on excavations, perforations and geophysical surveys driven to depths greater than 30 meters from ground level and,

in the case of tunnels, more than 200 meters in length. Data correspond to the information declared in the communication without any interpretation during digitalization;

- database of composite log of deep boreholes for hydrocarbon and geothermal exploration and production. According to the national law, the database collect information on boreholes publicly available, one year after the end of the mining license they were drilled;
- gravity anomaly data measured at more than 358,000 stations on the Italian territory.

Additional data may be collected by other public institutes such as Istituto Nazionale di Geofisica e Vulcanologia (INGV), Consiglio Nazionale delle Ricerche (CNR) and Ministero Sviluppo Economico (MISE):

- Italian Seismological Instrumental and Parametric Data-Base (ISIDe) - INGV (ISIDe working group 2016) that contains the parameters of hundreds thousands earthquakes occurred in the Italian region in the time frame between 01-01-1985 and today. The locations are based on more than 500 stations of the National Seismic Network operated by Istituto Nazionale di Geofisica e Vulcanologia (INGV), and regional and international networks operated by several providers;
- Database of seismogenic sources, DISS 3.2.1 - INGV (DISS Working Group 2018), that is a compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas;
- seismic lines and exploration reports - MISE (ViDEPI Project). The ViDEPI Project enables the free access to information on oil and gas exploration activities, according to national rules on industrial data confidentiality;
- seismic lines for deep crust exploration - CNR (CROP Project). The CROP Project was a multidisciplinary research program, involving

multiple Italian agencies, focusing on the Italian lithosphere. During the '90s, the project collected, processed, and interpreted deep reflection seismic profiles on land (approx. 1,250 km) and at the sea (approx. 8,700 km).

Other relevant raw data, particularly those collected by oil and gas private companies, can be used on request under rules defined by confidentiality agreements. In general, no restriction applies to derivative models produced from these data, but the original data cannot be redistributed. Despite the overall high quality, distribution, and resolution of geoscience data in Italy, the resolution of the 3D models need to be defined on a case-by-case basis, considering the availability of the most relevant data for the target applications and uses of each 3D model.

## 3D Modelling Approach

The geological characteristics of the Italian peninsula, the type of available geoscience data, and the uses and applications of the 3D models, led the SGI to design a workflow for 3D explicit modelling that provides a significant control to the geologists in charge for the 3D model building. The workflow (Figure 7) proposed by D'Ambrogi et al. (2004) and then implemented by D'Ambrogi et al. (2010), Maesano et al. (2014), allows the user to manage and integrate input data and constraints characterized by different domains of the vertical axis: time (e.g., seismic lines, velocity data, time-depth or time velocity curves of wells) and depth (e.g., field data, published geological maps, cross sections, isobath and isopach maps). Separate steps in the workflow characterize each domain, sometimes connected to check the validity and consistency of the analysis and outcome. After the time-depth conversion of the 3D model (if needed) the steps are completely developed in the depth domain. The main phases of the workflow (Figure 7) are:

- 1) Data: harmonization and interpretation;
- 2) Elaboration of the 3D model in the time domain;
- 3) Calculation of the 3D velocity model;
- 4) 3D model time-depth conversion;
- 5) Consistency check and refinement of the 3D model in the depth domain;
- 6) Construction of the final 3D model.

The principal software used for 3D model production at SGI is MOVE (MVE Ltd.), that enables an easy integration of a wide range of data including outcrops, boreholes, and seismic lines, with an active role of the expert knowledge of the geomodelers, and supports the major needs for structural analysis of active and seismogenic faults in Italy. In order to better manage seismic data and time-depth conversion in areas with high geological complexity, a dedicated tool has been developed for 3D velocity model creation and time-depth conversion (Vel-IO 3D, Maesano and D'Ambrogi 2017), and is fully integrated into the modelling workflow. Vel-IO 3D is composed of three

scripts, written in Python 2.7.11, that perform different tasks: i) 3D instantaneous velocity model building, ii) velocity model optimization, iii) time to depth conversion (Figure 8A). Further, to improve additional analyses based on 3D geological models, SGI designed and tested methods for: i) analysis of sedimentary basins (Figure 8B) (Maesano and D'Ambrogi 2016), and ii) fault restoration and sediment decompaction for long-term slip rates calculation and active faults characterization (Figure 8C) (Maesano et al. 2015).

## Clients

The 3D models produced by SGI are mainly used by public authorities; these include, at the national level, i) the Civil Protection Department, ii) Ministries (i.e. Environment, Economic Development), iii) Research Institutes and Universities, iv) Regional authorities, and at international level, the European Union. In some case, the clients (e.g. National Civil Protection Department, European Union) commissioned and funded directly the realization of the 3D geological model for specific purposes such as seismotectonic characteriza-

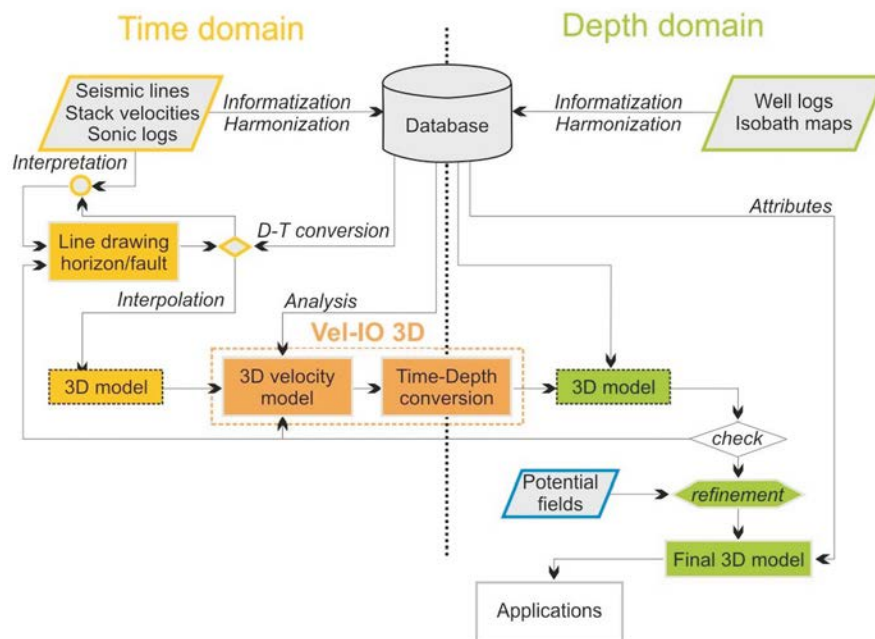
tion, monitoring of soil and subsoil conditions during infrastructure planning, geothermal assessment. On the other hand, the research institutes, universities, and other users are interested in more general subsurface geological information derived from 3D geological models, especially for scientific or communication purposes.

## Recent Jurisdictional-Scale Case Study Showcasing Application of 3D Models

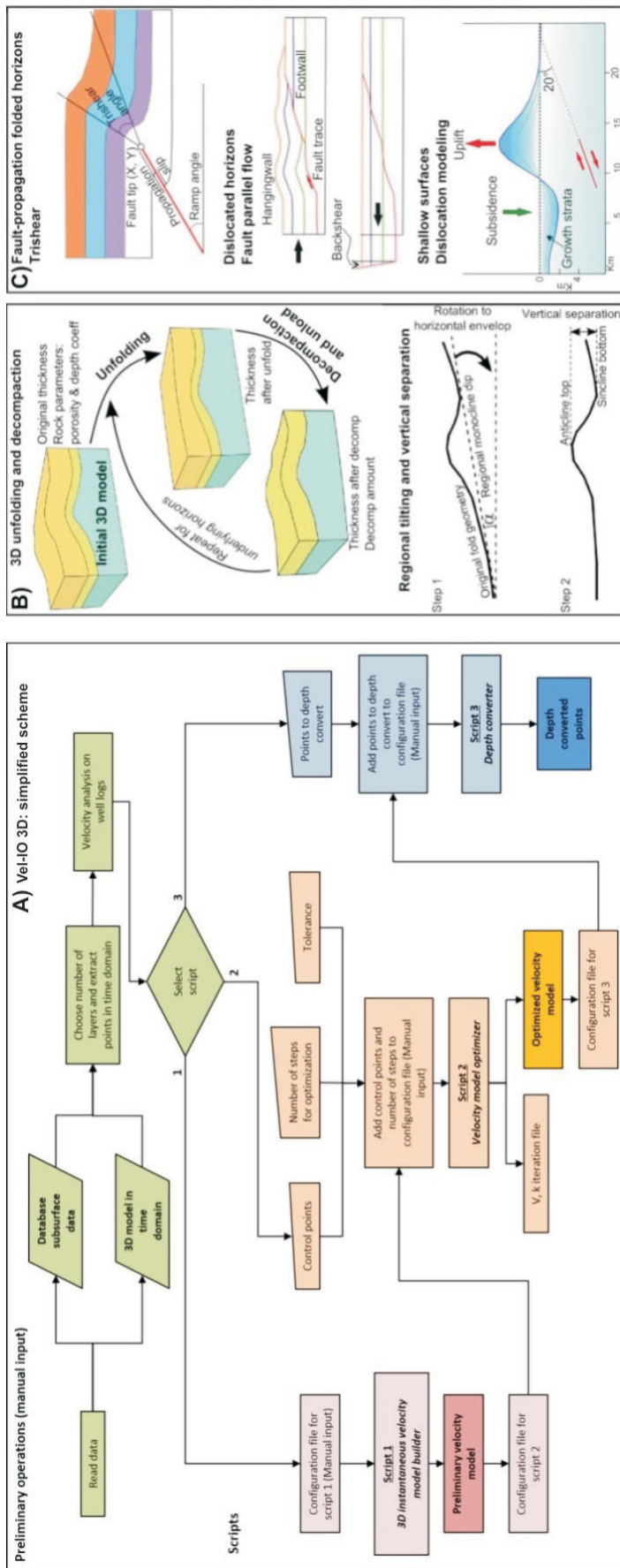
Geological 3D models at a regional scale, investigating depth of several kilometers, have been realized in Italy, including offshore areas (8 and 11 in Figure 3), and others are under construction. The 3D geological model of the Central Po Basin is definitely the most comprehensive for the number of modelled stratigraphic units (15 horizons from Triassic up to Holocene) and faults (170 surfaces, including thrusts and normal faults), and for the geological complexity (Figure 4). This model, produced during the GeoMol Project will constitute the starting point for the extension of the modelling to the entire Po Basin (an area of more than 30,000 km<sup>2</sup> extended on four different administrative regions) in the upcoming HotLime - GeoERA Project (12 in Figure 3). At the end, more than 25,000 km of seismic reflection profiles and 400 wells will constitute the input dataset for this enlarged area.

The workflow is that established and implemented by SGI (Figure 7), with the integration of geological with geophysical data, through the comparison of a preliminary 3D model with gravity anomalies map, the geometric refinement, and the check of model consistency.

The already completed part of this upcoming enlarged model (the Central Po Basin – GeoMol Project) represented the basic geological input for the assessment of geothermal re-



**Figure 7.** 3D modelling workflow implemented at SGI (modified after Maesano and D'Ambrogi 2017).



**Figure 8. A)** Simplified flowchart for Vel-IO 3D tool; **B)** restoration workflow for basin analysis; **C)** characterization of folds and faults.

source, but also contributed like never before to identify, and fully parameterize new seismogenic sources and active faults.

## Current Challenges

SGI increasingly embraced 3D geological modelling to support its institutional mandate of production and dissemination of geoscience data and information. Despite the major improvements modelling workflow and methods for the analyses have undergone, several aspects are still under-developed.

Current challenges involve not only some methodological topics, such as the calculation and visualization of uncertainties associated with the 3D models, and the parameterization of 3D volumes, but also technical aspects such as the creation of an IT structure enabling the storage and managing of 3D geological models. Moreover, SGI participated in the EU Project EPOS - European Plate Observing System for the development of the Thematic Core Service (TCS) “Geological Information and Modelling”; as regards the 3D geological models, the TCS focuses on promo-

tion and implementation of standards for metadata and accessibility.

Some test of uncertainties representation has been included already in static 3D model-derived maps (Figure 9) produced for the Central Po Basin 3D model (ISPRA 2015). In this case, data density has been considered as the expression of the uncertainty; where data density is low, the uncertainty is high (and vice versa), with uncertainty generally increasing for deeper horizons (with data density decreasing with depth). However further steps are needed to improve the communication of the quality of 3D models and uncertainty of the rock parameters, especially when 3D models are applied to societal issues.

## Lessons Learned

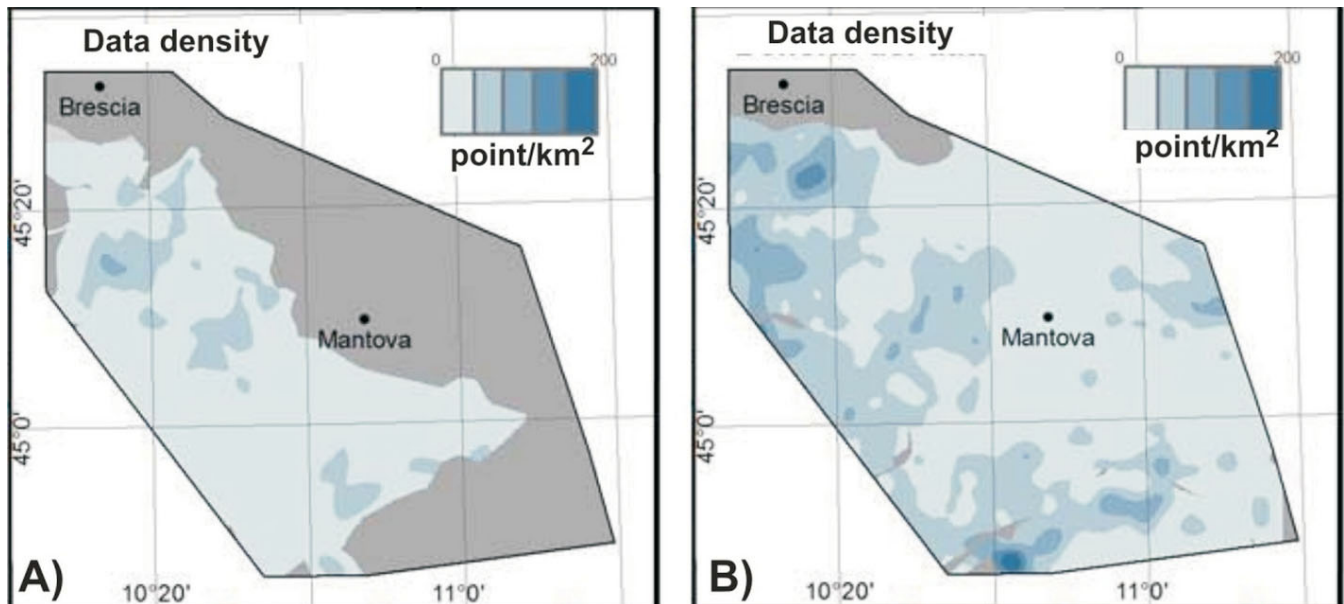
The SGI has been active in 3D geological modelling for 20 years now; the lessons learned over this time span can be summarized as follows:

- 3D geological modelling is currently the most important tool for a comprehensive understanding and representation of geological structures;

- the implementation of a dedicated workflow for 3D geological modelling should take into account the specific geological characteristics of the national territory, the type of available data, the most common applications of the 3D geological models;
- a large amount of informatized geoscience data is not sufficient to support 3D modelling activity if data are not structured taking into account the 3rd dimension. GSOs at the national level should harmonize the geometrical content of their database;
- 3D geological models are easy to read and use only for geologists; in order to exploit their informative power, especially towards non-geologist stakeholders, a greater effort is needed in the definition of user friendly formats, accompanied by a clear description of their reliability.

## Next Steps

SGI will implement its 3D modelling activity through the following steps:  
1) enlargement of the number of the SGI geologists involved in the modelling activities in order to be able to answer to the increasing



**Figure 9.** Uncertainty representation through data density map. Examples from the GeoMol Project: map **A)** deeper horizon, map **B)** shallower horizon.

need for knowledge of subsurface geology;

- 2) definition of national standard workflows for 3D modelling and analysis, in collaboration with regional geological surveys, and with the contribution of research institutes and universities;
- 3) building of an Italian Bedrock and Quaternary 3D model;
- 4) design and implementation of a national 3D models database strictly linked to the more traditional national geological database;
- 5) development of visualization and dissemination tools to engage a wider audience of 3D geological model users.

## Acknowledgments

Thanks to scientists and technicians, including those from Italian universities or research institutes, who participated in the development of the SGI 3D modelling activities over the past 20 years. Special thanks go to Francesco E. Maesano who, during the period he worked for SGI, significantly contributed to advancing the design and implementation of workflows and tools presented in this paper.

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# Chapter 16: Minnesota Geological Survey Geological Mapping

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Thorleifson, L.H. 2019. Minnesota Geological Survey geological mapping; Chapter 16 *in* 2019 Synopsis of Current Three-Dimensional Geological Mapping and Modelling in Geological Survey Organizations, K.E. MacCormack, R.C. Berg, H. Kessler, H.A.J. Russell, and L.H. Thorleifson (ed.), Alberta Energy Regulator / Alberta Geological Survey, AER/AGS Special Report 112, p. 171–178.

## Introduction

Minnesota Geological Survey (MGS) is fulfilling its responsibilities primarily through statewide 1:100,000 and 1:500,000-scale geological mapping. Institutional geological databases required for the mapping include field observations, drillhole data, karst features, as well as sediment texture and lithology. Geological collections include cuttings, geochemical samples, hand samples, sediment samples, and thin sections. Geophysical databases include borehole geophysics, gravity, magnetic, rock properties, and soundings; geochemical databases include groundwater, soil, and soil parent material; geochronological databases are in development. MGS coordinates with the state drill core library, the state fossil collection, and the state aquifer properties database. The resultant mapping that is published is also being assembled as a 2-resolution, layered set of databases that includes the offshore, is meant to underlie bathymetric and soil mapping, and that is as compatible as possible with neighbors. Parsing of legends, to facilitate queries, is using well-defined terminology, to facilitate inference of properties. Progressively more seamless geological polygons, at 1:100,000 and 1:500,000-scale, are tending to have thickness indicated, while properties, heterogeneity, and uncertainty will gradually be more specified. A layered 1:500,000-scale state bedrock geologic map is largely complete, although for Precambrian layers the thickness and underlying geology have not yet been specified,

while a layered state Quaternary geology map is in development. New 1:100,000-scale mapping is meant to be complete statewide within a decade. Three-dimensional mapping relies mostly on geophysics for the Precambrian, stratigraphic correlation of drillhole logs for the Paleozoic and Mesozoic, and for the Quaternary, a combination of cross-sections drawn through lithological data, with support from geostatistics, is being used.

## Organizational Structure and Business Model

Minnesota is one of fifty states in the USA. The federal survey, USGS, has a broad mandate, 9000 employees, and a budget of over \$1B/year. State geological surveys have 1900 employees, and total funding is now at \$240M – hence an average of roughly 40 employees and \$4.5M per state.

Minnesota has a population of five million, is 400 km wide and 600 km north to south, and is located in north-central USA, just west of the Great Lakes, and adjacent to Canada. To the west of Minnesota are the states of North and South Dakota, Wisconsin is to the east, and to the south is Iowa. To the north in Canada are the provinces of Manitoba and Ontario. Two thirds of the five million state residents live in the Twin Cities centered on Minneapolis and Saint Paul. Agriculture is prevalent in the south and west of the state, and the Iron Range in the forested northern portion of the state supplies iron ore to the US through Great Lakes ports.

The MGS, established as part of the University of Minnesota in 1872, now has a budget of ~\$3.5M/year and a staff of ~40 that has grown by 50% and stabilized over the past decade. MGS serves the people of Minnesota by providing systematic geoscience information needed to support stewardship of water, land, and mineral resources. MGS geological mapping and associated research evolve with the progress of science and technology, and the MGS works closely with university, government, industry, and community partners to ensure that we respond to the diverse needs of the people.

MGS activity almost entirely consists of a single, integrated geological mapping program that is meant to produce consistent, comprehensive, complete, statewide mapping. Mapping increments are conducted by county, of which there are 87; an average county is 50 km by 50 km. The nature of this program has been dictated by Legislative water resource planning that specifies the need for statewide completion, within a decade or so, accompanied and followed by updating, of multi-layered county geologic atlases constructed in partnership with the Minnesota Department of Natural Resources (DNR), and with counties. There is concurrent focus on the research, databases, outreach, and statewide mapping needed to optimize the Atlases.

Minnesota is known for its abundant lakes and rivers, although the majority of drinking water comes from

aquifers. Over a decade ago, Minnesotans became increasingly concerned about groundwater contamination, and over-pumping. A 2007 Minneapolis Star Tribune editorial, for example, called for steps to restore confidence in our drinking water, including enhanced funding to the state geological survey.

The Statewide Conservation and Preservation Plan was commissioned in 2006, and completed in 2008. The intent was to create an integrated inventory and assessment of Minnesota's environment and natural resources that could guide decision-makers on future short and long term planning, policy, and funding. A recommendation to improve understanding of groundwater resources focused on development of a large-scale, hydrologic-system framework for understanding how today's decisions may affect tomorrow's needs. This recommendation specified statewide coverage of county geologic atlases or comparable information products as being needed.

In 2011, the Minnesota Water Sustainability Framework further advocated that a measure of our progress in obtaining a complete picture of groundwater resources in Minnesota should be the rate of completion of county geologic atlases by MGS and DNR. The report therefore advocated that the pace of completion of the County Geological Atlases should, at a minimum, be doubled to allow completion within a decade, followed by review and updating on a regular schedule. These recommendations then guided the Six-Year Strategic Plan for Minnesota's Environment and Natural Resources Trust Fund (ENRTF), which is administered by the Legislative-Citizen Commission on Minnesota Resources (LCCMR). The Plan, completed in 2013, advocated statewide completion of county geologic atlases within a decade. MGS thus is focused on completing and updating of atlases, while ensuring that we take a broad approach,

and that we optimize the scientific quality of all related activities.

MGS therefore is working with the DNR to fulfill these responsibilities, through completion of statewide 1:100,000 and 1:500,000-scale surficial geology, bedrock geology, subsurface geology, bedrock topography, and sediment thickness – the mapping is comprehensive, and thus applicable to water and other applications. We concurrently are undertaking funded basic research that is needed to optimize our mapping, with an emphasis on enhanced hydrogeological characterization of sediment and rock strata.

Crucial to our work is support from the Environment and Natural Resources Trust Fund, established by voter approval in 1988. In addition, in 2008, the people of Minnesota voted for a tax increase – the Clean Water, Land, and Legacy Amendment. The resulting program also supports our work. Our geological mapping thus is being very strongly supported by the Minnesota Legislature, with roles also being played by programs such as the United States Geological Survey (USGS) National Cooperative Geologic Mapping Program, including the Great Lakes Geological Mapping Coalition.

## Overview of 3D Modelling Activities

The geological mapping is first published as authored and peer-reviewed paper maps. In addition to these born-digital publications, all of our publications back to 1872 - 50,000 pages and 700 maps - are now 100% scanned, searchable, and downloadable for free. New 1:500,000-scale geologic mapping provides context and supports statewide analyses. The new bedrock map (Figure 1; Jirsa et al., 2011) is layered, as Mesozoic and Paleozoic strata, with thicknesses specified, can be removed to reveal a Precambrian map, and we have plans to map Precambrian layers that also

will be removable, resulting in a basement map. Our 1:500,000-scale 2D map showing uppermost sediments was published in 1982 (Hobbs and Goebel, 1982), and a new state Quaternary map, which will be layered, is in development, due to support from the USGS Great Lakes Geological Mapping Coalition (Figure 2). The existing one-layer 1:500,000-scale Quaternary 3D model – also known as depth to bedrock, or sediment thickness, is updated regularly.

Our 1:100,000-scale mapping is packaged as County Geologic Atlases. A User's Guide to Geologic Atlases (Setterholm, 2014) helps non-geologists, especially decision-makers, understand the information products and their uses. Atlases are available in print, or in digital formats, including pdfs and GIS files. Atlases provide information essential to sustainable management of groundwater resources, for applications such as aquifer management, ground water modelling, monitoring, permitting, remediation, water allocation, well construction, and wellhead protection. Atlases define aquifer properties and boundaries, as well as the connection of aquifers to the land surface and to surface water resources. They also provide a broad range of information on county geology, mineral resources such as construction materials, and natural history. The atlases thus are also useful to consultants, exploration efforts, educators, and all residents.

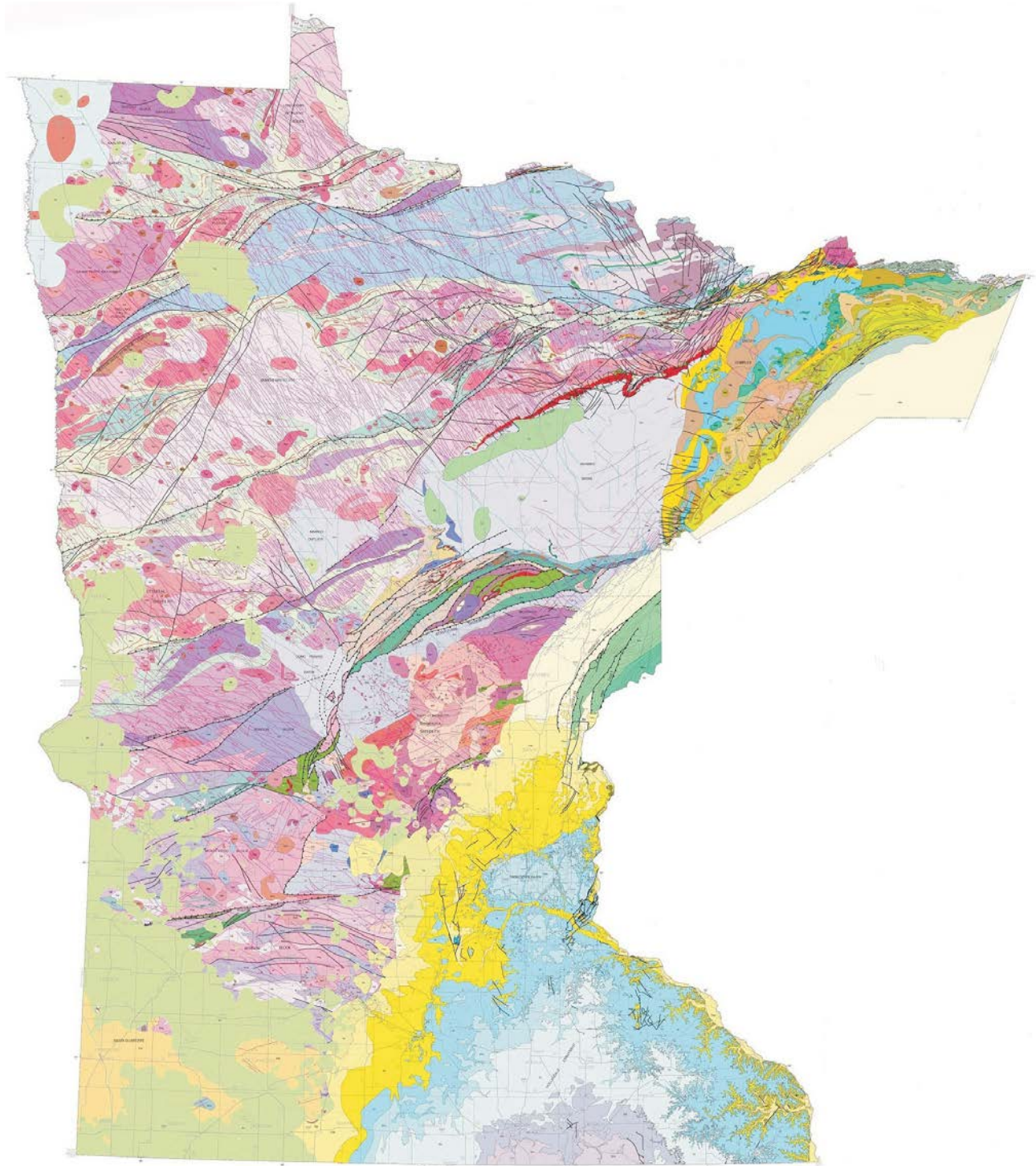
A complete atlas consists of a Part A prepared by MGS that includes the water-well database and 1:100,000-scale geologic maps showing properties and distribution of sediments and rocks in the subsurface, and a Part B constructed by DNR that includes maps of water levels in aquifers, direction of groundwater flow, water chemistry, and sensitivity to pollution. Atlases in most cases are initiated by a request from a county and an offer to provide in-kind service. A typical atlas requires a total MGS expendi-

ture of a half million dollars over about four years.

### Resources Allocated to 3D Modelling Activities

At MGS, we spent \$3.5M this past year, up from \$3.3M the year before,

due to variation in project activities. MGS relies on about \$1.3M in base funding and \$2.2M in grants and contracts, primarily from the ENRTF through LCCMR. Payroll was



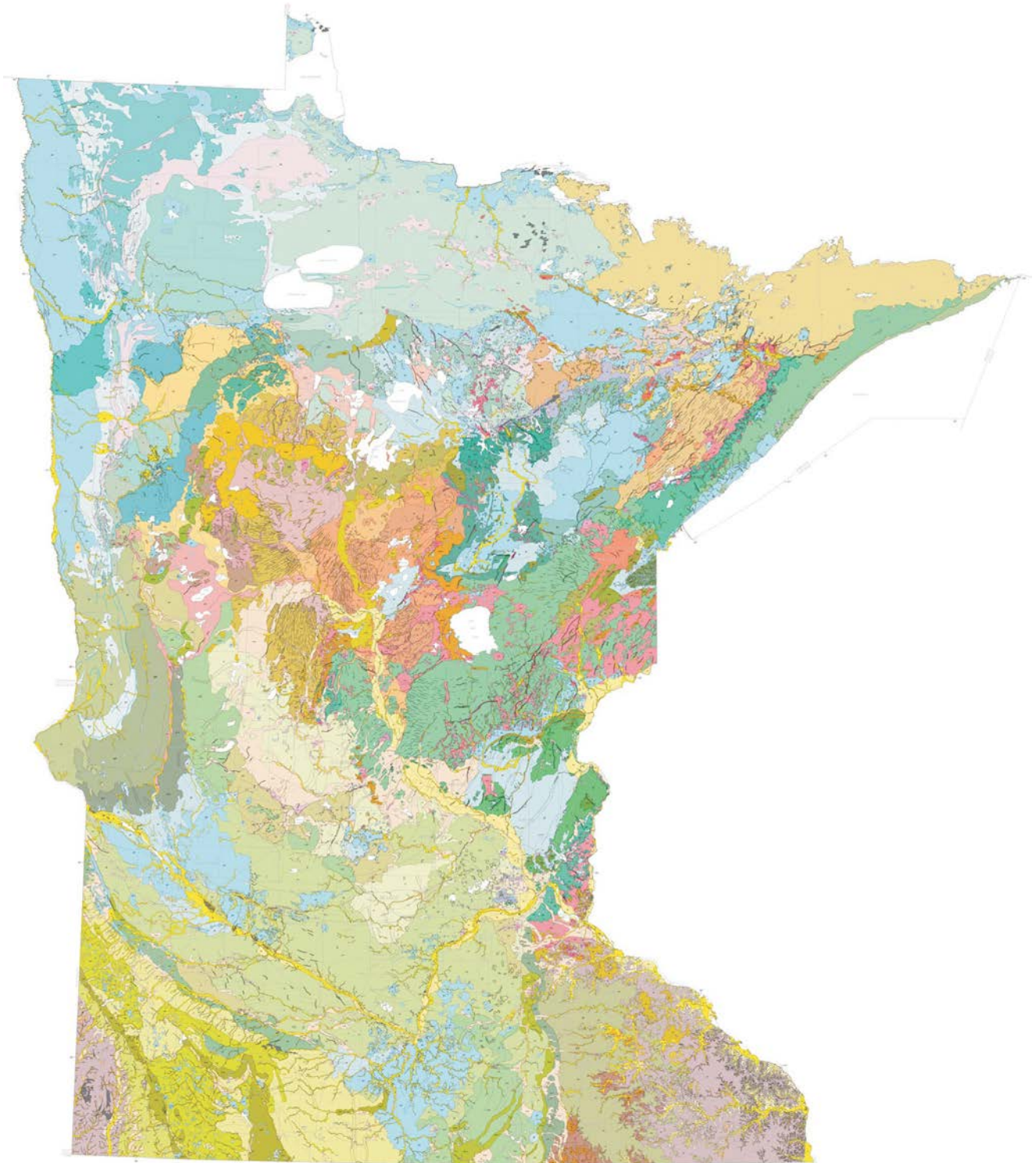
**Figure 1.** The 1:500,000-scale bedrock map, 400 by 600 km in extent, (Jirsa et al., 2011) is now a static view of an evolving, layered database. Mesozoic (green area mostly in the southwest) and Paleozoic strata (blue and yellow areas mostly in the southeast) are single removable layers for now. Work is pending on Precambrian layers, whose removal will allow development of a 1:500,000-scale basement map. North is to the top.

~\$2.75M last year. MGS funding averaged \$2.4M from 2003 to 2011, and the average since then has been \$3.2M. Additional funding from both sources covers non-personnel costs

such as travel, drilling, equipment, supplies, and services.

MGS staffing was stable at 28 full-time-equivalents (FTE) from 2003 to

2011; since then, staffing has averaged 36 FTE. We currently are 27 geologists, 3 information professionals, 2 administrative staff, and 6 students equivalent to ~3 FTE.



**Figure 2.** The new 1:500,000-scale Quaternary map will be layered, at least for removal of peat, as is shown in this draft depiction, which lacks peat (Lusardi et al., in press). Green colors, for example, are tills. Further layering will be facilitated by completion of ongoing statewide cross-section mapping, at a 5-km spacing. North is to the top.

MGS was located on-campus in Pillsbury Hall from 1872 until 1970. MGS then moved to an off-campus building on Eustis Street in Saint Paul in 1970, followed by a move to University Avenue in Saint Paul in 1983. In 2015, we moved to our current location on Territorial Road in St Paul.

## Overview of Regional Geological Setting

Precambrian igneous and metamorphic rocks occur at the bedrock surface across most of the state. Thin Mesozoic sedimentary rocks occur in the southwest, and Paleozoic sedimentary strata are present in the southeast and far northwest. Glacial sediments, of greatly varying thickness averaging 50 meters or so, cover most of the state.

## Data Sources

Our geological mapping includes much fieldwork mostly involving, depending on the field of study, observations, shallow augering, and geophysical surveys, as well as a considerable amount of new coring of the Quaternary in each county being investigated. In addition, the mapping is supported by several spatial databases. For example, the Minnesota Legislature funded acquisition of statewide lidar, which has very significantly improved our work. MGS also coordinates with the DNR drill core library and mineral exploration document archive, the Bell Museum fossil collection, and the DNR aquifer properties database.

MGS geological databases include drillhole data, field observations, karst features, as well as sediment texture and lithology. The water-well database is a major activity for MGS, with our partner in this role, the Minnesota Department of Health. Much effort goes into confirming the location of each water well to within a few meters. We now have over 500,000 wells in the database, including drillers' lithological profiles.

MGS geological collections include cuttings, geochemical samples, hand samples, sediment samples, and thin sections.

MGS geophysical databases include magnetic, gravity, rock properties, borehole geophysics, and soundings. We have reprocessed the state magnetic database, and the state gravity database; in both cases, feature resolution was significantly improved. Borehole geophysical surveys are an ongoing activity on a statewide basis. We have made much progress in digitizing previously-collected natural gamma logs, while our activity is broadening in multi-parameter, caliper, EM-flowmeter and borehole video logs. Whereas our work in soundings previously focused on refraction and reflection seismic, passive seismic is now a major emphasis, and a source of helpful new data on depth to bedrock.

Our statewide geochemical databases, constructed with partners, include groundwater, soil, and soil parent materials, while geochronological databases are in development.

## 3D Mapping Approach

Minnesota geology is first mapped in 2D, concurrently at 1:100,000 and 1:500,000-scale, as a mature 2D map is considered a precursor to 3D mapping. Ongoing efforts are being directed at assembling published 1:24,000 and 1:100,000-scale mapping as increasingly seamless databases. Layers, which are polygons whose thickness can everywhere be mapped, are being mapped in 3D to eventually show thickness, extent, properties, heterogeneity, and uncertainty in some manner. Layers will be removable from the mapping. Under the layers is a basement map. Whereas strata are the focus of 3D mapping in the layers, structures and discretized properties will be the focus of the basement mapping. Distinct approaches are being taken for 1) Precambrian igneous and metamorphic

rocks, 2) Mesozoic and Paleozoic sedimentary rocks, and 3) Quaternary glacial and associated sediments.

Precambrian geological mapping utilizes field observations, structural measurements, thin sections and analyses, as well as a heavy reliance on geophysical surveys, in particular magnetic and gravity surveys. Our current mapping was transformed by reprocessing of the magnetic and gravity databases a decade ago. The new 1:500,000, layered state bedrock geology map (Jirsa et al., 2011) was a major step forward in our Precambrian science, supported by this new generation of geophysical surveys, and included a new outcrop map, diabase dykes, and new nomenclature for features such as batholiths and structures. The new 1:500,000-scale map included much detail from preceding 1:100,000 mapping, causing much reflection on what should go in each of our two levels of resolution. Nevertheless, the 1:500,000 mapping is now mature, and we are embarking on a new seamless synthesis of 1:24,000 and 1:100,000-scale Precambrian mapping. The focus for 3D in the Precambrian mapping is on mapping the thickness and properties of Precambrian layers, principally through geophysical modelling. The Precambrian layers include: 1) the North Shore Volcanic Group/Duluth Complex that presently are the focus of Cu-Ni-PGE potential, 2) Sioux Quartzite, and 3) Animikie Group units, including the iron ore that is mined on the Range, and 4) Mesoproterozoic sedimentary basins along the Midcontinent rift associated with Lake Superior. Upon removal of these layers, and infill of underlying geology to the extent that it can be inferred, the first 1:500,000 statewide basement geology will be produced.

Paleozoic sedimentary rocks are mapped based on exposures and cores, and much reliance on borehole geophysical logs that, along with various analyses, allow stratigraphic correlation of intersections in each available

drillhole. These correlations allow mapping of strata, as well as meticulous analyses of structures such as faults. The 1:500,000-scale 2D mapping is stable at present, as seven outcropping layers. There is a high degree of congruence in the 2D 1:100,000-scale mapping (Figure 3) from county to county, although effort is needed to reconcile surfaces between mapping efforts that occurred at differing times. A key factor in the mapping is an updated Paleozoic stratigraphic naming scheme (Mossler, 2008), based on recent research, resulting in improved compatibility with neighboring states.

Mesozoic sedimentary rocks are mapped to a greater degree based on lithology, relative to the Paleozoic. Over most of the state, the Mesozoic is mapped as one layer. Judgment is needed in distinguishing Mesozoic deposits from weathered Precambrian, or either material reworked during the Quaternary. This often is done using water-well records. Nevertheless, a mature 1:500,000-scale map of the Mesozoic has been produced, as well as an indication of the extent of Jurassic in northwestern

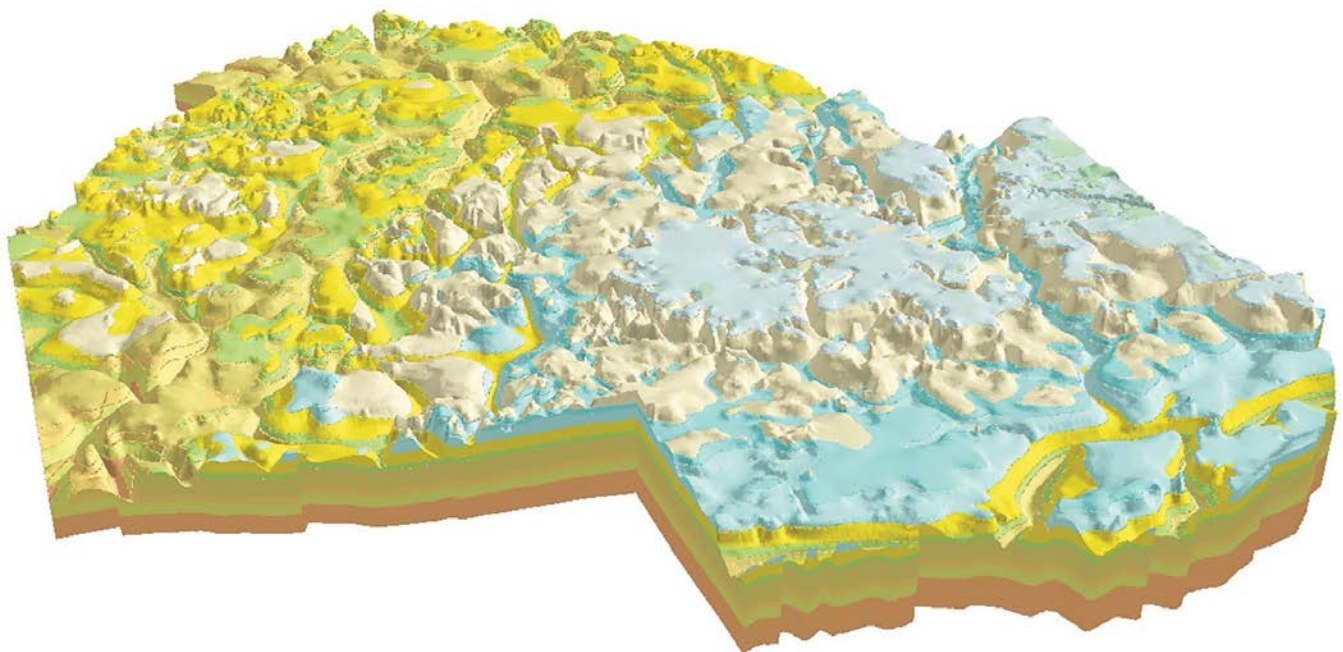
Minnesota. For the 1:500,000-scale map, the Mesozoic was outlined by contouring the top and base, from which an isopach grid was created. Because the distribution is patchy, unit boundaries were drawn from the gridded data to represent locations where more than 25 feet (8 meters) of thickness occurs. As a result, many areas outside of the unit boundaries may be overlain by thin Cretaceous strata and the unit is depicted without a contact line (Jirsa et al., 2011).

For the Quaternary, much current effort is being directed at a new 1:500,000-scale map that will be layered to the extent achievable, at least by making peat removable. The new map will have a lithostratigraphic legend for the first time, taking the place of the morphostratigraphic legend of its precursor (Hobbs and Goebel, 1982). Development of this new legend required a major effort over a decade, first involving development of a naming guide (Johnson et al., 2016), followed by mapping of pilot statewide cross-sections (Lusardi et al., 2016). Both steps resulted in a dramatic improvement in our stratigraphic model. For 1:500,000-scale

3D mapping of the Quaternary, the focus now is on a 5-year program of statewide cross-sections at a 5-km spacing, utilizing a ~60-layer legend.

At the 1:100,000 level of resolution, all 1:24,000 and 1:100,000-scale 2D surficial mapping has been assembled as a seamless database, with enhanced textural categorization of map units – using soil mapping textural categories – to better support inference of hydraulic conductivity for groundwater management applications.

For the 1:100,000-scale 3D mapping of sediments, geologists draw cross-sections at a 1-km spacing, guided by field work, auger holes, geophysics, cuttings, new drilling, analyses, water wells, and geostatistics. Careful attention is paid to sand and gravel bodies in the subsurface, which are crucial sources of groundwater. The cross-sections are oriented perpendicular to the prevailing elongation of the sand and gravel bodies. Interpolation between cores is guided by water wells and other data, along with the geologists' judgement based on insights into geological material, process, and history.



**Figure 3.** Paleozoic geology of Hennepin County, which includes the city of Minneapolis, and which largely consists of limestone and sandstone strata (based on Retzler, 2018). This 3D view extends across a 50 km-wide area. North is to the top.

Data distribution laterally and vertically greatly affects the resolution and accuracy of the models. Although sand and gravel can be present within diamict sequences interpreted as till, sorted coarse-grained sediments occur more frequently at the contact between two tills. According to Atlas authors, the contact between two tills that are related to different depositional events and not separated by sand and gravel may be recognized, in some cases, by a change in the driller's description of material, texture, density, or color. Using the available data, contact lines are drawn along each cross section, with each line representing the base of a geologic unit of sand or till.

GIS software is used to infer elevations for contacts and to convert those into a gridded surface using interpolation. The resulting grids represent the distribution of the geologic unit within the county in three dimensions. The surfaces may need to be iteratively modified until the geologist is confident that they adequately represent the aerial distribution and stratigraphic interpretation of each geologic unit derived from the subsurface data.

## Clients

MGS geological mapping is primarily used by state agencies, county administrations, consultants, and researchers. There is a high level of interaction with the user community, through partnerships with state agencies, through workshops in counties, and at conferences such as those held by the groundwater association, and the water-well drillers.

## Recent Jurisdictional-Scale Case Study Showcasing Application of 3D Models

Recently, MGS 1:100,000-scale 3D mapping of the Quaternary was used to support an accounting for depth-dependent features related to predic-

tion of geogenic arsenic (As) in drinking water wells (Erickson et al., 2018). It was found that specific well construction factors are influential in predicting As concentrations in drinking water wells, including position of the well screen relative to strata enclosing the aquifer, thus leading to identification of controllable well construction choices that will influence As concentrations in drinking water from wells.

## Current Challenges

Linear artifacts associated with cross section lines have been a challenge. Current efforts for the Quaternary are focussed on combining geologists' cross-section interpretations of fine-grained strata with an arrangement for

updatable sand bodies inferred using geostatistics.

## Lessons Learned

Crucial to our current success have been an absolute focus on the needs of the people statewide, and a commitment to statewide, consistent mapping in relation to achievable standards in the protection of public health.

## Next Steps

Atlases are complete for 42 counties and of these, 4 have been revised and 2 revisions are underway (Figure 4). There are 17 new atlases underway; 28 counties have not yet been started. At the current pace and a completion rate of ~5 per year, statewide cover-

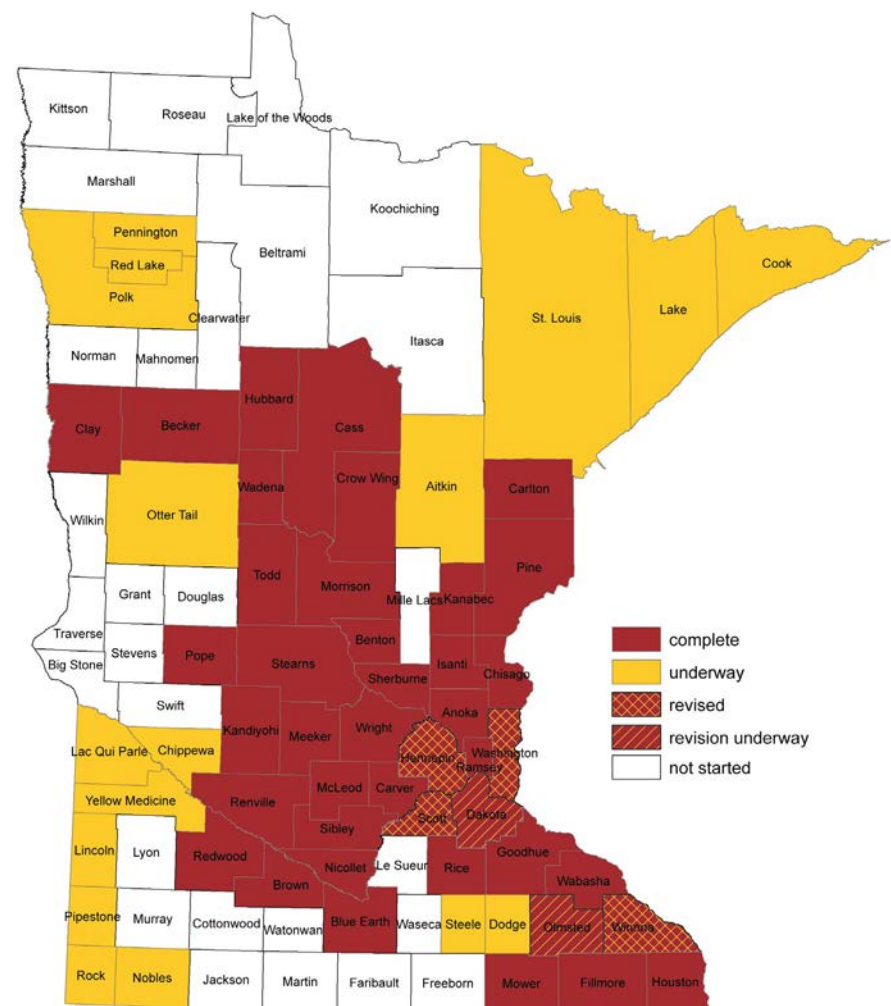


Figure 4. Status of the Minnesota Geological Survey County Geologic Atlas Part A program. North is to the top.

age will be achieved in less than a decade, depending on the pace of revisions and accompanying research – we foresee that we will then focus on Atlas revisions and associated activity.

A current focus is to more fully transition from production of paper maps to a concurrent focus on more fully realized seamless, layered geological mapping databases.

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# Chapter 17: Systematic 3D Subsurface Mapping in the Netherlands

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## Introduction

TNO – Geological Survey of the Netherlands runs four subsurface mapping programs that serve three main application domains. Down to a depth of about 7 km, the **DGM-deep** program maps 13 Carboniferous to Neogene seismostratigraphic horizons, using exploration data that energy and mining companies have to submit to the Survey under the Mining Law.

Down to about 500 m, the country is covered by the layer-based model **DGM**, which maps the geometries of Neogene to Quaternary lithostratigraphic units. While DGM is used in its own right for any application requiring geological information, its primary purpose is to serve as the framework for **REGIS II**, which subdivides DGM lithostratigraphic units into hydraulically parameterized hydrogeological units. **REGIS II** is a *de facto* standard used in groundwater flow models and other assessments for Dutch water and environmental authorities.

The fourth model **GeoTOP** is a 3D voxel raster having lithostratigraphic and lithologic attributes, covering the subsurface up to 50 m below MSL. A positive business case for its application in the planning of national infrastructure and hydraulic engineering works has been instrumental in pass-

ing a new law on subsurface information and getting the implementation funded, thereby securing the continuity, role, and data position of the Survey.

This chapter is largely based on the overview paper on geological surveying in the Netherlands (Van der Meulen et al., 2013), an earlier edition of this Synopsis (Stafleu et al., 2011a) and technical papers on the subsurface models DGM (Gunnink et al., 2013) and GeoTOP (Stafleu et al., 2011b).

## Organizational Structure and Business Model

The Geological Survey of the Netherlands is part of TNO (Netherlands Organization for Applied Scientific Research), an independent Dutch research and technology organization active in technical, earth, environmental, life, societal and behavioural sciences, focussing on healthy living, industrial innovation, energy, transport and mobility, built environment, the information society, and defence, safety and security.

The present Survey has its roots in 1) the former State Geological Survey; and 2) TNO's former Institute for Groundwater and Geo-energy. In 1997, these predecessor organizations merged into a new TNO institute, the Netherlands Institute of Applied

Geosciences. The current Geological Survey of the Netherlands is the result of a number of reorganizations of that institute, as well as the transfer of much of its shallow-subsurface expertise to Deltares, a research institute for delta issues established in 2008. While it previously covered the full range of applied geosciences, the Survey is now almost exclusively focussed on gathering, interpreting and delivering subsurface information, and on providing the Ministry of Economic Affairs and Climate Policy with advice on geological matters to the Mining Law.

The Survey activities are conducted under a single government-funded program, the main elements of which are **data management** (including ICT, the 'DINO Department') and **geomodelling** (systematic 3D subsurface mapping, the 'Geomodelling Department'). Data-management projects deal with main processes in the data-handling workflow, i.e., retrieval, quality assurance and control (QA/QC), storage and delivery. Geomodelling runs separate projects for shallow and deep subsurface models; the distinction is primarily based on application and modelling methods. The shallow modelling project includes product-oriented work packages for framework models (DGM, REGIS II), voxel models (GeoTOP),

parameterization and characterization, and 4D modelling. In addition, investments are made in quality control, communication, representation and maintaining and developing our knowledge base.

The work is subject to yearly planning cycles. The annual survey program as well as its results are approved by a board with representatives of the Ministry of Economic Affairs and Climate Policy and of the Ministry of Infrastructure and Water Management. The research aspects of this program (supplemented by externally funded research), are approved by a board with representatives of the three geoscience faculties in the Netherlands. The recommendations of both boards are then adopted by a council with high-level representatives from the same ministries, the academia and industry.

In support of our survey task, we develop our understanding of user needs in commissioned projects: how is subsurface information used, for which applications, now and in the future? The aim of every such project is to learn how to improve the products and services developed under our survey program. Two mechanisms are used to increase the momentum of our R&D efforts: collaboration with sister organizations abroad, mostly in EU-funded projects, and investments in our relationship with the academia (e.g. through the sponsoring of extraordinary professorships).

## Overview of 3D Modelling Activities

The Geological Survey of the Netherlands systematically produces 3D models of the Netherlands. To date, we build and maintain two different types of nation-wide models: 1) layer-based models in which the subsurface is represented as a series of tops and bases of geological, hydrogeological units and 2) voxel models in which the subsurface is subdivided in a regular grid of voxels attributed with a

number of geological properties. Layer-based models of the shallow subsurface include the national geological framework model DGM (Gunnink et al. 2013) and the geohydrological model REGIS II (Vernes and Van Doorn 2005). A third layer-based model is DGM-deep with Carboniferous to Neogene seismostratigraphic units up to a depth of 7 km. The two main voxel models are the aggregate resources model (Maljers et al. 2015) and the multi-purpose GeoTOP model (Stafleu et al. 2011b).

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

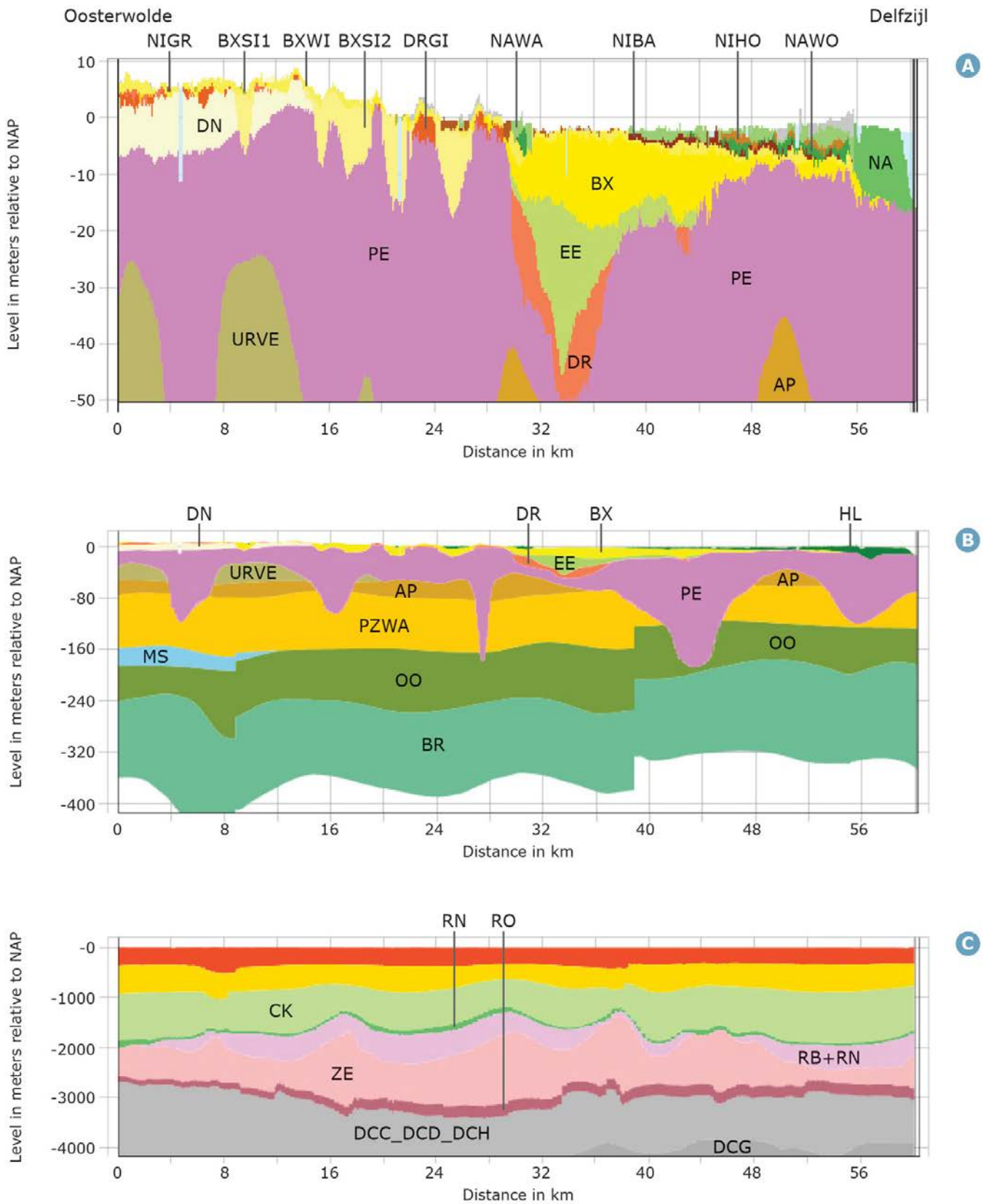
The deep mapping program was the first systematic modelling effort undertaken by the Survey. In 1985, we were commissioned to compile a consistent, regional-scale petroleum geological framework. Eleven geological horizons, ranging from Permian to Neogene in age, were mapped, the results of which were first published on paper and later became the constituents of a stacked grid model now referred to as DMG-deep (Figure 1C; Duin et al., 2006; Kombrink et al., 2012). The model is based on 2D and 3D seismic survey data, combined with a variety of well data, and supported by biostratigraphic, petrophysical and geochemical analyses. Attribution of hydrocarbon and later of geothermal reservoirs relies on well data as well as burial history analysis and basin modelling techniques. The latter approach is used to predict maturation levels of source rock, as well as reservoir and seal properties (porosity, permeability,

geothermal gradients). The general approach and workflow of the deep mapping program correspond to that of the hydrocarbon exploration and production industry, but on a regional instead of a reservoir scale.

Modern digital mapping of the shallow Dutch subsurface started in 1999 with the development of the so-called Digital Geological Model (DGM; Figure 1B; Gunnink et al. 2013). DGM, constructed using a set of c. 26,500 consistently interpreted boreholes, is a 3D stacked-layer lithostratigraphic model of the entire onshore part of the Netherlands up to a depth of c. 500 m (with a maximum of 1200 m in the Roer Valley Graben). It consists of a series of raster layers, where each lithostratigraphic unit is represented by rasters for top, base and thickness of the unit (cell size 100 × 100 m). Raster layers are stored in the raster format of ESRI (ArcGIS). The lithostratigraphic units are at formation level; the complex fluvio-deltaic Holocene deposits are represented by one layer only.

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

GeoTOP is the latest generation of Dutch subsurface models at the Survey. GeoTOP schematizes the shallow



**Figure 1.** Cross-sections through three of the four subsurface models in the Groningen area (northeastern Netherlands): **A)** GeoTOP; **B)** DGM; **C)** DGM-deep. Abbreviations are for groups, formations and members. The cross-sections were created using the DINO-web portal at [www.dinoloket.nl/en/subsurface-models](http://www.dinoloket.nl/en/subsurface-models). After Kruiver et al. (2017b).

subsurface in millions of voxels of 100 x 100 x 0.5 m up to a depth of 50 m below MSL, which is the main zone of current Dutch subsurface activity (Figure 1A; Staffleu et al. 2011b, Maljers et al. 2015). In GeoTOP, we are able to model all Holocene formations as well as several Holocene and upper Pleistocene members and beds as separate stratigraphic units by deploying virtually all borehole descriptions available in the national database (c. 456,000) complemented by some 125,000 auger holes of Utrecht University. The model provides probability estimates of lithostratigraphy and lithological classes (including grain-size classes for sand) per voxel, based on the average of 100 equiprobable model realizations. At present, GeoTOP covers 23,325 km<sup>2</sup> (57%) of the surface area of the Netherlands. We are currently extending the model towards the south-eastern part of the country and expect to reach a coverage of 28,605 km<sup>2</sup> (70%) in 2019.

## Resources Allocated to 3D Modelling Activities

The annual budget for geologists, hydrogeologists and modellers at the Geomodelling Department is about 7.5 million euros. There are approximately 23 geologists, 7 hydrogeologists, 11 modellers, 7 geochemists and 10 supporting staff working on the modelling projects, albeit not full-time. Each separate 3D modelling project allocates about 4 modellers and 2 geologists.

## Overview of Regional Geological Setting

The Geological Survey of the Netherlands operates in a northwestern European state, with a surface area of 41,500 km<sup>2</sup>, about 8,000 of which is inland water. Dutch territorial waters encompass about 57,000 km<sup>2</sup> of the North Sea. Introductions to the Quaternary geology of the Netherlands can be found in Zagwijn (1989) and De Gans (2007), amongst others. The

following summary is largely adapted from Rondeel et al. (1996).

The Netherlands are located on the SE rim of the North Sea Basin (Figure 2). The edges of this basin are close to the country's eastern and southern borders. The sediments at the surface are almost exclusively Quaternary. The thickest Quaternary succession (600 m) occurs in the northwest. Neogene and older sediments are only exposed in the extreme east and south of the country, where the edges of the North Sea Basin were uplifted and eroded. The southeast of the Netherlands is affected by a SE-NW striking fault system, which formed a number of horst and graben blocks during the Cenozoic. These faults are still active.

The Dutch landscape essentially consists of a Holocene coastal barrier and coastal plain, and an interior with Pleistocene deposits cut by a Holocene fluvial system. The coastal barrier is interrupted in the south by the estuary of the rivers Rhine, Meuse and Scheldt, and in the north by the tidal inlets of the Wadden Sea. The barrier bears dunes and is locally up to ten km wide. In places it had to be reinforced with dikes. The coastal plain covers the western half of the country and consists mainly of clay and peat. Much of it would be flooded in the absence of dikes. Not only the distribution of land and water is strongly influenced by man, but also the present-day limited extent of peat, for instance, is artificial. In the past, peat was exploited as fuel, both in the coastal plain and further inland where moors partially covered the Pleistocene deposits.

At the surface, the Pleistocene is largely sandy and of glacial, fluvial and aeolian origin. Ice-pushed ridges locally reach heights of 100 m, but most of the Pleistocene occurs as flat-lying land. The Holocene alluvial valleys of the rivers Rhine and Meuse, clearly expressed in the Pleistocene area, merge downstream with the

coastal plain. In many places the rivers are straightened artificially and virtually everywhere they are confined by dikes.

Pre-Pleistocene sediments are only exposed near the borders of the country. In the east, these sediments include various Mesozoic and Paleogene formations, whereas those to the southwest are of Pliocene age. In one particular valley in the hills of the southernmost province, Neogene and Paleogene sands, clays and lignites as well as Cretaceous chalk are eroded down to their Carboniferous substratum.

## Data Sources

The 3D modelling relies heavily on the national DINO database containing a carefully maintained dataset of standardized geological information of the Netherlands. The DINO database currently contains:

- Data from 6,300 deep exploration and production boreholes licensed under the Mining Law; mainly for hydrocarbons, but also for salt and geothermal energy. The data includes 28,000 borehole logs, 193,000 sample measurements, production statistics of 1,349 production wells, as well as 136,000 borehole-related documents.
- 456,000 standardized descriptions of shallow boreholes, ranging from a few meters (the majority) to hundreds of meters deep. This number includes 326,000 original survey boreholes, drilled for 1:50,000 geological mapping; the remaining 126,000 were supplied by third parties, and drilled for a variety of purposes, for example groundwater mapping or monitoring.
- Data of 150,000 cone penetration tests (CPT's).
- 7,000 digital seismic lines (post-stack) with a cumulative length of 360,000 km, and 29,000 km of analogue lines (with digital

metadata) spanning 1.5 million km.

- 335 3D seismic surveys (post-stack) covering an area of 146,000 km<sup>2</sup>.
- Groundwater level data from 74,000 filters in 49,000 monitoring wells.
- Chemical and physical analyses of more than 195,000 samples, including almost 150,000 groundwater composition analyses.
- 23,000 core sample photographs.
- The four 3D subsurface models DGM-deep, DGM, REGIS II and GeoTOP.

Because different types of borehole descriptions had to be combined during designing and filling of the database, standardized data formats were developed for a uniform, coded description of borehole lithology, grain size and admixture information. Several systems existed throughout the years but at present, all data is available in the SBB 5.1 coding system (Bosch, 2000).

The Geological Survey also developed a standardized lithostratigraphic coding system. The latest system, published by Westerhoff et al. (2003), is a revision of the classification of Doppert et al. (1975). The new system better follows lithostratigraphic rules of macroscopic recognition and mappability, allowing a more practical use in lithostratigraphic coding.

Both the well maintained DINO database and the standardized coding systems strongly facilitated the construction of a uniform dataset for the 3D models. Without these standardized systems, which took decades to develop, the modelling would not have been possible.

### 3D Modelling Approach

3D modelling at the Geological Survey of the Netherlands is primarily data-driven which puts us on the implicit end of the implicit – explicit

### Surface geology

#### Holocene

- Coastal deposits
- Marine deposits
- Fluvial deposits
- Peat

#### Holocene / Pleistocene

- Fluvial deposits
- Eolian deposits

#### Pleistocene

- Ice-pushed ridges
- Glacial deposits
- Other deposits

#### Older deposits

- Older deposits
- Main faults

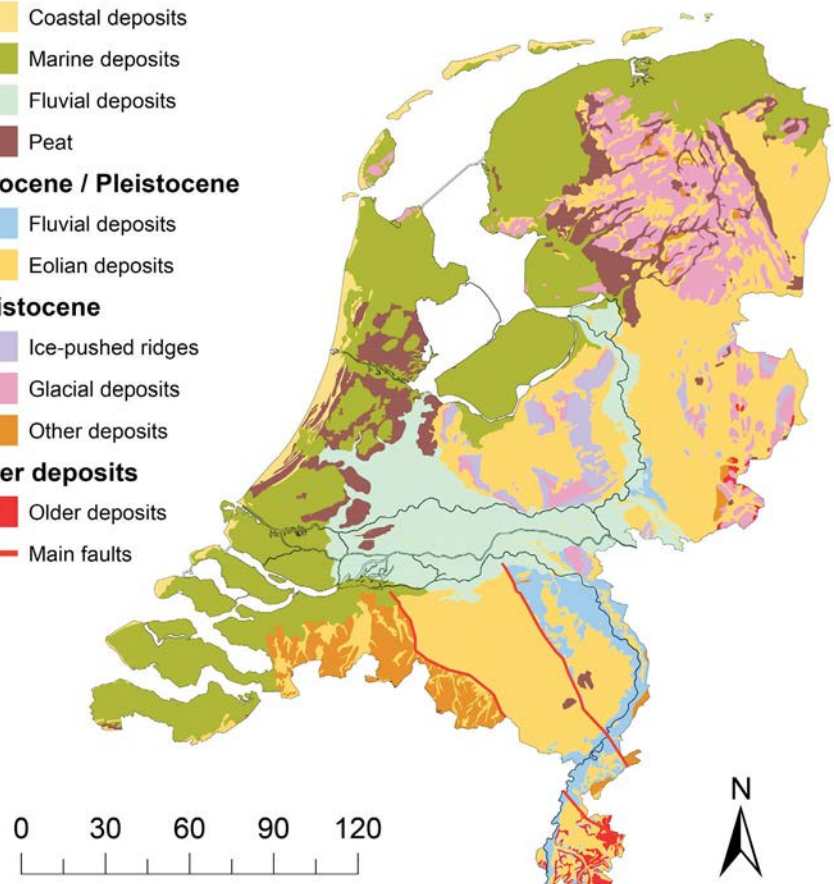


Figure 2. Schematic surface geological map of the Netherlands.

modelling spectrum. However, the emphasis on data does not imply that explicit geological knowledge is ignored. Both DGM and the GeoTOP voxel model are good examples of implicit models incorporating explicit geological knowledge. Details on the modelling approach of these two models are described below.

*Borehole data and interpretation* – DGM uses a selection of 26,500 borehole descriptions from the DINO database. This selection aims at an even distribution of good quality borehole data derived from the Quaternary and Neogene deposits. The selected boreholes are stratigraphically interpreted by assigning the revised lithostratigraphic classification (Westerhoff et al., 2003) to the individual description intervals. The base of each of the lithostratigraphic units

in the boreholes is subsequently used for interpolation and modelling. The basic strategy for the lithostratigraphic interpretation was to work from nation-wide cross-sections to regional-scale cross-sections that constitute the geological framework for the final interpretation of individual boreholes. These cross-sections are however not explicitly used for interpolation.

*Fault mapping* – In addition to the boreholes, a tectonic map showing all known major faults in the Cenozoic deposits was constructed. The map is a thorough revision of fault patterns from earlier publications, including maps based on seismic data acquired for the exploration of oil and gas. Additional seismic data came from high resolution surveys in the Roer Valley Graben which is the most prominent

tectonic feature in the Netherlands. For every lithostratigraphic unit, the faults that influenced the base of the unit are selected and used as ‘barriers’ in the interpolation process.

*Interpolation* – The depths of the base of each lithostratigraphic unit as derived from the borehole data are interpolated to raster surfaces using the ‘block-kriging’ algorithm (Goovaerts, 1997; Chilès & Delfiner, 2012) as implemented in the geostatistical software-package Isatis® by Geovariances. The top surface follows indirectly from the joined basal surfaces of overlying units when all units are stacked (see ‘stacking the units’ below). The base surface was chosen because this surface is formed by depositional processes that are linked to the unit itself, whereas the top surface is often the result of multiple geological processes (e.g. erosion, incision).

*Assisting the interpolation* – Block kriging alone often fails to produce a result that corresponds to the geological concept one has in mind. Therefore, additional information is taken into account, including maps with the maximum spatial extent of each lithostratigraphic unit; trend surfaces showing geological structures (basins) or trends (dip direction and dip angle); guiding points (‘synthetic boreholes’) inserted at locations with specific geological features like thinning out or incised channels.

*Stacking the units* – The last step in the modelling process consists of stacking the basal surfaces of each unit in a stratigraphically consistent way. In the stacking process, the basal surfaces may intersect with each other. In general there are three types of intersection possible: 1) The upper unit has eroded the lower units. In this case the lower units are clipped by the upper unit; 2) The upper unit has been deposited against the relief of the lower unit. In this case the upper unit is clipped by the lower unit; 3) The intersection is an artefact of

the interpolation process occurring between two conformable units. In this case the basal surfaces of the two units are adjusted in such a way that the intersection is removed.

The choice of the type of intersection one wants to apply depends on the geological concept one has in mind. The stacking process is performed within Isatis®, using grid-to-grid operations that are also available in standard GIS software.

An impression of the resulting DGM model is shown in Figure 3.

The **GeoTOP** workflow consists of four main modelling steps (Figure 4). In the first two steps, a layer-based model is constructed (Figure 4A, B). This layer-based model is more refined than the DGM model described above because it features all Holocene formations that DGM combines in one unit, as well as certain Holocene and upper Pleistocene members and beds, and it uses in principle all available coded digital borehole descriptions rather than a subset. Given the large number of boreholes – tens of thousands per model region and c. 580,000 in total – we developed automated stratigraphical interpretation routines. A region-specific lithostratigraphical concept, featuring superposition, areal extent, diagnostic properties and approximate depth ranges, is used to identify and label the units in each borehole. This procedure delivers a uniform, consistent and reproducible set of interpreted boreholes (Figure 4A).

Next, 2D interpolation techniques are used to construct surfaces bounding the bases of the stratigraphic units (Figure 4B). The interpolation algorithm allows for calculation of a mean depth estimate of each surface and its standard deviation. Subsequently, all surfaces are stacked according to their stratigraphic position, resulting in a consistent layer-based model with estimates of top and base of each stratigraphic unit (Figure 4B). Top surfaces

are derived from the bases of the overlying units. The surfaces are then used to place each voxel in the model within the correct lithostratigraphic unit.

In the third step, the boreholes are revisited and classified in six different lithological classes (peat, clay, sandy clay, fine sand, medium sand, coarse sand and gravel; Figure 4C). In the last modelling step, a 3D interpolation is performed for each stratigraphic unit separately. The interpolation results in 100 equiprobable realizations of lithological and grain-size class for each voxel. Post-processing of the realizations results in probabilities of occurrence as well as a ‘most likely’ estimate of lithological and grain-size class (Figure 4D).

Figure 5 shows an impression of the GeoTOP model in the central part of the Netherlands.

## Clients

The DGM-deep model is used to attract investments in exploration, up until now primarily for hydrocarbons, but gradually shifting to geothermal energy and other new uses of the deep subsurface.

Typical clients of the shallow subsurface models are regional authorities (i.e., provinces, municipalities, and water management agencies), water supply companies, construction companies, and consultancy firms commissioned by the aforementioned organizations.

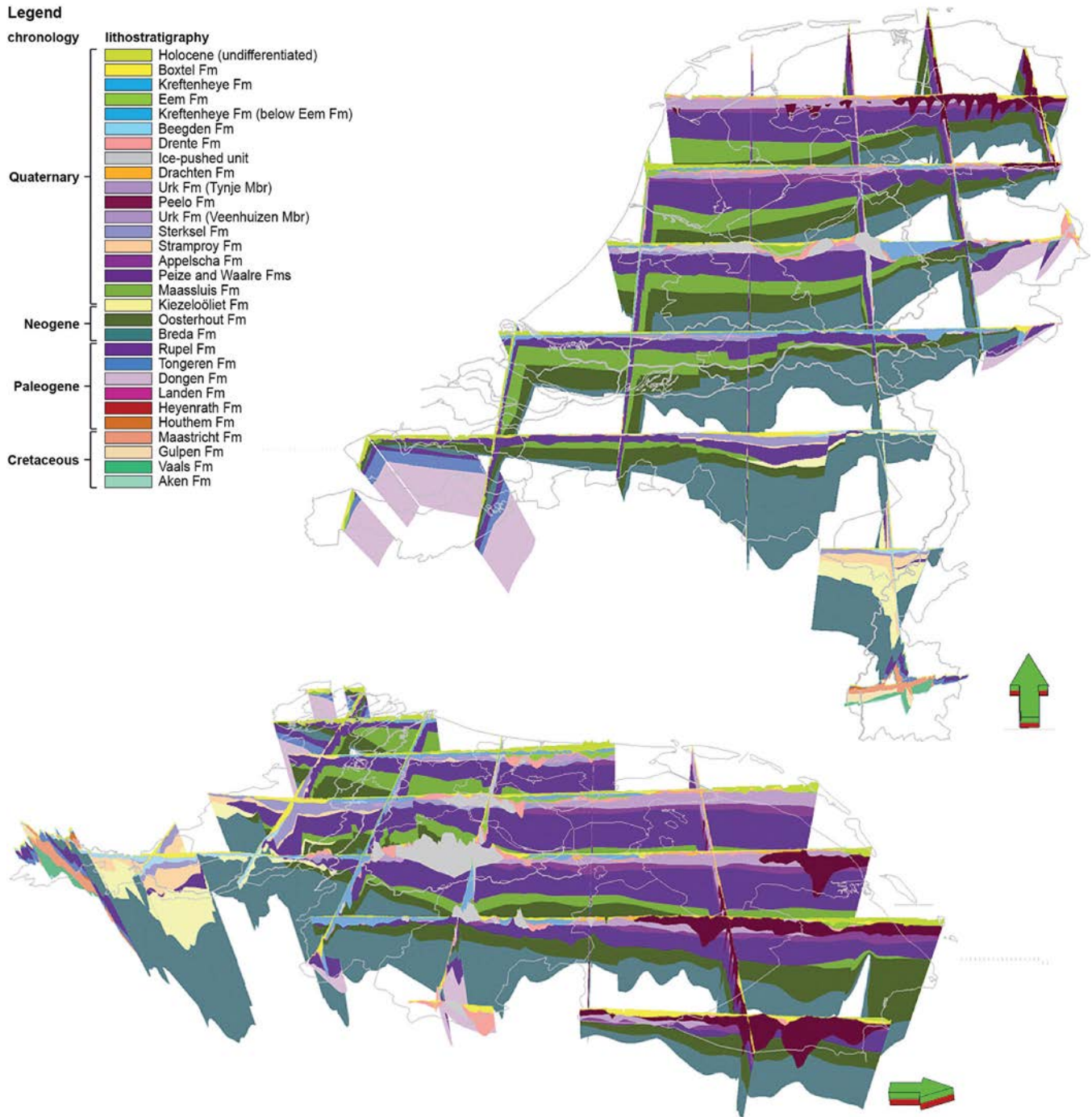
REGIS II is widely used by regional authorities (i.e., provinces and water management agencies), and water supply companies in groundwater flow models.

The lithological detail that is characteristic for the GeoTOP model is used in several areas, including, amongst other applications: exploration for aggregate resources, detailed groundwater studies and the study of the propagation of contaminant plumes,

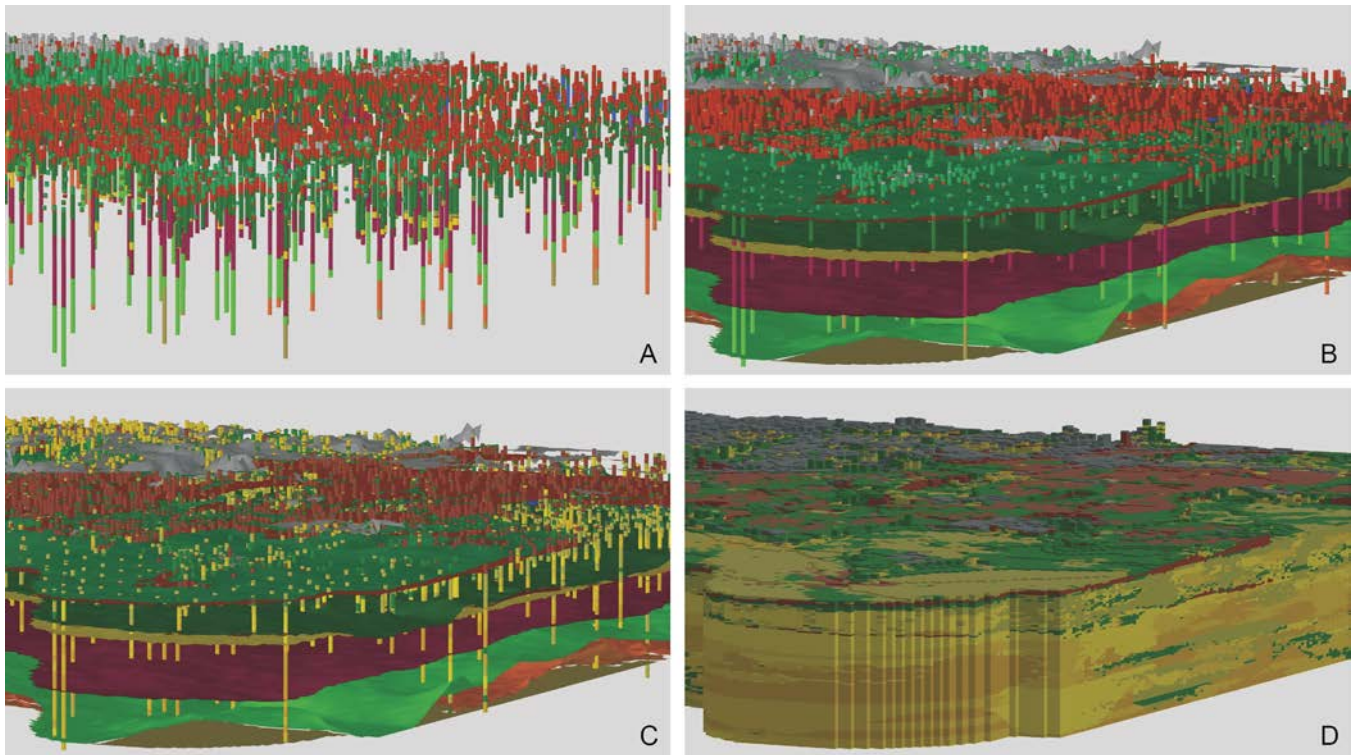
detailed studies of salt penetration from sea-water, land subsidence studies and the planning stage of large-scale infrastructural works such as tunnels and railroads.

During the construction of the models, we collaborate with stakeholders from the region under investigation. For example, we constructed several detailed layer-based models for the

two southernmost provinces in a series of commissioned projects. The results of these projects will be used in future updates of DGM-deep, DGM and REGIS II. Furthermore, the



**Figure 3.** Cross-sections through DGM, top panel looking north, bottom panel looking west. The figures show the North Sea Basin fill in the middle and western part of the Netherlands (Breda, Oosterhout and Maassluis formations) and the shallower fringe of the basin in the east, to which the above-mentioned formations pinch-out. In the southern part of the country the Roer Valley Graben with its thick deposits of late Neogene and early Quaternary sediments is seen. In the southwest and easternmost part of the Netherlands, Paleogene units (Rupel Formation and older) are close to the surface, while in the southernmost part the oldest sediments (up to Cretaceous) are shown. After Gunnink et al. (2013).



**Figure 4.** The four main modelling steps in the construction of layer-based and voxel models from borehole data: **A)** automated stratigraphic interpretation of borehole descriptions; **B)** 2D interpolation of stratigraphic surfaces; **C)** subdivision of boreholes into lithological and grain-size classes; **D)** 3D interpolation of lithological class for each stratigraphic unit separately. In part C, yellow colors indicate sand in three different grain-size classes, green colors are clays and brown peat.

GeoTOP model of the same two provinces will be attributed with hydraulic conductivity as an additional parameter to the standard set of the model.

### Recent Jurisdictional-Scale Case Study Showcasing Application of 3D Models

The addition of physical properties to voxels enables the deployment of GeoTOP in a wide range of applications such as: groundwater management, risk assessments, the planning of infrastructural works and aggregate resource assessments. The underlying assumption is that the spatial variation of many subsurface properties, such as hydraulic conductivity and seismic shear-wave velocity, strongly depends on the two main geological properties in the model: stratigraphy and lithology. A recent application of the GeoTOP model is the hazard and risk assessment of damage caused by

induced seismicity in the Groningen gas field (Kruiver et al. 2017a; 2017b).

The Groningen gas field in the Netherlands is one of the largest gas fields of Europe and has been in production since the 1960's. Due to the progressive depletion of the reservoir, induced seismic activity has increased in recent years. In 2012, an earthquake of magnitude 3.6 initiated further research into the prediction and management of risks related to man-induced earthquakes.

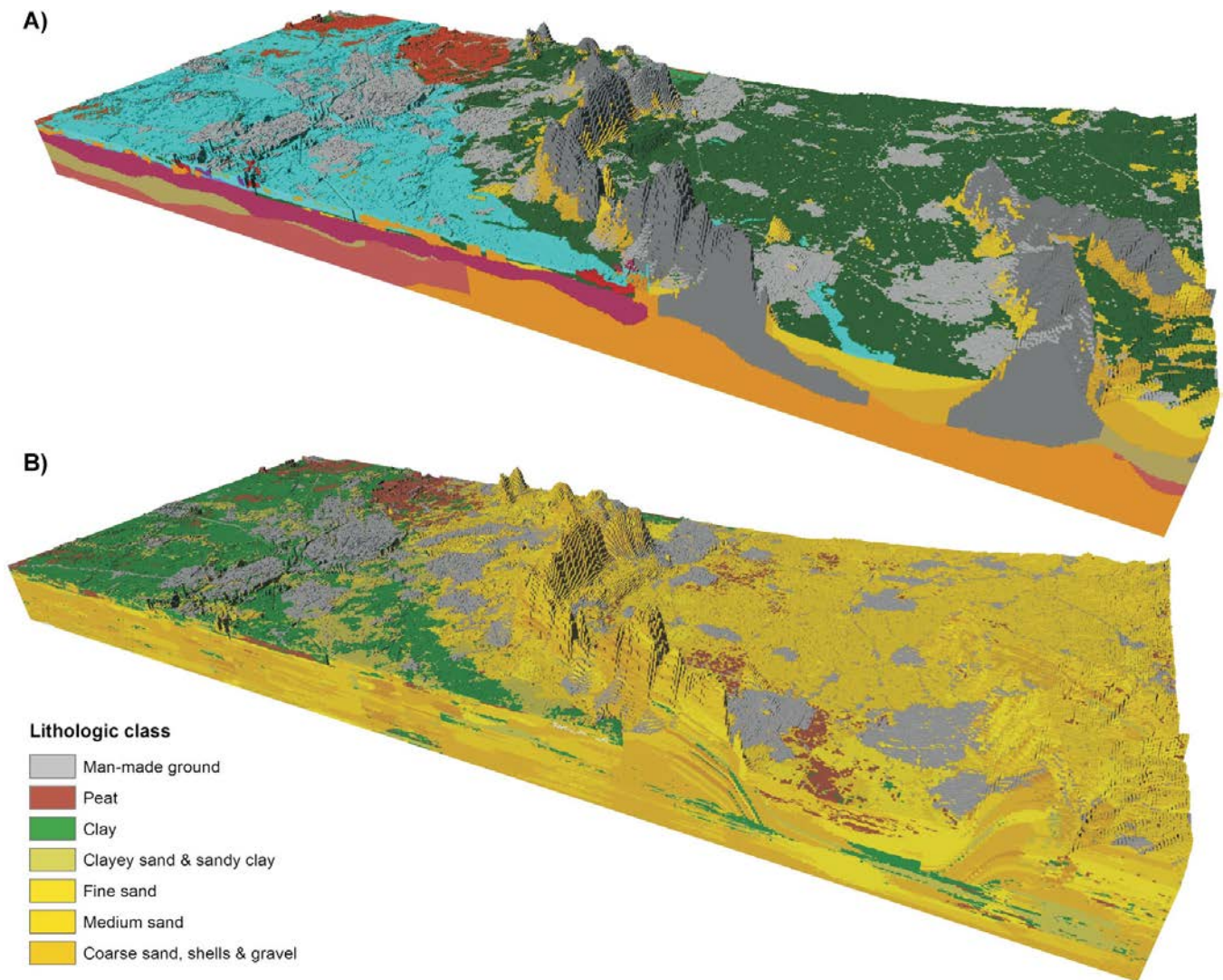
In risk-assessments of earthquake damage, the shear wave velocity ( $V_s$ ) for the upper 30 m of the subsurface column ( $V_{s30}$ ) plays an important role. Kruiver et al. (2017a; 2017b) combined the GeoTOP model of the Groningen area and Seismic Cone Penetration Tests (SCPT's) into a  $V_s$  model of the area covering the gas field. Statistical distributions (with mean and standard deviation) of  $V_s$

for each combination of lithostratigraphic unit and lithologic class derived from 60 SCPT's were used to randomly assign a specific  $V_s$  to each voxel in the model (Figure 6).

The  $V_{s30}$  for each voxel stack was then calculated using the harmonic mean of the  $V_s$  of the 60 voxels that cover the upper 30 m and plotted as a raster map. The uncertainty in  $V_{s30}$  was determined by repeating this procedure 100 times.

The resulting 3D  $V_s$  model and 2D  $V_{s30}$  map reveal zones with distinct  $V_{s30}$  characteristics: areas containing predominantly soft Holocene deposits with low  $V_{s30}$  are differentiated from areas with predominantly stiff Pleistocene deposits with high  $V_{s30}$ . Previously only a single  $V_{s30}$  value was used for the entire in the Groningen gas field. Both the new  $V_{s30}$  map and vertical voxel stacks attributed with  $V_s$  and other soil properties have been used as input for site amplification





**Figure 5.** GeoTOP 3D views of the Gelderse Vallei area in the central part of the Netherlands. **A)** Lithostratigraphic units of Holocene and upper Pleistocene formations, members and beds; **B)** lithologic classes (below). The displayed block measures 62 x 24 km; depth of the base is 50 m below MSL; vertical exaggeration is 75x. After Stafleu & Dubelaar (2016).

predictions (Kruiver et al., 2017a; 2017b).

## Current Challenges

In 2015, Dutch parliament passed a new law, which puts subsurface data and information in the system of so-called key registries ('Basisregistraties'). The key registry for the subsurface ('BRO', or 'Basisregistratie Ondergrond'), to be managed by the Geological Survey of the Netherlands, will hold subsurface data, including the four subsurface models (DGM-deep, DGM, REGIS II and GeoTOP), as well as information

on permits and underground infrastructure.

The new law invokes a number of challenges. First of all, the design, development, testing and implementation of a complex information system with 28 different data types and many stakeholders allowing thousands of users to interact with the data using fully automated procedures (mainly webservice), is a major challenge in its own right. Most of this work is carried out by the DINO data management department.

Secondly, the obligatory delivery of data is expected to substantially en-

large our borehole and cone penetration test datasets, allowing us to create more accurate subsurface models. As a consequence, users will expect a high update frequency of the models so they can benefit from the data they were obliged to deliver. However, our current update frequency is rather low: it takes 2 – 3 years to develop a new GeoTOP model area and eight years have passed between the publication of the two most recent versions of REGIS II. We expect that *model integration* (see below) is part of the solution to this problem.

Thirdly, the obligatory consultation will increase and formalize the Survey's accountability and responsibility associated with its modelling efforts, potentially up to the level of liability. Model reliability will have to be better resolved: while we presently limit ourselves to calculating standard deviations and probabilities based on multiple model realizations, we will eventually have to address data uncertainty, and possibly the propagation of both data and model uncertainty to downstream applications.

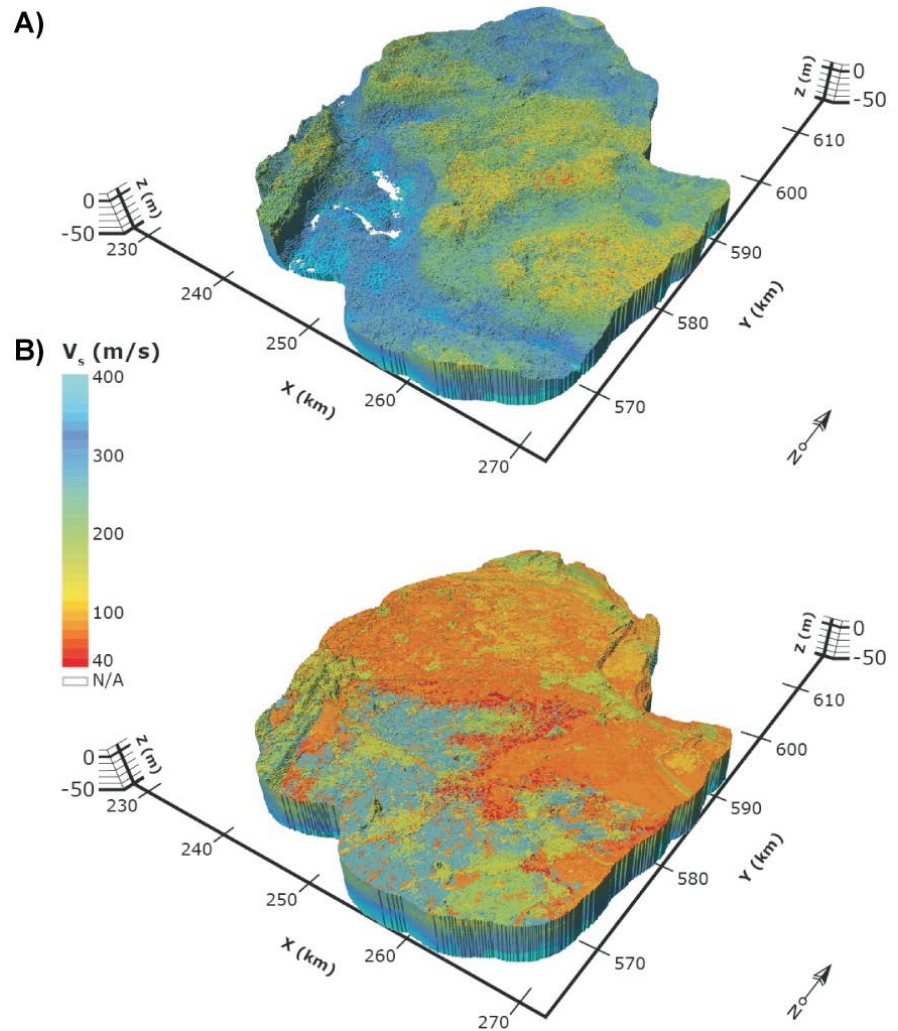
## Lessons Learned

As described above, the availability of a single national database with standardized geological information (borehole descriptions, cone penetration tests, seismic data) has proven to be key to systematic 3D modelling of the subsurface of the Netherlands.

Another important lesson is that in order to run a successful 3D subsurface modelling program, it has to become the centerpiece of the Survey's activities rather than a sideshow that has to compete for budget with other tasks. In our case, focussing on 3D models implied the discontinuation of our 1:50,000 onshore and 1:250,000 offshore geological mapping programs.

### Next Steps

*Model integration* – A new model directive (DGM+) was initiated in 2015 to integrate the national framework model DGM with GeoTOP on a national scale. DGM+ will incorporate the GeoTOP workflow of a more refined layer-based model including all Holocene formations that DGM nowadays models as one unit, as well as additional Holocene and Pleistocene members and beds. Furthermore, the original regional GeoTOP models will dissolve into a single national layer-based model that displays a great amount of detail in the upper tens of meters, but at the same time reaches, albeit with less detail, depths of several hundreds of meters. In doing so



**Figure 6.** GeoTOP model of the Groningen area in 3D, attributed with shear wave velocity ( $V_s$ ) estimated from the mean of 100 randomly drawn values from the statistical distribution of measured values: **A)** the model with all strata younger than the glacial (Elsterian) Peelo Formation removed; **B)** the full model from 50 m below MSL up to land surface. (After Kruijer et al., 2017b).

we eliminate differences between models of the same geological units for the subsurface reaching down to c. 500 m depth. In addition, the work efficiency and reproducibility will increase by using a single national framework model.

The integration of the shallow framework models appears to be a relatively straightforward step, mainly because they are constructed using comparable datasets (mainly boreholes) and the same modelling software (Isatis®), but is nevertheless time-consuming. The new integrated model will serve as the future carrier

of the GeoTOP voxel models with detailed lithological information as well as our hydrogeological REGIS II model with aquifers and aquitards.

*Other data types* – The GeoTOP model captures sedimentary architecture down to the detail level of depositional units such as barrier and tidal systems. At the chosen voxel resolution, there is still a considerable residual heterogeneity, associated with smaller-scale phenomena such as bedforms. Such heterogeneity needs to be better resolved for an adequate appraisal of, for example, hydrological and geotechnical behaviour. How-

ever, borehole data density is a limiting factor, and it is therefore worthwhile to explore using other data types. At present, effort is put in incorporating cone penetration test data: if successful this would make a very large set of data available to GeoTOP modelling. Other data types under consideration are high resolution seismic profiling, ground penetrating radar and airborne electromagnetic prospecting.

*4D modelling and the urban environment* – Our 3D subsurface models are static and therefore not particularly suited to be used in areas with a more dynamic subsurface. These dynamics may be either the result of active natural processes, man-induced natural processes (e.g. layer compaction and land subsidence due to artificial groundwater lowering), or active anthropogenic alterations and additions to the natural subsurface stratigraphy, e.g. in connection to building activities. Especially in heavily populated areas, integrated 3D planning of the above-surface and subsurface domains asks for more detailed, up-to-date subsurface information than is currently available. To optimize the applicability of 3D subsurface models in urban areas and being able to incorporate the small-scale heterogeneity that is often associated with anthropogenic subsurface alterations, we therefore focus our modelling efforts in the built environment on 1) increasing the resolution of our models by increasing the amount and diversity of input data (see also ‘other data types’ above); 2) Develop new techniques to map and characterise man-made deposits; and 3) develop methods to integrate 3D models of the geology, man-made deposits and subsurface infrastructure, and visually combine these with above-ground information.

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# Chapter 18: Statewide 3D Mapping Project at the Geological Survey of New South Wales

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## Introduction

The Geological Survey of New South Wales (GSNSW) is creating a statewide 3D geological model as part of its flagship New Frontiers Initiative. The model is being developed in conjunction with the NSW Seamless Geology geodatabase (Colquhoun et al., 2018) which combines all New South Wales (NSW) geological information and presents the geology at the present-day topography, as well as at major geological time interfaces. The statewide 3D model is consistent with structures and lithologies from the Seamless Geology geodatabase, and incorporates data and interpretations from drillholes, seismic sections, and magnetic, gravity and airborne electromagnetic images and models.

The statewide 3D model delineates major basins, orogens, deep-crustal faults and fault networks. These features are represented as interlocking sets of 3D surfaces and volumes located within a common reference frame. Hydrocarbon, coal, mineral, geothermal and groundwater resource models and other detailed small-scale models will be embedded into the regional-scale framework provided by the statewide 3D model.

## Organizational Structure and Business Model

The New Frontiers Initiative (NFI) commenced in its current form in

2012 and is funded directly by area-based rental fees placed on all NSW mineral and petroleum exploration and production titles. Detailed NFI project deliverables are set on an annual basis under the guidance of a rolling five-year plan, with the first version of the statewide 3D model due in July 2021. The organizational structure of 3D modelling capability at the Geological Survey of NSW is illustrated in Figure 1. Construction of the regional- and basin-scale components of the statewide 3D model is the responsibility of the Geoscience Acquisition and Synthesis (GAS) unit, while mineral, hydrocarbon and geothermal resources models will be produced by the Strategic Resource Assessment and Advice (SRAA) unit. The 3D modelling project team works closely with the Seamless Geology project team that is also part of GAS. The models also draw heavily on drillhole data, which is collated and delivered by the Geoscience Information (GI) unit. GI are also responsible for the collation and delivery of all GSNSW datasets and products, including 3D models.

## Overview of 3D Modelling Activities

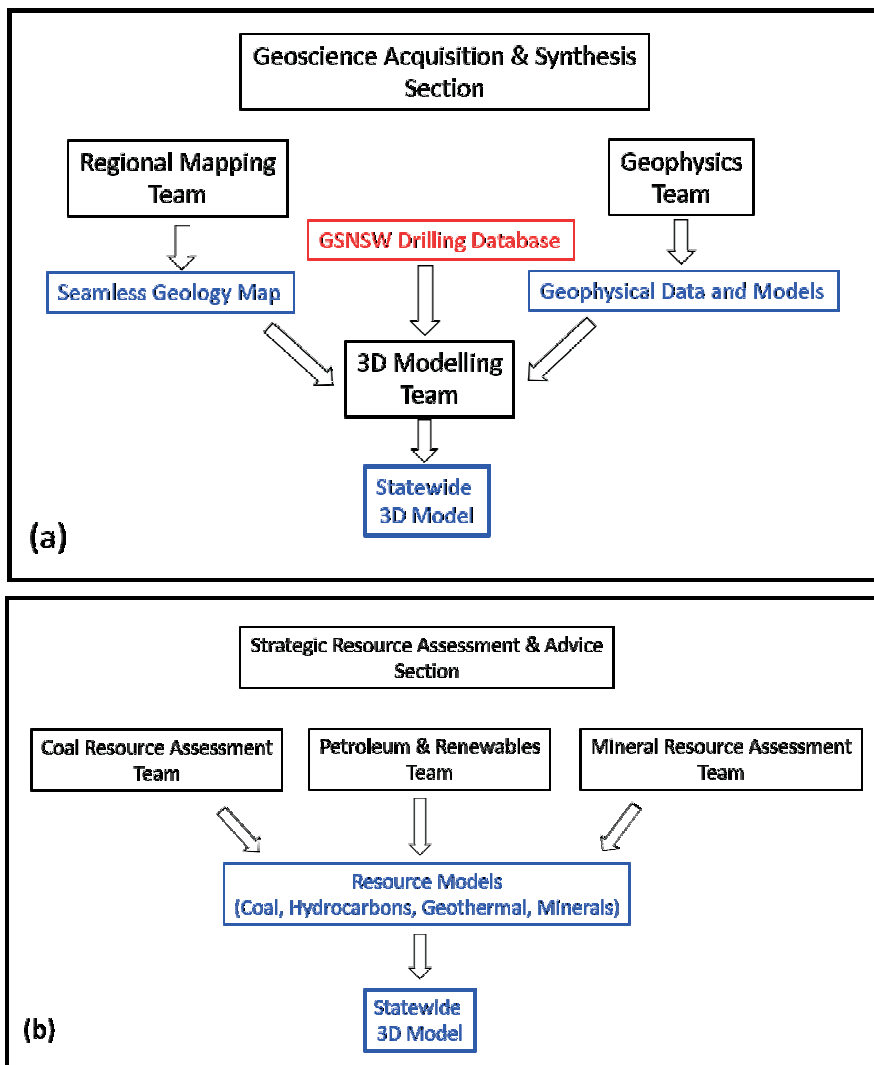
The major focus of 3D modelling activity within GSNSW is the NFI program to create a statewide 3D model, comprising a series of interlocking province-scale models coupled with a

statewide 3D fault network. Models at this scale will incorporate digital terrain, basin and basement interfaces, major tectonic subdivisions, crustal-scale structures, major stratigraphic horizons and geological age boundaries. Small-scale models of coal, gas, petroleum, water, geothermal and mineral resources will be embedded in the surfaces and volumes of the statewide 3D model framework.

The statewide 3D model has applications for land use management, mineral and energy exploration, scientific research, water resource management, civil engineering and waste management. GSNSW also undertakes 3D modelling on a more detailed scale for interpretation and presentation of specific resource assessment projects such as coal seams or groundwater aquifers.

## Resources Allocated to 3D Modelling Activities

Roles currently committed to 3D modelling activities within the GSNSW are listed in Table 1. The deployment of the various teams within the organizational structure is shown in Figure 1. Staff in the GI unit also contribute to modelling by populating and maintaining drillhole databases that are base data for modelling projects, and through delivery of 3D models through GSNSW data systems.



**Figure 1.** Geological Survey of NSW organizational units undertaking 3D modelling activities. The Geoscience Acquisition and Synthesis section (a) is building the statewide 3D geological model while Strategic Resource Assessment and Advice (b) provides the resource models which are embedded in the statewide model framework.

**Table 1.** GSNW staff undertaking 3D modelling activities.

GSNSW Organizational Unit	Number of staff
Geoscience Acquisition and Synthesis: 3D modelling	3
Strategic Resource Assessment and Advice: Coal Resource Assessment	2
Petroleum & Renewables	3
Mineral Resource Assessment	1
<b>Total</b>	<b>10</b>

## Overview of Regional Geological Setting

The evolution of the orogens and basins in NSW are described in Schneibner and Basden (1998) and

summarised below. The locations are shown in Figures 2 and 3.

### *The Curnamona Craton*

The oldest rocks in NSW occur in the Curnamona Craton around Broken Hill in the state’s far west and are

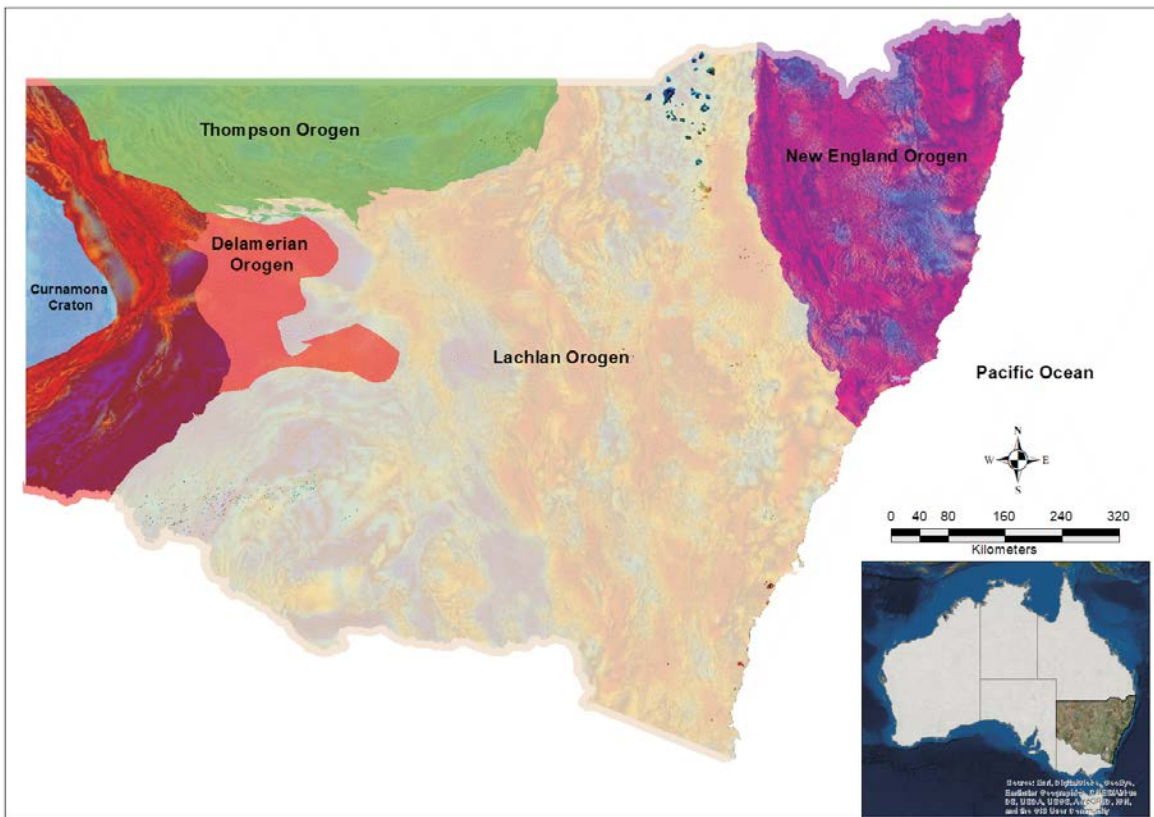
placed into the Willyama Supergroup, which comprises meta-sedimentary rocks and meta-volcanic rocks deposited in one or more rift basins about 1730–1650 million years ago. These Paleoproterozoic rocks were later incorporated into the Rodinian supercontinent, which was assembled around 1100 million years ago and started breaking up about 800 million years ago (Li et al., 2007). In the Rodinian supercontinent, North America lay to the east of Australia and Antarctica. It was a forerunner to Gondwanaland that existed for much of the Paleozoic (540–250 million years ago).

### *The Delamerian Orogen*

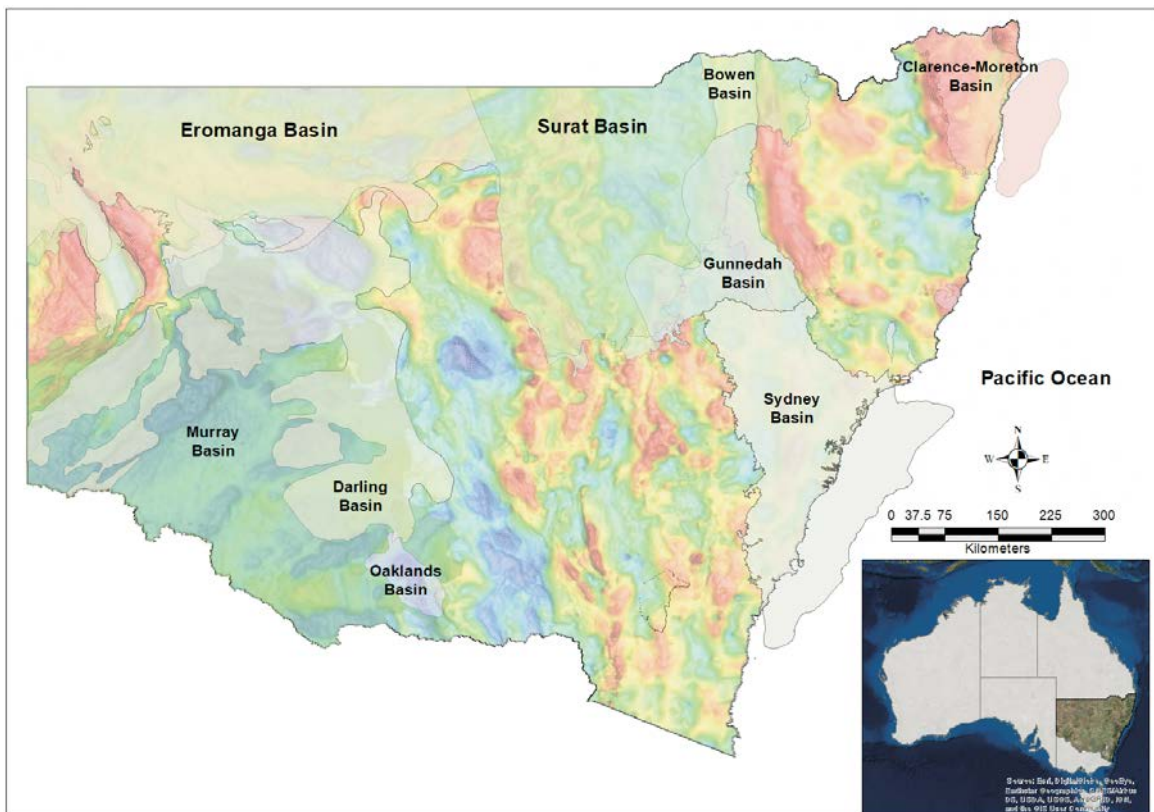
The Late Proterozoic to Cambrian (1000–490 million years old) rocks of the Delamerian Orogen record the break-up of Rodinia, which occurred over a period of 200 million years. This orogenic belt mainly occupies the eastern third of South Australia where the Adelaide Rift Complex contains mixtures of sedimentary and volcanic rocks that record the rift and sag phases of crustal extension. The eastern part of the Delamerian Orogen extends into far western New South Wales (Figure 2) where rocks north of Broken Hill form part of the Adelaide Rift Complex. Stretched crust thinned to form rift basins, some containing volcanic rocks and glacial deposits, and thinned even more to give way to oceanic crust and sea-floor spreading. Seafloor spreading changed to east-dipping subduction about 530 million years ago, with the formation of Cambrian island arc volcanic rocks.

### *Palaeozoic Plate Interactions with the Proto-Pacific Ocean – the Lachlan Orogen*

The erosion of mountains formed by the deformation and uplift of the Delamerian Orogen shed vast amounts of mud and quartz-rich sand into ocean basins to the east, where they covered the Cambrian basalts that formed the oceanic igneous crust.



**Figure 2.** Map of New South Wales showing the extents of the Pre-Permian orogens over an image of the total magnetic intensity.



**Figure 3.** Map of New South Wales showing the Permo-Triassic, Mesozoic and Cenozoic basins over an image of the isostatically corrected bouguer gravity.

These sediments are now preserved as the widespread turbidites of the Lachlan Orogen. Destruction of the Cambrian subduction zone caused a new subduction zone to form hundreds of kilometres to the east. A new island-arc system, the Macquarie Arc developed above a west-dipping subduction zone. Several phases of volcanism have been documented in the arc from earliest to latest Ordovician. Quiet periods in volcanism are marked by the formation of tropical limestone reefs. Arc volcanism died out at the end of the Ordovician with the intrusion of monzonites, before plate tectonic movements in the Early Silurian caused the arc to collide with the back-arc basin turbidites. This caused the major Benambran deformation which rifted the Macquarie Arc into several belts, separated by rift-sag basins.

### ***Paleozoic Darling Basin***

The Late Silurian to Early Carboniferous Darling Basin is interpreted to have formed during syn-rift, short-lived thermal sag and foreland basin phases (Willcox et al., 2004). The rift fill phase was terminated by an Early Devonian inversion event that relates to the Taberraberan Orogeny. During the Middle Devonian, subsidence driven by thermal relaxation resulted in deposition of 'layer cake' sedimentary units, before the basin moved into a foreland basin tectonic setting. Mid Devonian to Early Carboniferous sedimentary units deposited to the west of a convergent plate boundary. Middle Carboniferous inversion coeval with the Kanimblan Orogeny resulted in inversion and erosion of the basin (Willcox et al., 2004).

### ***Thomson Orogen and New England Orogen***

The Thomson Orogen lies north of the Lachlan Orogen and extends north into central Queensland (Figure 2). In NSW, the orogen has an arcuate east-west orientation and is mostly covered by younger sedimentary sequences that have prevented detailed geo-

logical study. The Thomson Orogen may have a similar tectonic history to the Lachlan Orogen because it also contains Ordovician basalts and turbidites, Mid-Silurian to Mid-Devonian rock packages and interpreted Late Devonian basins (Li et al., 2007).

The evolution of the New England Orogen began with the deposition of fragmentary Cambrian to Ordovician convergent-margin volcanic and volcanoclastic rocks, as well as disrupted Cambrian ophiolites and Ordovician blueschists. A second phase was marked by plate convergence between the Australian Plate with the Proto-Pacific Plate, resulting in a mix of intra-oceanic arc and accretionary prism rocks. During a third phase, the New England Orogen was the site of a Late Devonian continental-margin arc of mafic character sitting above a west-dipping subduction zone. Multiple deformation, metamorphism, and emplacement of granites occurred in the Late Carboniferous and Permian. Convergence along this plate margin became extensional in the Early Permian leading to the formation of small rift basins and a major back-arc rift basin that formed the early stage of the Sydney and Gunnedah basins.

### ***Permo-Triassic Basins***

The Sydney and Gunnedah basins lie between the Lachlan and New England orogens. Starting as back-arc rifts in the earliest Permian, they developed into foreland basins. Most of their fill was generated by uplift in the New England Orogen and this alternated with lesser fill from the Lachlan Orogen. These basins gradually converted into west-verging foreland fold and thrust belts during westward migrating deformation which persisted until the Mid-Triassic (Figure 3).

### ***Mesozoic and Cenozoic Basins and Modern Topography***

In the north-eastern corner of New South Wales, the Triassic to Jurassic

Clarence-Moreton Basin covers about 27 000 km<sup>2</sup> and contains up to 3 km of predominantly continental sediments. The basin formed by crustal extension of long-lived, north-trending dextral strike-slip faults (Korsch, 1985). Trans-tensional tectonics was followed by a period of thermal relaxation and subsidence (sag phase) in the latest Triassic to Late Jurassic (Harrington and Korsch, 1989). During the Cretaceous, an eastward shift in tectonic activity occurred. Activation of sinistral strike-slip faults was associated with continental rifting and formation of the Tasman Sea (O'Brien et al., 1994). Jurassic and Cretaceous rocks were deposited in the Great Australian Basin which covers the northern inland of New South Wales, and adjoining areas of Queensland and South Australia. The basin is sub-divided into the Eromanga and the Surat basins and date from the Early Jurassic to Late Cretaceous (Figure 3).

About 90 million years ago, the Tasman Sea between Australia and New Zealand began to open by seafloor spreading. The western edge of this rift basin was tectonically and thermally uplifted to form the Great Dividing Range and the broad shallow Cenozoic Murray Basin formed to the west of the range as a sedimentary response to this uplift (Figure 3).

### ***Data Sources***

Base data for 3D modelling are sourced from the NSW Seamless Geology geodatabase (Colquhoun et al. 2018), seismic sections, drillholes (petroleum, minerals, coal and water bores) structural measurements and geophysical images (gravity, magnetics and radio-element). The models are dynamic and are updated after new data are collected. The spatial distribution and resolution of data varies across the state, from very dense to very sparse.

NSW legislation requires that all drilling, geological, geophysical and



geochemical data acquired by companies on mining and exploration titles be submitted to GSNSW. These data are then incorporated into GSNSW databases. Industry data may remain confidential for five years after submission, however can still be used by GSNSW geologists for 3D modelling. GSNSW has also scanned and digitized a significant amount of pre-digital legacy data. These data are catalogued and archived using DIGS (Digital Imaging Geological System) and then linked to the MinView online search and discovery tool, where non-confidential data can be accessed by the public.

Data are mainly sourced from GSNSW databases, supplemented by data from Geoscience Australia (topography and geophysics) and NSW Land and Property Information (topography and satellite imagery). Further data and interpretations are sourced from journals, reports, maps and cross-sections.

Full 3D models are primarily based upon; the NSW Seamless Geology, wells and drillholes, seismic profiles and interpreted geological cross-sections. Compiling, verifying and integrating data takes a lot of the time allocated to building a 3D model. Clean datasets often do not exist for modelling projects and considerable effort is needed in the early stages to digitize, translate, clean, consolidate, validate and interpret source data. For large models, data often extend across UTM zones and location information is carefully verified before modelling commences.

During the construction of a model, data may be re-interpreted or otherwise modified and improved. This is especially the case for complex data such as drillhole information. Any modifications to drillhole intersection data made during modelling are uploaded into the GSNSW drillhole database using a purpose-built template called DRINDA.

When a modelling project is completed, the constraints for the model surfaces are exported and saved as a snapshot of the data in the BACON database. BACON lists the spatial XYZ location of the constrained points for each model surface and categorizes them as either a drill hole intersection, seismic interpretation, or other constraint. The data stored in BACON provides a quick way of checking whether parts of a model are well constrained or poorly constrained and allows an experienced modeller to re-create the model surfaces without having to recompile the separate constraining datasets.

### 3D Modelling Approach

Robinson (2016) described the 3D modelling process developed by GSNSW. The workflow recognizes the scalar and interlocking nature of orogenic provinces and basins, as well as the structures and stratigraphy contained therein. It prioritizes large-scale features and then works down in scale to infill models with increasing detail.

All models are constructed using implicit modelling that relies on relatively sparse constraining data. The exact methods selected will depend on the type, quality and spatial distribution of the constraining data.

There are three basic end-member modelling methods:

- 1) Compile a series of key datasets in the areas where they occur. These data are usually the drill hole intersection tops and bottoms, seismic interpretation point-sets, geophysical models, and surface maps. Then use stratigraphic tables and the Seamless Geology to link the datasets to create surfaces that span the areas with sparse or no data.
- 2) Work directly from seismic and drillholes to interpret horizons and structures. Then link these together guided by surface mapping line-work.

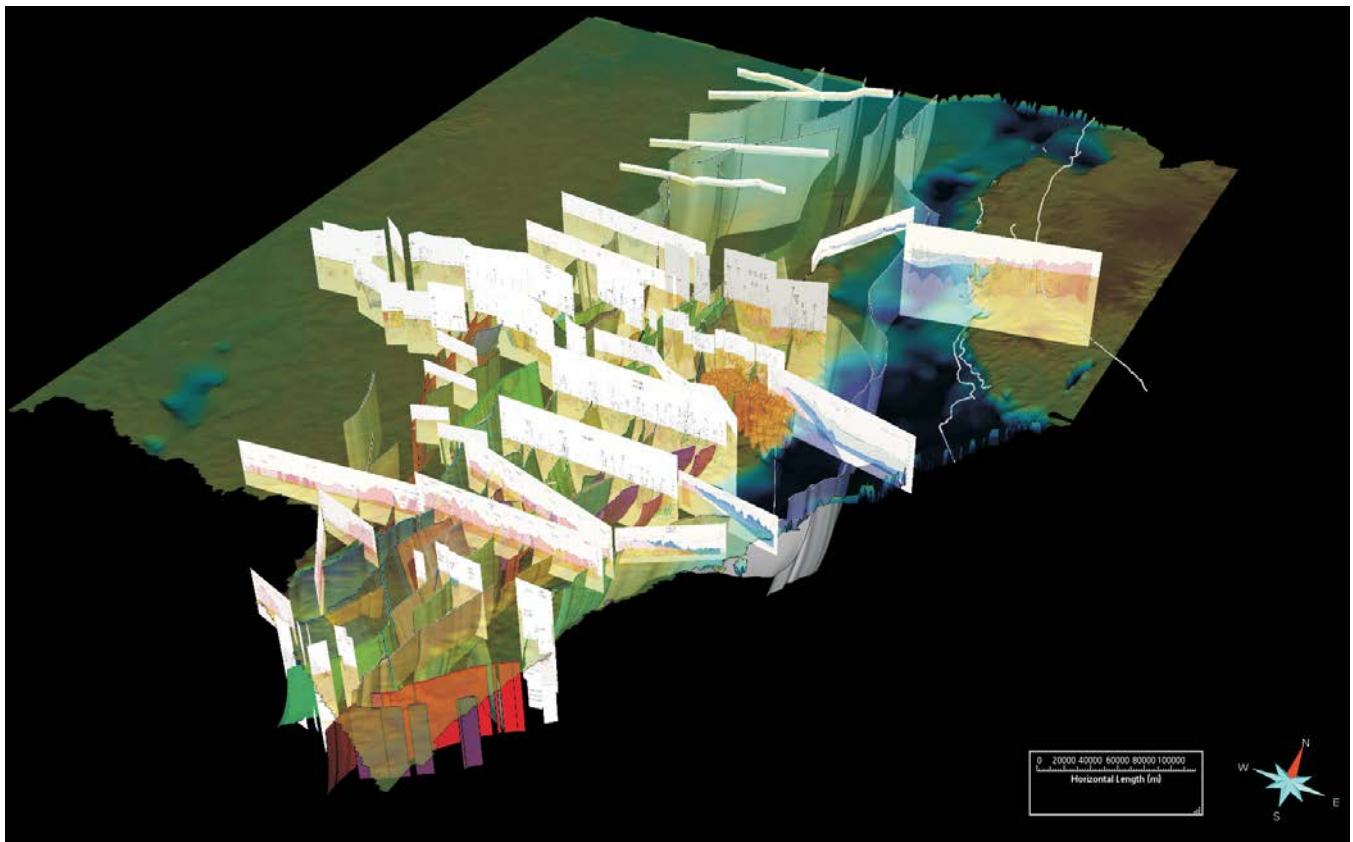
- 3) Use the surface mapping line-work from the Seamless Geology as the primary reference dataset. Constrain the dips of horizons and structures in the surface mapping with information from structural measurements, drillhole intersections, seismic interpretations and potential field modelling.

A combination of these methods may be used in a single model as required.

One of the major challenges of the NSW Statewide 3D model is to match the surface geology shown in the NSW Seamless Geology geodatabase (Colquhoun et al., 2018) with the horizons interpreted from the drillhole and seismic data. It is paramount that all geological synthesis products (maps, GIS, 3D models) released and distributed by GSNSW be consistent with each other. In areas where the NSW Seamless Geology geodatabase was compiled from limited information (i.e. poor outcrop, or coarse-scale mapping) then the modelled 3D surfaces may contribute to improving the interpretation and modifying the NSW Seamless Geology geodatabase. In other situations, the coarse scale of the NSW 3D model creates a mismatch in resolution between the 3D surface elements and the line segments in the NSW Seamless Geology geodatabase. This is addressed through the creation of smaller model surface elements near the intersection with surface mapped geology.

Geological cross-sections are used to link interpretations to seismic sections, establish structural and stratigraphic relationships and to assess the interpretations from gravity and magnetic forward models. Figure 4 shows cross-sections used to constrain the location and geometry of faults in the Eastern Lachlan Orogen.

Where available, seismic horizon picks are combined with the NSW Seamless Geology geodatabase and drillhole data to interpret cross-sections. In the absence of seismic data,



**Figure 4.** Cross sections with major structures and stratigraphic groups in the Eastern Lachlan Orogen. The model is approximately 1100 km from south to north. (After Spampinato, 2018).

the geometry of horizons or faults is constrained using mapped relationships and magnetic and gravity data. Variations in width and gradient of geophysical anomalies across structures are particularly useful for estimating the dip of major faults. Horizons are also constrained by applying previously defined stratigraphic relationships. Where more than one relationship exists within horizons, manual post-processing of modelled surfaces and volumes is necessary to ensure the correct relationships are maintained.

An example of the layers and datasets used to construct the structural-stratigraphic models that comprise the GSNSW statewide 3D model is shown in Figure 5.

## Clients

The GSNSW collaborates with other governmental agencies and industry partners through the delivery of 3D

models and accompanying advice which support:

- the strategic release of exploration areas
- assessment for economic potential
- decisions about land use
- assessing environmental impacts
- addressing community concerns about land-use decisions.

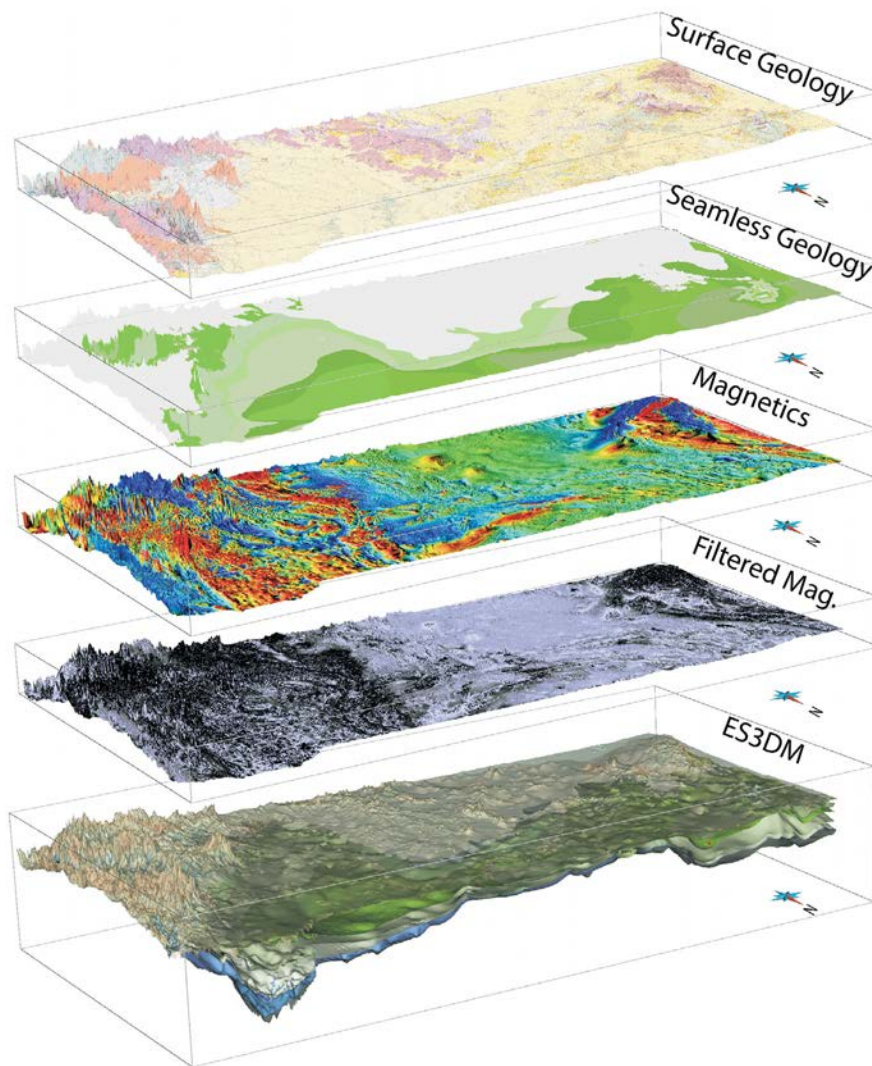
The 3D modelling will benefit the NSW Government, the resources industry, academia and, at more detailed levels, civil and environmental engineering.

For example, the NSW Office of Water referred to a GSNSW 3D model of the southern Sydney Basin to assess the possible impact of a proposed coal mine extension on the groundwater resources within the Sydney metropolitan water supply catchment (see below). The 3D model was used to predict depth to aquifer and water flow rates for proposed monitoring

wells and to estimate the recharge areas for each well.

In 2018, GSNSW used LiDAR data and Shuttle Radar Topography Mission data to construct a 3D model of the volcanic terrain of the extinct Warrumbungle volcano in central NSW for the NSW National Parks and Wildlife Service. The model was transformed into a physical diorama by a specialist 3D printing and routing company in the USA for display at the new visitors centre at the Warrumbungle National Park.

The GSNSW's 3D modelling benefits the resources industry by improving the understanding of regional architecture and its broad-scale relationships to resource distribution through improved understanding of crustal structure, the distribution of key source units at depth and mapping large-scale fluid pathways that assist in the reduction of the exploration search space and recognition of areas



**Figure 5.** Some of the datasets used for the Eromanga-Surat Basin region of the NSW 3D modelling Project and the final model surfaces (ES3DM). The view is 900 km east-west by 300 km north-south.

of mineral and hydrocarbon potential not previously identified. Constraint on depth to target horizons is also a key outcome and includes depth of sedimentary cover overlying potential metalliferous resources, depth to aquifers for water resources and depth to target stratigraphy for energy resources.

### Recent Jurisdictional-Scale Case Study Showcasing Application of 3D Models

The NSW Office of Water referred to a GSNSW 3D model of the southern Sydney Basin to understand the possi-

ble impacts of potential future mining activities on aquifers and groundwater flow within the Sydney metropolitan water supply catchment. The boundary of the model area is shown in Figure 6. The model was constructed in stages, with robust scoping and planning early in the project's lifecycle to ensure changes in design could be made before major effort was expended constructing model surfaces.

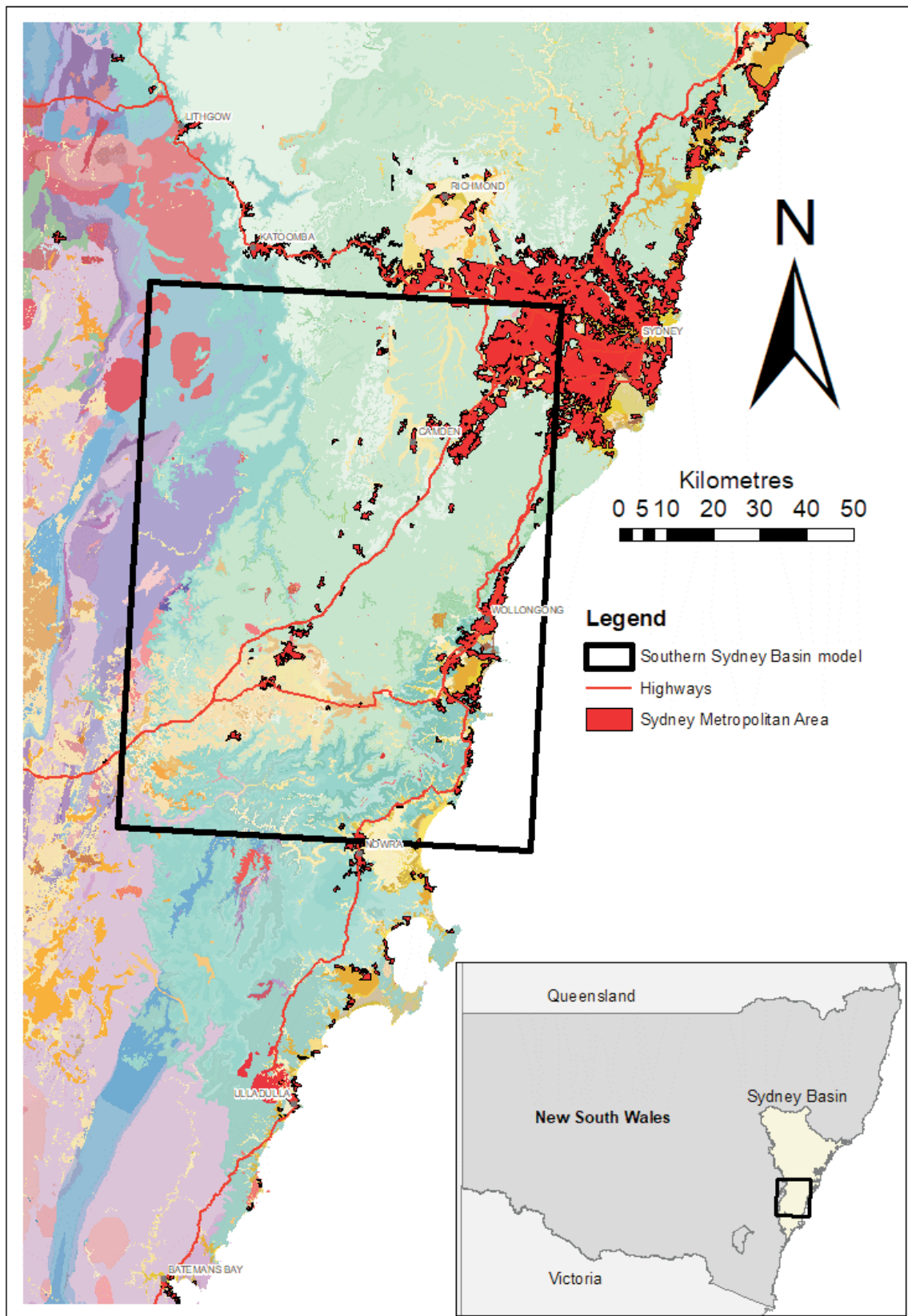
A total of 130 wells were imported and assessed. Four wells were discarded due of inconsistencies in the interpreted horizons. No seismic data was used to constrain the model, but pre-existing interpreted geological

cross-sections provided constraints for the structure of the basin throughout the modelled area. The NSW Seamless Geology geodatabase provided constraints at the topographic surface. The resolution of the model was 200 m x 200 m horizontally and 50 m vertically. Modelling focussed on the depth to stratigraphic formations. Faults were not modelled because of time limitations. However, fault surfaces were incorporated into a later model created for the entire Sydney Basin.

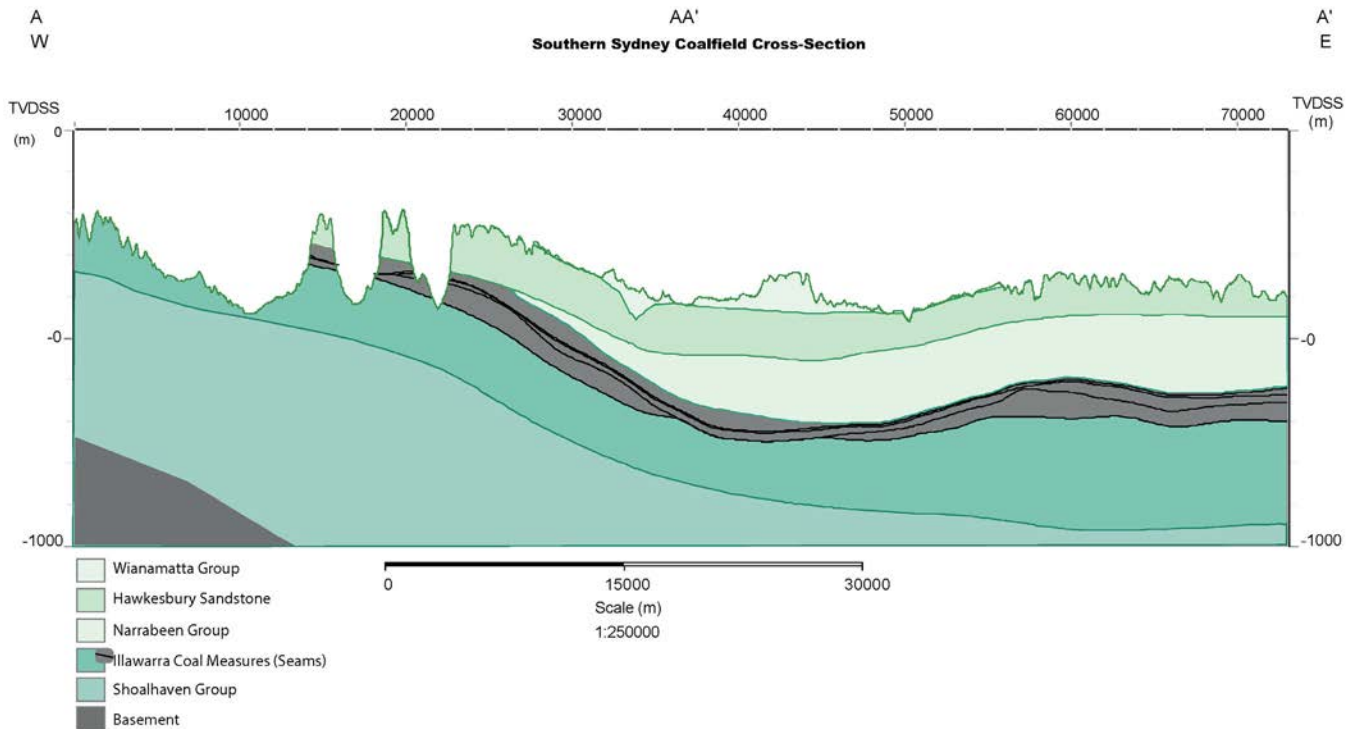
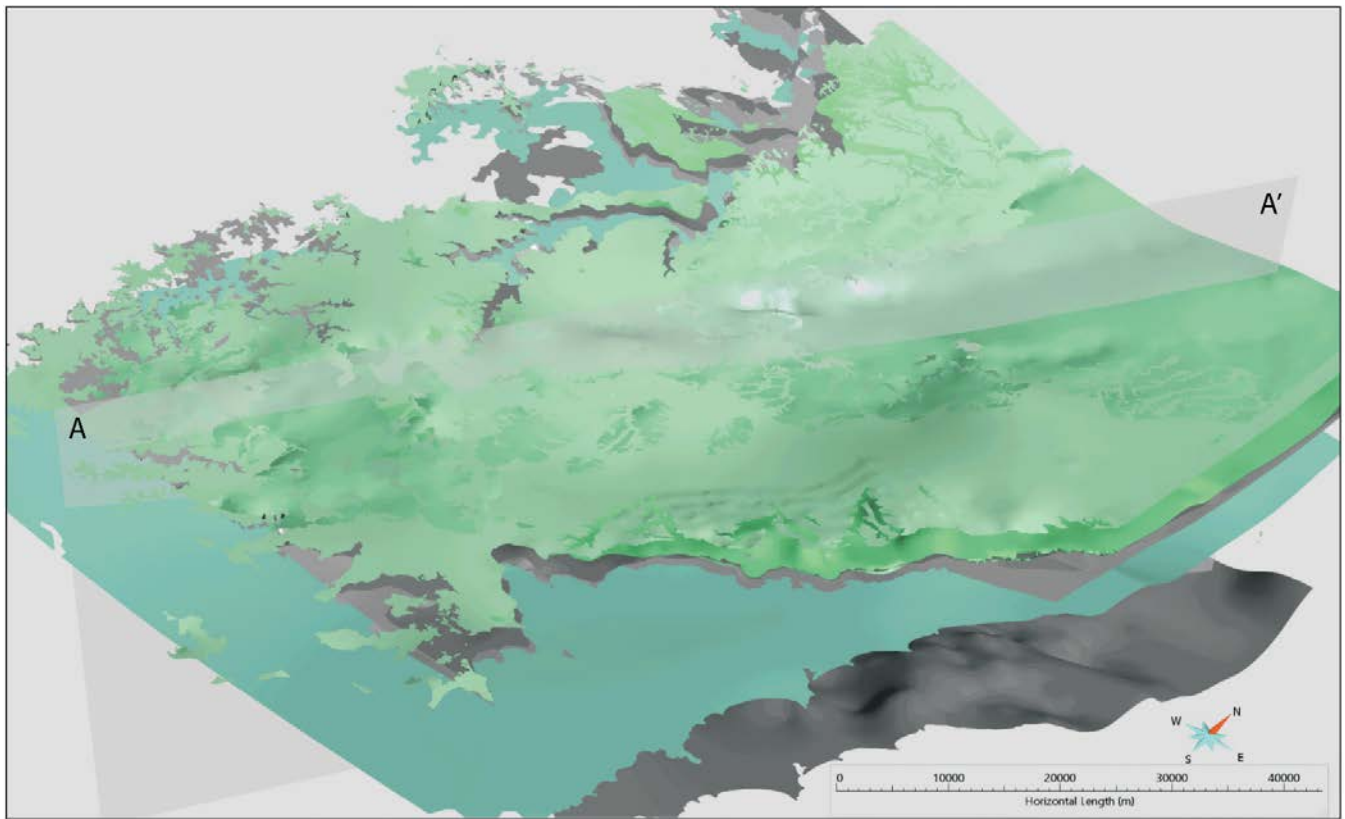
The accuracy and fitness for purpose of the model were peer-reviewed by geologists within the GSNSW. The final model provides an overview of the geology, structure and geometry of the southern Sydney Basin, as well as mapping the extent and depth of coal resources. Figure 7(a) shows a perspective view of the final model while Figure 7(b) shows a cross-section derived from the model depicting the depth to the coal measures and the relationship with the water-bearing Narrabeen Group, Hawkebury Sandstone and Wianamatta Group.

### Current Challenges

Current challenges facing the 3D modelling projects at GSNSW include the selection of an appropriate model scale, and the integration of datasets with a wide range of scales, spatial densities and resolutions. Data quality is also highly variable and is often related to the age of the data. With a team of 10 staff, GSNSW currently has the largest number of active 3D practitioners in the NSW Government, from a range of technical backgrounds, with access to up-to-date computer hardware and industry-standard modelling software. Despite this, there are still significant computational hardware and software constraints on the modelling resolutions that can be delivered, particularly when representing spatially dense datasets such as the NSW Seamless Geology geodatabase at statewide and regional scales. The GSNSW is cur-



**Figure 6.** Southern Sydney Model boundary over the Seamless Geology Map of NSW. The Permo-Triassic sediments of the Sydney basin are shown in blue and aqua colours while the pink, purple and red colours denote the meta-sediments, volcanics and granites of the Lachlan Orogen. A stratigraphic column showing the main formations in the Sydney Basin is shown in Figure 7(b).



**Figure 7.** Perspective view of the Southern Sydney Model showing location of section A-A' (**Top**). The view has a 50x vertical exaggeration. Cross section along A-A' derived from the model showing coal seam depths under the greater Sydney Metropolitan area (**Bottom**).

rently investigating the issue of delivering multiple model resolutions through a single online viewing platform. There are also resolution issues when detailed, data-dense resource models are embedded within the less-detailed data-sparse regional models.

## Lessons Learned

Potential improvements in procedures and workflows are documented upon completion of each 3D model. Improvements which have been implemented include:

- the difference in density of points between two datasets can cause undesired gridding effects when creating 3D surfaces. Reducing the number of points by distance (usually 30 m) or adjacent angle (usually 60°) from the contact produces a smoother result
- small ‘workarounds’ which ensure the best fit of the modelled surfaces to the NSW Seamless Geology geodatabase and the topography
- adjacent modelled grids and surfaces are usually added to each new modelling project to ensure a perfect fit between models
- for large-scale models, creating a basement layer using topography where orogenic provinces are outcropping will ensure that grids and surfaces for adjacent basins do not extend beyond their limits or above the current topographic surface.

## Next Steps

The statewide framework model of basins and orogens will be finished by mid-2021. In parallel with the development of the framework, GSNSW will focus on resource-scale models that will be embedded in the

statewide model. Models will also incorporate soil character and thickness, small-scale faulting, and other geotechnical data collected prior to and during major construction projects. These models will inform decision making about the location and form of major infrastructure as well as site assessments for future civil engineering works. GSNSW is also a member of the Loop Consortium led by Monash University, which is developing next-generation open-source tools to enable 3D geological modelling guided by statistical analysis of probabilities. The Loop Consortium algorithms will increase the productivity of 3D modellers as well as quantifying the error and uncertainty of models.

GSNSW commenced a major 10-year program in 2018 to drill through post-Permian sedimentary rocks to investigate the underlying basement in five under-explored regions of central and western NSW. This drilling and the supporting data acquisition will generate new geological information that will constrain ongoing re-interpretation of model surfaces. The statewide 3D geological model of NSW will continue to provide a versatile platform for data integration and visualisation to support the development of new geological concepts, guide mineral and energy exploration in the state, and inform decisions about land use and resources.

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# Chapter 19: New Zealand 3D Geological Mapping and Modelling

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## Introduction

The islands of New Zealand straddle the Australia-Pacific plate boundary in the south Pacific and are geologically complex, both spatially and temporally, abounding in geological resources and prone to geological hazards. The North and South islands have abundant petroleum, coal, gold, iron sand, groundwater and geothermal energy resources. Electrical power generation is greater than 85% renewable from hydroelectric, wind and, importantly, high-enthalpy geothermal sources. The Taranaki area has been a consistent producer of natural gas and oil since the 1970s and had smaller production over a century prior to that. Much of the country is generally well-endowed with clean surface water although groundwater adds significantly to meet agricultural, industrial and domestic needs.

New Zealand is subject to episodic, damaging geological hazards such as volcanic eruptions, earthquakes, landslides and tsunamis. In only the last decade, the devastating 2010  $M_w$  7.1 Darfield, 2011  $M_w$  6.2 Christchurch and 2016  $M_w$  7.8 Kaikoura earthquakes have had wide and long-lasting repercussions. Those involved in the reconstruction process are acutely aware of siting and designing buildings and other infrastructure appropri-

ately for local ground conditions, reinforced by mandatory Building Code requirements requiring knowledge of subsurface materials.

The geological resources and hazards of New Zealand have been the focus of surface geological mapping and other investigations for over a century. The increasing sophistication of 3D modelling software has resulted in growing construction and use of 3D geological and applied models over the last two decades.

## Organizational Structure and Business Model

GNS Science is a government-owned research institute that provides leading geoscience and isotope research and consultancy services for the benefit of New Zealand. Since the formation of its oldest predecessor organisation, the New Zealand Geological Survey in 1865, the production of geological maps and applied geoscience research have been mainstream activities. Funding has changed from entirely government allocation to a mix of strategic base funding, secured contestable funding and commercial revenue. In 2017–2018, around two-thirds of the total revenue to GNS Science of \$88M NZD (2018) was derived from research contracts to the New Zealand Government and the remainder from

commercial contracts including the GeoNet geohazards monitoring service. The 400 staff include geologists, geophysicists, material and isotope scientists, technicians and administrative support, 80% of whom are based in two campuses in Lower Hutt, Wellington region, 17% in Wairakei near Taupo, 2% in Dunedin and 1% in Auckland. The organisation is structured around discipline-based groups and cross-cutting research themes focussing on underpinning earth science, geological hazards and risks, environment and climate, and energy, minerals and materials. GNS Science has recently undergone significant strategy development and has structurally reorganised to align to these themes in 2019. One of the likely outcomes of the restructure will be improved coordination of expertise such as 3D geological modelling across geoscience domains.

## Overview of 3D Modelling Activities

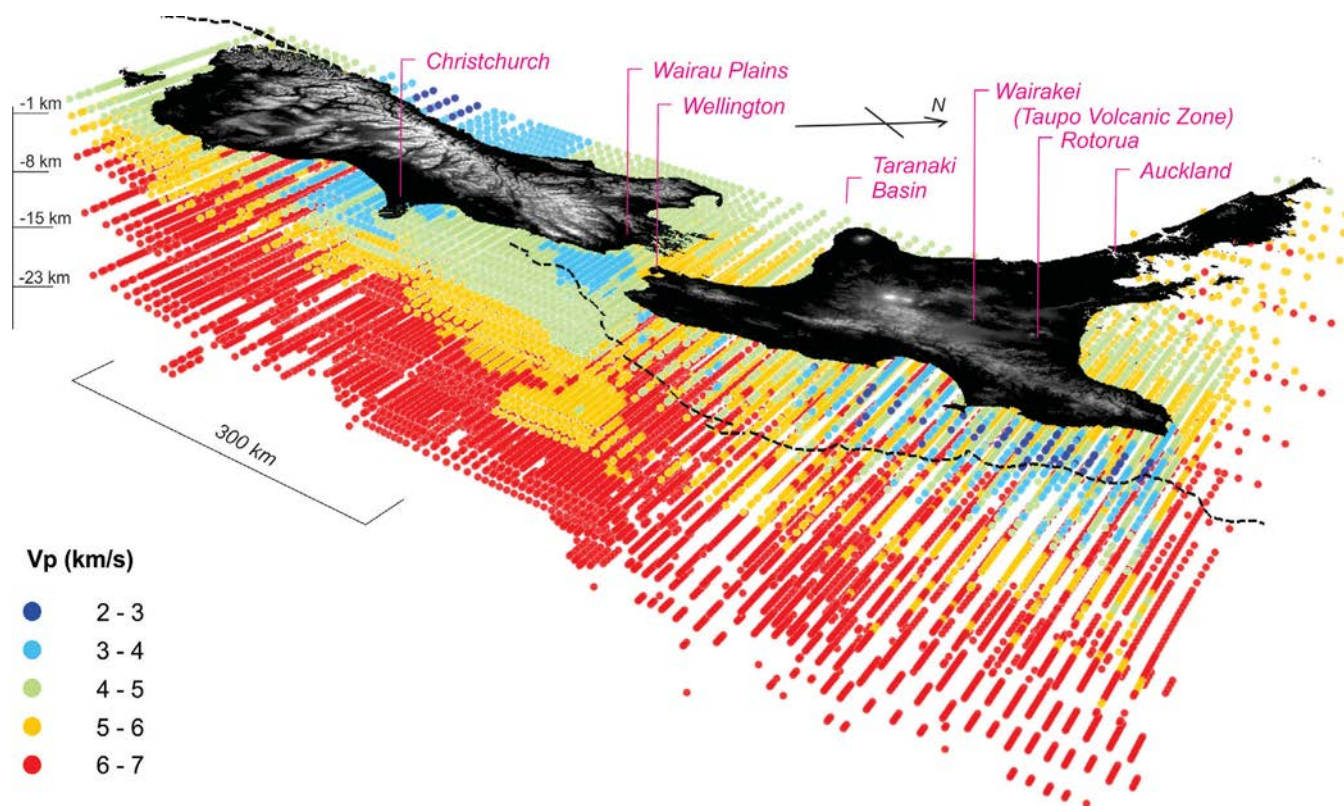
Three-dimensional modelling activities at GNS Science are principally spread across the geoscience domains of groundwater, urban geology, geothermal and petroleum. These activities are project-led through research and commercial contracts, and there has been limited organisational coordination across these domains until now.

Computer-based 3D modelling techniques were first applied in New Zealand for representing geology and groundwater hydraulic properties (White 2001) and are now commonplace in groundwater research. Groundwater-focussed models have been built for many parts of the country (White and Close 2016), particularly where groundwater provides a critical contribution to water supply, for example, Christchurch, Wairau Plains, Wellington and the Taupo Volcanic Zone (Figure 1). These models typically represent Quaternary sedimentary basins classified in terms of hydrogeological units, that is, geological layers that are grouped by hydraulic properties. They inform on groundwater system characterization, groundwater-surface water interaction, protection and restoration of lake environments, groundwater allocation, and drilling programmes. Depending on the application, strati-

graphic layer models and/or property voxel models are developed typically at sub-regional-to-catchment scales.

Geothermally-focussed 3D geoscience models guide exploration and sustainable extraction of hot water for power generation and industrial/domestic use. Three-dimensional modelling of geothermal fields began in New Zealand in the 1960s with a physical model (including temperature contours and geology) of the Wairakei geothermal field (Figure 2; White and Dawson 2018). Today, geothermal 3D models are built at all stages of geothermal development, from exploration to production stages, and range in extent from regional (the Taupo Volcanic Zone in the central North Island) to specific geothermal field areas. Modern digital 3D geothermal models integrate multidisciplinary data relevant to a region or a particular geothermal field,

to understand the constraints on the location and characteristics of the heat source, the fluid preferential pathways related to formation and/or structural permeability, and the reservoir extent, thickness and overall characteristics. To achieve this, a geological framework model is built with surface and subsurface geological and structural data/interpretation, as well as rock property models, alteration zoning, natural state temperature models and information from geophysical datasets. The resulting model(s) enable visualisation of dynamic reservoir properties, such as changes in reservoir parameters under production. Aside from geophysical datasets and surface mapping, the primary source of data is from geothermal wells. These vertical or deviated wells are usually deep, ranging from 500 m to 3000 m depth.



**Figure 1.** The New Zealand region characterised in terms of a 3D seismic velocity model ( $V_p$  data extracted from the New Zealand Wide model 2.1 of Eberhart-Phillips et al. 2017). The ocean floor subduction front (dashed line) is where much of the displacement occurs across the Australia-Pacific plate boundary. Slower seismic velocities persist to greater depth in the continent-continent collision part of the plate boundary below the northern South Island. Place names refer to specific 3D geological, geothermal and groundwater models mentioned in the text.





**Figure 2.** Co-author and 3D geomodeller Conny Tschrutter with the wooden Wairakei Geothermal Field physical model, built circa 1960 (White and Dawson, 2018). The Wairakei Geothermal Power Station (2018) is in the background.

Urban geological mapping involves a component of 3D geological modelling to provide subsurface as well as surface geoscience information for New Zealand cities. This information enables better resource management, hazard mitigation, infrastructure development and general planning. The subsurface geology of cities, or parts of larger cities like Auckland (see Figure 1), is being modelled through digital drillhole log interpretation, surface geology and geophysics. Where data density permits, 3D geological models have been built and a near-surface geotechnical model was built from abundant cone penetration test (CPT) probe data in the Christchurch area (see Figure 1; Begg et al. 2015; Rattenbury et al. in press). The high resolution of digital CPT data helped define the extent of sensitive earth materials, contributing to the re-building of the city and its infrastructure after the destructive 2010-2011 earthquake sequence. Recent work in central Wellington is focussing on understanding the seismic

response of near-surface materials and basin edge effects. The research follows the damaging Kaikoura 2016 earthquake and is driven by a need to better mitigate the effects of seismic amplification around Wellington harbour.

Petroleum 3D geological modelling has been undertaken to support the exploration of oil- and natural gas-prospective areas, notably capitalising on the substantial research and exploration undertaken in the Taranaki Basin of western North Island (see Figure 1). This effort has concentrated on developing high resolution 3D models to help understand the sedimentary and structural architecture of the Taranaki region. Three-dimensional seismic reflection data have been analysed to reconstruct sedimentary strata and lithology distributions. The results are integrated with high resolution mapping of faults. Well data were analysed to reconstruct stress fields and to map fault properties. Temporal components have been introduced into the model such as information on geological age to reconstruct the evolution of the sedimentary basin. Subsurface geometries have been restored through time to assess the architecture of carrier beds for fluid migration and their effectiveness in charging oil and gas accumulations at different times in basin history. These results are being integrated with geochemical information on source rocks and fluids to create advanced models of the movement of oil and gas in the subsurface.

Abundant seismic arrival data across a dense network of seismographs over many decades or recording have enabled the building of a detailed national seismic velocity model (see Figure 1, Eberhart-Phillips et al. 2010). A national 3D geological model is under development. The first iteration will model two layers; the Quaternary superficial sediments and volcanic deposits, collectively, and the Late-Cretaceous-Pliocene cover

sedimentary rock dominated succession.

## Resources Allocated to 3D Modelling Activities

There are few dedicated 3D modelling staff within GNS Science. Those with the requisite skills, 10-15 in number, are also typically engaged in other functions, either as scientists or in technical support. Modelling is commonly part of a defined project in a geoscience domain; a 3D geological or other model may be a product resulting from the project, and a process such as fluid flow may be modelled from that 3D geological model framework. A total annual budget for 3D modelling is difficult to calculate and investment levels vary each year depending on the number, size, duration and stage of the projects.

## Overview of Regional Geological Setting

The New Zealand land mass is underlain, in simplistic terms, by thinned continental crust basement of Paleozoic-Early Cretaceous metasedimentary and plutonic-dominated igneous rocks, exposed over much of the South Island and in ranges of the North Island (Edbrooke 2017). These basement rocks are overlain by variable thick and semi-continuous succession of Late Cretaceous-Cenozoic sedimentary rocks, with significant volcanic outpouring at various periods, notably in the Miocene-Quaternary in northern and central North Island. The rocks are complexly faulted, in part a consequence of the present Australia-Pacific plate boundary that divides the South Island and lies east of the North Island coast. Discrete plate boundary processes were active in the Cambrian, Devonian-Carboniferous and Permian-Mesozoic, and these have resulted in major basement structures that have preconditioned the structural complexity of the modern plate boundary. The plate boundary is wide and is actively extending across the central North Is-

land whereas shortening is occurring across the South Island and eastern North Island. Deformation is expressed in contractional, extensional and lateral faults through the country, locally elevating or subsiding ground. This in turn has resulted in major downslope movement of eroded material through alluvial processes and the formation of extensive alluvial plains. Many of these alluvial sand and gravel layers are important aquifers.

The steep topography in many parts of the country has focussed people, buildings, roads and other infrastructure into valleys and coastal plain areas and these are floored in poorly consolidated sediment, commonly bounded by or masking active faults. Changing sea levels through the Quaternary have resulted in marine incursions into low-lying coastal areas. The sediments associated with these incursions have been susceptible to liquefaction in historic earthquakes, most notably during the 2010  $M_w$  7.1 Darfield and nearby 2011  $M_w$  6.2 Christchurch events.

## Data Sources

New Zealand has abundant high-quality surface geoscience data onshore. The modern digital topographic base is accurate for district and smaller-scale applications and abundant and growing LiDAR coverage is particularly useful for larger scales. High-quality surface geological map data are available nationally at regional and smaller scales in richly attributed GIS formats. Some areas of greater geological detail exist in many cities and other areas. The stratigraphic framework is well established and there are specific digital databases for active faults and landslides.

Drillhole and well data are dense in many places, depending on their purpose. Petroleum-related exploration and production wells are numerous in onshore and offshore Taranaki and are sporadic elsewhere. These have detailed logs of geological and geo-

physical parameters. Major urban centres have abundant geotechnical and engineering drillholes and probe data, particularly in their inner-city areas. The quality of drillhole logging is highly variable although recent trends are towards digital capture to industry data standards (AGS4 <http://www.agsdataformat.com>). Geothermal areas are typically abundantly drilled through their exploration to production transition and their drillhole logs are typically very detailed. The logs are commonly confidential to the companies that are developing geothermal fields and therefore may be unavailable for building public domain 3D models. Some areas have significant extraction of groundwater through a network of wells, for example, Canterbury has more than 40,000 wells, many with useful geological logs. In general, however, most groundwater wells only have lithological logs of variable quality and no geological interpretation. Additional analysis of the well data is required to use these logs for geological modelling.

Different types of geophysical data are available in many areas and these include gravity, magnetics, magnetotellurics, active source seismic surveys, passive seismic and ambient noise methods and ground-penetrating radar. These surveys include crust-mantle tomography (Eberhart-Phillips et al. 2017), upper crustal 3D seismic (Bull et al. 2010) and surficial cone penetration test data (Begg et al. 2015). Approximately one third of New Zealand's land surface is covered by high resolution airborne geophysics (aeromagnetics  $\pm$  radiometrics  $\pm$  aerogravity  $\pm$  electromagnetics at 200-300 m line spacing). Some of these data have been forward modelled or have inversion techniques applied to derive shapes and constrain depths of subsurface boundaries. Urban areas are challenging places to acquire many of these types of data without significant noise. Active source seismic surveys, particularly

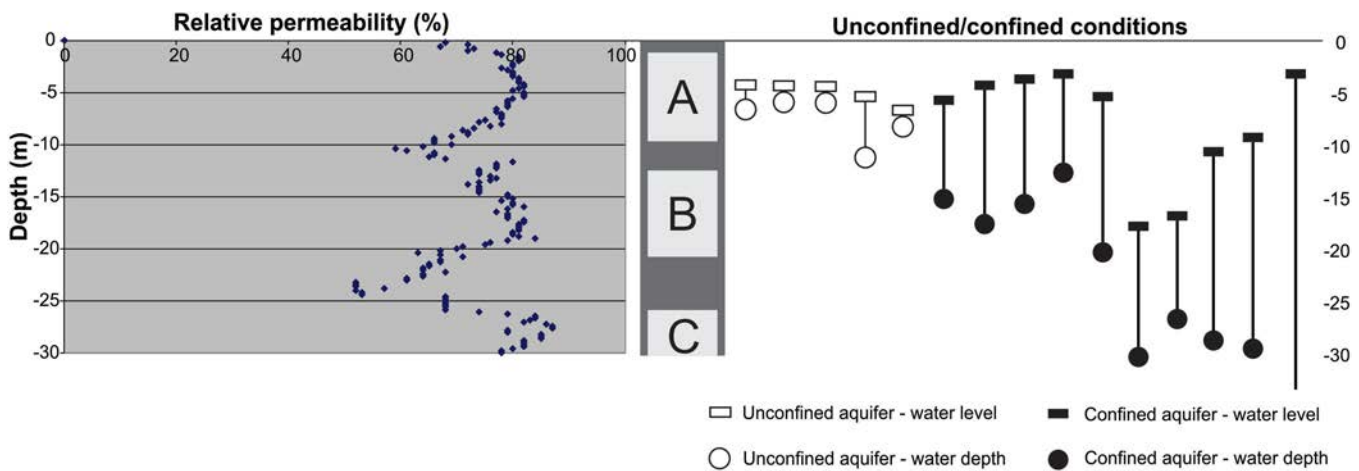
when tied to well data, can provide useful constraints and extend geometries.

Most of the data obtained for government or councils on public land are publicly available and are subject only to light attribution licence constraints. Some data, however, when supplied by a commercial client and used in 3D models can result in confidentiality restrictions placed upon them. Data obtained from private land and used in published models that could disadvantage the owner would contravene the Privacy Act 1993. The growing trend to supply input data with the 3D models to better ensure product longevity requires diligence from GNS Science to ensure data confidentiality and privacy requirements are met.

## 3D Modelling Approach

The modelling approach varies between, and to some extent within the geoscience domains, and is in part dictated by the choice of modelling software. The petroleum models are built with a combination of explicit Gocad and implicit Skua software approaches. The geothermal, urban and many of the groundwater models use implicit modelling tools from Leapfrog Geo/Geothermal and EarthVision software but commonly utilise explicit control points to guide surface generation. In general, only single models are built although probabilistic models are important in groundwater research, where aquifers and aquicludes occur side-by-side in similar geological materials (Figure 3).

Model confidence has been empirically assessed for some 3D models, typically based on distance from input data, subjective estimate of the quality of the input data and depth below surface. Probabilistic models of gravel distribution were found to produce reasonable predictions of aquifer location (White and Reeves 1999).



**Figure 3.** Model of gravel distribution in Quaternary sediment that identifies aquifers (A, B and C) with statistics on gravel descriptions in well logs (White and Close 2016).

## Clients

The primary end users and stakeholders for the 3D models vary between and within the various geoscience domains and include central and regional government, industry, consultants and the general public. The level of interaction with the end user varies accordingly. In some cases, the 3D model can be interrogated through a web application, for example, the groundwater-based Earth Beneath Our Feet <https://data.gns.cri.nz/ebof/> or virtual cross-sections in the Taranaki Basin [https://data.gns.cri.nz/pbe/index.html?map=South\\_Taranaki](https://data.gns.cri.nz/pbe/index.html?map=South_Taranaki), and the model itself is not transferred.

In some cases, the 3D model is part of a published product, for example, the Christchurch geological map (Begg et al. 2015). The client will use the presented model typically through a 3D viewer application. Derivative layers and volumes provided as part of the data product may be used by the client in GIS or other specialist software. Free 3D viewer software is an important visualisation tool for all clients. The limited functionality of the 3D models provided for these software is balanced by them being free-to-use and comparatively easy to manipulate. The 3D viewer models are commonly used for technical educational training. Movies derived from 3D models are another important way

of conveying understanding of modelled earth systems to many end users (White et al. 2018a).

Many geothermal and groundwater models have been built and retained within GNS Science with industry or regional council collaboration. This may include their ongoing support for development of the model in return for specific information from it, particularly where there are ongoing temporal changes to model inputs. Groundwater levels and flows are recorded by sensors in many aquifers and these result in changes to water allocation models. For geothermal fields, new drilling results are incorporated into the 3D model for the client as part of a standard contractual service.

## Recent Case Studies Showcasing Application of 3D Models

### *Wairau Plains 3D Groundwater Model*

Groundwater is a very important resource in the Wairau Plains (see Figure 1) located in the Marlborough region in northern South Island. Water management challenges in the Wairau Plains include an increase in water use over time and degradation of groundwater quality that has been linked to land use. These challenges

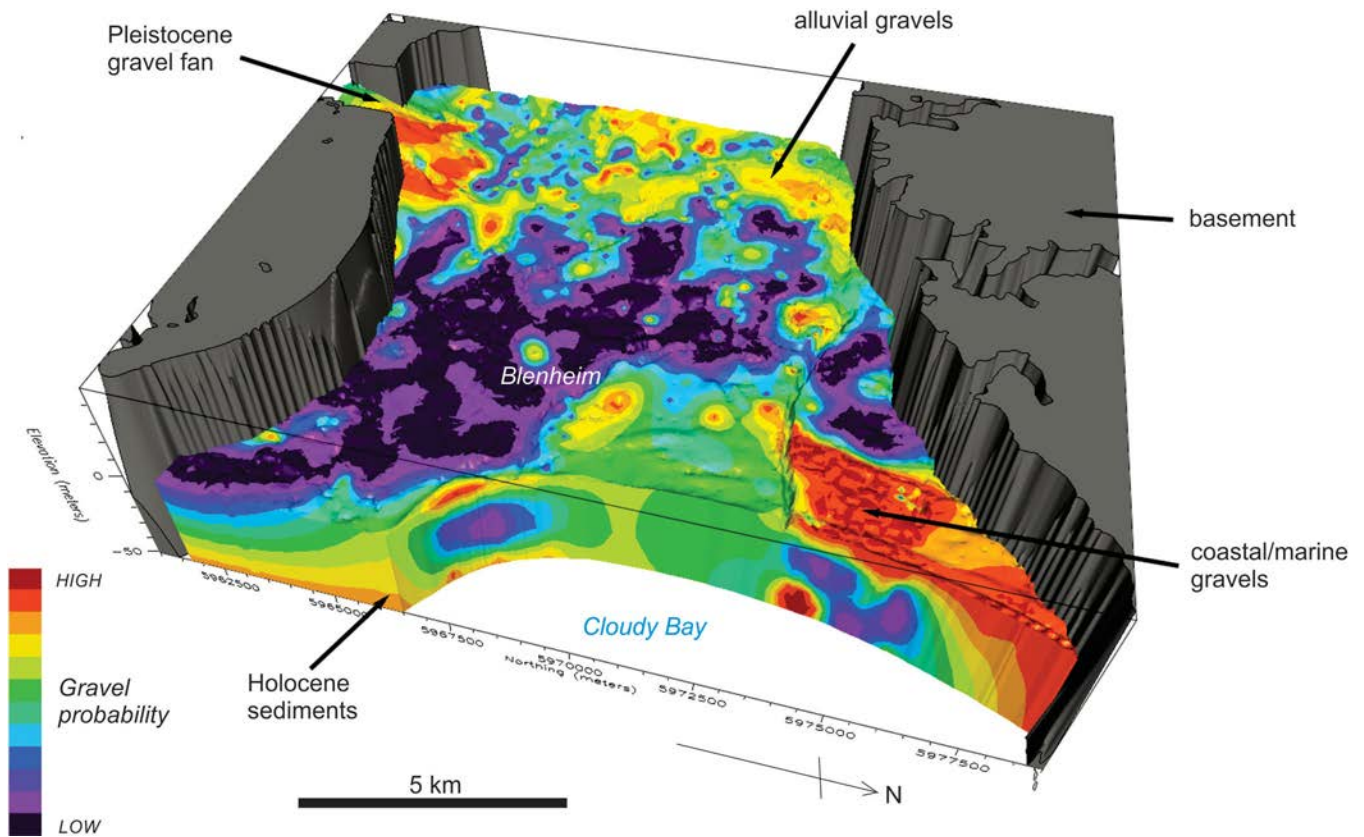
require better characterisation of the system's hydrogeology, including the coastal Holocene gravel aquifer, and surface hydrology. To achieve this, 3D lithological models can be used that represent the 3D distribution of lithological descriptors, for example, gravel identified in well logs.

One of these lithological models, a probabilistic model of gravel distribution in the coastal Wairau Plains (Figure 4) was used to develop a groundwater budget of the Wairau Plains that showed that co-management of land and water is required to address current pressures on water resources in the study area because of the hydraulic links between land, the Wairau River, the Holocene aquifer and spring-fed streams (White et al. 2016).

Current 3D-related research in the Wairau Plains include time-series facies models and the 3D printing of physical models (White et al. 2018a).

### *Rotorua 3D Geothermal Model*

A 3D geoscience model of the Rotorua Geothermal Field (see Figure 1) and surrounding areas of the central North Island have been built with Leapfrog Geothermal software to better understand and visualise its geological setting. The Rotorua geological model was built for the Bay of



**Figure 4.** Probabilistic model of gravel distribution in the coastal Wairau Plains, Marlborough District, viewed from the coast. Gravel is common where coloured red to orange and rare where coloured dark blue to purple (White et al. 2016).

Plenty Regional Council (Figure 5; Alcaraz and Barber 2015) to support the council policies and decision making for managing the sustainable use of the resource. The model facilitates conceptual understanding of the field and constrains numerical simulations of the geothermal reservoir behaviour and response to utilisation (for example, Ratouis et al. 2017).

The Rotorua Geothermal Field is located in the southern part of the Rotorua caldera. Active faults are mapped south and north-east of the caldera rim, while the structures within the caldera have been buried under young sedimentary and volcanoclastic layers.

The drilling of geothermal bores started in 1920 and there are now more than 1,300 boreholes in the area. Most bores are shallow (< 150 m drilled depth) and reliable subsurface geological data are scarce.

Results from geophysical surveys (seismic, gravity, magnetotellurics) have been used to define geological structures at greater depth.

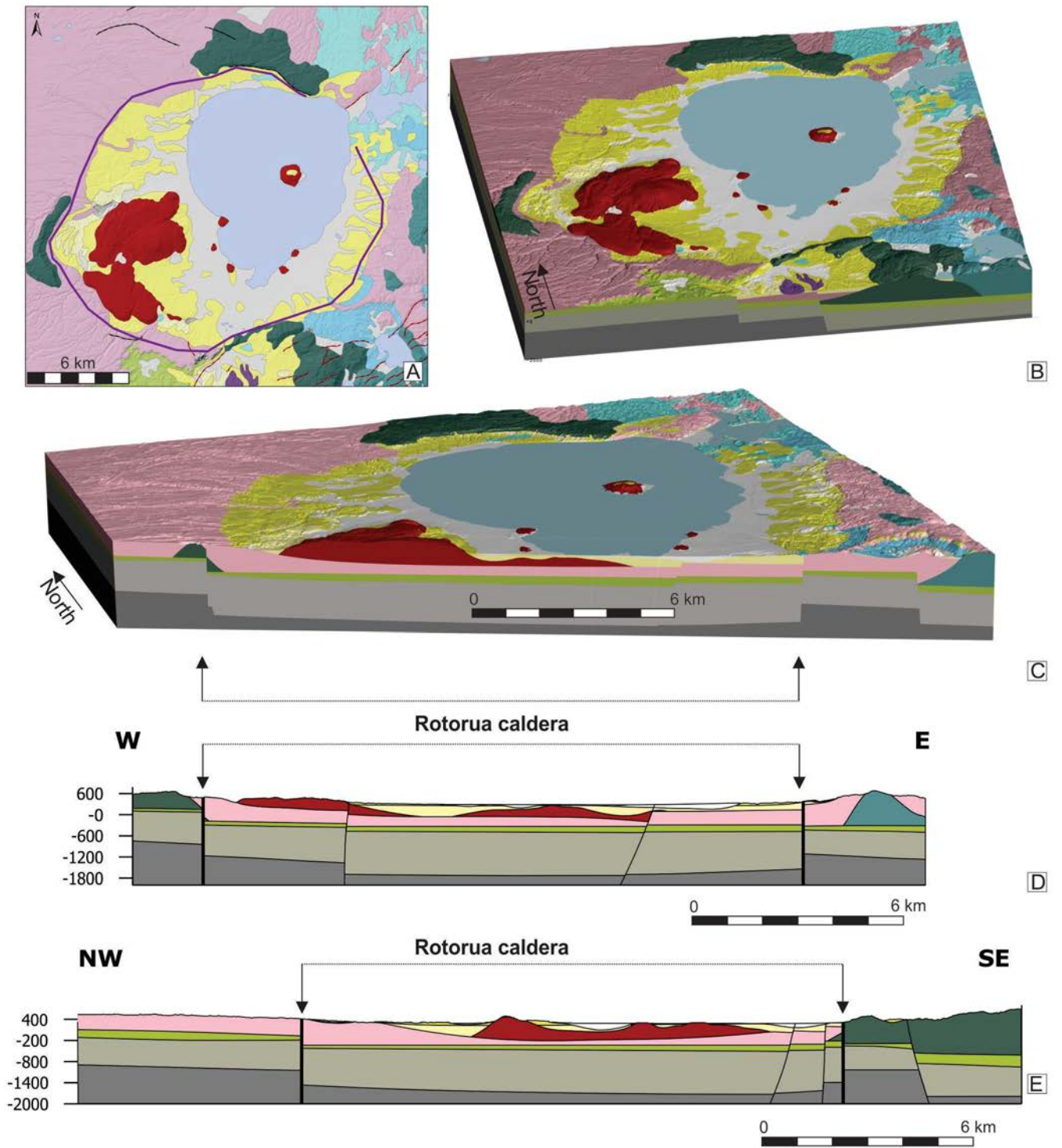
Lithological models have since been built from rock type descriptions to represent permeability variation in the rhyolite and sediments forming the shallow part of the Rotorua reservoir. These models help identify fluid flow pathways within the heterogeneous sediments.

Temperature logs from monitoring bores and surveyed features at the ground surface enables modelling of the temperature distribution within the reservoir. Combining the temperature model with a 3D magnetotelluric model allows us to better understand the hydrology of the system and better constrain the conceptual model that underpins the reservoir simulation grids (Figure 6).

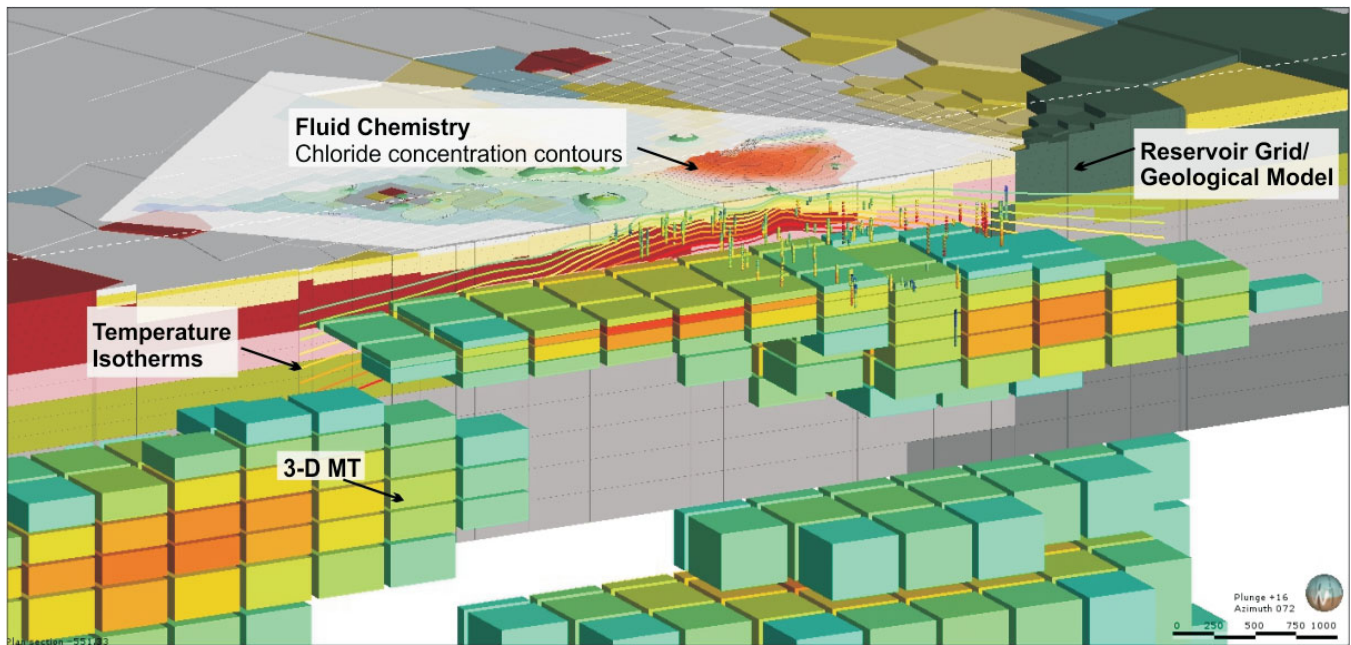
### **Christchurch 3D Urban Geotechnical Model**

The aftermath of the 2010  $M_w$  7.1 Darfield and 2011  $M_w$  6.2 Christchurch earthquakes resulted in a massive rebuilding of the mid Canterbury area involving reinstatement of buildings, roads, pipe and cable networks and other infrastructure. The susceptibility of some earth materials to seismic shaking was exposed during these earthquakes and precipitated more than 10,000 cone penetration test (CPT) soundings to better understand near-surface ground conditions.

These CPT sounding data are measures of sleeve friction, cone penetration resistance and pore water pressure. Earth material proxies such as soil behaviour type can be derived from them. The 3D geotechnical numerical model (Figure 7; Begg et al. 2015; Rattenbury et al. in press) was built with Leapfrog Geo software utilising 0.2 m aggregated measurements



**Figure 5.** 3D geological model of Rotorua: **A)** Geological units mapped at ground surface. The Rotorua caldera boundary is indicated by the purple line. **B)** 3D view of the Model. **C)** WNW-ESE slice through the model. **D)** and **E)** Cross-sections through the model.



**Figure 6.** The reservoir grid derived from the Rotorua Geothermal Field geological model in the background is categorised here by rock type and has a chloride concentration overlay and temperature isotherms depicted on the sectioned face. In the foreground, a 3D grid of magnetotelluric values (3D MT) shows variation in electrical conductivity attributable to degrees of geothermal alteration.

from around 1,500 selected soundings at an average horizontal spacing of 127 m. Spatial interpolation between CPT soundings was conditioned by an oriented spheroid that reflected trends defined by a conceptual model of depositional geometry, that is, interfingering terrestrial and marine sediments dipping very gently south-east.

### **Taranaki Basin 3D Geological Modelling**

The Taranaki Basin petroleum province (see Figure 1) is being progressively modelled in 3D (Figure 8) as part of the “4D Taranaki Project”. The overall objective of the project is to improve our knowledge of the structurally complex Taranaki Basin and better define its remaining petroleum potential through seismic interpretation and 3D static structural modelling.

Interpreted seismic horizons and faults are modelled in two-way-time (TWT) using Paradigm® SKUA-GOCAD™ software. The aim of the implicit static modelling was to best

represent the basin fill on a sub-regional scale.

Lateral modelling resolution is variable (ranging from 500–2000 m) and was adjusted for different volumetric regions according to computation limitations, seismic line spacing, and in some cases to better fit prominent anticlinal structures and well markers. Computation limitations meant that the mapping area could not be modelled as one volume, but as a small number of constituent volumes. The modelled results from each constituent area were then merged together to produce output grids that are continuous across the mapping area (Bull et al. 2015).

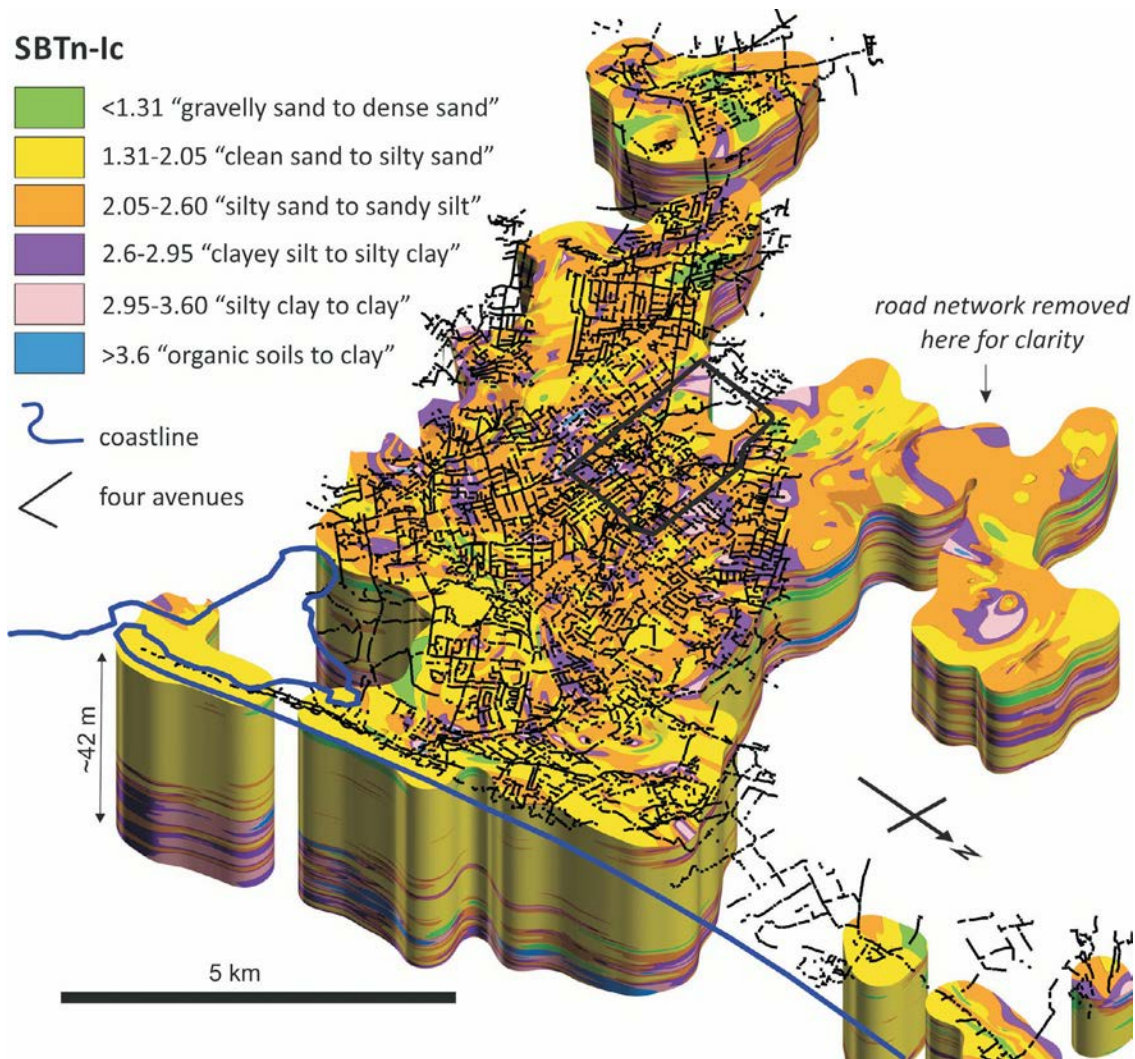
### **Current Challenges**

The main challenge GNS Science faces with 3D modelling is organisational; our applications necessarily vary between geoscience domains and are further constrained by an organisationally-imposed project-driven structure. Different software, needed for specific domain modelling, requires software-specific specialisation

and this restricts interchangeability of staff and methodologies. There is limited overview and coordination across domains. Finding, using and understanding 3D models across geoscience domains is not commonly needed, and is made harder by project-focussed network folder storage and insufficient metadata availability.

Complex 3D models stretch computing resources to breaking point. File sizes and memory requirements are constantly pushing hardware limits and some software have internal limitations. There is an ongoing tension between resolution and model extent dictated by computing capabilities. Modelling at the limits of computing constraints can significantly slow progress and can result in frequent software crashes and potentially model corruption.

New Zealand has a comparatively low investment in subsurface infrastructure, attributable to our relatively low population density, and this has restricted the amount of information relevant for 3D geological modelling. Some urban geology and groundwater



**Figure 7.** Soil behaviour type (SBTn-Ic) calculated for Christchurch 3D geotechnical model based on cone penetration test data (after Begg et al. 2015). Data ranges are proxies for different earth materials and these materials correlate to known sea level changes that influenced the deposition of marine and terrestrial sediments. The “four avenues” are well known streets in the city’s central area.

study areas are not well constrained by available drill hole data, to the extent that 3D models have not been considered because of the large uncertainties. Conversely data overload can also be challenging for the modeller as well as the end user, particularly for applications such as geothermal systems where there are multiple variables interacting in 3D space (and further complicated by a temporal dimension).

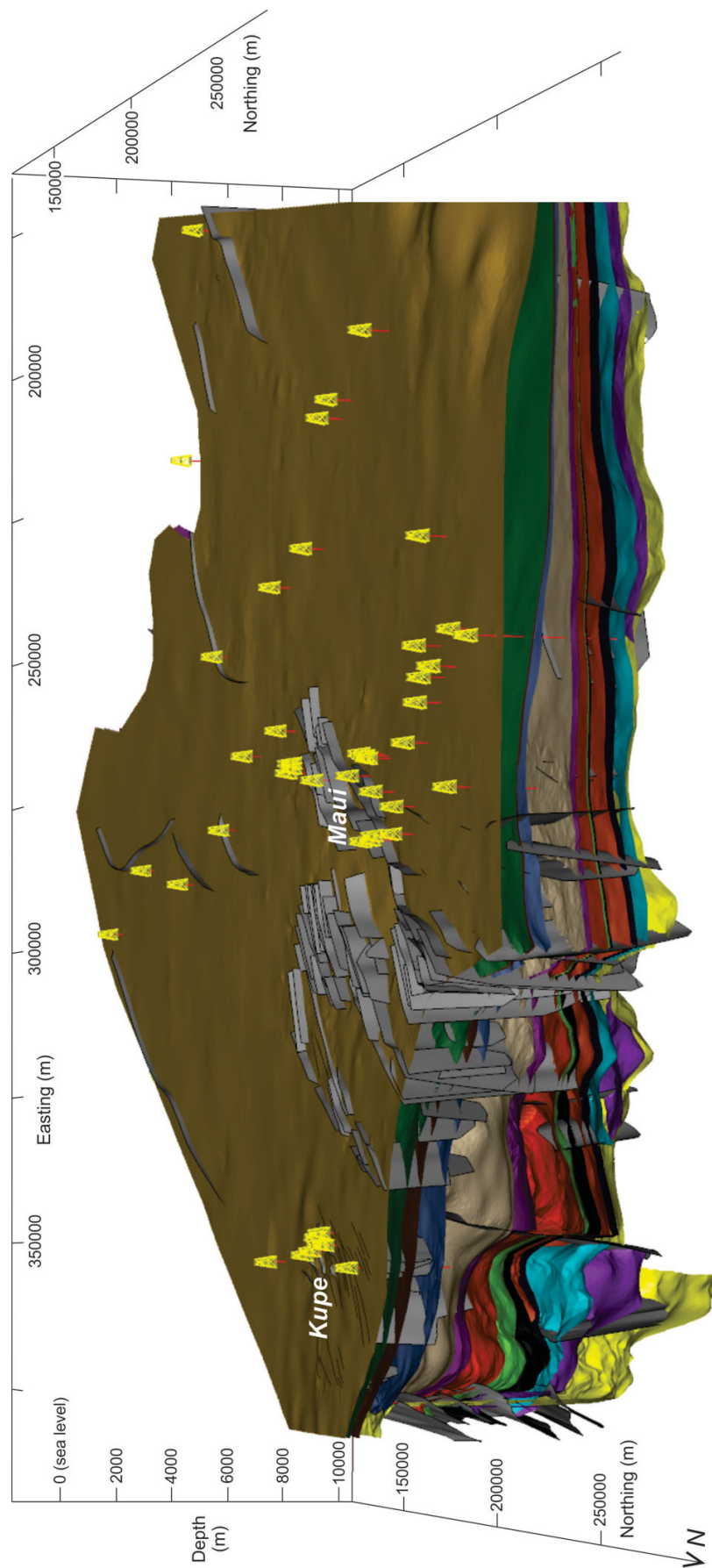
As a geological survey, an important function for GNS Science is to preserve geoscience information for the long term. The rapid evolution of 3D

modelling software has already resulted in some early-version models being unreadable in later-version software. Unless completed models can be regularly upgraded with new software, an impost on already stretched resources, then significant work could become digitally unreachable. Solutions for the moment include generic databases to store raw data (such as spreadsheets to store well log data) and to deconstruct completed models into component parts such as individual surfaces and volumes in generic ASCII or widely interchanged file formats such as T-surfaces, shapefiles and common raster types (Rattenbury

and Jones 2015). Most GNS Science 3D models are accompanied by a report that describes construction of the model and the input data, but some historic models are not well described.

## Lessons Learned

Our experience is that expectations associated with 3D modelling can be unrealistically high. The models can be visually compelling and appear authoritative but conveying often high levels of uncertainty and non-uniqueness of the interpretation where data are lacking is challenging. Many



**Figure 8.** Cross section slice through South Taranaki static model, part of the 4D Taranaki Project (after Bull et al. 2015). The coloured surfaces are key stratigraphic horizons, locally offset by faults (grey), including the basin-defining Taranaki Fault on the left edge. Kupe and Maui are the major oil and gas producing fields in this view.



model features have limited attributes attached and end users can struggle to understand what is being depicted. Their usability in real-world applications can be more limited than expected as end users typically do not have 3D modelling software to work with production models. Free viewer software is available, but functionality is typically limited and the end user can struggle to interleave their own data, commonly from GIS platforms, to contextualise the 3D geological data supplied.

For some applications, 3D geological models have proved to be a useful adjunct to, but not a replacement for, surface-based geological mapping and other data. Interpreted drillhole data can be effective enough for conveying subsurface lithological or stratigraphic variation where data are sparse, and they also convey where constraining data are.

Three-dimensional geological models can be re-engineered in terms of other properties and this has proved to be useful for validating surface measurements, for example, seismic site period, and interpolating or extrapolating them. For the geothermal industry, the models have been really successful for well planning, effective for integrating all available information, and promoting multi-disciplinary studies.

## Next Steps

Three-dimensional modelling, for geological and applied purposes, is an important part of GNS Science's research programme and information management and delivery. For some geoscience domains such as urban and petroleum geology, 3D models and interpreted drillhole datasets are provided to complement other more conventional data products such as 2D maps and cross-sections. Providing a variety of map and model data products caters for end users who have varying levels of technical capability and different applications; 3D

geological models are unlikely to supplant surface geological maps for urban applications, for example. Other domains use 3D geological models as starting points to model processes, notably fluid flow relating to groundwater and geothermal applications as well as petroleum. The development of some of these models already involves collaboration with specific clients who require results generated by these models rather than the acquiring the models themselves.

Coordinated 3D geological modelling across geoscience domains will be facilitated by the implementation of GNS Science's new organisational structure that is currently being rolled out. There is also accelerated implementation of good dataset management practise in general across GNS Science. There is a clear need to improve data management of our 3D models and their associated data, starting with metadata to enable their discovery and understand their lineage.

## Acknowledgements

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# Chapter 20: Ontario Geological Survey Three-Dimensional Mapping Activities

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## Introduction

The Ontario Geological Survey (OGS) is mapping southern Ontario's Quaternary deposits in 3D by developing interactive models that can: 1) aid in studies involving groundwater extraction, protection, and remediation; 2) assist with the development of policies surrounding land use and nutrient management; and 3) help to better understand the interaction between ground and surface waters. The goals of each project are to reconstruct the regional Quaternary history, assemble standardized subsurface databases of new and legacy geological and geophysical information, build 3D models of regional-scale sediment packages, and generate both technical and user-friendly products. Understanding the architecture and inherent properties of the Quaternary sediments that overlie bedrock will assist in the development of provincially-mandated source water protection plans and with geoscience-based management plans for groundwater resources. Guided by the Places to Grow Act (2005), priority 3D mapping areas are identified with advice from local conservation authorities who are knowledgeable of local water issues and long-term pressures facing groundwater resources.

## Organizational Structure and Business Model

The OGS is a provincial organization that is within the Mines and Minerals Division of the Ministry of Energy,

Northern Development and Mines. The OGS is the principal government organization responsible for the collection, documentation, and distribution of regional geoscience data. The OGS is funded by the provincial government and our operating budgets are set on an annual cycle. As the steward of Ontario's public geoscience data and information, the OGS provides public access to this information free of charge.

There are 4 administrative units within the OGS, and each provides specific core functions. These are:

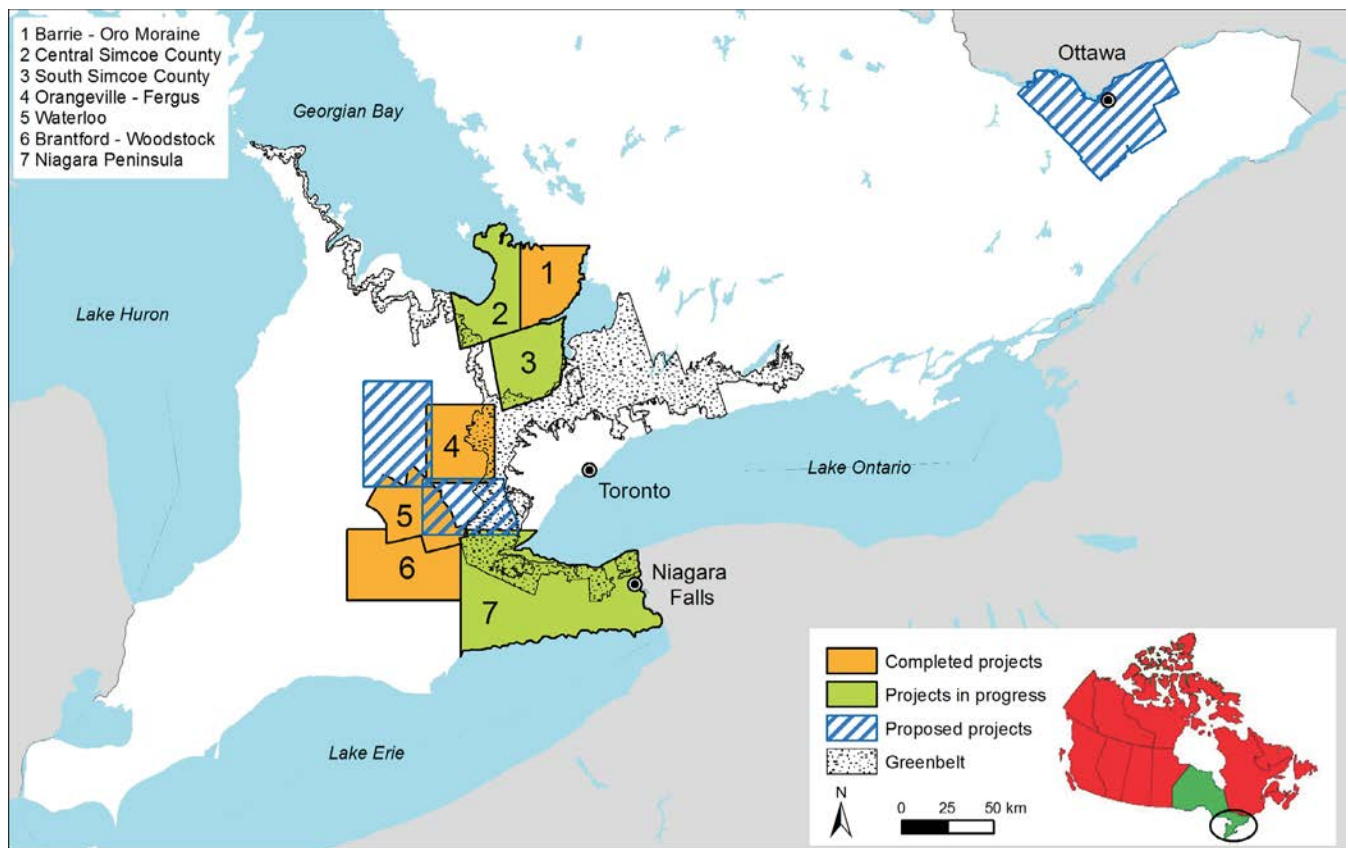
- **Director's Office**
- **Geoservices Section:** chemical and physical analyses of inorganic geological materials; cartographic, editorial, and publication services; library services and warehouse services
- **Resident Geologist Program:** local area geologic knowledge and expertise as it applies to mineral resource assessment
- **Earth Resources and Geoscience Mapping Section:** geoscience data collection, interpretation, and dissemination

The mapping section conducts field-based geological surveys aimed at better defining and understanding geological processes and earth resources to support the minerals industry and clients engaged in science related to the environment, natural hazards, public health and safety, and climate change adaptation. While the

collection of geoscience data pertinent to understanding groundwater has been ongoing for over 125 years, the pace has accelerated in the years since the 2000 Walkerton contaminated water tragedy. In that time, we have migrated from adhoc projects to an integral, Ontario Public Service Amethyst Award winning initiative that includes 3D sediment and Paleozoic bedrock mapping, as well as ambient groundwater geochemistry.

## Overview of 3D Modelling Activities

OGS led 3D sediment mapping activities are concentrated within the densely populated southern regions of the province (Figure 1). In 2002, a pilot project was initiated in the Regional Municipality of Waterloo (Bajc and Shirota 2007). This area was selected for the initial study as it is one of the leading municipal users of groundwater in Canada and is within an area of intense population growth where pressures on the groundwater resource are expected to increase significantly. Protocols for 3D sediment mapping were established as part of this project, guided by experiences gleaned from national, state, and provincial geological surveys doing similar work across the globe, including collaboration with the Geological Survey of Canada on a 3D study of the Oak Ridges Moraine Planning area (Sharpe et al. 2007). To date, the OGS has released 4 Groundwater Resources Studies – the culminating



**Figure 1:** Completed (orange), in progress (green) and proposed (blue hatching) OGS 3D sediment map areas. The protected greenbelt that surrounds the greater golden horseshoe is shown in black stipple. Ontario is shown in green on the small inset map. Southern Ontario is circled on this map.

products of sediment mapping projects – as part of its 3D sediment mapping program (Figure 1, Table 1) with one nearing completion and another two studies in progress (Bajc et al. 2012; Bajc and Dodge 2011; Bajc and Shirota 2007; Burt 2013; Burt and Dodge 2011, 2016; Mulligan 2014). The total area covered by these surveys exceeds 26 000 km<sup>2</sup> which is over 20% of the populated area of southern Ontario. Future studies are planned for both the extreme south-western corner of the province as well as within the Ottawa-St. Lawrence lowlands where municipal, agricultural, and industrial pressures on both the surface and groundwater resources are mounting. The OGS is additionally collaborating with the Geological Survey of Canada on the development of a regional model of Quaternary sediments and bedrock for southern Ontario (Carter et al. 2018).

### Resources Allocated to 3D Modelling Activities

Staff availability is an important consideration when initiating a new 3D mapping project. There are typically 2-3 concurrent projects, each run by a Quaternary geoscientist. Each project is both time and labour intensive, taking approximately 5 years from inception to final reporting assuming a one-year project overlap. The geoscientist is responsible for collaboration with core client groups to identify geoscience gaps, the compilation and standardization of legacy data, the collection of new geological data (one reconnaissance field season and 2 to 4 drilling programs), geological interpretations and development of conceptual geologic models, creation of the 3D model, and delivery of interim and final products.

The geoscientist is assisted by additional staff on a part-time basis as required. Summer field assistants are drawn from local colleges and universities. An OGS geophysicist reviews existing geophysical data, works with the geoscientist to develop a strategy for collecting new data, directs the procurement process for data acquisition, oversees the survey and product generation in conjunction with the successful contractor, and provides interpretations and advice to the lead geoscientist. A GIS applicationist assists with the assembly and management of legacy and newly collected data as well as with the creation of gridded surfaces and Google Earth products for the final data release. A drafter is responsible for ensuring that figures and posters meet publication standards.

**Table 1:** Summary of OGS 3D sediment mapping projects. The number and total depth of continuously cored boreholes, geophysical survey methods, the number of standardized subsurface records released in the associated Groundwater Resources Study, the number of picks used for modelling, the number of hydrostratigraphic units modelled, the size of blocks in the final model, and year of release are presented for completed projects. Where available, information is also listed for projects currently in progress.

Study	Area km <sup>2</sup>	OGS Boreholes	Geophysical Survey	Database Records	Picks	Layers	Block Size	Release Date
Waterloo Region	1 385	13	Shallow seismic, downhole, ground penetrating radar, Radarsat	17 023	38 629	19	100 m	2007
Barrie-Oro Moraine	1 290	32 holes 2376.25 m	Shallow seismic, downhole	7 155	28 272	23	100 m	2011
Brantford-Woodstock	2 715	36	None	15 106	42 026	20	100 m	2011
Orangeville-Fergus	1 550	43 holes 1918.54 m	Ground gravity	11 117	46 208	20	100 m	2016
South Simcoe	1 455	25	Ground gravity, airborne time-domain electromagnetic, regional shallow seismic, downhole	24 939	70 926	18	100 m	In progress
Niagara Peninsula	5 000	99 holes 3192.1 m	Ground gravity, regional shallow seismic, downhole	NA	NA	NA	NA	In progress
Central Simcoe	1 375	33 holes 2942.75 m	Ground gravity, regional shallow seismic, downhole	NA	NA	NA	100 m	In progress

OGS projects require robust budget allocations for the acquisition of new high-quality geophysical and geological datasets. Sample analysis (grain size, geochemistry, mineralogy, paleoecological analysis, dating) further increases project costs.

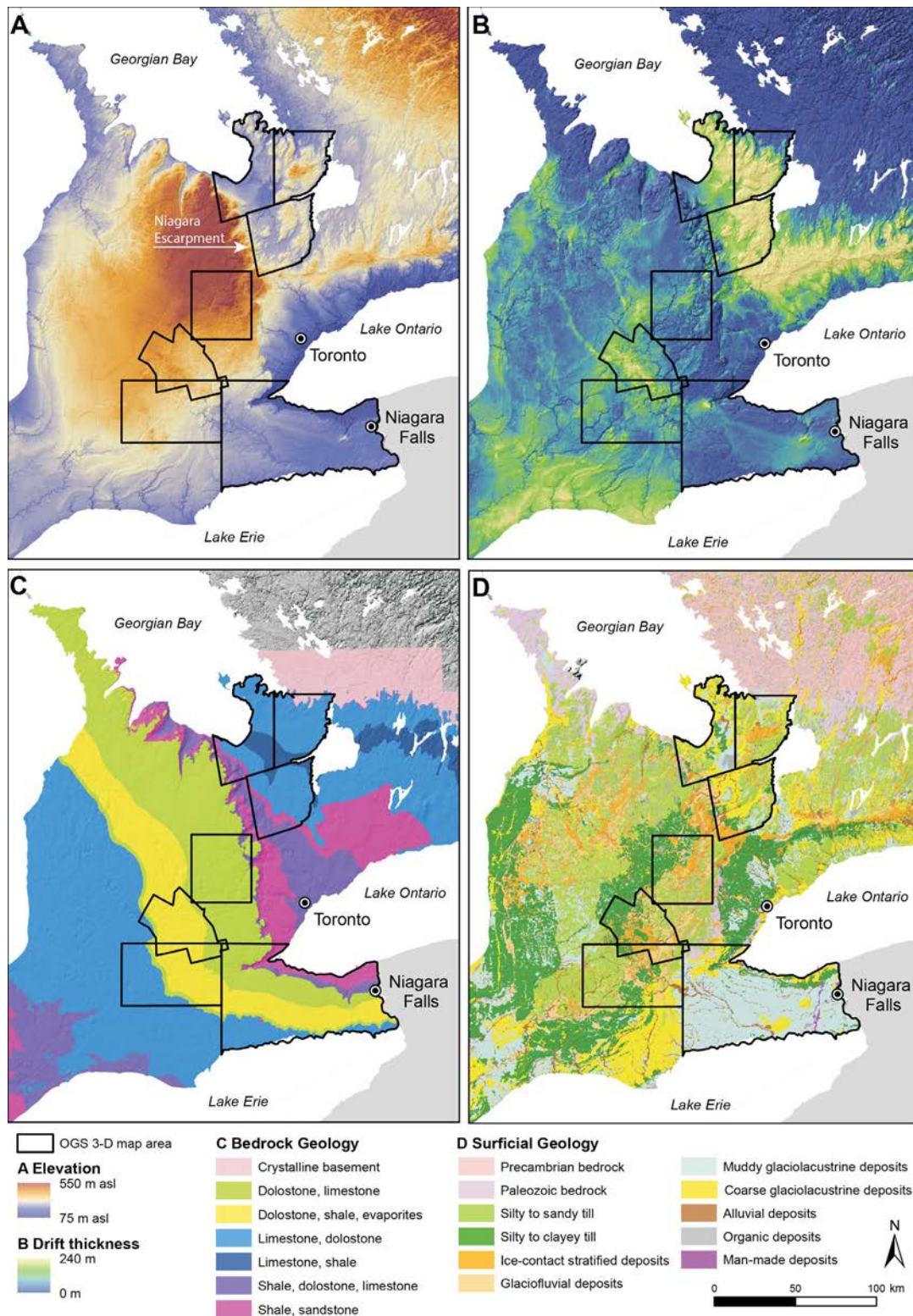
## Overview of Regional Geological Setting

Southern Ontario is bounded by the Algonquin Highlands of the Canadian Shield to the north and low-lying (commonly overdeepened) basins of the Great Lakes and St. Lawrence River to the west, south, and east. Paleozoic strata overlie the crystalline basement rocks and consist of gently south and southwest-dipping carbonate, clastic, and evaporite strata (Fig-

ure 2; Armstrong and Dodge 2007). Prominent bedrock cuestas, particularly the Niagara (200-300 m high) and Onondaga (20-30 m high) escarpments, exist where resistant strata (primarily dolostone) overlies softer shale or evaporite successions (Brunton et al. 2009). Inset into the broader regional bedrock topography are a series of bedrock valleys, locally buried by up to 260 m of Pleistocene sediments (Figure 2; Gao et al. 2007). Large re-entrant valleys along the Niagara Escarpment commonly mark the surficial expression of more significant buried bedrock valley features extending into thick drift areas, which locally host pre-Late Wisconsin sediments, some of which consist of productive aquifers (Russell et al.

2004; Bajc et al. 2018; Burt 2018; Steelman et al. 2018).

Sediments overlying Paleozoic bedrock in southern Ontario span at least the last two glaciations (marine oxygen isotope stage (MIS) 1-6; Eyles 1987; Dreimanis 1992; Karrow et al. 2000; Mulligan and Bajc 2018). Sediment successions that pre-date the Late Wisconsin (MIS 2) glaciation are rarely exposed and preferentially occur within bedrock depressions or within interlobate zones where glacial lakes were present during the build up and retreat of ice sheets resulting in their burial and protection from erosion. They consist of a series of tills capped by interglacial and interstadial deposits, that in turn can be overlain by thick successions of predominantly



**Figure 2:** Regional setting of completed and in-progress OGS 3D sediment mapping projects. **A)** Digital elevation model draped over a hillshade. Note the large elevation change at the Niagara Escarpment (arrow). The Onondaga Escarpment is much more subdued and is often buried. **B)** Drift thickness map (Gao et al 2007). **C)** Summary bedrock geology (Armstrong and Dodge 2007). The Niagara Escarpment is at the contact between Ordovician shale, dolostone, limestone (purple), and Silurian dolostone and limestone (green). The Onondaga Escarpment is at the contact between Silurian dolostone and limestone (green) and Devonian limestone and dolostone (blue). **D)** Surficial geology (OGS 2010).

glaciolacustrine deposits recording the evolution of extensive lakes developed in southern Ontario during the build-up and advance of ice during the Late Wisconsin (MIS 2). These deposits are of interest as they locally host significant confined aquifers (Burt 2018; Mulligan and Bajc 2018; Gerber et al. 2018).

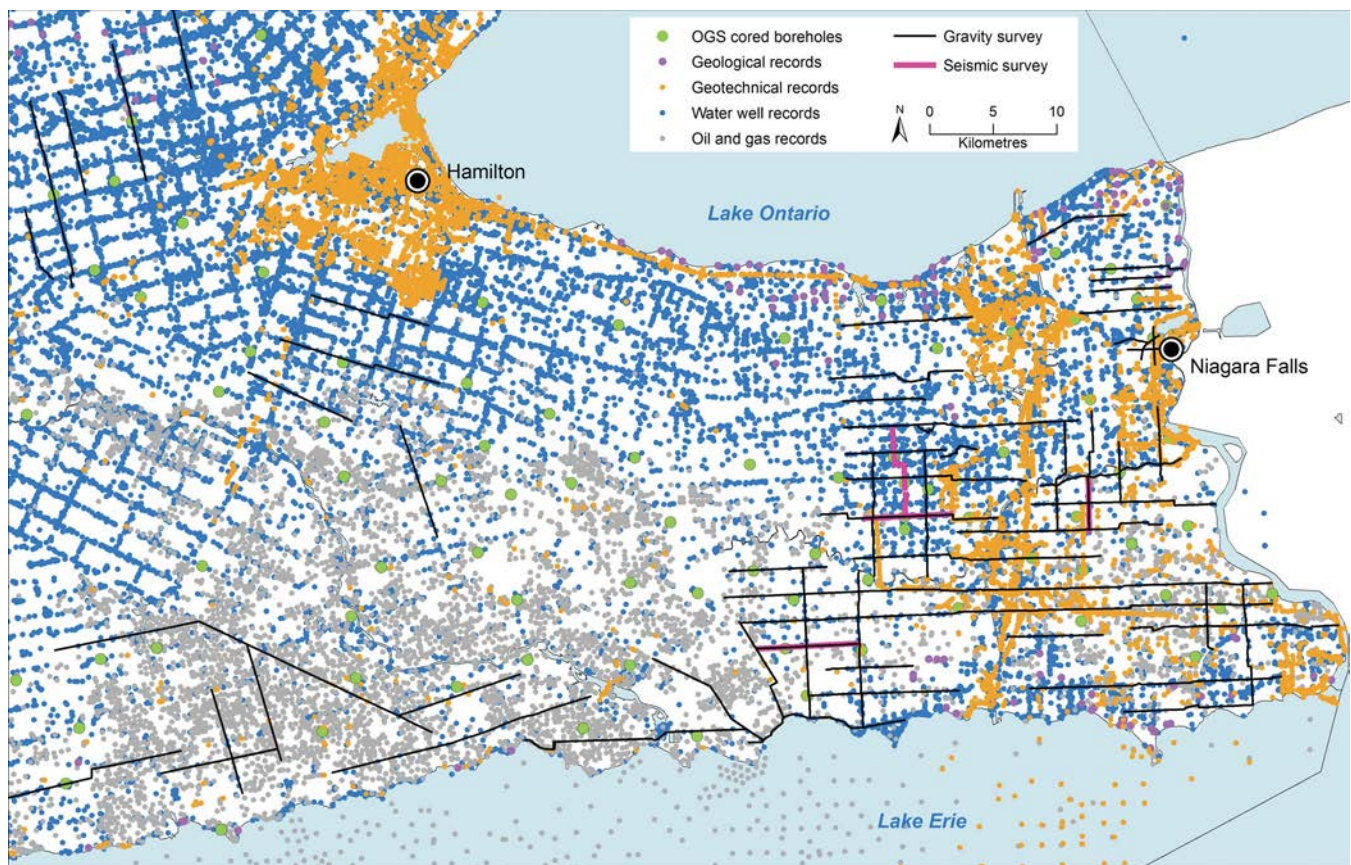
Thick regional till sheets cover older sediments and bedrock and record the main phase of Laurentide Ice Sheet advance southwestward into the northern United States during the Late Wisconsin (MIS 2). During deglaciation, thinning of the LIS resulted in the reorganization of the ice sheet into distinct lobes and/or ice streams (Barnett 1992; Sookhan et al. 2018) due to topographic funnelling into the low-lying Great Lakes basins

(Eyles et al. 2018). Initial break-up was associated with extensive melt-water production and (predominantly coarse-grained) sediment deposition into growing interlobate areas, promoting the deposition of large, sandy stratified moraines including the Waterloo, Orangeville, Oak Ridges, and Oro moraines (Barnett 1992; Bajc and Shiota 2007; Burt 2018; Mulligan et al. 2018a; Sharpe et al. 2018). Subsequent re-advances and/or readjustments of ice lobe/stream margins partially overrode the flanks of the moraines and deposited younger, primarily fine-grained till sheets (Arnaud et al. 2018; Burt 2018). As ice lobes withdrew from southern Ontario, extensive lakes developed, locally covering the surface tills with deposits of sand, silt, and clay, with local gravelly sediments deposited

near former shorelines (Barnett and Karrow, 2018; Mulligan et al. 2018b).

## Data Sources

The OGS' 3D models are based on legacy data sets further informed by new geophysical and geological data (Figure 3). Legacy data sets have a highly variable spatial distribution (Figure 3), resolution, and quality. Water well records are the most plentiful, but also of the lowest quality. The data are publicly available and can be downloaded for free from the Ministry of Environment, Conservation and Parks (MECP) as a Microsoft Access database that includes well location, material, well screen, and pumping test information. Scanned well submission records can also be downloaded from the same site. As



**Figure 3:** Distribution of legacy datasets (orange, blue and grey dots), new geological information (purple and green dots), and geophysical surveys (black and pink lines) on the Niagara Peninsula. Note the lack of water wells (blue) in areas with large numbers of oil and gas wells (grey). Geotechnical records are concentrated along the major highways, the Welland Canal, and in some urban areas. Note the records with obviously incorrect location information plotting outside of Ontario. Sources: Water wells <https://www.ontario.ca/data/well-records> accessed December 3, 2018. Oil and gas records <http://www.ogsrlibrary.com/> accessed December 3, 2018.

expected, the data are concentrated in the populated southern portions of the province where groundwater is used for domestic, industrial, and agricultural purposes. The water well database is standardized using a two-step translation process before it is used for 3D geological mapping (Burt and Bajc 2005). Some detail is lost during this process, but this is justified in a regional-scale modelling project.

The remaining databases vary in accessibility and coverage and range in quality from low to high depending on the original purpose, drilling method, and material descriptions. Each database is prepared as described above. Oil and gas records are publicly available, but a subscription fee is required. The records are focused on specific bedrock formations and have limited use for sediment models with the exception of depth to bedrock information. Geotechnical records range from low to high quality and are generally shallow, targeting the first significant load-bearing unit. They can be publicly available or privately held by consultants. It is often necessary to manually enter the records into a database from scanned logs. This is labour intensive but does provide the opportunity to better interpret the original descriptions. The Urban Geology Automated Information System was created for 11 urban centres in Ontario during the 1970's and 1980's. Although recent data is missing, these databases provide geotechnical data in an accessible digital format. The Ministry of Transportation geotechnical records from road building and inspections (typically only 1-2 m in depth), as well as clusters of deeper records from bridge and overpass construction, are available for use as well. Finally, partner conservation authorities and municipalities generally make proprietary and/or confidential geotechnical records obtained by consultants available for modelling. Archived OGS reports and field notes, university theses, and rarely journal publications

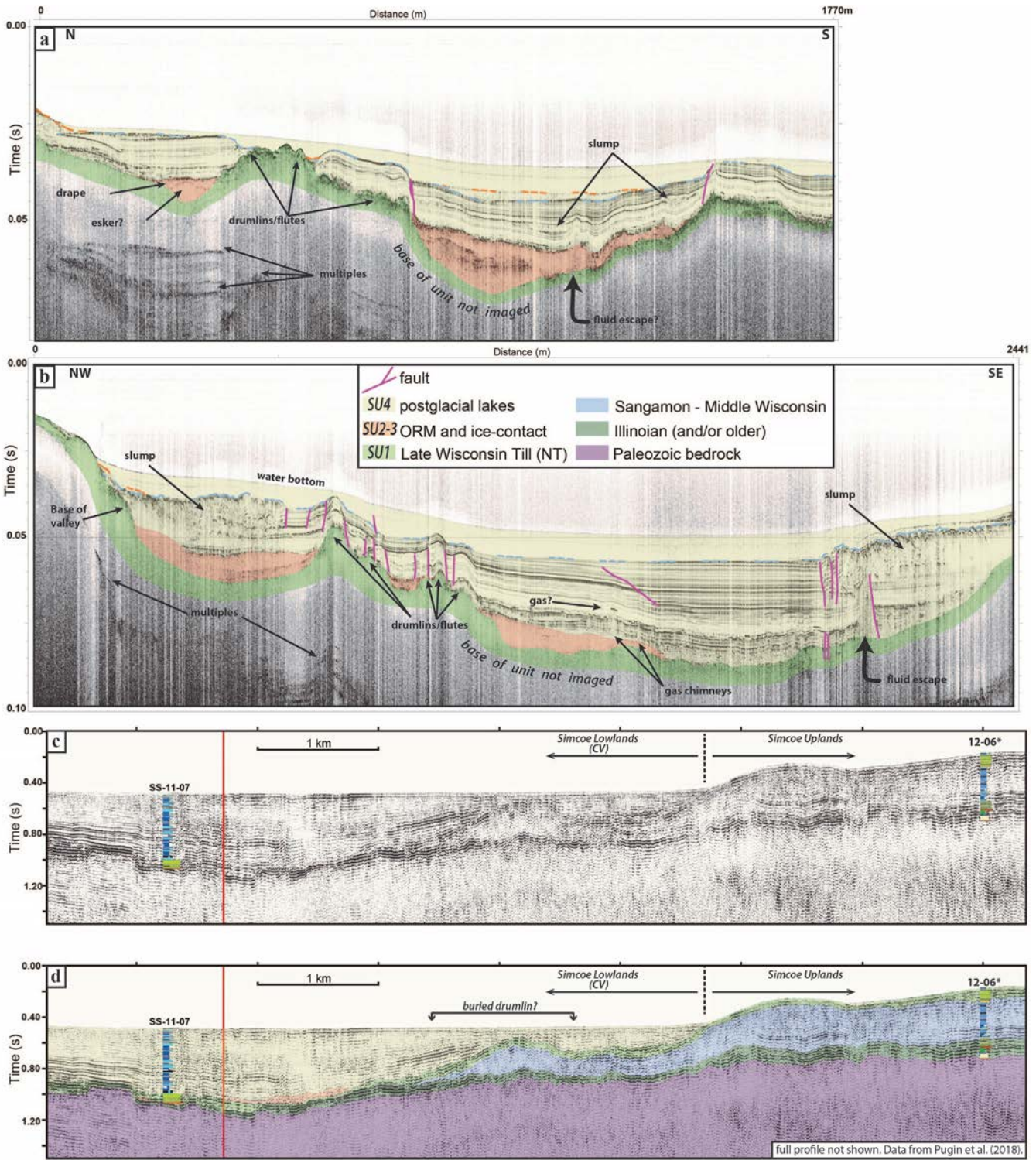
are sources of high-quality data. Unfortunately, the data are typically of limited coverage and rarely penetrate the full sediment cover.

A variety of geophysical methods have been used to identify drilling targets and to define the lateral extent and geometry of sediment packages. Ground-based gravity surveys are completed under contract to the OGS before drilling commences. The surveys help to identify the location of buried-bedrock valleys and escarpments but do not differentiate between infilling sediment types. A pilot project is underway to evaluate the possibility of converting residual bouguer gravity profiles into depth to bedrock profiles. Additional geophysical work has been completed in several project areas by the Geological Survey of Canada's (GSC) Near Surface Geophysics Section as part of a 5-year collaborative effort (Russell and Dyer 2016). Seismic reflection lines ranging from 4.5 to 21.5 km in length have been acquired to define the bedrock surface and provide insight into the architecture of overlying glacial sediments (Figure 4) (Pugin et al. 2018). Downhole geophysical surveys were conducted by the GSC in monitoring wells located adjacent to the seismic lines and in representative sediment packages. Downhole compression ( $V_p$ ) and shear ( $V_s$ ) seismic logs are used to calibrate the seismic data and convert two-way travel time profiles to true depths. Apparent conductivity and magnetic susceptibility logs are used to characterize lithological variations within and between sediment packages (Crow et al. 2017a, b). In some locations, regional groundwater temperature variations were determined from high-resolution fluid temperature logs (Crow et al. 2017a, b). A pilot time-domain airborne electromagnetic survey was undertaken within a portion of one of the 3D mapping project areas to assess its use for mapping lithostratigraphic units of varying resistivity in the subsurface. The

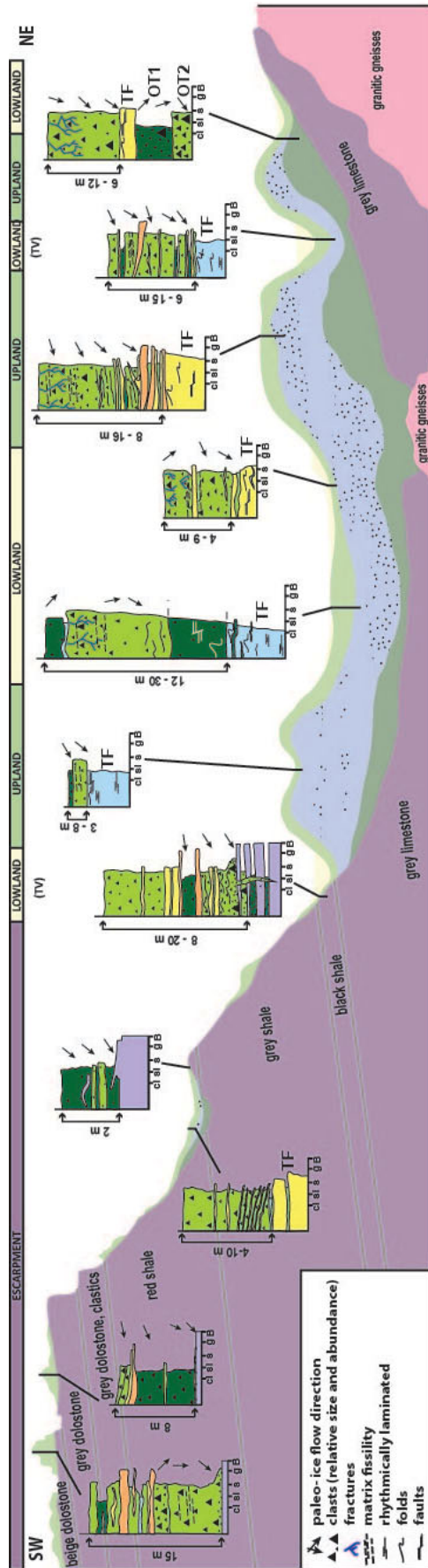
method proved to be useful for defining the bedrock surface, especially in areas of shale, but failed to effectively discriminate overlying aquifer and aquitard units because of the limited range of conductivities of the Quaternary sequence that was present.

The highest quality data in each project area is collected by the lead geoscientist. A reconnaissance field season focuses on the examination of surficial, natural, and man-made exposures. The overall quality of existing surficial mapping is assessed and where necessary, new surficial maps may be produced with the assistance of high resolution elevation models. The goal of this reconnaissance field season is to allow the geoscientist to gain an appreciation for the Quaternary history and sediment-landform relationships of the project area. During subsequent field seasons, drilling targets are selected to refine the stratigraphic relationships of tills and associated stratified sediments, establish sediment-landform associations, and determine the nature of bedrock valley fills (Figure 5). The number of boreholes and metres of core retrieved, varies across and between project areas (Table 1). Track or truck mounted mud-rotary drills with 1.5 m samplers retrievable by wireline are used to continuously core the Quaternary sediment cover and upper 1.5 to 5 m of bedrock. The 8.5 cm diameter core is logged, photographed at 0.25 m increments with representative samples collected every 1.5 m or when significant changes in lithology occur for grain-size analysis, carbonate and heavy mineral content, radiocarbon dating, and paleoecological analysis. In clay-rich areas, a pocket penetrometer is used to perform field penetration tests. The resulting high-quality dataset allows the lower-quality legacy datasets to be interpreted more accurately. Monitoring wells (2.5-inch diameter threaded, flush-joint polyvinyl chloride (PVC)) with 1.5 or 3 m long slotted screens are installed in some boreholes by conser-





**Figure 4:** a) and b) High-resolution CHIRP sub-bottom profile displaying the sediment architecture in the eastern part of Kempenfelt Bay (submerged eastern extension of the tunnel valley forming the northern boundary of the south Simcoe study area; see Figure 1; modified from Mulligan, in prep); c) uninterpreted and d) interpreted S-wave seismic reflection profile across the Cookstown tunnel valley (CV) and adjacent uplands collected by the Geological Survey of Canada (data from Pugin et al., 2018) with borehole logs and surficial mapping as geologic constraints. SS-11-07 is 200 m south of the profile and SS-12-06 is projected from 2.7 km south for reference. Vertical red line shown where an intersecting seismic reflection profile intersects the displayed line (figure from Mulligan et al. 2018).



**Figure 5:** Conceptual geological framework for Central Simcoe County illustrating the stratigraphic architecture and facies variability within Newmarket Till across the physiographic regions and subglacial environments in the study area. No scale implied but typical thickness ranges are provided at the left of each log. Arrows denoting paleo-ice flow directions are interpreted from clast provenance, till sheet morphology, clast faceting/striae orientations and/or substrate deformation features. TV=tunnel valley. Figure from Mulligan et al. 2018c.

vation authorities and municipal partners for ongoing monitoring of groundwater levels and potential changes in water chemistry (Campbell and Burt 2015).

### 3D Modelling Approach

The OGS uses an implicit approach for regional-scale 3D modelling. As a first step, a conceptual framework subdividing the Quaternary sediment cover into regional-scale hydrostratigraphic units and typically one undifferentiated bedrock unit is developed (Table 1). These units are identified based on age and the sediment characteristics resulting from deposition in different environments (Burt and Dodge, 2016). Although the number of units varies between projects, an effort is made to correlate units from adjoining mapping areas. Bedrock is only subdivided where both crystalline Precambrian basement and overlying Phanerozoic sedimentary formations occur within the study area. The conceptual geologic framework functions as a guide for the interpretation of legacy data sets.

The 3D models are generated using commercially available Datamine Studio 3<sup>®</sup> software adapted to regional-scale modelling using a series of scripted routines commissioned by the OGS (Bajc and Newton 2005). Location and geological material tables, created from the master subsurface database, are used to generate borehole traces that can be viewed as 2D cross-sections or in 3D space. A static water depth table defines the depths of water well-screens and static water levels. When plotted beside the borehole traces, the data can aid in aquifer correlation.

Three-dimensional points, referred to as picks, identifying the top of a given hydrostratigraphic unit are manually digitized onto the borehole traces. The number of picks made on an individual borehole trace is dependent on the number of hydrostratigraphic units that can be interpreted

from the primary material types. In many cases, it is only possible to identify one or two units on the lowest quality traces whereas all units present in an area can be identified on the highest quality continuously cored boreholes. The picking process automatically generates a new table containing the borehole identifier, X, Y, Z coordinates of the pick, the hydrostratigraphic unit, and the quality rating of the borehole trace. Additional picks are digitized off the borehole traces to refine the geometry of the modelled surfaces. Wells that appear to be in the wrong location (i.e. dubious elevations, sediment thicknesses, or bedrock elevations) are either ignored or removed from the project database throughout the modelling process. The number of picks varies according to the size and complexity of the model area, and this has resulted in 28 000 to 71 000 picks made on completed models (Table 1).

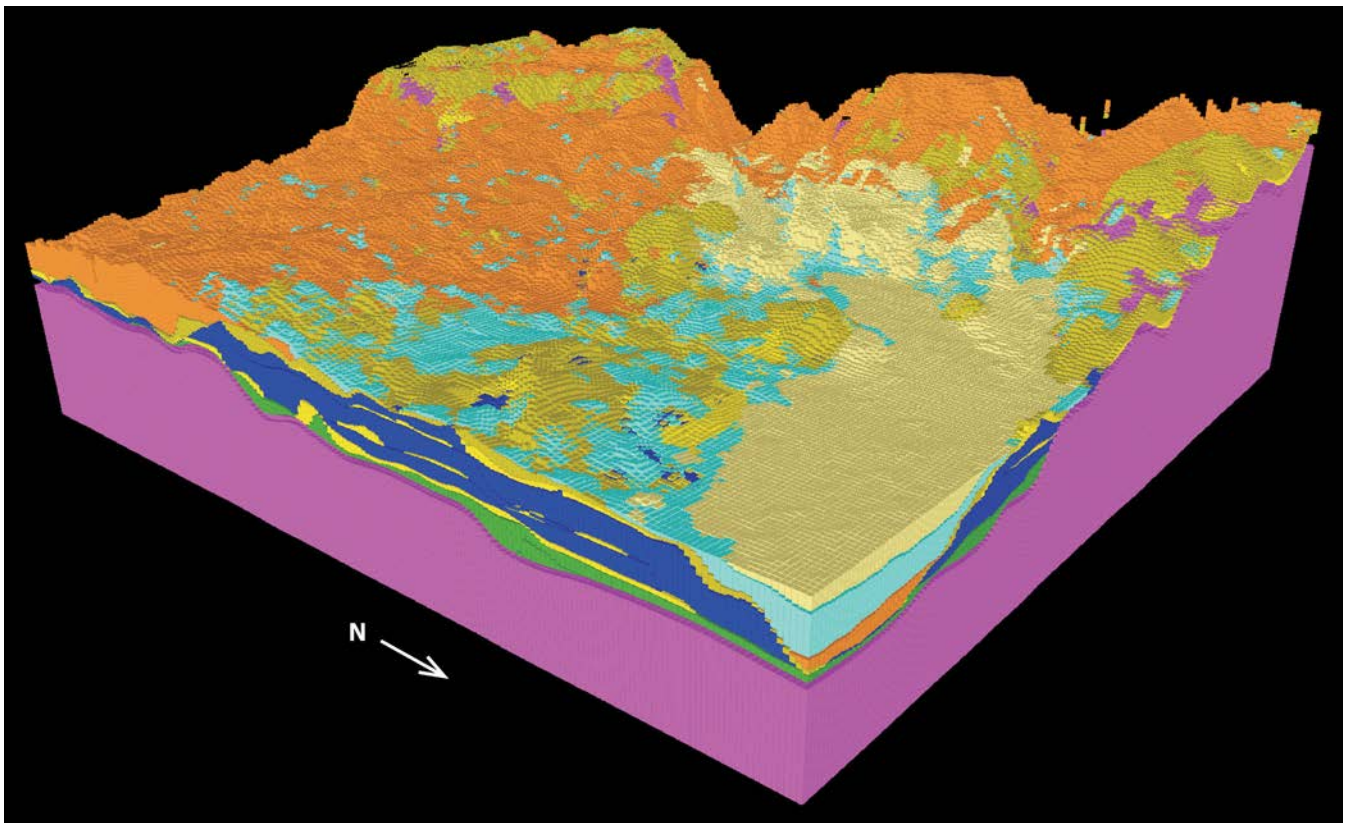
Once a preliminary set of picks has been made, the scripted routines use the picks and a high-quality surface material database derived from the digital seamless surficial geology map to generate interpolated wireframe surfaces representing the tops of each hydrostratigraphic unit. The interpolation method used for OGS 3D modelling is isotropic inverse power of distance cubed (Bajc and Shirota, 2007). First, the picks are validated to ensure that the hydrostratigraphic units are in the correct sequence. Out of order picks are flagged for correction and then ignored by the software during the current run. In an attempt to reduce problems with overlapping wireframe surfaces, especially in data sparse areas, hydrostratigraphic unit elevations are interpolated onto a grid of virtual boreholes. The grid size can be adjusted throughout the modelling process: 200 to 500 m cells can be used to quickly generate surfaces early in the process whereas 100 m cells are used to refine the model and to generate final products.

During the interpolation process, each hydrostratigraphic unit is considered individually. A search radius, defined by the geologist to reflect the perceived extent of the unit, is drawn around each virtual borehole. An interpolated elevation is then assigned to the virtual borehole when a minimum of one high-quality, two medium-quality, or three low-quality picks are found within the search radius. If there are insufficient picks, the unit is considered absent and the elevation is automatically set as equal to the underlying unit. This process results in all hydrostratigraphic units being represented in each virtual borehole although units may have zero thickness at some locations.

Finally, a continuous set of wireframes are generated from the interpolated elevations and a set of rules are applied to remove any overlaps. Pinch-outs are accommodated by draping units on top of each other. These continuous surfaces are a requirement of most groundwater flow modelling software packages. A second set of wireframes are created by comparing the elevations for each triangular element. Locations where any unit had zero thickness are identified and those triangular elements were removed. This introduces holes, or pinch-outs, into the surfaces and more accurately represents the spatial extent of the units.

A 3D block model is then created by filling the space between each modelled wireframe surface with blocks of variable thickness (Figure 6). The planar dimensions of the columns match the virtual borehole grid size and the vertical dimension of each column is calculated automatically to fill in exactly between the surfaces. The resulting block model is used to calculate the volume, thickness, and surface contour of each unit.

Once a model run is complete, the results are visually compared with the borehole traces. Out of order picks are corrected, interpretations are re-



**Figure 6:** Subarea of the South Simcoe County 3D sediment model. Paleozoic bedrock is shown in pink, aquitard units in blue and green, and aquifer units in yellow and orange. Note the variable thickness of blocks.

fined, and additional off-trace picks are added. The model is then re-run.

Each modelling project is released as a Groundwater Resources Study containing:

- A detailed report describing the geologic setting, protocols developed for the construction of the model, the distribution and properties of each hydrostratigraphic unit, and important recharge areas as well as aquifer vulnerability.
- Portable document format (.pdf) versions of structural contour and isopach maps of all modelled units, west-east and south-north cross-sections at 2 kilometre intervals, and depth to aquifer maps that can be used to assess aquifer vulnerability and recharge areas.
- Logs and analytical data from continuously cored boreholes.
- A stripped-down version of the subsurface database (.mdb) con-

taining borehole location and stratigraphic information, data picks and static water level and screen depth.

- Comma-delimited text (.csv) files of both continuous and discontinuous surfaces designed as inputs to other software packages such as hydrogeological modelling, or visualization software.
- ESRI® ArcInfo® structural contour grids of discontinuous surfaces.
- A hypertext mark-up language (.kml) file that portrays transparent overlays of the structural contour and isopach maps as well as borehole locations and lithologic logs in a web-based (Google Earth™ mapping service) environment allowing for enhanced user interaction with the spatial data.

## Clients

The OGS 3D sediment mapping team serves a diverse range of client

groups who utilize different interim and final products for different purposes. These include:

- Conservation Authorities (responsible for protecting Ontario's groundwater resource as part of Source Water Protection planning)
- Towns and municipalities (groundwater quantity and quality concerns and land-use planning)
- Geoscience consultants (contracted to produce groundwater flow models and water budget assessments for Conservation Authorities, towns, and municipalities). Also studies involving remediation of contaminated sites.
- Provincial and federal government agencies (for example internal OGS clients, Ministry of the Environment, Conservation and Parks, Ministry of Natural Resources and Forestry, Ministry of Municipal Affairs and Housing)
- Academia

Conservation authorities, towns and municipalities have firsthand knowledge of local issues, pressures and emerging concerns involving water, other resources, and associated planning scenarios. These client groups are instrumental in establishing model area priorities through yearly project proposal submissions that are evaluated by OGS geoscientists and management. Once a region has been selected for study, topics pertinent to that area are identified and updated during the life-cycle of the project. The project geoscientist acts as a go-to person for expert geological knowledge during data collection, the modelling phase, and then following completion of the project. OGS clients facilitate access to drill sites, partner to install long-term monitoring wells, and provide access to legacy datasets.

Reaching an audience that goes beyond primary contacts at project area conservation authorities or local municipalities and cities can be a challenge. The OGS has adopted a range of strategies that target different audiences. Since 2014, the Geological Survey of Canada and Conservation Ontario have collaborated with the OGS to offer a free yearly open house event featuring overview and project-specific talks and posters for conservation authority practitioners, policy makers, planners, municipal water specialists, consultants, and academics. The open house is a popular networking and educational opportunity. The OGS also participates in an annual conservation symposium, offering workshops, program and project specific talks, and a corporate booth. Field visits and tours have proven popular with groundwater professionals from sister ministries, municipalities, conservation authorities, and project area consultants. Topical presentations at colleges and universities and working with faculty to provide topical and geographically relevant teaching material provides an excellent opportunity to reach a young technical audience. Hiring stu-

dents from universities within or close to project areas facilitates student learning and encourages future collaborations, including thesis work. Working with museums and local interest groups has great potential for reaching the general public. The OGS has provided presentations to staff, donated core, and helped develop displays and material for exhibits and educational programming.

### Recent Jurisdictional-Scale Case Study Showcasing Application of 3D Models

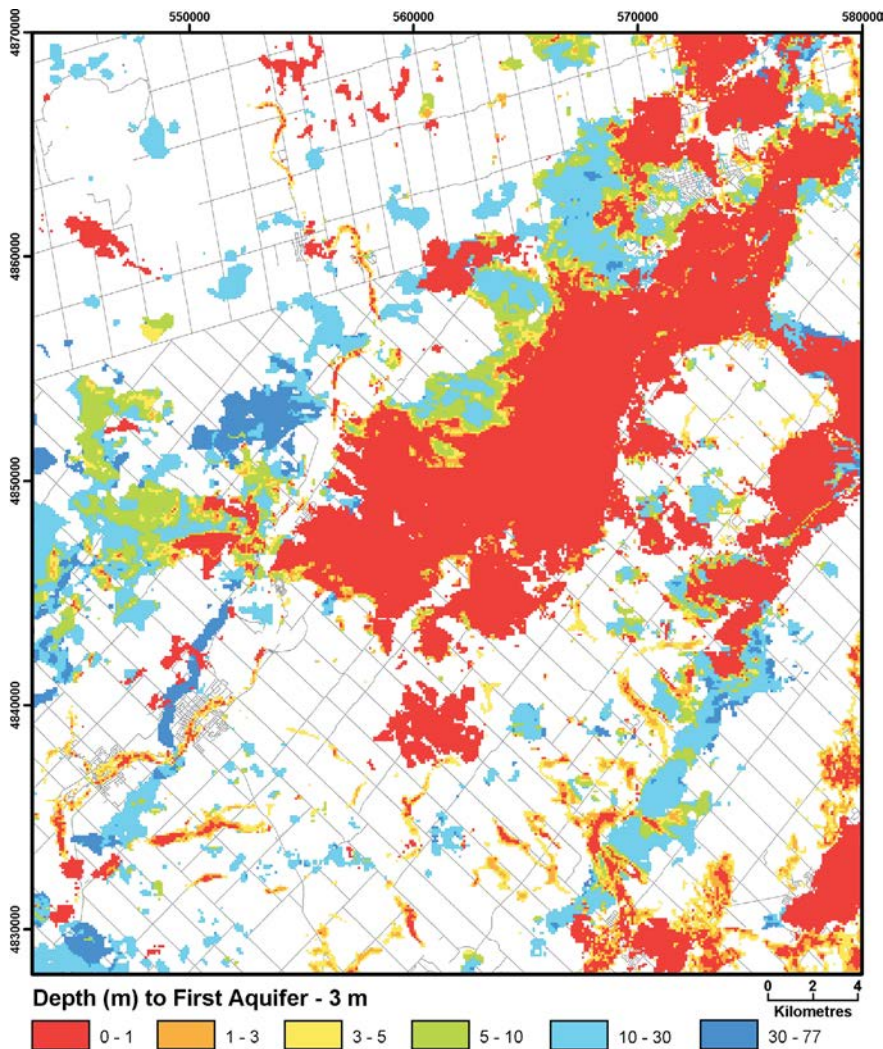
OGS 3D sediment mapping products have been used as model inputs and to inform groundwater and planning decisions at pan-provincial to sub-watershed scales. Some examples of these are:

- **Southern Ontario 3D model:** The OGS is collaborating with the Geological Survey of Canada to produce a provincial scale 3D model that summarizes the Quaternary sediment cover into seven layers (Figure 7). OGS cored boreholes and geological interpretations from completed and on-going projects were incorporated into the model.
- **Municipal water supply studies:** Many clients require an improved understanding of the internal architecture of large stratified moraines to address concerns over water quality and quantity. Several early projects identified windows through regional aquitards and the locations of untapped aquifers with the potential to support future needs (Figure 8; Bajc and Shirota 2007; Bajc and Dodge 2011; Burt and Dodge 2011, 2016). Several clients are interested in whether buried-bedrock valley aquifers are capable of meeting municipal demands and how much groundwater is entering and leaving their watersheds along the valley system. In Waterloo Region, a secondary project was initiated that involved in-

stalling monitoring wells in logged boreholes, and drawing cross-sections delineating valley aquifer systems. In the Town of Erin, a large pumping station and associated infrastructure was decommissioned due to aquifer contamination. They needed to know whether a buried valley ran under the facility and whether it hosted an aquifer. In this case the OGS completed a ground gravity survey and drilled a borehole as part of the Orangeville moraine project.

- **Improved monitoring well network:** On the Niagara Peninsula, clients required a geologic framework, as well as monitoring wells, to improve groundwater flow models and to better understand surface water – groundwater interactions within several subwatersheds. Drill sites suitable for monitoring wells were prioritized and 29 wells, several later converted into nested wells, were installed.
- **Stressed watersheds and drought management:** White-man’s Creek, a world-class cold-water fishery with groundwater dependent base flows, is under stress. An OGS 3D model, watershed specific cross-sections, and interpretations and recommendations for further study were used to assess and manage water withdrawals. The Innisfil Creek watershed has high groundwater usage for agriculture and golf course irrigation and in recent years, base flow in Innisfil Creek temporarily fell to extreme low levels. An OGS conceptual model and borehole data was used for a subwatershed-scale Mike-SHE hydrological model and development of a drought management plan.
- **Green Belt Expansion:** Several ministries required information on the subsurface extents of important aquifers contained within hydrologically significant moraines in the Greater Golden Horseshoe surrounding the Greater Toronto Area





**Figure 8:** Example of a simple depth to aquifer vulnerability map generated for the Orangeville-Fergus area of southwestern Ontario. The map depicts the depth below the surface of sand- and gravel-rich 3D model units (Burt and Dodge 2016).

Changing technology has already impacted product delivery. Previous projects included a cross-section viewer capable of drawing sections along user-defined lines drawn on a Virtual Earth base map. These sections could be saved, and then imported into Google Earth™ mapping service in conjunction with overlays of structural contour and isopach maps and this allowed for enhanced user interaction with the spatial data. The section viewer used Microsoft® Virtual Earth® which is now Bing Map and the coding and links have changed. This will require a rebuild of the cross-section viewer, and a possible migration to another platform.

Discoverability and data retrieval are a constant challenge for ministry staff and clients alike. OGS clients have difficulty finding the correct page on our ministry website, and once there, it is difficult to find project specific publications. OGS Earth, a web portal that allows geoscience data collected by the Mines and Minerals Division to be viewed and downloaded using Google Earth, has proven to be an effective solution. However, many products are large and are downloaded as a series of .zip files that must be merged. This is cumbersome, and errors often occur.

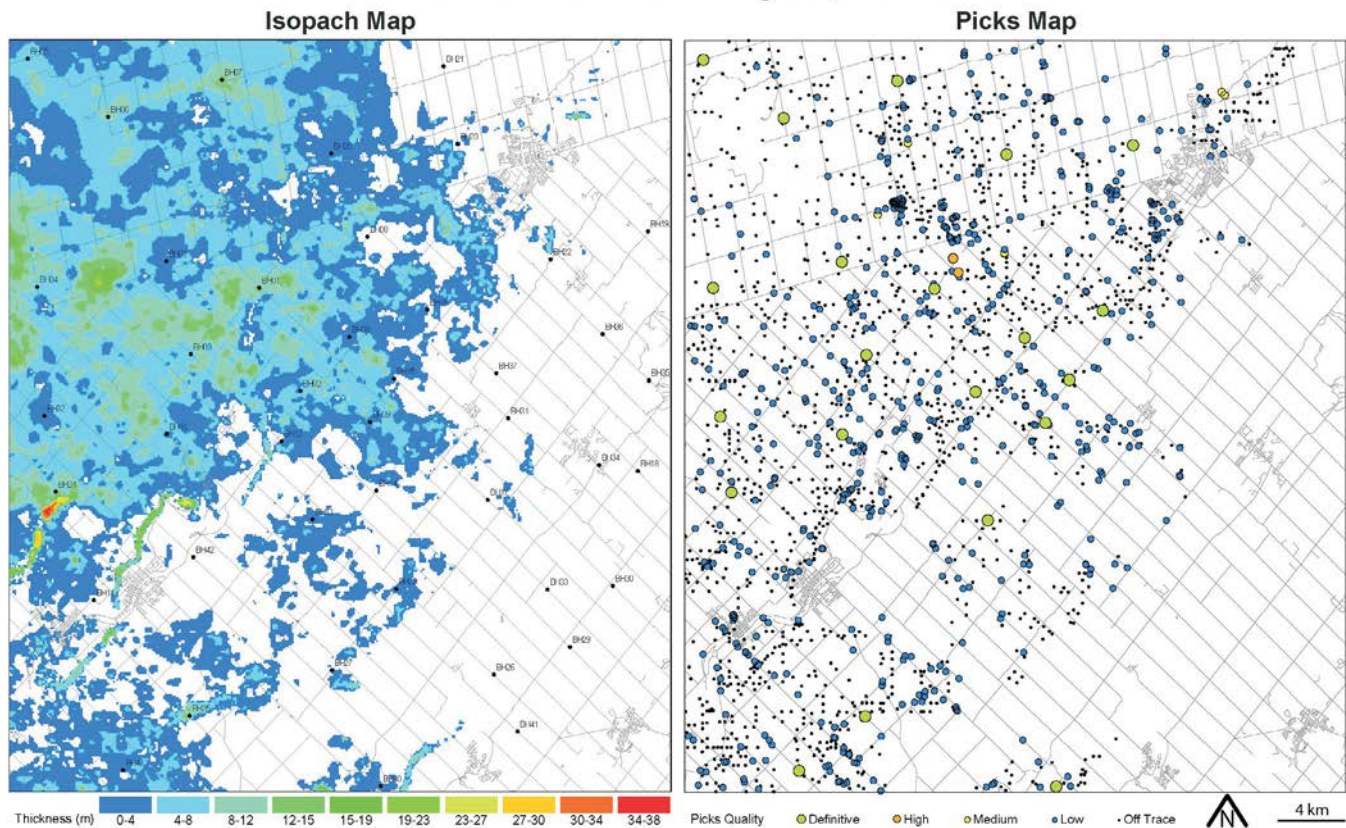
Field programs and analytical work result in large-scale, rapid data collection. Collaborating with other surveys, ministries, and academia can be an effective way to ensure that data reaches its maximum potential.

## Lessons Learned

One of the most important things that the OGS has learned is the value of communication and active collaboration throughout the life cycle of a project. Discussions with experts at sister ministries, conservation authorities, and municipalities during project planning provide an excellent opportunity to find out whether there are specific areas of concern, emerging issues, and/or future development projects. Conservation authorities and municipalities can facilitate site access and provide legacy datasets from consultants. Early communication also increases the potential for converting boreholes into monitoring wells to gain additional useful information for modelling efforts. Partner funding can take months and it can also take months for permits for permanent infrastructure to be approved (especially during summer holiday periods). Communication ensures that clients have a realistic idea of what they are going to get, can identify opportunities for releasing interim products, and provide input as to how products can be improved. Communication with local universities and colleges will identify common areas of interest. Collaborating with university graduate students can be an excellent way of conducting site-specific studies or addressing scientific questions that are beyond the scope of the project.

Critical to the success of the program is ensuring that the geological and hydrogeological information presented within the reports is delivered in a manner that can be understood by both technical experts and non-technical users. Derivative and value-added maps, such as those that estimate aquifer recharge or vulnerability, are

# ATG1 - Pre-Canning Aquitard



**Figure 9:** Example of paired isopach and dot maps for an aquitard in the Orangeville-Fergus area (Burt and Dodge 2016). The dot maps show the quality of the source data used to model the aquitard surface.

particularly useful. An attempt has been made to produce standardized products that allow for models to be merged and this also facilitates the creation of a provincial-scale 3D model of Quaternary geology. This is balanced with the development of new products, such as interactive drilling data and borehole maps, that take advantage of advancements in technology (Burt and Webb 2013; Burt and Chartrand 2014).

Communicating the uncertainty of geological maps and reports to their users is a relatively new venture for geoscience and a variety of approaches are being trialled. The OGS is currently using a visual approach to address uncertainty in 3D hydrostratigraphic mapping projects (Burt and Dodge 2016). Each isopach or structural contour map is complemented by a dot map that indicates the location and the quality of picks used to

interpolate the surface (Figure 9). The dot maps provide an estimate of the reliability of the source data and give an immediate visual indication of the distribution of data across the study area. Clients find this visual representation intuitive and the 3D team can focus on interpreting and mapping geology rather than mapping uncertainty.

## Next Steps

OGS 3D sediment mapping activities have been well-supported by our senior management and divisional leadership team and core client base who recognize the importance of OGS data and products. The OGS team provides the regional geologic framework for hydrogeological modelling and policy decisions in areas where 3D sediment mapping studies have been completed. Proposals for future projects have been submitted that

would expand our efforts into south-eastern Ontario as well as infill gaps in coverage in the southwest. The future challenges are to improve the ease of data retrieval, address technological changes that impact product delivery, and expand uptake beyond our core client base to ensure that high-quality geoscience data remains a government priority.

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# Chapter 21: 3D Geological Modelling at the Polish Geological Institute

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## Introduction

3D geological modelling was initiated at the Polish Geological Institute (PGI-NRI) in 2003 by setting up the first 3D model of the geology of Poland, showing deep structure from 6000 to 500 m below sea level (b.s.l.; Piotrowska et al. 2005). Numerous 3D models have been constructed since then, thus finally starting to tilt the PGI-NRI towards a 3D geological modelling culture. Good proof of impact seems to be the fact that some diehard analogue geologists have been convinced recently to use digital 3D tools, so the effort is both promising and gaining ground.

Our models comprise a broad variety of topics – from the planned 3D Framework Geological Model of Poland through multiscale 3D models of individual sedimentary basins to various purpose-built models. The level of detail available within these models depends both on the quality of data available as well as importance of individual stratigraphic systems to end users. We particularly pay attention to mineral deposits, energy resources (including geothermal and hydrocarbons) and strata which may be important for underground storage

(such as natural gas) and environment protection (including major aquifers).

Our efforts shall soon become much more visible at the delivery end of the modelling process. Our web-viewer of 3D geological models is ready for release and will soon be available to demonstrate the geology to the geological community and the public in general – in a very accessible way. We hope it will provide a vehicle to significantly boost our client-base and, most importantly, increase interest in geological sciences and advocate for their importance to our everyday life.

## Organizational Structure and Business Model

The Polish Geological Institute (PGI) was established a century ago on 7 May 1919, several months after Poland regained independence, and for now it has the longest history of any Polish research institute. In recognition of its organizational contributions to the development of Polish science and its economy, in February 2009, the Council of Ministers awarded it the status of National Research Institute. The Institute is supervised by the Minister of the Environment.

Research projects delivered by PGI staff led to the discovery of Poland's key deposits of mineral resources: copper, silver, native sulphur, coal, lignite, rock salt, potassium salt, iron, titanium, vanadium, zinc and lead ores. Several thousand wells drilled by the institute enabled a detailed investigation of Poland's geology, one of the most detailed deep drilling programmes in the world.

Acting on behalf of the State Treasury, the Institute collects geological data across the country. The data are available, in digital and analogue formats, from the National Geological Archives, and several specialized databases, including the Central Geological Database CBDG, Midas, Infogeoskarb, the Register of Mining Areas, and the Hydro Bank. The Institute has initiated measures aimed at implementation of the INSPIRE Directive, intended to standardize spatial data across EU Member States.

The PGI-NRI operates laboratories that are specialized in chemical, microscale, geophysical and engineering geology analyses. The microscale laboratory boasts an Ion Microprobe SHRIMP IIe/MC and an Electron Microprobe CAMECA SX 100. The

accredited chemistry laboratory, counted among the largest in Poland, performs 500,000 determinations on 35,000 samples each year.

As a member of EuroGeoSurveys, an umbrella organization of European geological surveys, the Institute contributes to the development of reports by this Organization, and takes part in meetings of expert groups that provide advice to the European Commission. The PGI-NRI collaborates with geological centers in several dozen countries worldwide.

Almost 900 people are employed at the Warsaw PGI-NRI headquarters and seven regional branches (Gdańsk of Marine Geology, Kielce of the Holy Cross Mts, Kraków of Carpathian Mts, Lublin of Eastern Poland, Sosnowiec of the Upper Silesian Coal Basin, Szczecin of North-Western Poland and Wrocław of The Sudety Mts and the Lower Silesia). Most staff members hold academic degrees in geology, including several tens who are full or associate professors, and 140 PhD degree holders. Each year, the scientific staff of the Institute delivers several tens of national and international research projects.

The activity of the PGI-NRI is financed for the most part by the National Fund for Environmental Protection and Water Management and by the Ministry of Science and other scientific funding organizations. Commercial activities provide ca. 3% of PGI-NRI funding.

Pursuant to the Geological and Mining Law, the **PGI-NRI performs tasks of the Polish Geological Survey (PGS)**. The overarching task of the PGS is to take care of rational management of national mineral resources and to protect and monitor the status of the geological environment and to warn of natural hazards. Survey operations support key governmental strategies, including Po-

land's Environmental Policy and Poland 2030.

The Polish Geological Survey is primarily responsible for geological investigations, including projects of key importance to the national economy that are intended to identify new prospects for the mining industry, and to enhance mineral security of the country. PGS is involved in exploration for conventional and unconventional hydrocarbons, including coalbed methane. PGS also investigates the potential for tapping geothermal energy, as well as for the use of geological structures and formations for underground storage and disposal.

The Polish Geological Survey operates in close collaboration with central and local governments as well as with geological businesses and scientific research centres both in Poland and abroad, sharing experience and providing them with information. This arrangement allows for sustainable use of existing mineral resources and planning for mineral and economic strategies, as well as for counteracting the effects of natural disasters.

Detecting and monitoring of geoenvironmental hazards is a key responsibility of geological survey specialists. Our geologists investigate areas that are contaminated or subject to risk of mass movements. The latter are addressed by the Landslide Monitoring and Counteracting System (SOPO) established by PGS. The system is a project of national importance aimed at, first – creation of landslide susceptibility maps and, at a later stage, the development of a system for forecasting, assessing and reducing landslide risk in Poland. The project will have a major impact on the economy and finances of the Polish state and on the socio-economic wellbeing of its citizens.

The Polish Geological Institute also performs the responsibilities of the **Polish Hydrogeological Survey**

**(PHS)**, established by the Water Law of 2001. This document implements EU Directives on water management and protection. PHS primarily focuses on exploration, proving and protection of groundwater so as to minimize degradation of aquifers intended for consumption, and to ensure sustainable management of groundwater resources.

Research and data collected by the PHS are the key source of knowledge about the status of groundwater in Poland. PHS hydrogeologists monitor groundwater quantity and quality on a regular basis and collect information about the size of groundwater reserves and abstraction. They analyze reported changes, prepare forecasts, and draft hydrogeological maps, as required for efficient water administration and management planning.

PHS work is crucial, as seventy percent of Poland's population rely on drinking water supplied from freshwater aquifers. The safe yield of freshwater aquifers in Poland is almost 14 km<sup>3</sup> per year, while total groundwater uptake is in the order of 4 km<sup>3</sup> per year, thus Poland holds quite significant reserves of potable water. Nonetheless, effective conservation and sustainable management of these resources is key to counteracting degradation and assuring conservation of aquifers for future generations.

## Overview of 3D Modelling Activities

Modelling activities at the PGI-NRI follow three scale-dependent, interrelated paths: country-scale framework geological modelling, basin-scale (or major tectonic unit) modelling, and local-scale, for-purpose modelling (mine, geothermal, mineral deposit etc.). Throughout the last 10+ years, the focus has been shifting between the three. We started in 2003 with a country-wide, general stratigraphic model of bedrock geology released in 2005. Then, several local models

were built, a result of which was a greater recognition of modelling as an efficient research tool. We could thus embark on a more systematic approach to modelling: general-purpose 3D mapping of all sedimentary basins of Poland, and a strategy of systematic shallow model building, both outlined by Jarosiński et al. (2014). Recently, we made a loop by arriving at the conclusion that, besides basin-scale and local-scale models, we also need a greatly improved Framework Geological Model of Poland to hold together our more local interpretations and provide a tool for – surprisingly often requested – country-wide analyses. The current picture of our activities is thus the following:

The coming year (2019) will see a completion of our second basin-scale, general-purpose geologic model (Gorzów Block, Figure 1). It will be followed by the next basin-scale

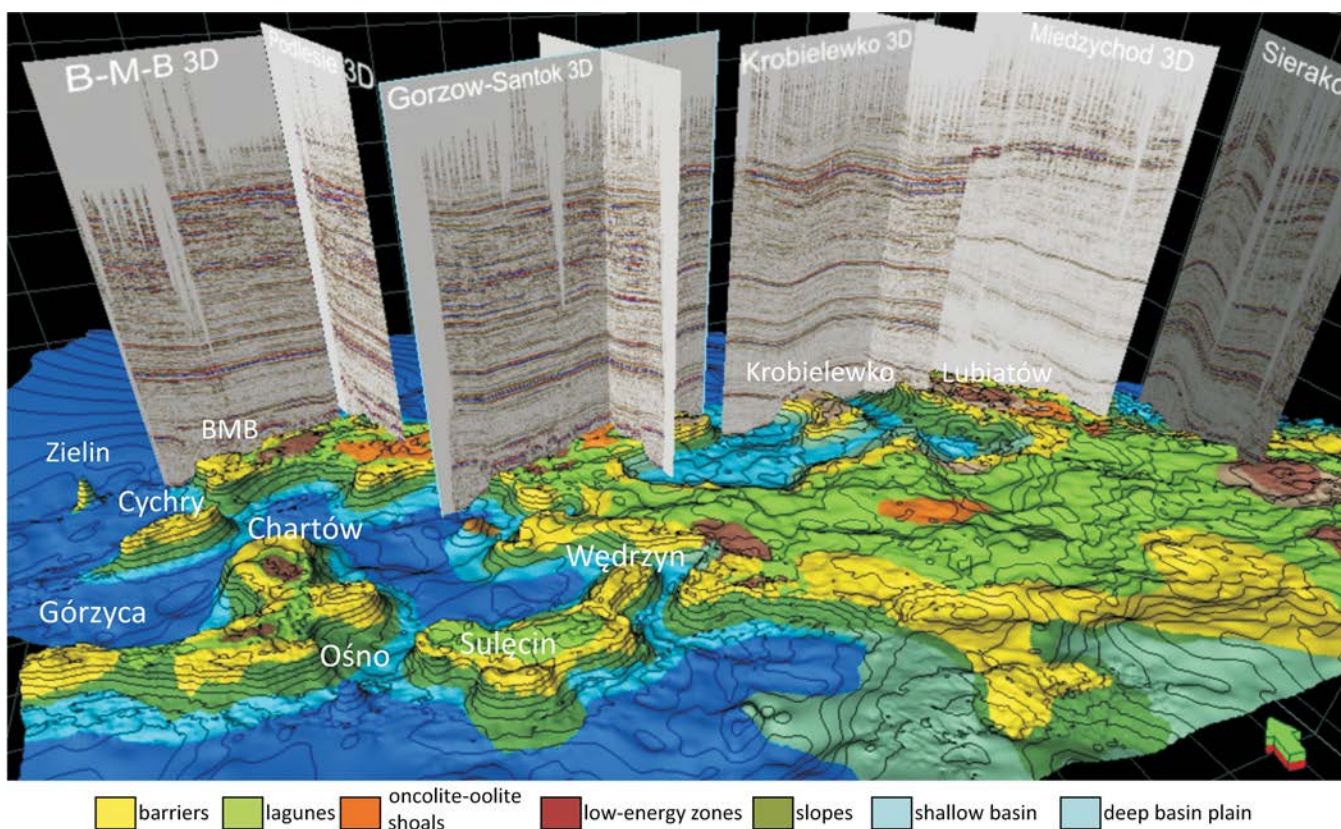
model located immediately to the north (Szczecin Syncline), thus allowing us to test cross-border harmonization with the Northern German Basin Model, within the pan-European GeoERA programme. It is our objective to gradually build multi-scale 3D geological models for all sedimentary basins, or large tectonic units in Poland.

In the same year, we will also start re-vamping our country-wide model – this time with much more data. Unlike the 2005 version, it will hold a geologic grid for parameter interpolation. The project is called Framework 3D Model of the Geology of Poland and will serve as a reference for all other models we produce. This project will also be an opportunity for a fundamental upgrade of our Central Geological Database and, hopefully, turning it into a 3D database.

Constructing purpose-built and local-scale models is finally arriving at the stage of a systematic activity for PGI-NRI. Most notable of these is 3D geological modelling down to 200 m for assessment of shallow geothermal resources, by making a series of heat conductivity maps that allow optimization of heat pump installations. This activity started within the framework of the TransGeoTherm project, and is currently conducted within the framework of the GeoPlasma project. The experience gained in these international endeavours is scheduled to be employed soon in most of metropolitan areas in Poland, and in the case of the capital of Warsaw with reuse of our existing urban geology 3D model.

### Resources Allocated to 3D Modelling Activities

Full-time core staff dedicated to general-purpose 3D geological mapping



**Figure 1.** Lithofacies distribution of the carbonate platform of Zechstein evaporites in Gorzów Block sedimentary basin 3D model, NW Poland. Surface depth 2200-3300 m. Structure interpreted from 23 seismic 3D surveys. Facies derived from 300 wells. Oil and gas fields indicated. The region depicted is ca. 100 km across (east–west), with north is indicated by the green/red arrow in the right lower corner of the figure.

consists of 9 people. However, these core personnel are supported part-time by several regional-geology experts, geophysicists, IT, and database personnel. Thematic models, such as geothermal or engineering geology models engage a further 15 people approximately, either full- or part-time. Altogether, about 60 people are engaged in 3D modelling at the PGI-NRI.

The Framework Geological Model of Poland, commissioned for 2019-2021, is funded by the Ministry of the Environment and the National Fund for Environmental Protection and Water Management, with a total budget of between 1 to 1.5 million PLN per year (230 to 350 thousand Euro/year). The Gorzów Block (2016-2019) project has a similar budget, similarly as the subsequent Szczecin Syncline geological model (2020-2023). Separate funds are provided in thematic

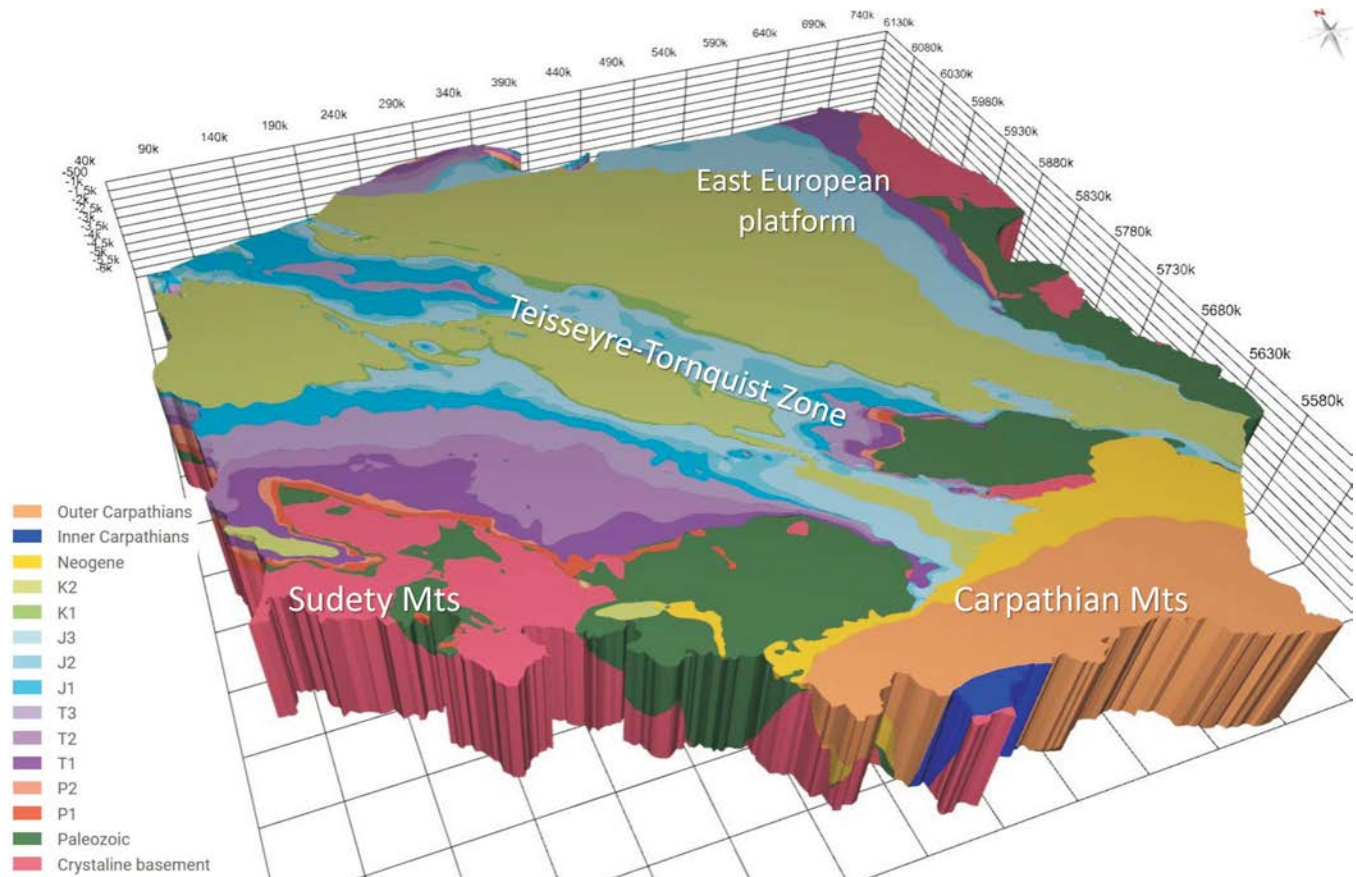
projects – such as engineering geology mapping of urban areas, or geothermal energy projects – to construct smaller, purpose-built geological models which will also finally be incorporated into the Framework Model of Poland. Altogether, estimated cost of modelling activities carried out at the PGI-NRI will approximately be 500 thousand EUR/yr.

## Overview of Regional Geological Setting

The area of Poland stretches over the north-eastern part of the West European Platform and the south-western edge of the East European Platform, with the Trans-European Suture Zone, i.e. the Teisseyre-Tornquist Zone (TTZ), trending northwest to southeast and dividing it into two, almost equal parts (Figure 2). The sedimentary cover on the East European Plat-

form started to form in the Late Proterozoic and its thickness ranges from less than 500 m in the northeastern corner of Poland on the Mazury Elevation to 5–7 km along the TTZ (M<sup>3</sup>ynarski 1982).

The slightly larger, southwestern part of Poland originated from the Early Palaeozoic accretion of Caledonian terranes at the southwestern margin of Baltica, which remained passive until the Late Ordovician (Nawrocki and Poprawa 2006). This Caledonian accretion was followed by the Variscan collision, and creation of the thrust-and-fold belt, covering the majority of the area to the south-west of the TTZ. The Variscan belt is bound from the south-west by the Bohemian Massif, with the Sudetes along the border with the Czech Republic. The foreland basin to the north and north-east of the Variscan front is underlain by the Caledonian basement, while to the



**Figure 2.** Bedrock model of Poland (2005) in depth interval 500–6000 m SSTVD. Vertical exaggeration x20. Legend abbreviations include Permian, Triassic, Jurassic, and Cretaceous strata.

east by the Brunovistulian and Małopolska Terranes associated with the Cadomian Orogeny.

The Lower Palaeozoic basement of the West European Platform is covered by Carboniferous and Permo-Mesozoic strata with a total thickness of between a few and several thousand metres. This sedimentary cover had the largest thickness immediately to the south-west of the TTZ, i.e. in the Mid-Polish Trough. During the Alpine Orogeny, however, the Mid-Polish Trough underwent tectonic inversion which transformed it into the Mid-Polish Swell (Pożaryski and Brochwicz-Lewiński 1979). At the local scale, the sedimentary cover was also deformed by salt tectonic movements associated with activation of the Upper Permian evaporates which started in the Triassic (Krzywiec 2002).

The southern edge of Poland lies within the reach of the Carpathian thrust-and-fold belt with its foreland basin filled by Neogene deposits in the Małopolska Region (Figure 2). Despite the significant rejuvenation of topography during the Alpine Orogeny, almost the entire area of Poland – with only exceptions for the southern parts of the country – was generally levelled by the Paleogene and Neogene sedimentation as well as by the Quaternary glaciations. During the latter, elevations were eroded and a thick cover of locally derived material mixed with that brought from Scandinavia was left, locally reaching well over 300 m.

Generally, the geological setting of Poland provides significant challenges for 3D geological modelling across the country, particularly with several km-high salt domes in the axial part of Polish Basin, and crystalline basement structures of the Sudety Mountains and the East European Platform. These bedrock modelling challenges are accompanied by further difficulties in shallow strata, such as thick Quaternary deposits left by

several glaciations, with frequent glaciotectonic deformations, covering almost the entire country.

## Data Sources

In accordance with Polish regulations, the State Treasury is the owner of all geological information obtained within Polish territory. This information can be used by the State (thus also by the Polish Geological Survey) to fulfill its tasks. It can be released to stakeholders (for a fee payable to the State and dependent on intended use of information) five years after the exploration license of the data provider expires. Earlier release is possible only after obtaining the permission from the exploration company. This does not apply to data obtained during most of the 1990s – in which case the company that collected the data is still its only owner and thus controls the right to use it.

Polish regulations indicate that geological interpretations (thus also geological models) can be released to the public without restrictions. Nonetheless, when models are built with the use of restricted-access data it is a good practice to agree with the data provider on the resolution and content of the final product to convey meaningful information without compromising the market competitiveness of the data owner. The legalities of access to data are thus largely favourable for the Polish Geological Survey.

In practice, our access to data is limited by the content of the Central Geological Database (CGD) managed by the PGI-NRI. This database is the largest Polish collection of geological data with over 11,250 seismic reflection profiles, 98 3D seismic datasets, over 13,000 boreholes deeper than 500 m and almost 200,000 shallower boreholes. These archives, except the well database, are nonetheless largely analogue, most notably in the case of seismic data and borehole geophysics, both key components of almost any

modelling project. Digital versions of these data must thus often be obtained for a fee from third parties, which up to now requires a separate agreement for every project.

The whole country is also covered by gravity data with a density of between 2 and (locally) 10,000 measurement points per square kilometre. These data are stored in the CGD and is fully digital. We have a similar database for magnetic susceptibility data and there are also other geophysical surveys such as magnetotellurics or abundant electrical resistivity profiles used for shallow subsurface interpretations.

## 3D Modelling Approach

The PGI-NRI uses a spectrum of implicit and explicit modelling strategies. Intermediate (basin)-scale to country-wide models are constructed with either Petrel or Gocad/Skua, where a combination of the techniques is used, as both raw data (borehole and geophysics) but also interpretations (maps, outlines, cross-sections) and interpreter-driven corrections feed into a model and influence the final result. The result is explicit at a more general level, given that a model contains defined geobodies and a 3D grid constructed according to the decisions made by the interpreter, and semi-implicit at a level of populating the grid by parameters. The latter is mostly data-driven and input from the interpreter is restricted to cut-off levels, choice of interpolation algorithms, and choice of procedures to deliver the most likely scenario.

The modelling approach for large scale models actually tends to occupy either end of the explicit-implicit spectrum. In the case of models where seismic and well data are scarce, we rely on gravimetric and magnetic data. These models are constructed with Geomodeller and the approach is implicit, – although we can derive geobodies for the final pre-

sentation, the model itself neither contains fixed 3D surfaces, nor is there much room for interpreter-driven adjustments within the modeling workflow. On the other end of the spectrum are geomodels that are feeding into calculations of shallow geothermal potential maps. These models are explicit – they are constructed from interpreted cross-sections that are averaged into a 3D space, without much smoothing of the resulting surfaces. Subsequently, however, they are employed for calculating heat conductivities at any point in the geospace, and this procedure is in turn fully implicit, as it populates the grid according to measurements and a fixed calculation procedure.

## Clients

General-purpose 3D mapping, such as the upcoming 3D Framework Geological Model of Poland or sedimentary basin-scale models, have a wide array of potential users – from educational institutions, academia, professionals and state and local administration. The scope of information conveyed in these models is purposefully broad so as to make them usable for a wide range of applications. Nonetheless, principal groups of stakeholders were identified and are the following:

The integrated 3D Framework Geological Model of Poland is aimed most of all as a decision-making aid for geological administration at the state level, in its most detailed form serving both the Ministry of Environment and the PGS. A generalized version will be freely available both as educational material delivered in a web viewer, and for research as downloadable files. It will be a powerful tool to bring the attention of society to the subsurface, and to raise awareness of its use for economic growth and environmental protection.

The individual models of sedimentary basins will inform both state and local administrations, academia, and pri-

vate companies interested in geological contexts of areas of their interest. They will also be freely available for viewing and downloading. Regions selected for these kinds of models generally follow the “hot topics” for exploration companies, as this is where they have the potential to make the most difference. Nonetheless, for both – the Framework Geological Model of Poland and the sedimentary basin models – we increasingly recognize that we need a better insight from users so as to make our models still better adjusted to their needs.

Local-scale modelling is where interaction with stakeholders is the closest and recognition of their needs is best – for a simple reason that these models are either on-demand products or for-purpose endeavours, clearly aimed at solving a specific societal need. The best examples of the latter are models made for calculating geothermal potential maps or engineering geological models prepared in the Polish Geological Institute Department of Geohazards and Engineering Geology. The latter are usually site-scale models, developed to visualize geological conditions in the subsoil of a planned large engineering projects (for example: high rise buildings, metro tunnels or stations) with deep foundations like piles or trench walls. Geotechnical site investigation is carried out mostly within the area of the parcel where the construction works will be performed, on the base of detailed geodetic plans in scale 1:500 or smaller.

The provided engineering geological models are intended to fill the gap between geological regional mapping and databases (scales 1:10,000 and bigger) and geotechnical designers’ needs. To perform proper geological risk management in such engineering projects, visualisation of geological conditions in a context broader than just the construction site is necessary (for example – to visualize the glaciotectonics of Pliocene clay

layers, as it is presented on Figures 3 and 4).

The primary clients of such models are geotechnical and structural engineers, and project managers who represent the investor. Collaboration with clients at the stage of model preparation is mostly focused on access to all available archival data. Models after development are given to the client to facilitate decision making, both in means of time/budget issues and detailed technical design.

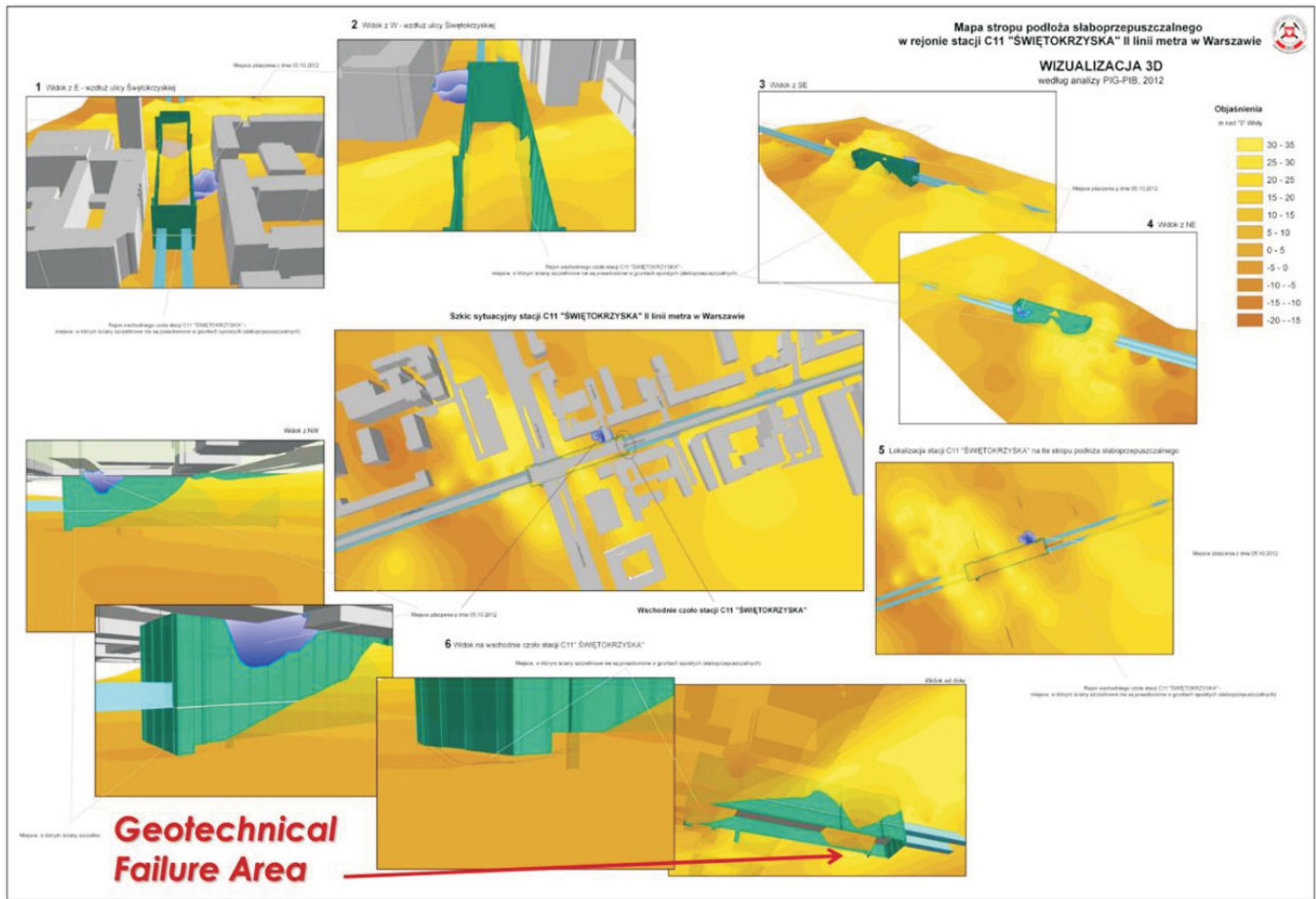
## Recent Jurisdictional-Scale Case Study Showcasing Application of 3D Models

As an example that can showcase application of jurisdictional-scale 3D engineering-geological models developed at the Polish Geological Institute, we present the model of subsoil of a planned location of contaminated waste landfill (Figure 5). This model was developed to allow numerical simulations of contaminant transport in subsoil of a planned landfill. The main aim was to ensure that the thickness of natural non-permeable layers of glacial tills will be enough to act as a protective barrier for drinking groundwater reservoir.

The model was developed in Geoscene3D software as a voxel model. At first the layer model was prepared, including over 30 layers used to precisely model sand lenses. The next step was rectification of the layer model into a voxel model. Voxel size was chosen as  $10 \times 10 \times 0.5$  m. The criterion for model layers was based on lithology, genesis and permeability, followed by statistical evaluation of data and upscaling, in order to finally derive 3 main rock types that were modelled in 3D.

The model was developed on the basis of interpreted cross sections based on borehole and geological soundings data (CPTU, DMT). Geophysical methods, including electric tomogra-





**Figure 3.** 3D visualisation of Pliocene clay deformation in an area of Warsaw Metro Line 2 Station “Świętokrzyska”, where a geotechnical failure occurred due to hydraulic seepage of liquefied sands located in a clay pocket just below the trench wall foundation level. Each area depicted is about 0.7 km across. Green indicates the trench wall contour, blue is the area of sand liquefaction, and yellow to orange indicate the elevation of top of Pliocene clay layer.

phy (ERT) and seismic tomography (SRT) were used for model verification. The main issue in model preparation was to properly model small, isolated lenses of saturated fluvioglacial sands, that are crucial for contaminant transport.

The voxel model was saved in native Geoscene3D format and then exported to an ASCII file. This model was used for numerical modelling in Tough2 software that allowed a decision if an analysed location for land-fill fulfils the safety criteria for groundwater protection. The numerical modeller was in constant contact with the geological team at PGI during the process of model development. The final model resolution in terms of voxel size and total voxel

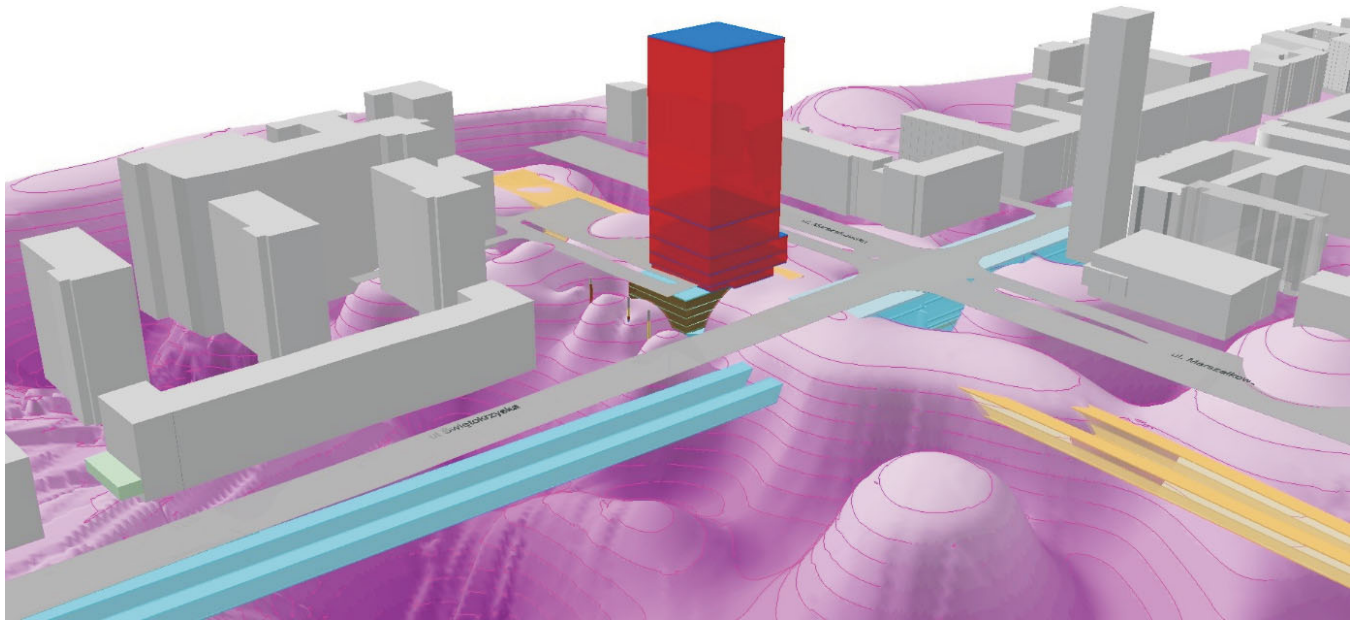
number was defined during project meetings.

### Current Challenges

The most important challenges that we currently face relate to two factors: 1) quantity, quality and access to digital data; and 2) lack of an overarching policy to advance 3D geological mapping and modelling within the organization. Both of these factors make our urgently needed organizational switch to 3D geological data analysis and delivery still a somewhat remote goal.

In the case of digital data issues, although significant progress in digitisation of geological data has been made, a large proportion of these data is still stored in analogue format in

CGD and, although formally state-owned, must be obtained in digital format for a fee from third parties. This is especially true in the case of seismic data and well geophysics – both the key base for most modelling projects. Moreover, as the PGI maintains several databases, there are issues relating to data integration, compatibilities between datasets, and the ability to trace the same objects, such as wells, between databases and related products, including CGD, the hydrogeological database, 1:50,000 geological maps, etc. Digital data stored in the CGD have quality issues too, such as roughly 10% of mislocated boreholes, and unharmonised stratigraphic interpretations.



**Figure 4.** 3D Visualisation of glaciotectionic deformation of Pliocene clays in an area of a planned high-rise building in Warsaw, near the crossing of two main Metro lines. This visualisation was aimed at the geotechnical designer, to convince him that more dense borehole spacing below the planned building would be necessary to properly design the foundation pile depths and diameter. The area depicted is about 0.6 km across, north is to the left, and the colour gradient represents the elevation of top of Pliocene clay layer.

There is also still a lack of general confidence in the 3D approach to geological mapping and modelling within our organisation, partly due to large organisational and technological changes which would be necessary to set us on track towards a full 3D mapping policy. According to our experience, specialized staff would be eager to embrace 3D geology and the opportunities that come with it, however, for efficient employment of this approach we would need to re-think established workflows, database schemes, and data flow, as well as establishing schemes for quality assurance and storing of modelling results. This cannot be done without greater conviction and effort throughout the organization. The need to switch our geological mapping to 3D is becoming more and more urgent, and the drive to do so is emerging among staff, although this is a painstaking and not always successful enterprise. Understaffing is therefore a collateral issue, especially acute in the case of far too few geophysicists available to undertake data interpretation for

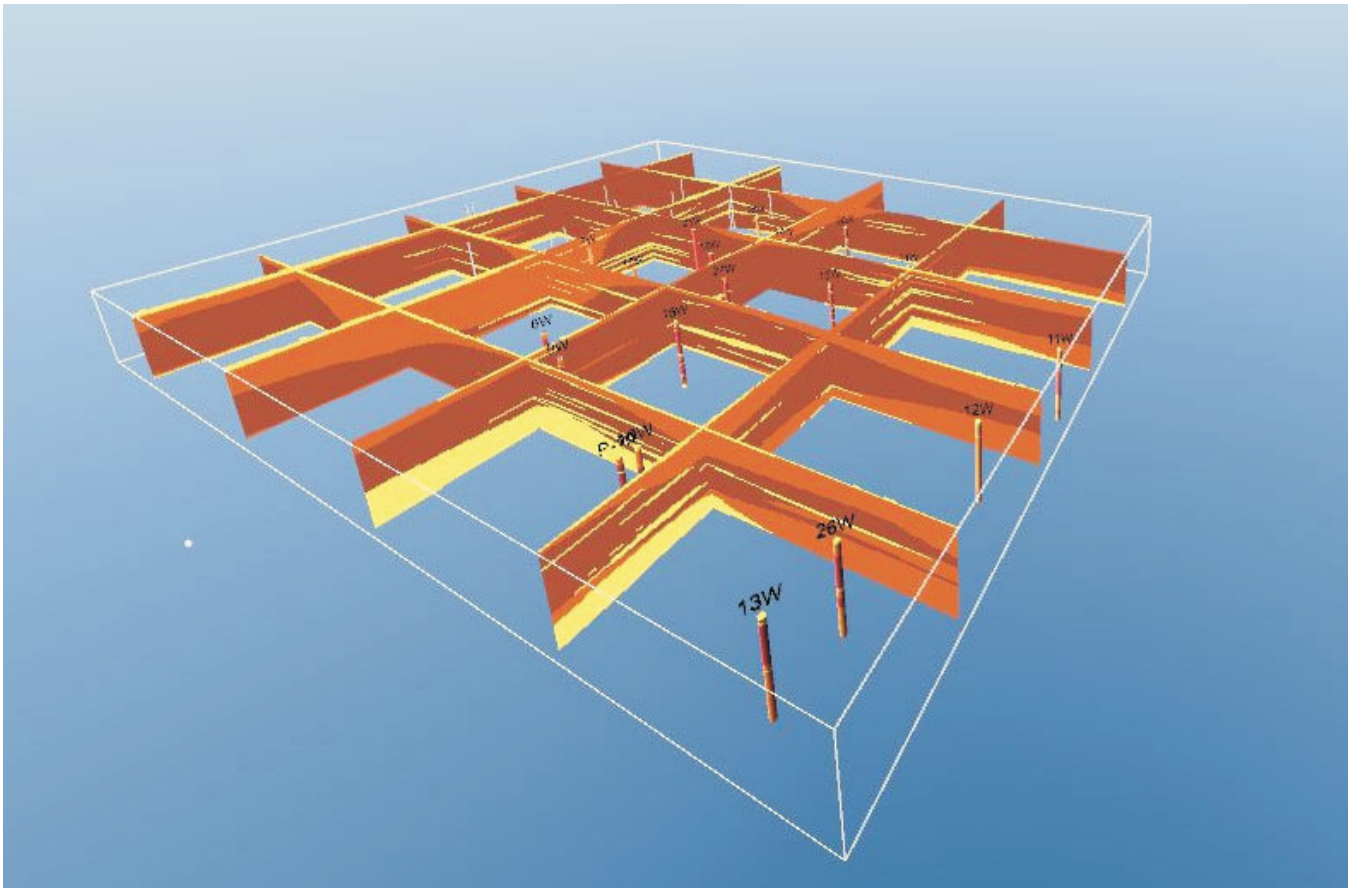
modelling workflows, but also experienced geomodellers.

## Lessons Learned

We can only describe here the lesson learned by a small group of geomodellers working for 15 years in the field of 3D geological mapping. The rest of our organization is still undertaking initiatives in this topic and we can foresee outcomes of this activity in a few years.

First, 3D geological modelling is a natural way of expression of geological knowledge on the rock formations and their structures. Unfortunately, large technology gaps visible in geological surveys stop most of staff from this natural approach. Those lucky people with access to adequate computers and software may undertake the task of building 3D geological maps with different modelling approaches. As we may observe, despite numerous international meetings and associated initiatives on standards of geological modelling, almost every geological survey follows its own

way of modelling, discovered at some point of dealing with geospatial data. It seems naturally easier to give away the developed methodology to others than adopt methods offered by standardizing initiatives. Thus, we have parallel streams of modelling approaches, which are often incompatible at many points of the process. An opinion expressed recently in one of the modellers' meetings, about "not being able to harmonize models and workflows unless we really start working together" seems to express this point clearly. It follows that gathering information on our different approaches will not be enough to come up with workable standards that could be helpful to everybody. It seems to be time for a serious reflection about what such a common standard could be, and how to circumnavigate various legacy, site-specific issues that prevent us from producing a set of tools that would ease our modelling and exchange efforts and could kick-start 3D approaches in less-advanced organizations.



**Figure 5.** Fence cross-sections prepared in Geoscene3D software. The model was developed on the basis of interpreted cross sections based on borehole and geological soundings data (CPTU, DMT). Geophysical methods, including electric tomography (ERT) and seismic tomography (SRT) were used for model verification. The main issue in model preparation was to properly model small, isolated lenses of saturated fluvioglacial sands that are crucial for contaminant transport. Total depth is about 50 m, north is up, text annotation refers borehole number, yellow colour represents permeable fluvioglacial sand, light brown represents medium permeable glacial tills (sandy and silty clay) dark brown represents low permeable glacial tills (clay).

## Next Steps

Our view is that the Polish Geological Institute needs to embrace a 3D culture as soon as possible. Both the geological community and the general public's interests drift away from 2D maps and towards 3D, data-rich, interactive geology. It therefore is our compelling need and our immediate plan to facilitate a switch to such culture. Notably, there is a growing interest within the organisation to incorporate and integrate into a single 3D space all available geological data such as information related to mineral resources, rock properties, formation temperature, hydrogeological data as well as interpretations such as 2D

geological maps and, of course, existing 3D models.

To do that we need to build an integrated system for data digitization, verification and access – in other words to rethink and reorganize our Central Geological Database. This is already starting to happen, but will necessarily be executed in stages over the next several years. One near-future stage of this process is the establishment of a spatial relational geological database for mining data from Upper Silesia that will be a pilot for testing a full-scale extension of the CGD that could accommodate modelling data and results.

Selected modelling projects that are planned in the near future and that respond to different needs, taking into account differing levels of detail are the following:

- Framework Geological Model of Poland – for overarching geological context and data integration.
- Sedimentary cover of Szczecin Syncline (the northernmost part of the Polish–German border region) – the next sedimentary basin model and the continuation of cross-border harmonization.
- Several shallow geothermal potential models in different geological settings – for providing a pilot to satisfy societal demand for ready-

to-use tools that make a difference to real life problems.

In the longer term, we plan to model all sedimentary basins of Poland in 3D, and start realizing the strategy of systematic high-resolution modelling of the most vulnerable parts of the country – such as metropolitan areas and highly industrialized regions – in order to aid efficient spatial planning, allow better-informed risk mitigation, and avoid conflicts of use. We hope that our next steps in 3D modelling will be closer to standardized methods developed internationally, and will be visible to the public at home

and to the modelling community abroad.

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# Chapter 22: Saskatchewan 3D Phanerozoic Stratigraphic Framework

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Marsh, A. and Music, T. 2019. Saskatchewan 3D Phanerozoic stratigraphic framework; Chapter 22 in 2019 Synopsis of Current Three-Dimensional Geological Mapping and Modelling in Geological Survey Organizations, K.E. MacCormack, R.C. Berg, H. Kessler, H.A.J. Russell, and L.H. Thorleifson (ed.), Alberta Energy Regulator / Alberta Geological Survey, AER/AGS Special Report 112, p. 239–242.

## Introduction

In 2014, the Saskatchewan Geological Survey (SGS) published provincial-scale structure and isopach maps for all of the mappable Phanerozoic-age strata in the province, as part of the Saskatchewan Phanerozoic Fluids and Petroleum Systems (SPFPS) project (Marsh and Love, 2014). Following the completion of that project, in 2015 the SGS began creating a 3D model for the Phanerozoic in Saskatchewan, based on data derived from existing datasets, including those created for the SPFPS project. The plan, at that time, was to use the Phanerozoic 3D Modelling project as the next step in the generation of a geological framework for the Phanerozoic in Saskatchewan. Data resulting from the Phanerozoic 3D Modelling project would then be available for future pool-scale reservoir characterization projects, that could be used to advance knowledge of hydrocarbon and fluid-flow systems and thereby potentially expand hydrocarbon production within the province. A memorandum of understanding (MOU) in place with the Alberta Geological Survey (AGS) at the start of the 3D modelling project allowed for the sharing of knowledge and data between the SGS and AGS.

## Organizational Structure and Business Model

The SGS is a branch within the Saskatchewan Ministry of Energy and Resources and is responsible for investigating, compiling and maintain-

ing information on the geology, mineral and petroleum resources of the province. The SGS comprises three work units (Petroleum Geology, Minerals and Northern Geology, and Data Management) that are overseen by the provincial Chief Geologist. The Phanerozoic 3D Modelling project falls under the responsibility of a geologist from the Petroleum Geology work unit and a GIS analyst from the Data Management work unit.

## Overview of 3D Modelling Activities

Previously completed 3D projects involving Saskatchewan's Phanerozoic strata include: the geological characterization of the Weyburn pool in southeastern Saskatchewan, as part of the International Energy Agency's Greenhouse Gas Weyburn CO<sub>2</sub> Monitoring and Storage project (Whittaker, 2004, 2005); a study of localized coal deposits within the Mannville Group in the Hudson Bay area of eastern Saskatchewan (Berenyi, 2010); and a detailed study of the potash-bearing members of the Prairie Evaporite in southern Saskatchewan (Yang, 2015).

Previously completed 3D projects by the Minerals and Northern Geology work unit of the SGS include: a model of the Fort à la Corne kimberlite in north-central Saskatchewan (Harvey, 2004); studies related to uranium deposits within the Athabasca Basin in northern Saskatchewan (Bosman et al., 2011, 2012, 2014); modelling of the sub-Phanerozoic basement at the margin of the Cana-

dian Shield in the Hanson Lake area of northeastern Saskatchewan (Morelli, 2012); and a summary report describing the processing of airborne magnetic and electromagnetic data to generate a 3D model of sub-Phanerozoic features in the Flin Flon area of northeast Saskatchewan (Mahmoodi and Morelli, 2017).

To date, for this particular project, 'workflows' have been designed that will take grid files generated as part of the SPFPS project and create a 'sealed volume' model for Lower Paleozoic strata, using the Lower Paleozoic unconformity as the upper bounding surface and the top of Precambrian as the lower bounding surface. As well, preliminary 'surfaces' have been generated in GOCAD using all of the SPFPS structure grid files.

## Resources Allocated to 3D Modelling Activities

Information on this topic is currently not available.

## Overview of Regional Geological Setting

Many papers have been written over the years describing various aspects and details of the geology within Saskatchewan's Phanerozoic strata. This paper is not designed to go into the details of the geology within Saskatchewan, rather it is meant to provide the reader with a very general understanding of the geological framework for Saskatchewan's Phan-

erozoic strata, from the top of the Precambrian basement to the uppermost mappable lithostratigraphic unit below surface casing within the province.

The Phanerozoic in Saskatchewan is composed of an up to approximately 3,300 m thick southward-thickening wedge of clastic, carbonate and evaporitic rocks that were deposited in the portions of the Western Canada Sedimentary Basin (WCSB) and the Williston Basin (Wright et al., 1993) that extend into the province. For the purpose of this project, there are 71 regionally mappable stratigraphic intervals within the lower and upper limits described in the paragraph above. These strata, from oldest to youngest, span from the Cambrian Deadwood Formation to the Upper Cretaceous Belly River Formation and retain evidence of differing environments of deposition. The Paleozoic and lowermost Mesozoic through Lower Jurassic rocks were deposited within relatively shallow epeiric seas during four major second-order sequences. In contrast, rocks deposited following the Middle Jurassic vary greatly in depositional environment and depth of water in which they were deposited, and were subjected to only two major second-order sequences (Sloss, 1963, 1987). Various structural elements were also active throughout the Phanerozoic, which contributed to control on depositional patterns and, to some extent, hydrocarbon distribution and subsurface economic mineral deposits within the WCSB and Williston Basin (Wright et al., 1993).

Amount and type of hydrocarbon production (i.e., either oil or gas, and, if oil, whether light, medium or heavy) in the province varies greatly depending on the strata, region or pool. In general, there are pools of heavy oil in members of the Mannville Group around the northwest part of the province; pools of heavy to light oil and/or gas in the Bakken Formation, Success to Viking Formation and the Milk River Formation of west-central

Saskatchewan; pools of medium and heavy oil of Jurassic age (Shaunavon and Roseray formations) in the southwest; and pools of light to medium oil in the Ordovician to Mississippian strata in the southeast. Saskatchewan's Phanerozoic strata is also well known for other subsurface economic resources, such as the Devonian Prairie Evaporite potash deposits, Cretaceous diamondiferous kimberlites north of Prince Albert, helium in the southwest, and industrial elements (lithium, bromine, iodine, etc.) within the brines from strata of various ages.

## Data Sources

This project will make use of xyz data points (.dat files) from 156 grid files, generated with a 2 km grid spacing, for 85 stratigraphic structural surfaces within Saskatchewan's Phanerozoic. These grid files, created as part of the SPFPS project (Marsh and Love, 2014), each contain 244,122 data points; these data points will form the building blocks for the provincial-scale 3D model.

Other datasets that we plan to incorporate into the Saskatchewan 3D model include the Shuttle Radar Topography Mission (SRTM) Digital Elevation Map (DEM) data, and grid files from the hydrogeological component of the SPFPS project (Jensen et al., 2015). The DEM will form the upper bounding surface for the Saskatchewan 3D model.

## 3D Modelling Approach

The SGS is currently using GOCAD software for this project. Data processing issues encountered in early testing resulted in the following general workflows that will be used to generate the 3D model for the Phanerozoic within Saskatchewan.

- 1) The grid files generated at a 2 km grid spacing for the SPFPS project resulted in a volume of data points that significantly increased data processing time. Therefore, each major structure surface that was

generated as part of the SPFPS project (Marsh and Love, 2014) will be re-gridded, using Golden Software's Surfer 12 application, from a 2 km grid spacing to a 15 km grid spacing. The upside of this new grid spacing, which results in a decrease of data points from 244,122 per grid file to 32,550 per grid file, is greatly reduced data processing time. The downside, however, is that the volumes created by this broader grid spacing are very coarse, and have extremely low resolution.

- 2) The provincial DEM will also be re-gridded, from a 1 km grid spacing to the same parameters as the SPFPS grids. The rationale behind this is firstly to make the data more manageable within GOCAD by reducing the data volume and thereby reducing processing time and refresh rate, and secondly so that the grid points within each layer overlie one another, thereby making it easier to 'stitch' stratigraphic layers where they converge at their zero edge.
- 3) The .dat files (xyz data points) from each regenerated grid file will then be imported into GOCAD as a pointset and clipped, where appropriate, to the SPFPS isopach zero edge closed curve (shapefile).
- 4) 'Regions' will then be generated within the closed curve for each stratigraphic interval, and new pointsets created from these regions.
- 5) From this point in the process, GOCAD surfaces will be built from these new pointsets and then sealed as a 'voxet' along the appropriate SPFPS zero edge, as well as the project's bounding extents (south, east and west provincial boundaries).

## Clients

The Saskatchewan 3D Phanerozoic Stratigraphic Framework model is designed to be used by Ministry of En-

ergy and Resources staff, industry and academia as a starting point for future pool- or local-scale modelling projects. The plan is to make the 3D model and all of its components available to the public through the Ministry's website.

## Recent Jurisdictional-Scale Case Study Showcasing Application of 3D Models

Information on this topic is currently not available.

## Current Challenges

There are a couple of challenges that are currently impacting the progress of the Saskatchewan 3D Phanerozoic Stratigraphic Framework project. The primary challenge is related to the extreme volume of data that has currently been collected for the project's basic components (SPFPS project grid data). Work on the project has met with some success—mainly, the creation of a sealed volume for the province's Lower Paleozoic strata—however, this success is somewhat limited, as the 'voxels' for the volume generated are extremely coarse (with dimensions of 15 km<sup>2</sup> x 225 m). The other current main challenge is the limited availability of resources (manpower, time) to work on the project.

## Lessons Learned

The primary lessons learned during the initial stages of this project revolve around data, technological resources and time. The data that are being used for this project appear to be at a volume and density that is too great for both the application and hardware to process, which led to the development of an extremely coarse initial model. Attempts to process the data with a 2 km grid spacing generally failed, due to extremely excessive processing times and application processing issues. Once the data had been re-gridded, the processing time became more manageable; however,

the model was still very cumbersome and the voxels far too coarse to be of much use. The SGS will be changing their approach to 3D modelling based on the initial results of this project, as discussed below.

## Next Steps

With a view to lessening the impact of the issues encountered during the initial stages of this project (related to data volume, processing time and the cumbersome nature of the current provincial-scale 3D model), it has been proposed that the modelling process might meet with more success if models were created at a smaller scale rather than a provincial scale. As such, all major mappable Phanerozoic structure surfaces that were to be created as part of this project will be used in conjunction with pool-scale 3D projects, in order to constrain the localized stratigraphic data. As required and when feasible, stratigraphic volumes for various Phanerozoic strata at the pool scale will be generated.

Products generated from the provincial framework data, that were to be used as part of this project, are currently available on the Ministry's website in various formats (Marsh and Love, 2014; Jensen et al., 2015). As well, the 2D contour maps generated from the provincial stratigraphic framework data (Marsh and Love, 2014) have recently been made publicly available as layers on the Saskatchewan Mining and Petroleum GeoAtlas.

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# Chapter 23: Three-Dimensional Geological Mapping and Modelling at the Geological Survey of Sweden

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## Introduction

The Geological Survey of Sweden – SGU – is the expert agency for issues relating to bedrock, soil and groundwater in Sweden.

Our key task is to meet society’s need for geological information. SGU is also responsible for the national Good-Quality Groundwater objective, which also involves reducing the use of natural gravel.

## Organizational Structure and Business Model

The Geological Survey of Sweden – SGU has its main office in Uppsala and local offices in Luleå, Malå, Stockholm, Gothenburg and Lund. The total staff of SGU is 300. SGU is an agency under the Ministry of Enterprise, Energy and Communication.

SGU is organized in five departments, Mineral resources, Physical Planning, Geohydrology, Mining Inspectorate and Operational Support.

SGU has copyright on its products and databases. SGU applies license fees for the use of digital information except for use in non-commercial research. All view services and INSPIRE download services are free for use. The open datasets are published under CC BY 2.5 SE license. Generally, all information at SGU is

available for the public with some exceptions for information collected as commissions and information sensitive for homeland security issues.

All the developments of geodatabases and web map services are based upon national and international standards where available.

## Overview of 3D-Modelling Activities

Until a few years ago, the 3D-modelling activities at SGU were restricted to the interpretation of different geophysical data, both from airborne and ground surveys. Now, 3D-modelling, including layer-modelling, implicit as well as explicit, is undergoing a rapid development at SGU. We expect that in the near future, modelling will be incorporated into our standard mapping methods, for example, involving the ore-bearing structures, local and semi-regional subsurface geology and layered geological formations in general.

Below are listed some of our ongoing projects/activities that include 3D-modelling aspects.

- Soil-depth/rockhead modelling (implicit modelling): the national soil depth model, one of SGU’s most requested products, is remodelled /updated at least once a year, using new information from

bore holes, geophysical measurements and surface mapping.

- Aquifer identification and modelling: SGU is commissioned by the government to identify and map aquifers needed for the water supply in areas frequently subject to shortage during drought. The modelling activities include producing resistivity-models from airborne TEM-measurements (Transient Electromagnetic Measurements), geological layer sequences and voxel modelling. The geological features modelled are eskers and other glacial deposits (see case history below), as well as sedimentary bedrock (Proterozoic and Mesozoic).
- Fault modelling in urban areas: engineering geological information from existing tunnel systems is combined with data from other sources to produce a 3D-model of the fault network in the Stockholm region. The faults are characterized and combined with soil depth, rock and soil type profiles in a 3D presentation on our website. The aim is to provide a basis for the initial planning stages of future infrastructure projects.
- Mapping 3D-distribution of acidic sulphate soil in coastal areas of northern Sweden (implicit modelling).

- Mapping 3D-distribution of quick clays (based on resistivity models).
- Overview 3D-model of Swedish bedrock (Figure 1): a three-dimensional model has been created representing the lithotectonic units and their bounding regional deformation zones in the bedrock of Sweden. The model is a development of the existing lithotectonic subdivision included in the bedrock map of Sweden at a scale of 1:1 million. The model has linked descriptions and is available on our website. The aim is to provide a basic framework and background information for more detailed regional and local scale models.
- Near mine semi-regional 3D-modelling in Bergslagen area, Lindesberg (Figure 2).

### Resources Allocated to 3D-Modelling Activities

About 10 geoscientists (bedrock- and Quaternary geologists, hydrogeologists and geophysicists) are involved

in geological (explicit) modelling, of which 2-3 allocate most of their working hours to modelling.

The total budget of the projects which include 3D-modelling is in the order of 20 MSEK (200,000 euros). It should be mentioned that these projects comprise not only actual modelling, but also field investigations, airborne geophysical surveys (TEM), collection of data from various external archives, development of database and webservices. In fact, the actual modelling constitutes only a minor part of the total costs.

### Overview of Regional Geological Setting

The bedrock of Sweden consists of three main components: Precambrian crystalline rocks, the remains of a younger sedimentary rock cover and the Caledonides.

The Precambrian rocks are part of a stable rock area known as the Baltic Shield (or Fennoscandian Shield).

The oldest rocks in Sweden are Archaean, i.e. they are more than 2,500 million years old and only occur to a limited extent in the northernmost part of Sweden. The rocks in the rest of the north of Sweden and in the eastern and southern parts of the country are mostly between 2,000 and 1,650 million years old. They formed, and were in many cases also metamorphosed, in connection with the Svecokarelian orogeny. That orogeny has also affected the Archaean rocks. The bedrock in southwestern Sweden is mainly between 1,700 and 1,550 million years old. It was metamorphosed during the Sveconorwegian orogeny, which occurred about 1,100–900 million years ago.

Phanerozoic sedimentary rocks are resting upon the Precambrian shield area. They are less than 545 million years old and cover large parts of Skåne, the islands of Öland and Gotland, the Östgöta and Närke plains, the Västgöta mountains, the area around Lake Siljan in Dalarna and areas along the Caledonian front

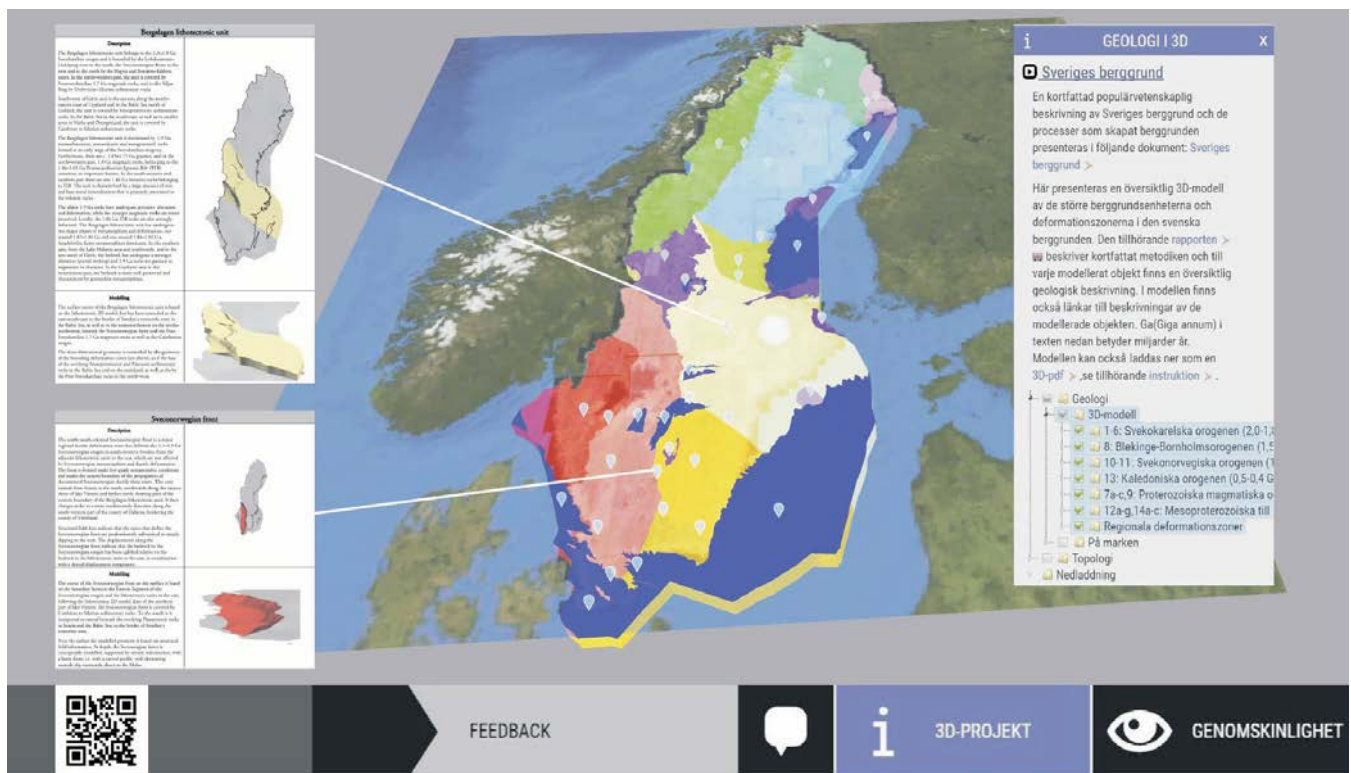
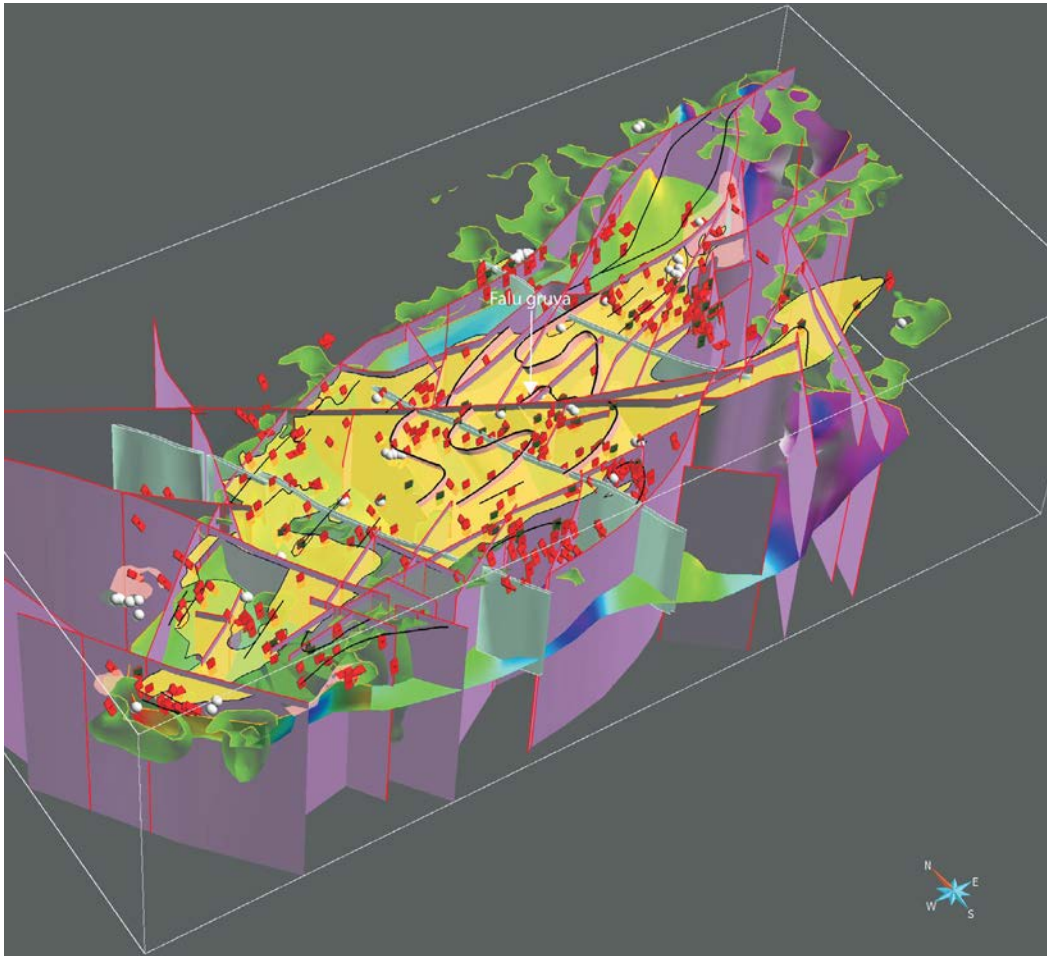


Figure 1. Overview 3D-model of Swedish bedrock. Produced in GoCad/Mira Geoscience software.



**Figure 2.** Near mine semi-regional 3D-modelling in Bergslagen area, Lindesberg. Produced in GoCad/Mira Geoscience software.

in northern Sweden. The youngest rocks in Sweden are Tertiary rocks, formed about 55 million years ago. They occur in the most southerly and southwestern parts of Skåne.

The Caledonian orogeny is the most recent in Sweden – it occurred about 510–400 million years ago. The rocks in the mountain chain vary in age from Precambrian to Silurian, which means that they are more than about 420 million years old.

The overburden is mainly formed by numerous periods of glaciation and deglaciation. The most common soil type is till, covering about 75 % of the landscape.

The average thickness of the till deposits is less than 10 m. A network of glaciofluvial eskers appears all over

the country. Many of these eskers are aquifers of great importance to the supply of drinking water. Low-lying areas of Sweden were covered by the sea subsequent to the last glaciation, due to the isostatic subsidence of earth crust. In these areas, there are widespread sedimentary clays and frequently occurring littoral sediments.

### Data Sources

- Updated 2D-geological maps (bedrock and Quaternary deposits including marine geological maps); harmonized codes, revised geometry, scale 1:25,000 – 1:50,000. For regional models, maps in smaller scale (<1:100,000) may be used.
- DTM (2 m grid) - national data set.
- Soil depth/rock-head model - national dataset developed by SGU (undergoes revision during the modelling process).
- Published geological sections - various sources and quality.
- Bore hole data from the national well archive at SGU: providing information of depth-to-rock head, sometimes also lithology. Variable accuracy. At present about 0.5 million wells are registered. Well-drilling companies have a statutory obligation to deliver drilling logs to SGU.
- Bore hole data from groundwater investigations from SGU's own surveys as well as from technical consultants. Consultants have a statutory obligation to deliver results from groundwater investiga-

tions performed in connection with ground water extraction.

- Geotechnical information, mainly from the Swedish Transport Administration and municipalities – voluntary agreements. At present, information from about 300,000 geotechnical drillings are included in SGU databases and used mainly for soil depth/rock-head modelling.
- Resistivity models based on airborne TEM-measurements (transient electromagnetic measurement). There is an ongoing program which includes airborne TEM-measurements mainly in areas with younger (Paleozoic and Mesozoic) sedimentary bedrock.
- Information from geophysical ground measurement from a variety of investigations and methods.
- Marine geological sections based on seismics.
- Bore hole data from the drill core archive in Malå (exploration drill cores)
- Potential field data (magnetic and gravity)
- Electromagnetic data
- Petrophysical data

When working with data that we have collected ourselves, often from our soil and bedrock mapping campaigns, we have a good understanding of the applied mapping standards, appropriate scale and locational accuracy, even though all of these are variables rather than constants and have changed over the years. This type of observational point information, along with its interpretation into traditional maps, has formed the basis for further interpretation into 3D visualizations and models.

There is a growing trend now of incorporating information produced by others into our datasets and resulting interpretations, with associated advantages, disadvantages and challenges. Legal issues concerning the definition and division between raw

data, information, design and intellectual property are currently proving to be barriers to the efficient use of much of this information. Data security and secrecy issues, especially those connected to underground infrastructure, have become more sensitive over recent years. This has led to data being effectively isolated, with organisations unwilling to take the risk of losing control of what they perceive as being ‘their’ data, even though often it is the Swedish taxpayer who has directly or indirectly paid for it.

### 3D-Modelling Approach

The applied modelling approach is naturally dependent on the type and aim of any particular model. For example, 3D bedrock models have been a further development from our bedrock maps and additional information. These have involved largely explicit techniques. Other types of models have used explicit techniques to generate a basic model framework that has been further developed using implicit techniques with numerical modelling. An example would be local aquifer models, assessing groundwater fluctuations and availability.

### Clients

For the most part, current 3D-modelling has most focus on groundwater, aiming at ensuring a sustainable water supply and, therefore, municipal water authorities are an important client group. Close cooperation with these clients is essential. When modelling an aquifer, the aim of the modelling is defined after consultation with the client. The client is expected to contribute with information *e.g.* bore hole information and, if needed, complementary field investigations. This means that we only model aquifers at a detailed scale (1:50,000) when there is a client that is willing to contribute.

Other important client/client groups for SGU’s 3D-information:

- The Swedish Transport Administration, using the national soil depth/rock-head model and modelled deformation zones. This client contributes by providing bore hole information for modelling as well as financially to the development of the soil depth model in areas where new railway routes are planned.
- The Geotechnical institute of Sweden, using 3D-information on soil type distribution (including the soil depth model) for developing methods for predicting construction costs and also for mapping quick clays and landslide risks. The institute, and other stakeholders within this sector, contribute financially to some extent.
- We see an increasing interest from local and regional environmental authorities and physical planners to use 3D-geological information, although only in a few cases have we established cooperation with these client groups.
- Exploration and mining companies.
- Universities.

If any client needs support in using the aquifer models, they may take advantage of SGU’s “Loan-a-geologist” free service.

### Recent Jurisdictional-Scale Case Study Showcasing Application of 3D-Models

The city of Uppsala, the fourth largest Swedish city, is located 71 km (44 miles) north of Stockholm. Uppsala Water provides municipal water to the city of about 141,000 inhabitants by extracting groundwater from the Uppsala esker. With a growing population, safeguarding the esker’s continued viability as the main water supply for Uppsala, is a major concern for Uppsala Water.

The Uppsala esker is a key water source. It trends northeast to southwest across the Uppland region and

has a total length of 200 km (125 miles), a maximum width of 1 km (3300 ft), and a maximum height of 75 m (245 ft) (Johansson 2006). Most of the esker is covered with clay, providing some protection against contamination from adjacent land uses, but regulation of nearby activities is very important where the esker is more exposed. In 2013 Uppsala Water, in cooperation with the Swedish Geological Survey (SGU), initiated a strategic study of the central portion of the Uppsala esker. SGU developed a digital database and a 3D geological model to investigate the geometry and stratigraphy of the Quaternary deposits of the entire groundwater catchment area. The 3D geological model covers an area of about 300 km<sup>2</sup> (117 miles<sup>2</sup>) and extends about 42 km (26 miles) in a north-south direction (Figure 3). Subsequently the 3D geological

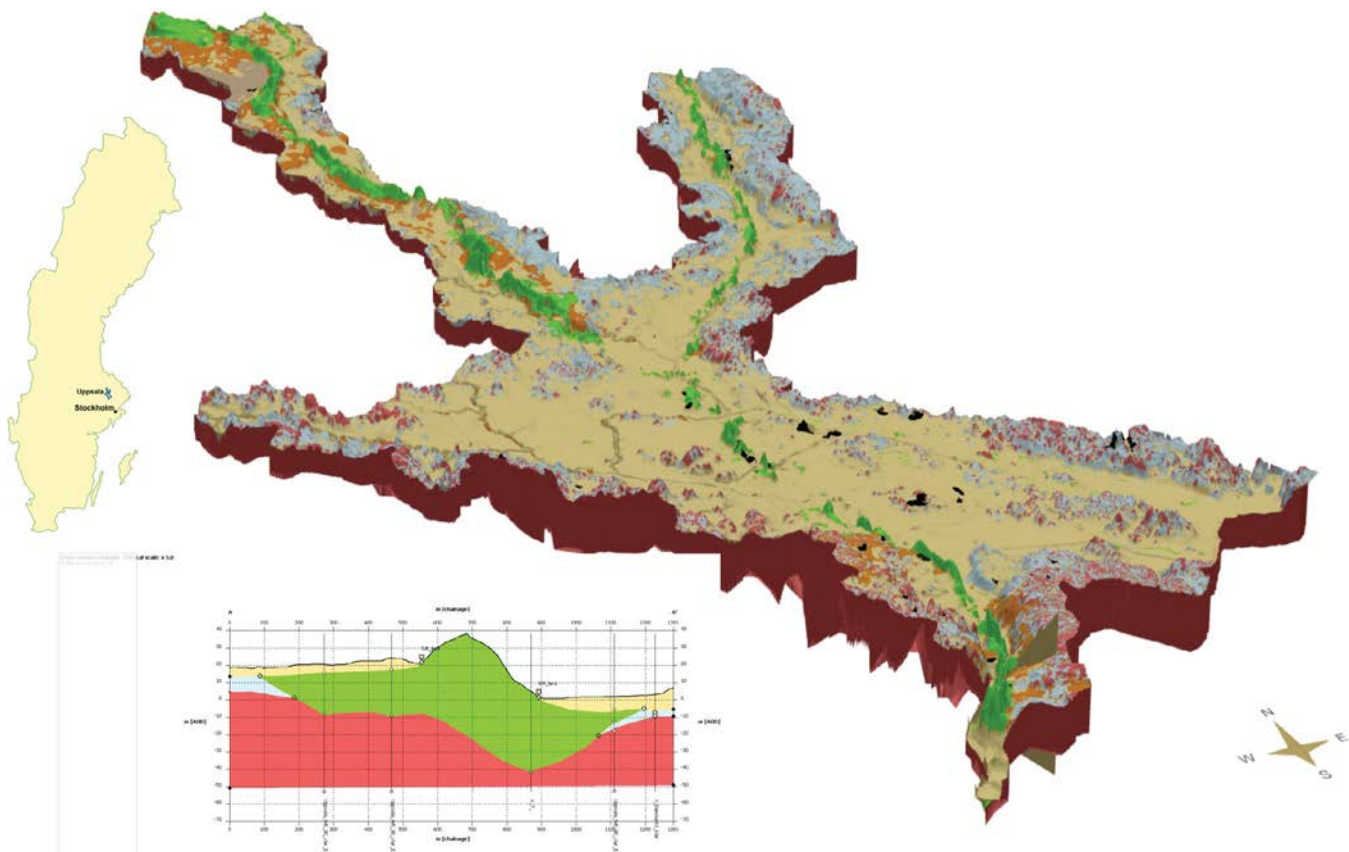
model units were assigned appropriate hydraulic properties, producing a conceptual 3D hydrogeological model of the main Uppsala esker, smaller tributary eskers, and the entire recharge area. The model revealed that the maximum thickness of the main esker to be at least 30 m (100 ft), and it is often in direct contact with the bedrock. The tributary eskers are thinner, usually with thicknesses of 5-10 m (16-33 ft).

Uppsala Water used the 3D hydrogeological model to develop a numerical groundwater flow model. The process is similar to that described by Royse et al. (2010). The groundwater model is an important tool for evaluating the viability of current and future water supplies. Groundwater conditions are controlled by a predominant flow from north to south and annual recharge of approximately

250-300 mm/yr (10-12 in/yr) in areas where the esker outcrops.

The model has also been used as a base for a vulnerability map helping the city planners and the local environmental authority to minimize the risks of contamination of the groundwater body. In 2018, there was an emission of diesel oil from an overturned tanker within the esker area. The model, visualized by a web-based “section visualizer” was successfully used to plan the remediation actions. This web-service is run by the British Geological Survey.

A printed physical 3D-model of the Uppsala esker, with removable layers, has proved to be a very efficient eye-opener to planners, decision makers and politicians, in making them understand the importance of being aware of the subsurface geology,



**Figure 3.** Overview of Uppsala esker model. The inserted section shows a representative generalized lithostratigraphy of the esker. Red: crystalline bedrock, light blue: till, green: glaciofluvial sand and gravel (esker), yellow: clay. Vertical exaggeration of section: 5x.

when planning for smart cities and a sustainable urban development.

## Current Challenges

Due to the stresses on Sweden's groundwater supply the survey received funding for a 3-year 3D programme (2018 – 2020) with focus on 3D-modelling of groundwater resources and development of modelling workflows. The modelling activities are based on TEM geophysical surveys in areas with sedimentary rocks and on quaternary mapping, georadar, boreholes and geophysics when modelling ground water within eskers.

The main challenge for the survey is to develop processes for modelling, storage, life-cycle management and distribution of 3D data and models as well as connecting these processes to a geological framework/architecture, while at the same time solving standardization and quality issues.

SGU is using several 3D-modelling software solutions depending on the purpose of the modelling. The diversity of modelling software results in interoperability problems regarding storage, sharing and distribution of 3D-models.

## Lessons Learned

- When working with '3D' it is natural to have an initial focus of the modelling and visualization software tools available. As our experience grows it becomes obvious more emphasis needs to be placed

on all aspects of the input data and storage of the output products. The key phrases being data quality, product compatibility and flexibility.

- Concerning the input data, complex fundamental issues still need to be resolved. These issues involve data ownership, right of use, secrecy and security. Security is a never-ending issue as technology continues to rapidly develop. These are difficult issues for any geological survey to solve by themselves and require external specialist resources, however, unless they are resolved, they remain a significant barrier to effective modelling work.
- As our experience grows with 3D-modelling and it becomes incorporated in all our workflows, it becomes less and less relevant to single out '3D' as being a specific subject area.

## Next Steps

- Creation of high-resolution 3D geological models for the underground in the major cities and areas with large investments in the national infrastructure (railroad, road and housing) to meet the ever-increasing demand for a quantitative characterization of the subsurface.
- Solving the interoperability issues when providing 3D-models and geological data to support Building Information models (BIM) in urban underground planning have a high priority for future work.

- Updating the geology part of the national framework for geodata in 3D.
- Providing data for pan-European 3D initiatives i.e. the European fault database within the GeoERA project.
- Participate in Nordic cooperation on 3D geological model database development.

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# Chapter 24: Swiss Geological Survey: Modelling a Small but Complex Country

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## Introduction

Over the past years, the society has become increasingly aware that geological data contribute to many aspects of daily life. For example: the security of supply (e.g. energy, water, mineral resources, building material), civil protection, infrastructure, waste disposal, public health, culture, civil engineering as well as design and arts all require geological data to some degree. The Swiss Geological Survey (SGS) has been working on the completion and harmonization of its datasets for several years now in order to provide for the requirements above. The efficient and productive usage of geological data not only necessitates their harmonized description, but also an easy way to provide and access the data. Specialists of all disciplines and the public need to be able to easily access and combine geological data (maps, cross-sections, 3D models and corresponding input data such as wells, seismics, etc.) and information (conditioned data) with information not originating in earth sciences (e.g. engineering, environmental, economics) to generate data compilations specific to their tasks and questions. The SGS aims to enable interdisciplinary collaboration in order to increase the usability of geological data. The introduction of 3D geological models added complexity to the product range and increased the number of datasets available. Their importance has changed dramatically over the years. Today they are one of

the core instruments for many purposes and come to use in project planning, permitting, surveillance, etc. For the SGS 3D geological models form the core to achieving the vision outlined above and will play a key role in its future strategic direction.

## Organizational Structure and Business Model

The SGS is a division of the Federal Office of Topography, swisstopo, under the auspice of the Ministry of Defense, Civil Protection and Sports. Currently 42 staff members work at the survey (incl. interns and administrative staff). The Swiss government funds 80% of its budget and third parties contribute the remaining 20% by research projects or service contracts.

Geological Mapping and Mineral Resources, Data Management and Geoenergy, Rock Laboratory and Deep Waste Repositories form the three branches of the SGS and a small staff group supports the director of the survey. All three branches have 3D modelling specialists assigned with specific tasks related to the division's core topics (mineral resources, geoenergy, and research, respectively).

Three-dimensional models related to mineral resources and geoenergy are available for our clients, whereas models covering aspects of the research for deep waste repositories stay within SGS. The SGS does not

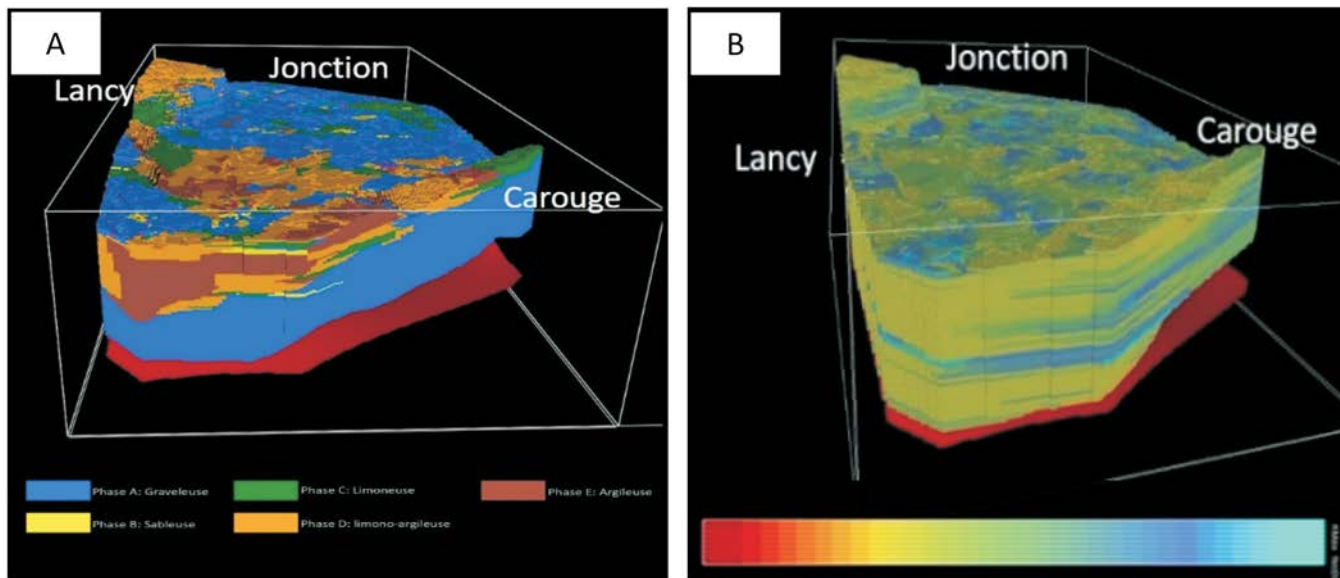
charge for the utilization of its 3D models. Parallel to the current Open Government Data discussion, the SGS is investigating the commercialization of parts of its business towards a “freemium” approach: while basic data remain free of charge, there will be a fee for advanced tools and services.

## Overview of 3D Modelling Activities

Modelling activities at the SGS cover the following activities:

**Unconsolidated sediments:** Modelling of the unconsolidated sediments covers the volume between topography and bedrock. Several block models with different resolutions (Block size xyz, from  $10 \times 10 \times 1$  m to  $50 \times 50 \times 2$  m) were developed for different areas ( $5 - 400$  km<sup>2</sup>), now incorporating parameters such as lithostratigraphy, hydraulic conductivity and resource quality (Figure 1). Various maps (e.g. ground foundation class, groundwater vulnerability or groundwater volume maps) can be derived from those models by including further topic-specific data.

**Consolidated sediments:** Models of the consolidated sediments start below the rockhead and include the Cenozoic and Mesozoic sediments and in some areas Paleozoic troughs and their infill. Currently three models of the Swiss Midlands ( $\frac{1}{2}$  of the country) are available. Two are typical layer cake models (high and low-res-



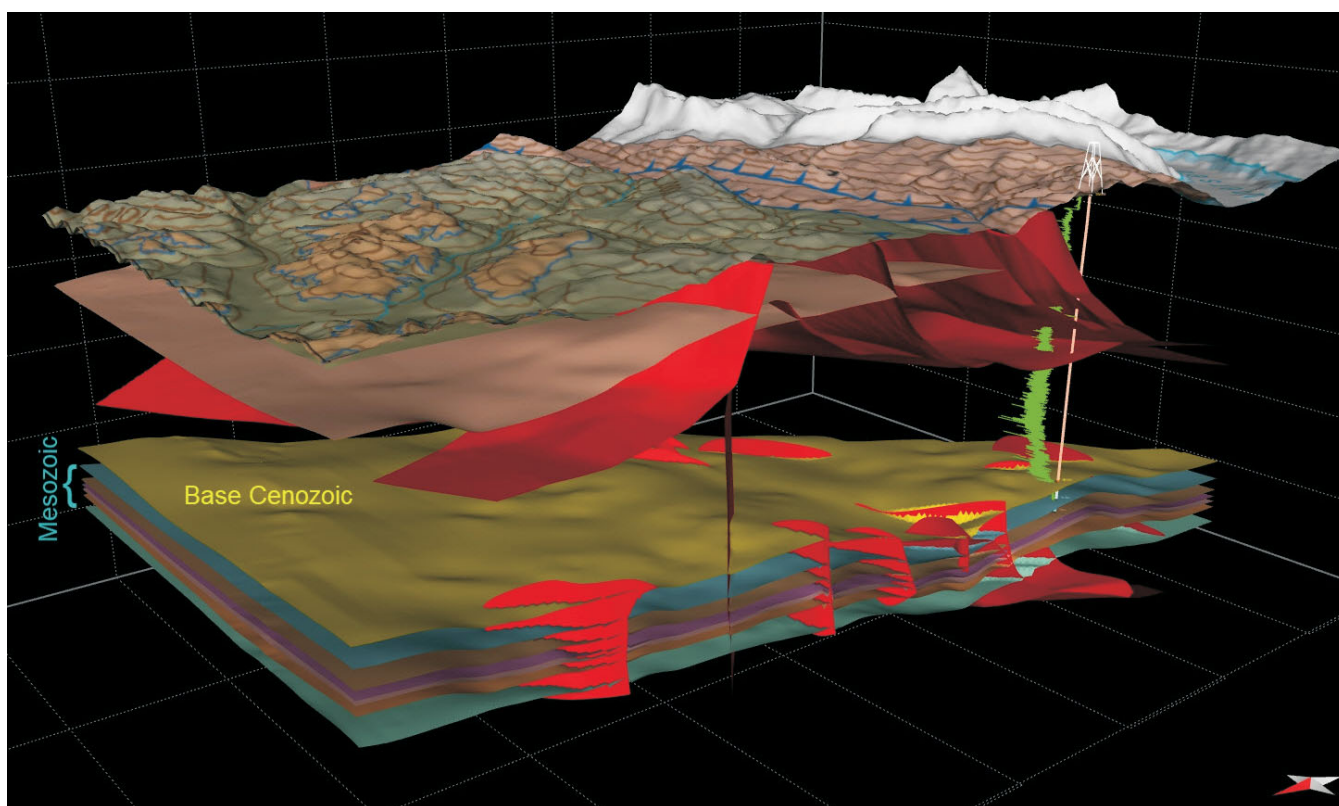
**Figure 1.** Block models of the greater Geneva area: A) geology, B) hydraulic conductivity [red = low, blue = high].

olution) incl. fault zones (Figure 2); the third, derived from the low-resolution layer cake model, hosts temperature data.

**Numerical Hydrodynamic (HM) Modelling:** In the framework of the extension of the Mont Terri rock laboratory, the SGS has decided to increase its own knowledge of numerical modelling, especially in the field

of hydromechanical-coupled processes. There are four basic objectives:

- modelling of hydraulic and mechanical processes in geological formations such as weakly perme-



**Figure 2.** Portion of the GeoMol17 model as seen from the NW (VE 1.5) and the deepest well used in the model: Thun-1 (GR-log in green) with a TD of 4836 mbsl. Surface geology merged with topography forms the top-most layer. The Alps are beyond the model boundary and appear in white.



able argillaceous formations and also highly permeable Quaternary deposits,

- calculation of the design and scope of planned experiments in the rock laboratory,
- prediction of flow and transport processes that are coupled with rock-mechanical processes, and
- parameter estimation on different scales.

While focusing on the application instead of developing modelling codes, the SGS envisages the formation of an expert network consisting of universities and specialized companies (Figure 3).

### Resources Allocated to 3D Modelling Activities

Total financial resources allocated to 3D geological modelling amount to approximately CHF 1.5 million. This includes 10 staff members directly seconded to 3D modelling activities and their supervisors (6.0 Full-Time-Equivalents) and any service contracts with external contractors.

### Overview of Regional Geological Setting

The geological subdivision of Switzerland accounts for macro-scale morphological expressions (Jura Mountains, Molasse Basin, and Alps) as well as for geological-tectonic complexity (Pfiffner, 2008; Figure 4).

**Tectonics:** The Alps result from the discontinuous collision of the European and the Adriatic plate. Compressional and extensional tectonic phases interchanged in steps lasting several millions of years each. The Alps formed during the Cenozoic by “thin-skinned” tectonics resulting in nappe-stacks related to up doming of the entire tectonic sequences. Many of these nappes consist of Mesozoic-Cenozoic sediments, while crystalline rocks form others. A subdivision into Helvetic, Penninic, Southern and Eastern Alps is based

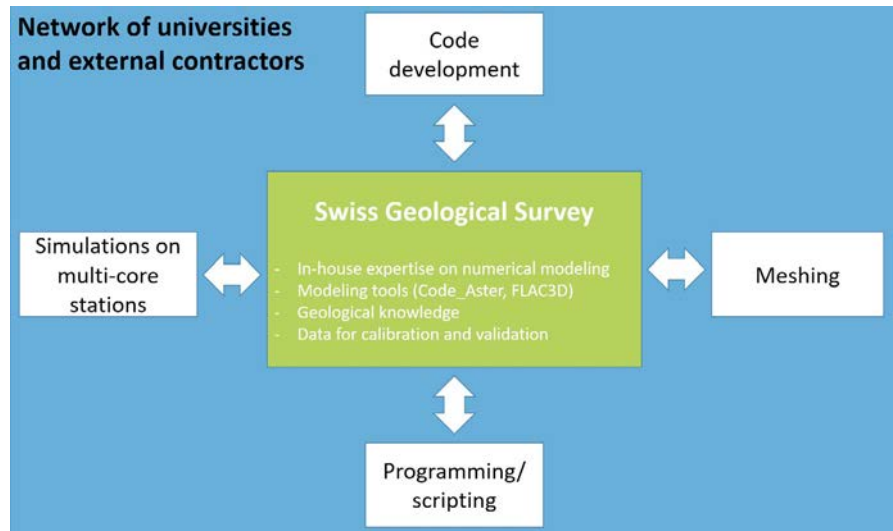


Figure 3. Strategy of numerical modelling at Swiss Geological Survey.

on the formation of the Mesozoic sediments. Within the Alps, other structural types exist, such as “basement-involved thin-skinned” movements in the more internal (Penninic) and the “thick-skinned” styled external massifs (Aar massif, Gotthard massif; Figure 5). In the latter case, the pre-Triassic crystalline basement forms a crustal-scale anti-form with an amplitude of several kilometers (Figure 5). The formation of the Alps subsequently progressed into their Alpine foreland (32-12 my). A “thin-skinned” tectonic style characterizes the Molasse Basin as the sediments were sheared from their basement (pre-Triassic crystalline and permocarboniferous sediments). The basin is subdivided into three regions: 1) The subalpine Molasse (thrust-belt that was thrust below the Alpine nappes); 2) undeformed Molasse (different tectonics in the western and the eastern part and steeply oriented towards the subalpine Molasse); and 3) the sub-Jurassic Molasse (characterized by several narrow-spaced anticlines). While the western part as well as parts of the central Molasse Basin were thrust northwards and were deformed on a regional scale, the eastern part shows only weak or even absent deformation. As one of the youngest events (5-10 my), the Jura Mountains formed as a direct

consequence of the Alpine orogeny (Figure 5). The sediments in the Plateau Jura are more-or-less horizontal, but dissected by narrow-spaced N-S fault zones. The former are still located on top of their pre-Triassic basement. On the contrary, in the Folded Jura, the sediments are detached from their substrate by a “thin-skinned” style. The detachment horizons were located within the evaporites of the older and middle Triassic. Transport direction was northbound and the transport distance increases from 0 km in the eastern Jura Mts. and reaches 15-20 km in the western Jura Mts. Landmasses are still moving on a measurable scale. However, the horizontal shortening is now restricted to the Po Plain in Northern Italy (Pfiffner, 2008).

**Rocks:** The pre-Triassic basement consists of polymetamorphic gneisses, amphibolites, migmatites and schists (the so-called *Altkristallin*) intruded by late- to post-Variscan intrusive rocks and young Paleozoic volcanic rocks. Seismic data and deep wells have revealed Paleozoic troughs within the basement below the Molasse Basin and similar Grabens with siliciclastic infill crop out in the Alps. Below the Jura Mountains and the Cenozoic of the Molasse Basin (European continental margin),

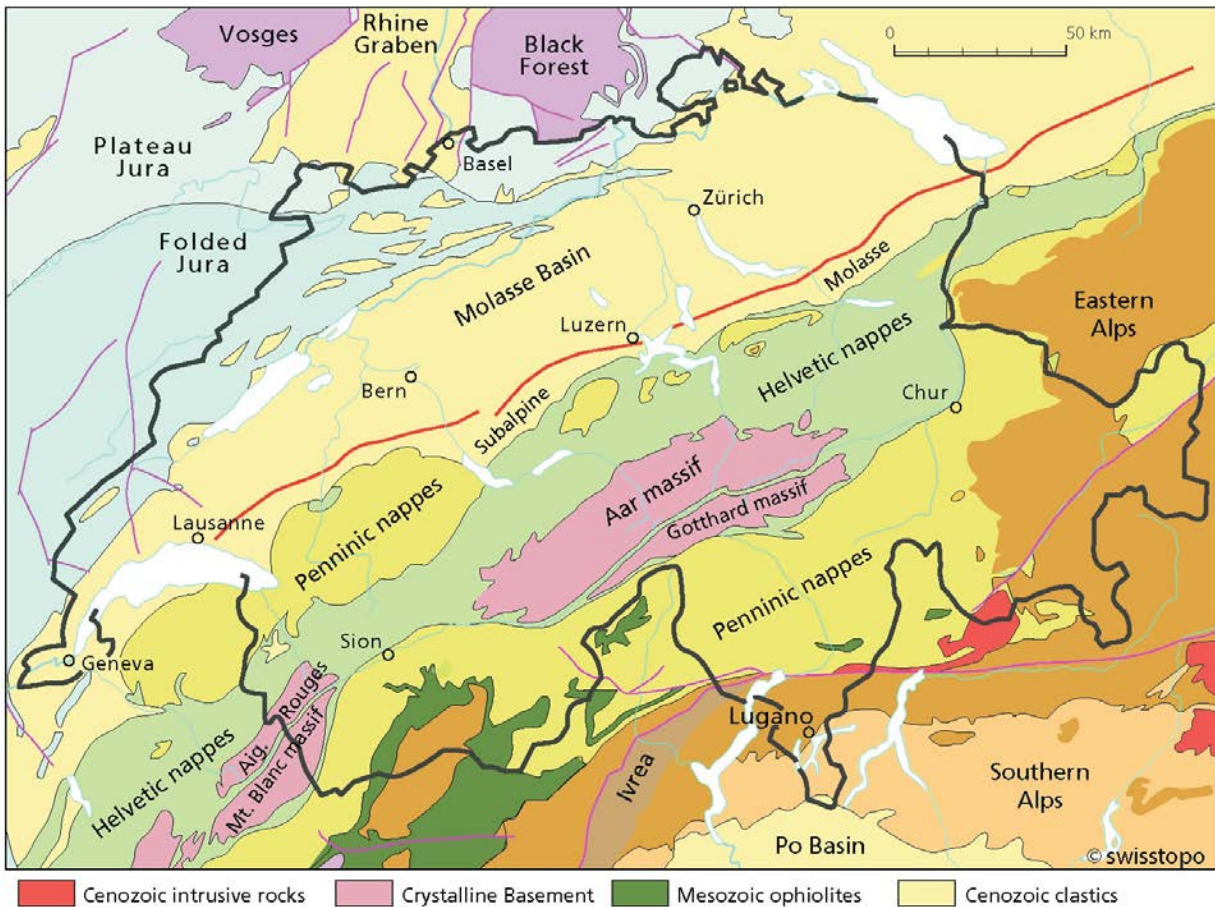


Figure 4. Tectonic overview map of Switzerland.

mainly shallow marine and some coastal deposits ranging from Triassic evaporates to Jurassic platform carbonates and shales dominate the stratigraphic record. In the Helvetic nappes, the complete Mesozoic stack is composed of epicontinental carbonates, gradually grading into shales towards the platform margin.

Siliciclastics deposited in four alternating sequences of marine and fresh-water environments in the basin forming north of the alpine orogeny dominate the Cenozoic sedimentary stack. The Penninic nappes (Alpine Tethys) is divided in to three zones:

- Valais Zone (very thick Jurassic and Cretaceous turbidites and upper Cretaceous to lower Eocene schistose, arenitic and conglomeratic deep marine clastics overlying epicontinental Triassic rocks),
- Briançonnais Zone (carbonates of Triassic to early Cretaceous age,

Jurassic breccias and upper Cretaceous and Paleogene pelagic and turbiditic sediments),

- Piemont Zone (ophiolitic sequences overlain by pelagic to hemipelagic Jurassic and Cretaceous sediments, e.g. radiolarites, limestones and marls)

In the Southern and Eastern Alps (Adriatic continental margin), Jurassic breccias follow on top of thick series of Triassic carbonates and evaporates. The latter are covered by pelagic to hemipelagic series of Jurassic and lower Cretaceous age. Younger sediments are predominantly abundant in the Southern Alps, where turbiditic sequences of the upper Cretaceous (Flysch) and deep marine clastics of the Oligocene (Pfiffner, 2008).

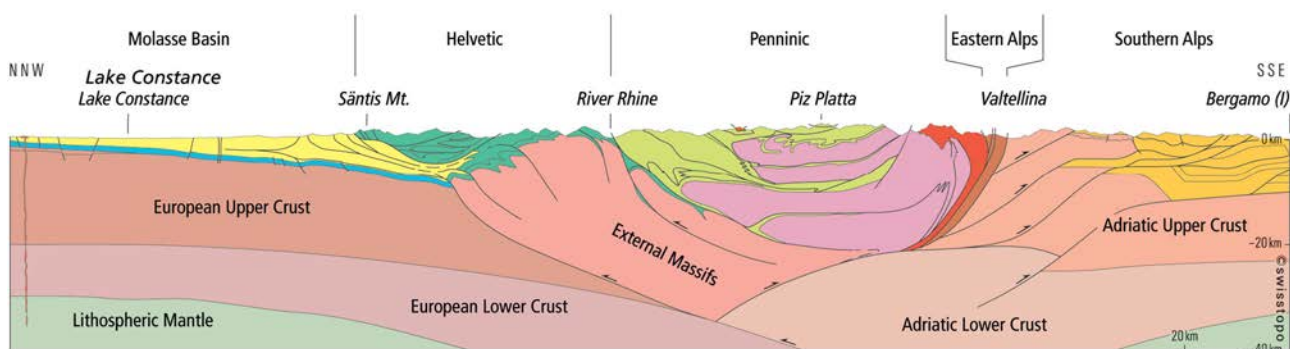
Unconsolidated sediments of the Quaternary cover significant parts of Switzerland. They are the product of

various erosion, transport and deposition processes (glaciers, water, and wind) and the composition varies largely in its lateral and vertical extent. The thickness ranges from few to several hundreds of meters and may reach up to a thousand meters in the main Alpine valleys. Areas covered with Quaternary sediments are the preferred settlement, industrial and cultivation zones in Switzerland, due to their predominantly flat to slightly inclined topography. In addition, these areas accommodate a large proportion of existing underground uses and subsequent usage conflicts.

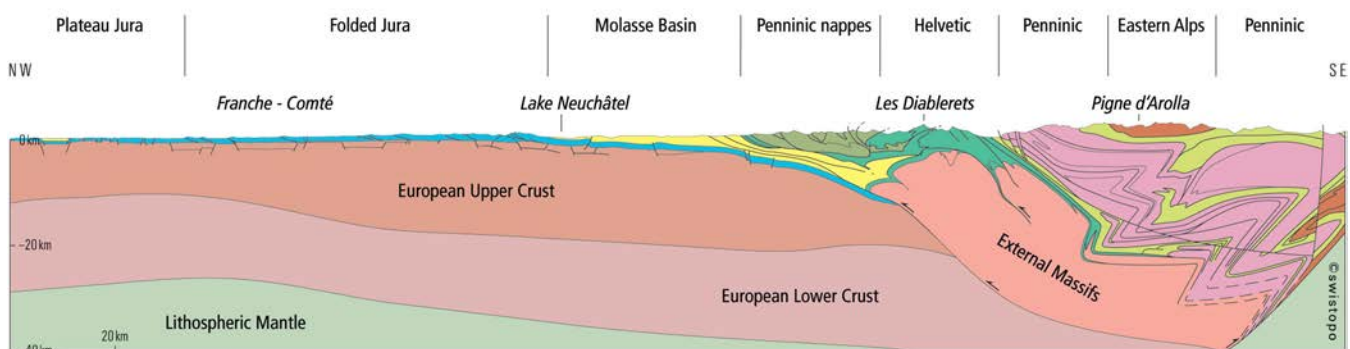
## Data Sources

Only a minor portion of the data that flows into 3D geological models has been acquired by the SGS itself and it therefore relies on data provided by third parties. This includes seismics, boreholes and to some extent even

## Geological cross section through Eastern Switzerland



## Geological cross section through Western Switzerland



**Figure 5.** Cross section through Eastern (above) and Western (below) Switzerland, showing the location of the tectonic units and the different tectonic styles mentioned in the text.

cross sections and maps. These datasets are of varying age, quality, and resolution as well as having been acquired for different purposes. The age of the input data often reflects different interpretations and the geological knowledge of a certain time, and the spatial precision of these datasets is often below modern standards. While data is very abundant in the shallow subsurface (annual increase is about 10,000 boreholes/year), the situation is very different in the deep subsurface. There are only around 200 wells deeper than 500 m available, many of them with restricted access privileges. Two private companies own most of the geophysical data and access and usage is partially restricted.

Switzerland is a directional federal republic, consisting of 26 cantons. The subsurface is under jurisdiction by the cantons, resulting in 26 different subsurface legislations and heterogeneous accessibility policies. Consequently, there is no obligation for a homogeneous nationwide data description. A further complication is that intellectual property rights, business or industrial secrets might protect parts of the geological data. Briefly put, there are many issues influencing the accessibility, data quality and publication restrictions due to the absence of a nationwide legislation.

To overcome these issues, the SGS negotiates usage and publication of data with each individual data owner. In addition to this, time consuming

preparation, data verification, data QC and data harmonization uses up a significant portion (20-50%) of the staff effort during geological modelling project.

### 3D Modelling Approach

The SGS uses three modelling approaches: geostatistical, explicit and numerical modelling. For all approaches, data is acquired, quality controlled, transformed (if needed), harmonized, classified and interpreted. Modelling starts only after the input data have passed the conditioning and QC workflows successfully.

**Unconsolidated sediments:** Models of the unconsolidated sediments are computed with geostatistical methods, based on boreholes, surface maps and cross sections. It is important that the

input data used are uniformly classified and harmonized. The choice of geostatistical method, cell size and other model parameters depends on various criteria, such as the parameter to be modelled, the extent of the model, the complexity of the unconsolidated rock geology and the distribution of the input data. For the validation of the realized 3D models different checks are performed: visual checks, variogram analysis and cross validation.

Annually a large amount of new input data is generated in the shallow subsurface, which is why it is of the utmost importance to automate as many steps in the workflow as possible.

Automation ensures the models are up-to-date and their development is traceable. The automated steps of the modelling workflow are colored yellow in Figure 6.

**Consolidated sediments:** The consolidated deposits of the deeper subsurface are modelled using explicit methods. Typical input data are seismic interpretations, wells, cross sections and geological maps. Human factors like education, knowledge and experience of the modellers may bias the model development. This rises the necessity of standardized data management and procedures, and if possible, easily reproducible automated procedures and workflows (Figure 7).

Data coverage maps (Figure 8) describe the data type (seismic, wells, section and map) available for each horizon in a model. While these maps do not convey the certainty of the model, they do give a very clear indication of which kind of data contributed to each horizon and what the density of data is in a given area of the model. Based on the information retrieved from the data coverage maps, a user can quickly recognize the areas based on algorithms and areas based on measured data, such as wells.

Deriving secondary products is possible from both types of models. In the model-type used for unconsolidated sediments, (semi-)automated workflows result in 2D and 3D products, such as maps showing the soil classification, groundwater volume, groundwater vulnerability or the volumes and quality of mineral resources, respectively (Figure 9). Models derived from the type used for consolidated sediments include the rock-head model (manual borehole correlation) or the all-new temperature model of the Swiss Midlands (Figure 10; developed further by following geostatistical approaches).

**Numerical models:** Currently swisstopo deploys two codes for numerical hydromechanical modelling at Mont Terri. The commercial code FLAC3D6.0 by Itasca is used for large-scale simulations of the entire rock laboratory, including geological

heterogeneity and topography, with all the lab's extension stages over time. These calculations allow us to simulate the large-scale behavior of the rock laboratory by using different built-in constitutive laws, e.g. simple elastic or more complex relations including strain-hardening/softening for improved pre- and post-failure prediction. The second code we deploy is Code\_Aster, which was developed by EDF (Électricité de France). In the framework of a PhD thesis (at the Federal Institute of Technology Lausanne), a custom-made constitutive law called APD that combines anisotropic plasticity with damage was developed (Parisio 2016, Parisio et al. 2018) for hydro-mechanical (HM) modelling with Opalinus Clay. This modelling procedure was successfully validated on a sequential excavation of a 50 m-long tunnel in the shaly facies. Recently the code was optimized for parallel computing and adapted for the 2D heterogeneous case.

**Large-scale numerical modelling (rock lab scale):** The kilometer-scale heterogeneous model of the Mont Terri rock laboratory includes the 100 m thick Opalinus Clay, dipping with 45 degrees to the southeast, in a depth of 300 m below surface. On top of the Opalinus Clay lies the Passwang Formation consisting of limestones and marls, and below lies the Staffelegg Formation consisting of marls (Figure 11a). We carried out the excava-

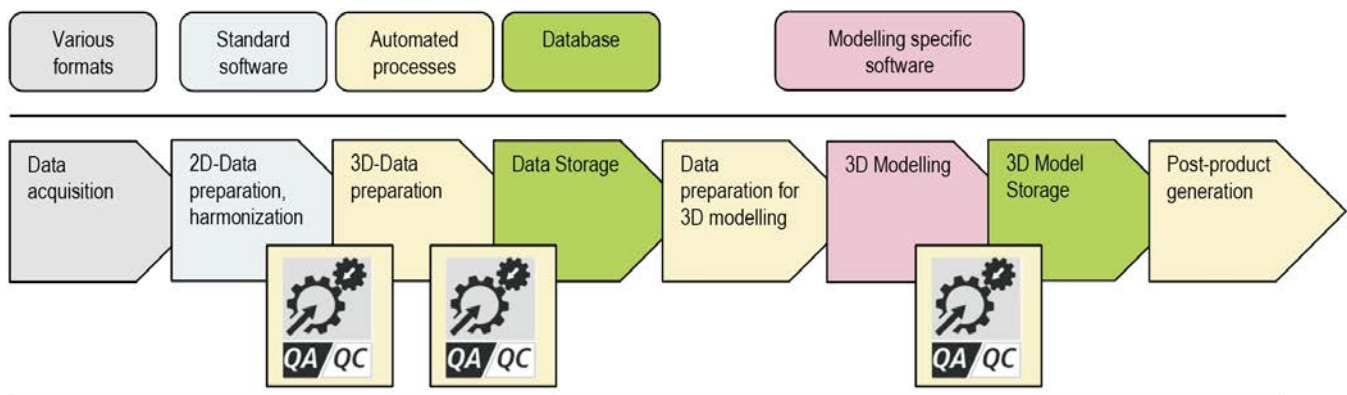
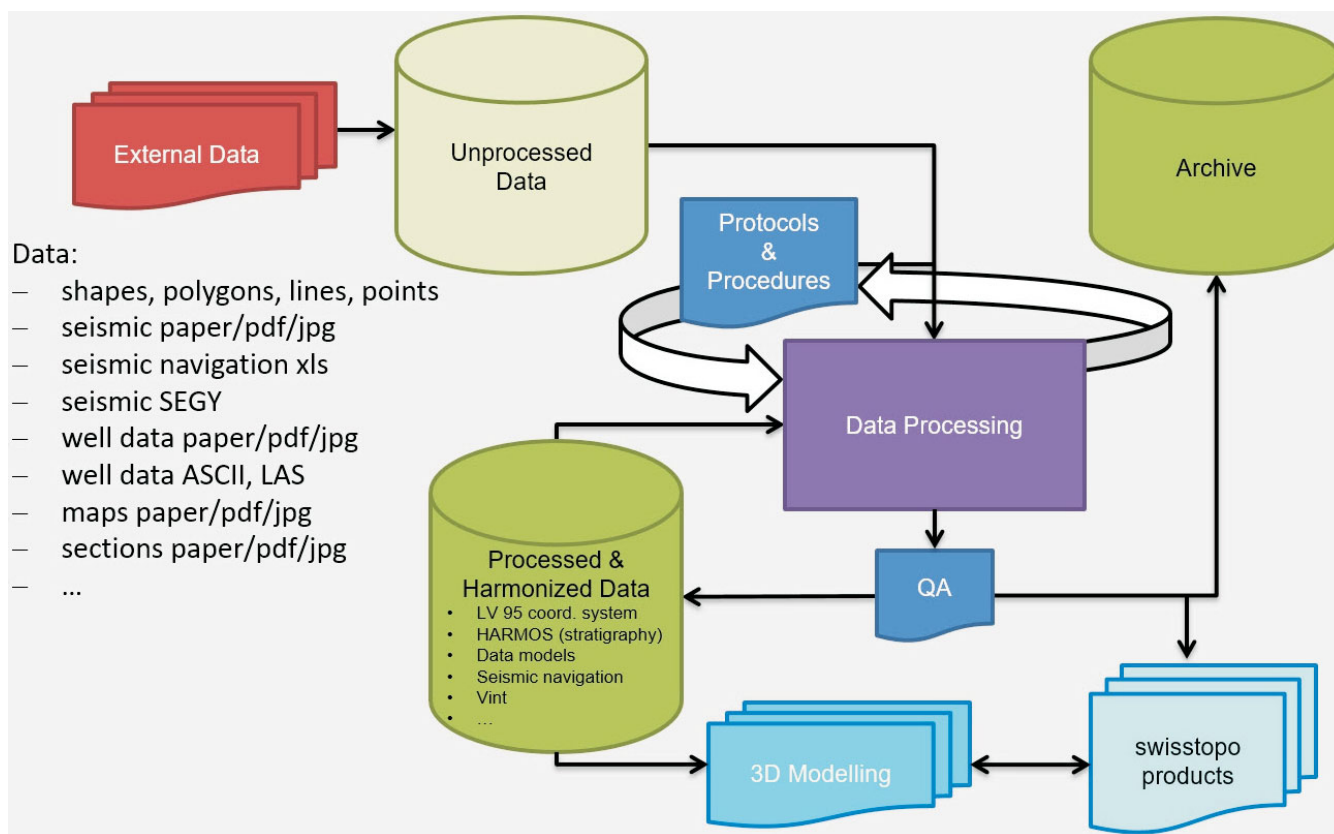


Figure 6. Modelling workflow: from raw data to block models and post-products.



**Figure 7.** The basic workflow developed for the 3D geological models of the deep subsurface. Much of the data used to complete the models (deep wells, seismic, gravimetry) did not come to use at the SGS prior to 3D modelling. This step forward in digital geology required the development of new protocols, procedures and QA steps.

tion in the model sequentially with four main excavation stages (1988, 1998, 2008, and 2018), leading to a better understanding of large-scale deformation and pore-pressure changes. It also helped to evaluate the influence of topography on the in-situ stress state at rock laboratory level.

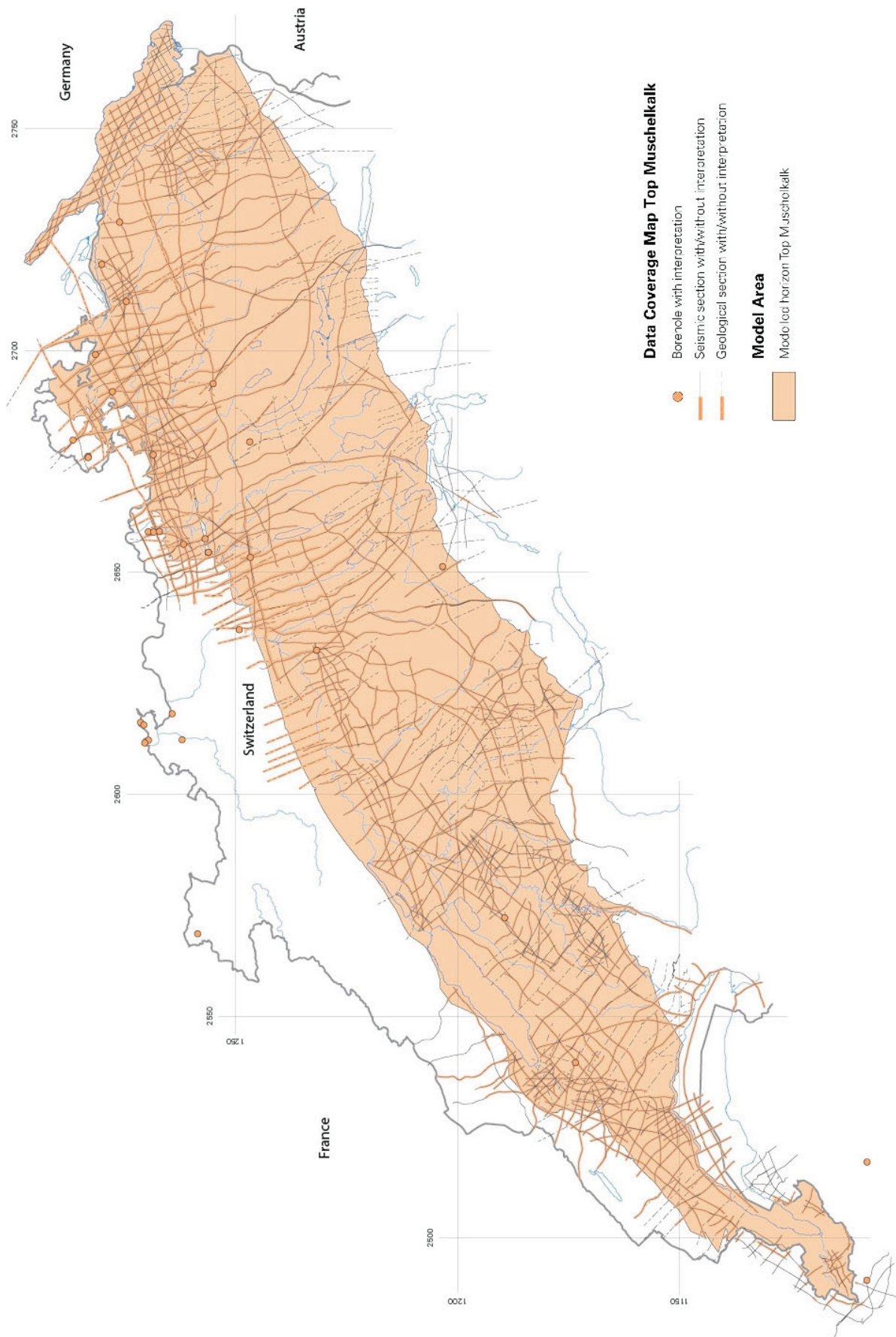
Modelling results are shown in Figure 11b, indicating a significant pore-water pressure decrease (blue areas around galleries in Figure 11b). Because of the different rock mass deformability, displacement magnitudes are highest within the shaly facies of the Opalinus Clay, intermediate within the sandy facies, and lowest within the overlying and underlying limestone formations. Due to changes in topography, slightly lower vertical stresses are obtained in the southern part of the rock laboratory.

**Predictive modelling of the MB-A mine-by test in sandy facies (niche scale):** A 10 to 100 m-scale model was elaborated to predict the hydro-mechanical behavior of the rock mass during a mine-by experiment. The highly instrumented target section is shown in Figure 12. The modelling sequence includes the pre-excavation of the two niches dedicated to instrumentation at the end of the 30 m-long mine-by section, the excavation of 20 m gallery before the mine-by section, a 15-day sequential excavation of a 30 m mine-by section (planned to be carried out in May 2019). We applied two approaches, both using Code\_Aster.

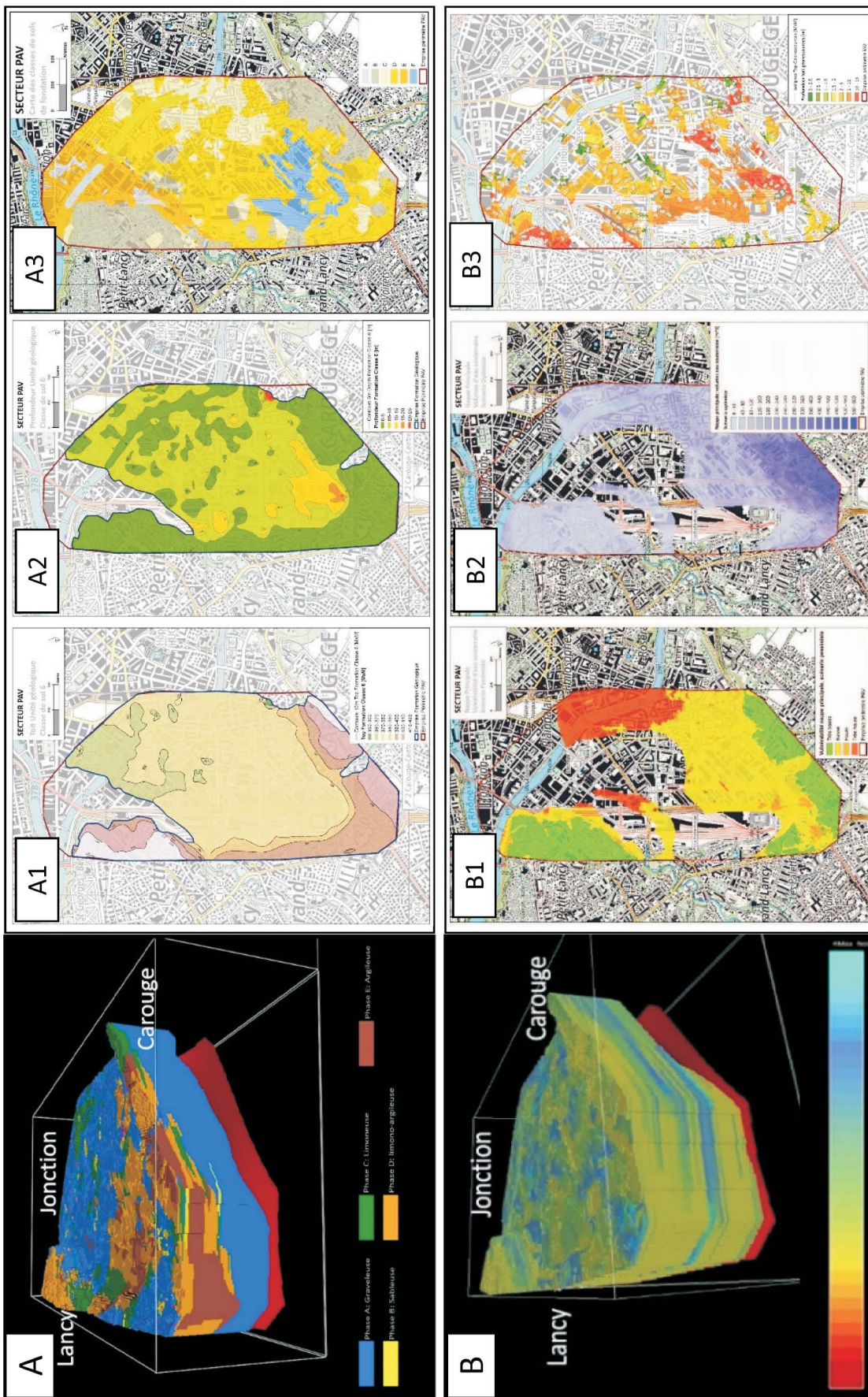
First, we used a simple 3D-elastic approach that included anisotropy and heterogeneity of the rock mass. The input parameter set is based on data from Jaeggi and Bossart (2014). Our focus was the highly instrumented tar-

get section in the middle of the MB-A tunnel. The results of our model predict overpressures along bedding immediately at the initiation of excavation and a pressure decrease vertical to bedding that results in a long-term pressure decrease parallel to bedding (Figure 13). Modelled pressures at instrumented boreholes rise from 2.0 MPa to 2.8 MPa just before excavation and drop to 1.2 MPa after excavation. Deformation within the rock mass at distances >3 m from the tunnel are in the mm-range, which seems to be reasonable for sandy facies. Modelled tunnel convergences are in the range of 10 mm and are comparable to existing monitoring data.

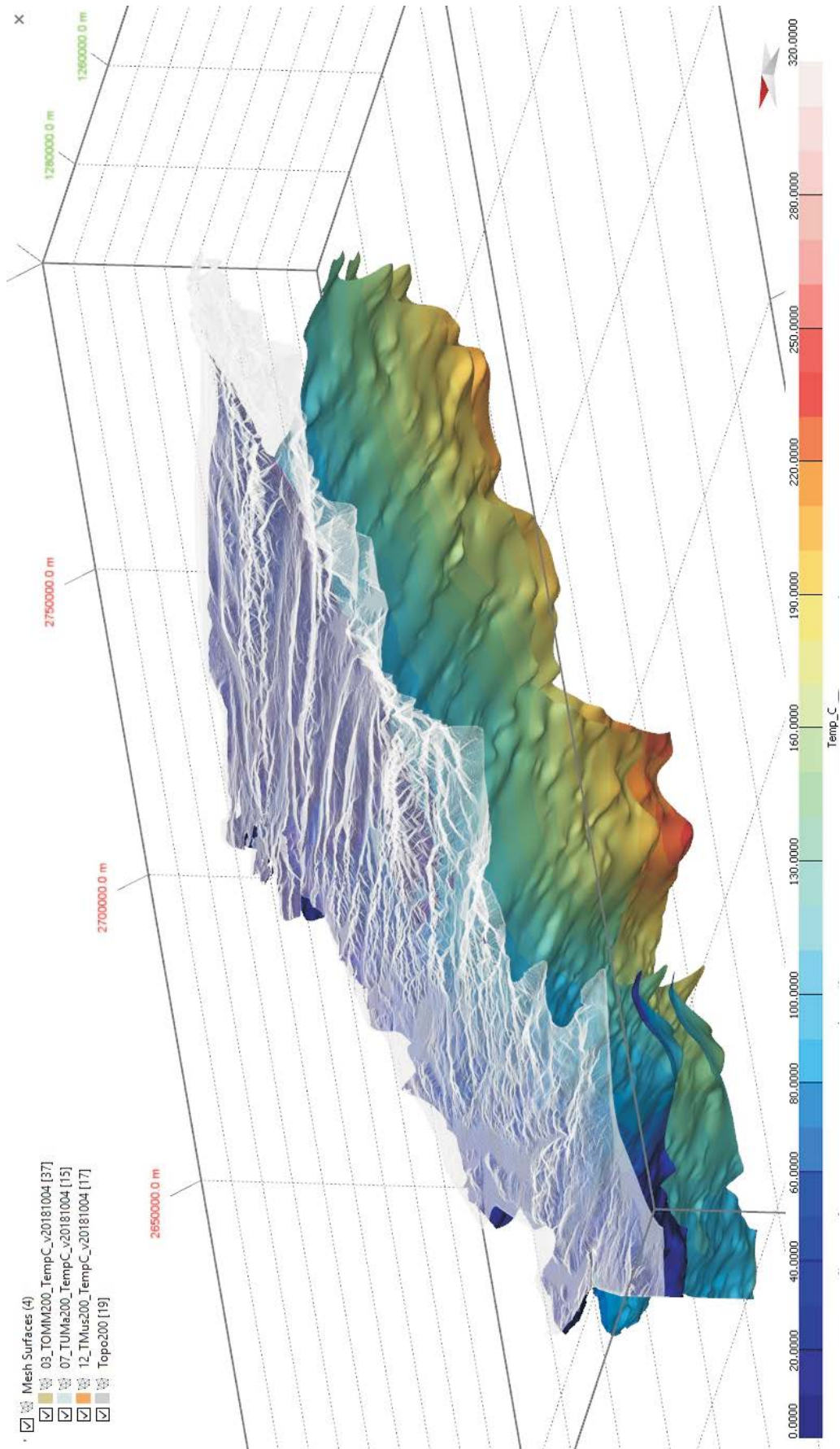
Second, we applied a two-dimensional approach taking into account Anisotropy, Plasticity and Damage (APD). Results from these 2D APD runs show a reduced plasticity, volumetric dilation-induced pore pressure



**Figure 8.** Detail of the Data Coverage Map of GeoMol17's Top Muschelkalk. High densities of seismic lines and deep wells in the NE of the model already indicate that these areas are of a higher certainty than areas lacking comparable input.

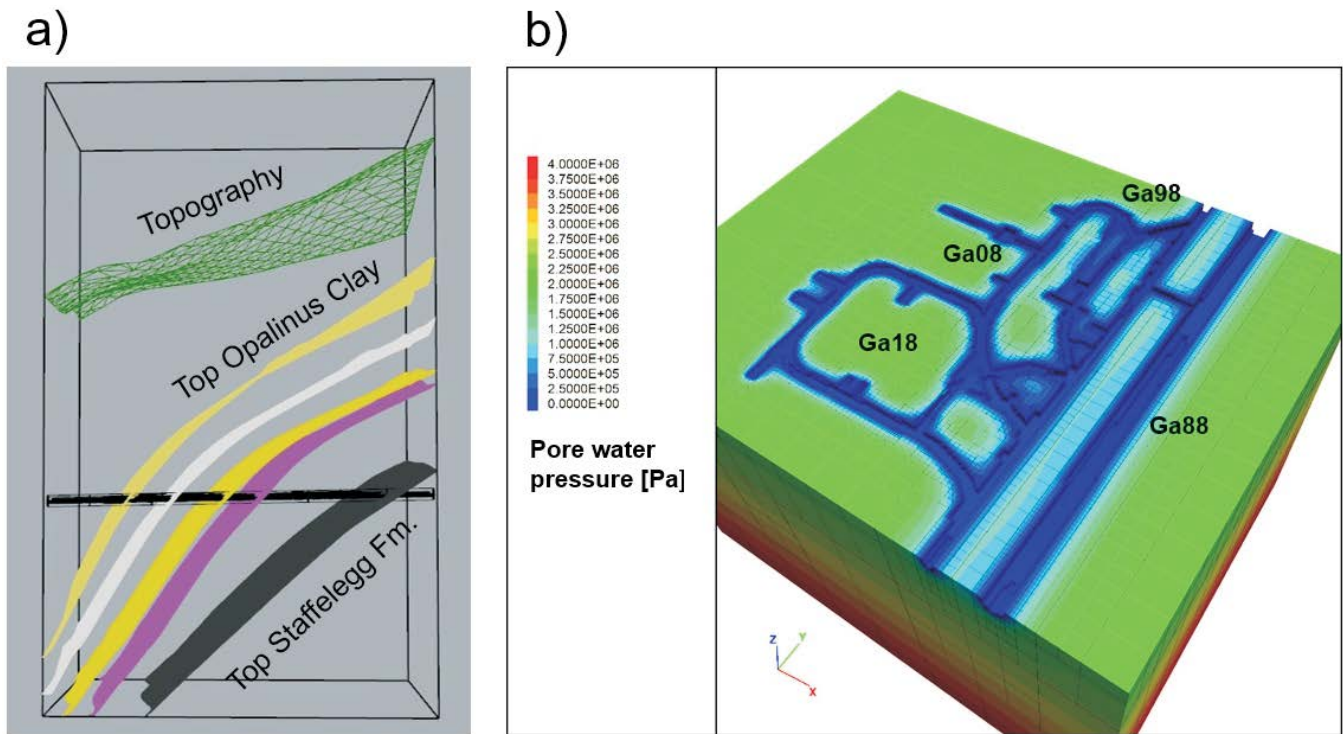


**Figure 9.** A) Geological model and post-products: A1) formation top map, A2) formation depth map, A3) ground foundation class map B) hydraulic conductivity model and post-products: B1) groundwater vulnerability map, B2) groundwater volume map, B3) mineral resources volume map).



**Figure 10.** Temperature gradients plotted onto three horizons of GeoMol15. The temperature values are from an earlier temperature model and now merged with the improved GeoMol15 structural model. The top-most translucent layer is the topography, two are Cenozoic and one is Triassic.





**Figure 11.** Large-scale modeling of the Mont Terri rock laboratory, a) model geometry including the most important bounding surfaces and the rock laboratory (horizontal black bar), b) pore-pressure distribution at rock lab level 10 years after excavation of Ga18.

with an enhanced hydromechanical effect along bedding (Figure 14). Vertical and lateral displacements are about 20 mm at time step 67.5 days after excavation, which leads to total convergences in the order of 40 mm. At the same time, stress-induced damage extends about 2 m into the rock mass along bedding.

Finally, both model approaches will be calibrated with the effectively measured mechanical and hydraulic measurements, and serve then for more reliable predictions of the rock mass behavior.

## Clients

While regulators (permitting, monitoring) and project planners (energy, water, mineral resources, civil engineering) are the primary users of our models, research, commerce and industry also use them models for their purposes. As explained earlier, the SGS is reliant on the cooperation with its clients, as most of them are also data providers at the same time.

Model development mentioned below in the “Jurisdictional-Scale Case Study” section was possible only, due to a very close collaboration between several administrative bodies, research institutes and industry.

The SGS uses the Geosciences in Space and Time (GST) software framework for the publication of the layer cake and block models over the internet. It allows a browser-independent visualization of 3D models without the need of a browser plugin. GST is based on a three-dimensional data storage, relies on OGC standards and supports several relational database management systems (e.g. Gabriel et al., 2011; Le et al., 2013) and Refer to GeoMol Team (2015) and Landesgeologie (2017) for technical and functional basics.

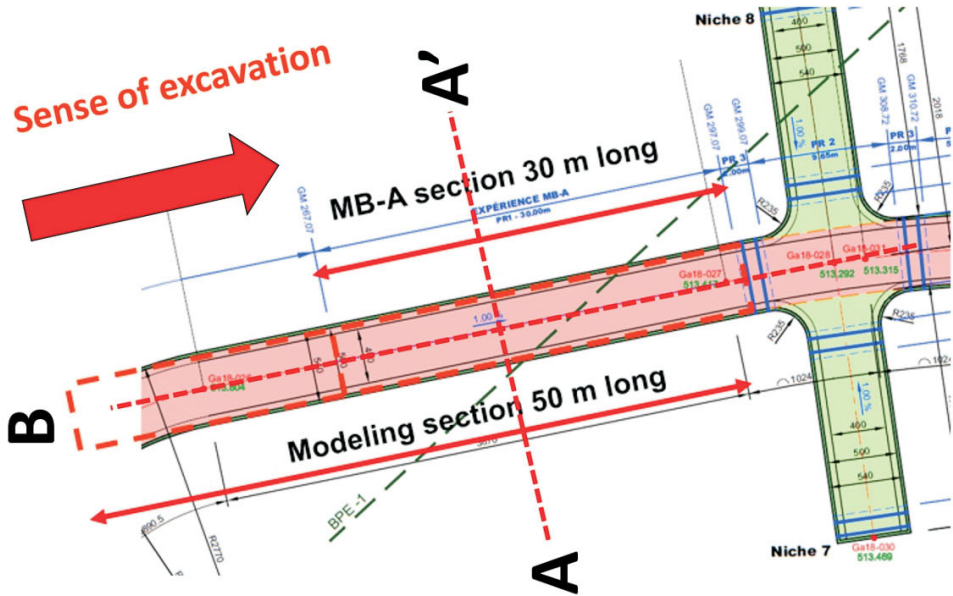
All the models published are available in a 3D viewer at <https://viewer.geomol.ch>. There is no direct support by SGS staff for the usage of the models. The website provides multi-lingual access and the data vi-

sualization is directly fed by the 3D database. The user can also extract cross-sections, depth slices and virtual boreholes from any location within the layer cake and block models.

Available models can be ordered free of charge in the most common 3D formats (ASCII, DXF, Move and GoCAD) as well as in ESRI (Grid, SHP). Continuing and use of regular updates regarding content (e.g. new parameters), geographical extension or corrections should encourage the continuing usage of the model.

## Recent Jurisdictional-Scale Case Study Showcasing Application of 3D Models

The Swiss Plateau (or North Alpine foreland basin in geological terms) is a place of work and residence for more than half the population of Switzerland, thus subjecting the region to intensive land use. On the one



21 boreholes with lengths between 15 and 40 m and diameters 86 to 146 mm

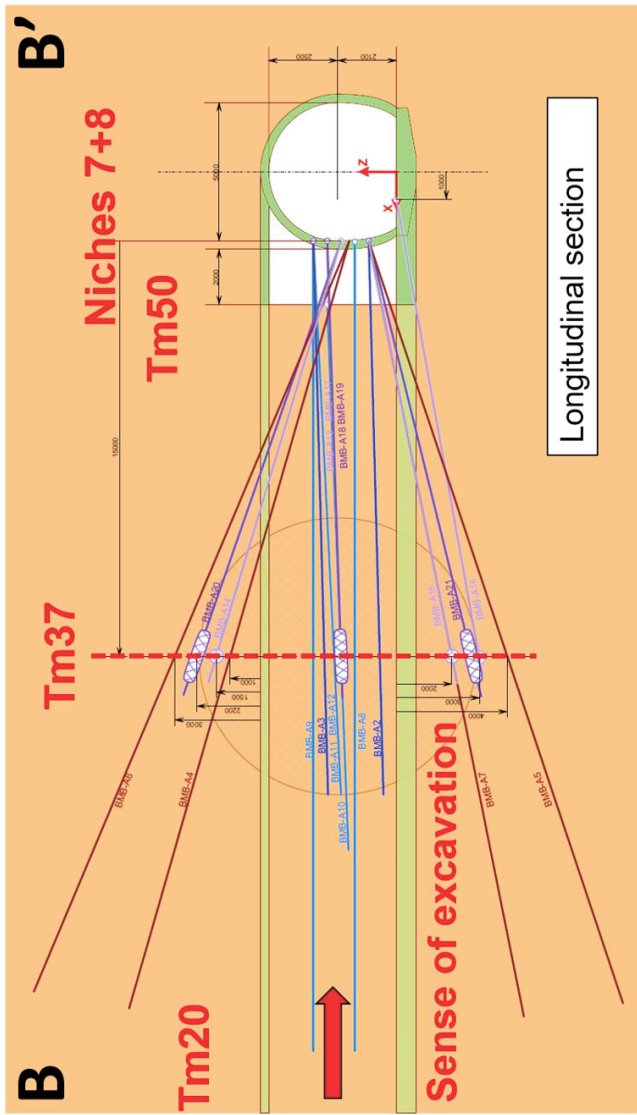
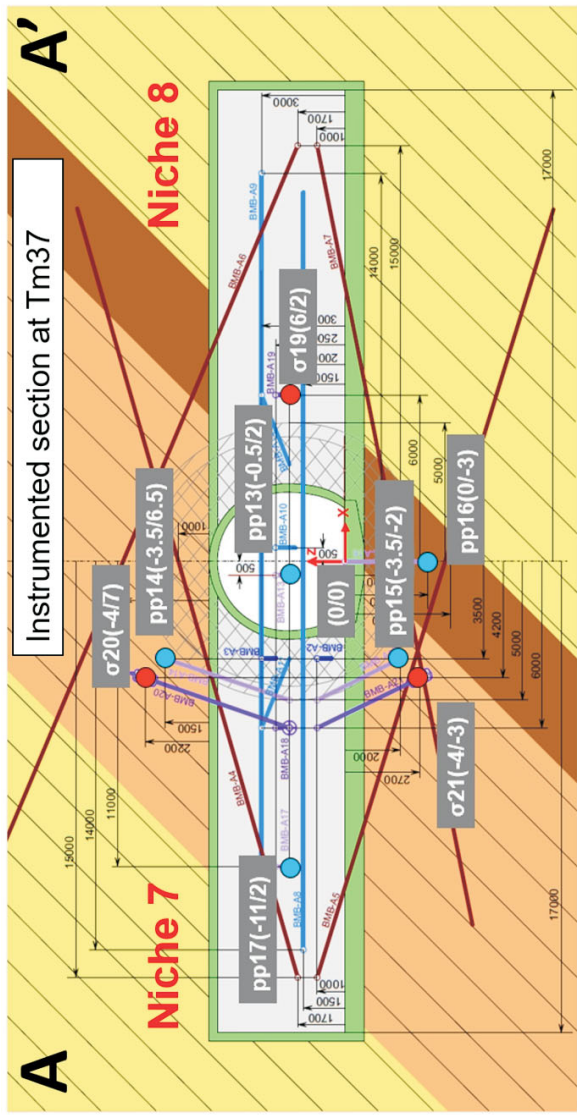
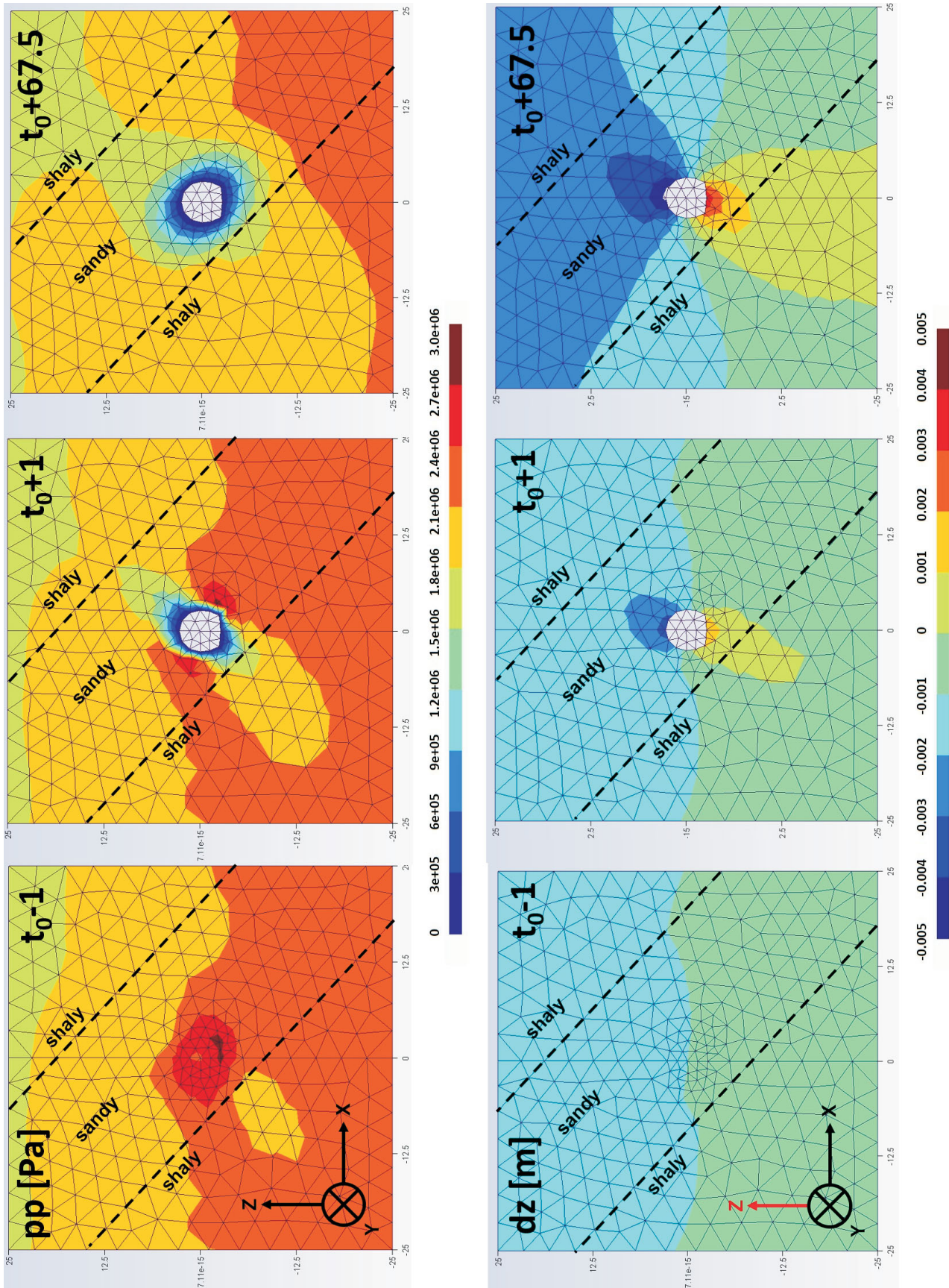
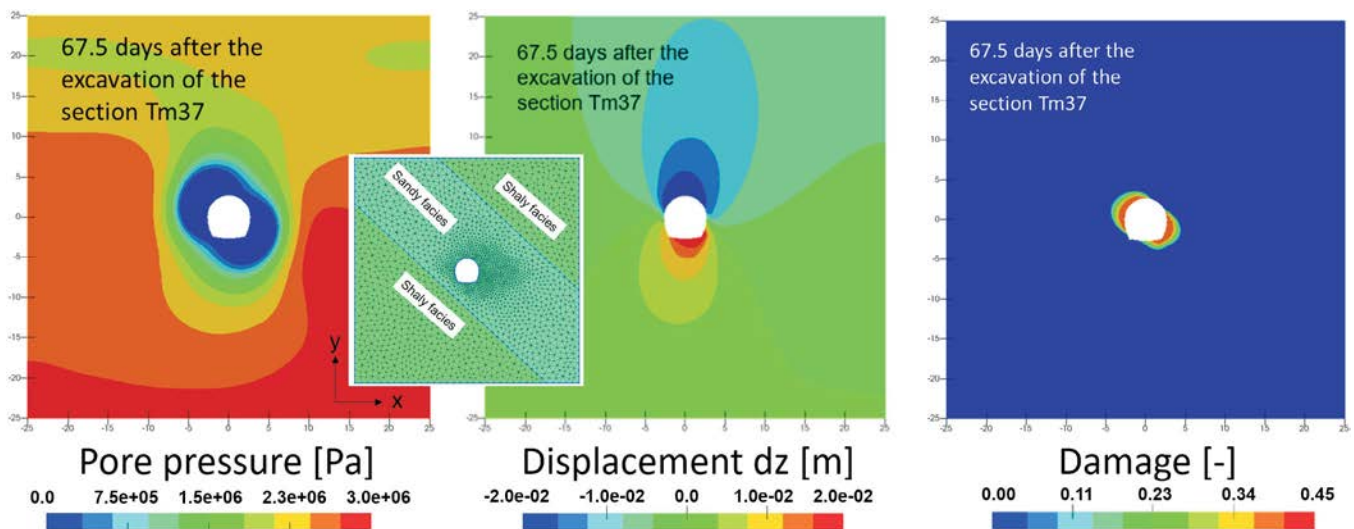


Figure 12. Layout of the MB-A mine-by experiment at Mont Terri rock laboratory. Colors in A-A' section are yellow for shaly facies, reddish for sandy facies, and brown for carbonate-rich sandy facies.



**Figure 13.** 3D elastic – pore pressure distribution (pp) and vertical displacement (dz) at TM37, just before excavation ( $t_0 - 1$ ), just after excavation ( $t_0 + 1$ ) and 67.5 days after excavation ( $t_0 + 67.5$ ).



**Figure 14.** 2D APD (anisotropic plasticity coupled with damage) – pore pressure distribution, displacement and damage at TM37, 67.5 days after excavation.

hand, there is a high demand for resources such as rocks and soils as well as groundwater and geothermal energy. On the other hand, those responsible for private and public infrastructure (public transport, roads, geoenery) are increasingly involved in planning in the same areas. The development of these geopotentials and the sustainable management of the finite resource of subsurface space has social, political, economic and geoscientific relevance.

A low-resolution 3D geological model of the Swiss Molasse Basin (GeoMol 15) was produced as part of the project “GeoMol – Assessing subsurface potentials of the Alpine Foreland Basins for sustainable planning and use of natural resources” (2012 – 2015), within the framework of the EU’s “INTERREG IV B Alpine Space” program (GeoMol Team, 2015). Recently the SGS produced a more detailed 3D geological model (GeoMol 17) of the same region in a separate sub-project (Landesgeologie, 2017). The results of GeoMol denote the first steps in systematically describing and visualizing Switzerland’s subsurface. For the first time ever in Switzerland, the SGS published a jurisdictional-scale 3D geological model that is available at no costs and accessible to the wider public. The

GeoMol project thus makes an active contribution to the sustainable management of the subsurface.

### Current Challenges

Several years ago, the SGS recognized the necessity of developing 3D modelling expertise as well as fundamentals in managing geological data in the digital age. This eventually led to the formation of a small modelling group made up of earth scientists with various backgrounds. Over the last five years, this group has evolved into a highly specialized team, which produced several 3D geological models. Following these successes, we will address challenges related to technological, work force, financial, and conceptual issues.

- **Organization:** The form of government (federal administration plus 26 cantons), the absence of a nationwide legislation regarding the subsurface, the necessity to generally coordinate activities between all these independent, but however interdependent institutions, the partly unwillingness to share (meta-)data (even to a minimum extent) of the right owners and the (partly) not up-to-date understanding of current and future challenges regarding the subsurface

impede jurisdiction wide, coordinated and effective modelling activities.

- **Bureaucracy:** A constantly increasing number of regulatory requirements in legal, financial, technological and organizational terms at the federal level hinder and endanger the forward-looking and real-time development of adequate frameworks for future activities.
- **Technology:** Technology continuously advances and directly challenges the way 3D geological models are developed, stored and published.
- **Work force:** According to political requirements, federal staff (incl. SGS) is limited, with new staff only available exceptionally or if funded by third parties. Therefore, the SGS contracts out parts of its modelling activities and collaborates with partners from the administration, industry and academia to push forward the Swiss 3D geological mapping program.
- **Finances:** Service-related finances have not been the limiting factor over the past few years. However, budget cuts may strike at any time. As any other governmental organization unit, the SGS follows the annual budgetary cycles, which

hinders on reliable and much requested forward planning.

- Concepts: New data and modelling approaches require an adaptation of methodologies, workflows and, consequently, of modelling concepts. As this topic is complex as well as time consuming, it probably does not receive the attention it deserves.

### Building Information Modelling

**(BIM):** Additional challenges and opportunities will arise with the advance of BIM into applied earth sciences. In Switzerland, efforts to combine BIM with subsurface models began in 2016 and have continued since. In a joint research project between the SGS, the Swiss Cadastral Survey and the University of Applied Sciences of Geneva, the partners investigated the

mutual dependencies of both approaches in a detailed 3D subsurface model of the city of Geneva (Figure 15). It became evident that the integration of geological data and models into the BIM process requires a high degree of standardization.

**Model updates:** Further challenges arise when attempting to combine 3D geological models of different resolutions. An excellent case study is the regional scale GeoMol 17 model, which is being updated by integrating a local-scale 3D geological model originating from a 3D seismic survey (Figure 16). Different resolutions and concepts converge in this type of update and have to be adjusted in order to fit together. The SGS will be confronted with this type of update as the Swiss Confederation is subsidizing

subsurface exploration in order to realize the requirements set for renewable energies. Data gained from these exploration campaigns will be made available to the federation and allow the SGS to continue updating the GeoMol models with modern data.

### Lessons Learned

To date, Private-Public-Partnerships (PPP) between regulators, industry and academia form the foundation for all the models produced by the SGS.

The essential lessons learned are:

- The regular discussion and exchange with an independent review board is highly recommended. First, the modelling team retrieves external advice on its

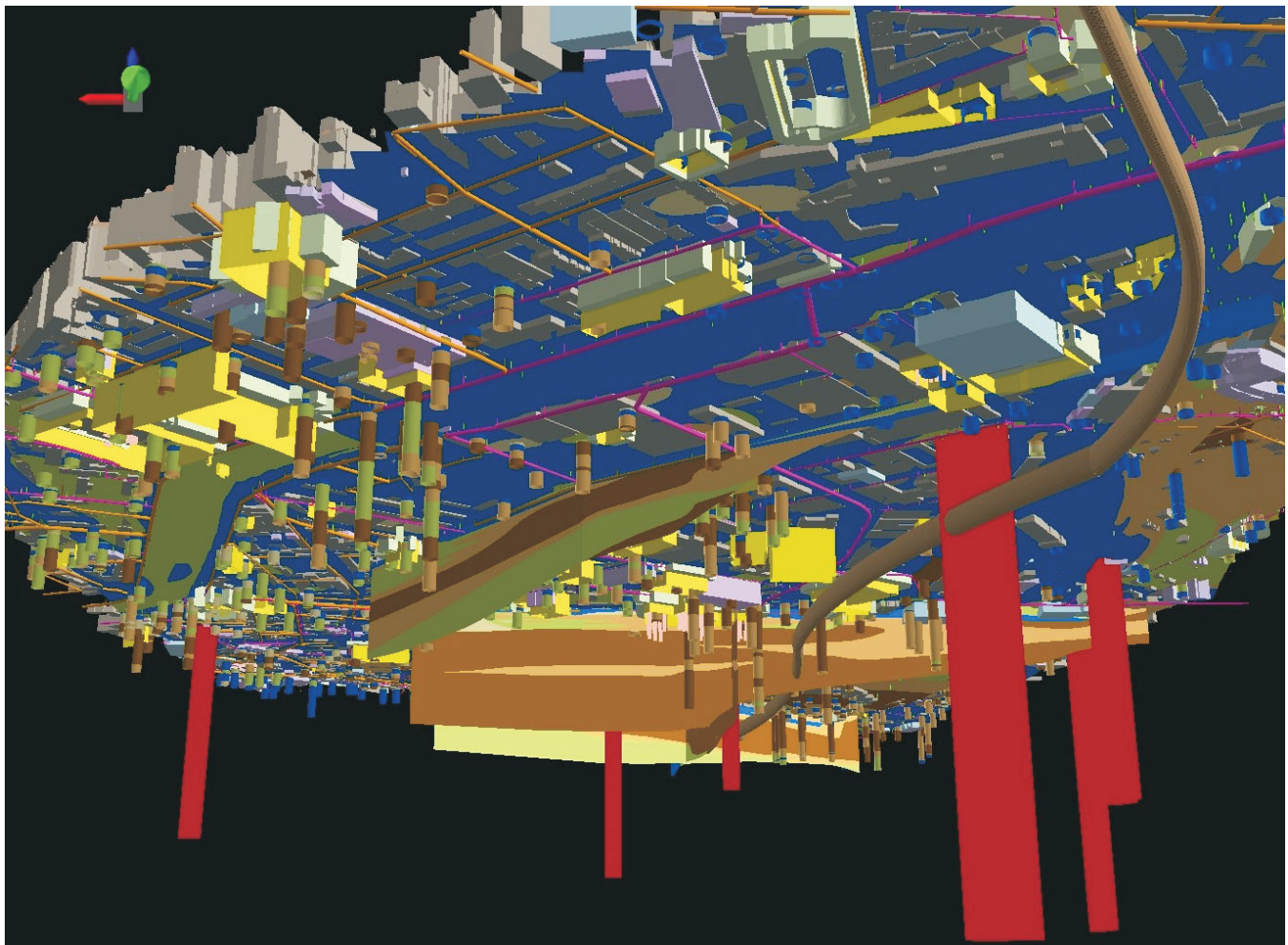
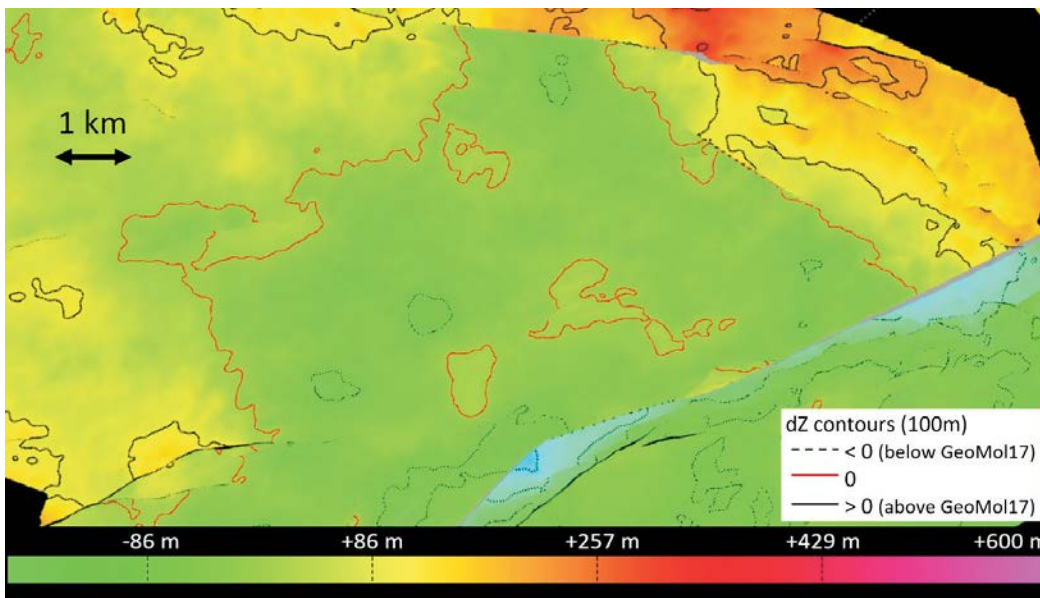


Figure 15. 3D view of building information and geological data within the Geneva model perimeter.



**Figure 16.** Grid depicting the difference in depth between a Triassic horizon from GeoMol17 model and its equivalent from a high-resolution model based on a 3D seismic survey. Towards the top-right, the seismic signal deteriorates within the 3D survey, probably contributing to the difference between the grids. Other discrepancy sources are, of course, the velocity models and poor data areas between faults (blue area).

modelling work and products. Second, it required to formulate and present its knowledge, progress and technical approach on a regular basis. Third, the team can establish a network and personal contacts with the experts.

- Data management must be a mandatory part of the project organization. Data acquisition, harmonization and storage is very time consuming and must be either part of the project work in close collaboration with the data management team or be done by the data management team itself. A retroactive pushback of project data is usually out of scope of the data-management-team capabilities and out of interest of the project team.

Regarding a PPP, the SGS emphasizes the following lessons learned:

- The collaboration between different project partners is an opportunity (e.g. exchange of knowledge and methodologies) and a challenge (e.g. the coordination of different approaches regarding time and methods) at the same time.

- The usage of different software packages may result in difficulties when it comes to data exchange. Overcoming these difficulties is possible by using the same data formats and attributes.
- The choice of methodology may cause problems when it comes to merging parts of the models.
- Contracts need to be unambiguous in terms of ownership, intellectual property, timelines, milestones, form and formats of the deliverables and input data required.
- The work of the project partners needs to be coordinated in terms of timelines, stratigraphy and methodologies.

### Next Steps

Models of the unconsolidated and consolidated sediments: The next big step is devoted to the validation of the geostatistical and explicit models of the SGS. The goal is not only to establish milestones for quality control along the modelling workflow, but also to define minimum and advanced

requirements and parameters for quality assessment.

Regarding numerical modelling, the SGS began with simple hydro-mechanical models and applied these with different codes. One of the codes (ASTER) was further developed to treat APD cases to consider Anisotropy, Plasticity, and Damage. Together with our specialist network, our combined knowledge is on such a level that we can extend our skills to cover further processes, and even to enter new modelling fields such as:

- incorporating reactive transport into the flow and transport processes,
- modelling heat transport in the framework of the Swiss Energy Strategy 2050, and
- modelling CO<sub>2</sub> hydro-mechanical processes in relation of caprock integrity (claystones).

Scale is important for all these subjects. We will start at a course scale (GeoMol) and refine the heterogeneity and processes down to the small scale. Private companies can then also use these models.

The work on BIM will continue. A joint collaboration between the SGS, the professional association of Swiss geologist CHGeol and the University of Applied Sciences of North-Western Switzerland FHNW aims at implementing BIM and geology in a applied research project starting in 2020.

In early 2018, the SGS started a national 3D geological mapping program, called the “National Geological Model” (NGM). For the next eight years, the SGS envisages a comprehensive coverage of entire Switzerland with integrated, harmonized and multi-dimensional geological data in different resolutions. To achieve that goal, all production activities from maps to models will be synchronized with respect to methodologies and data description based on data models. Besides that, the SGS complements the existing modelling activities mentioned above (mainly in the Swiss Midlands) with 3D models also covering the Jura Mountains and the Swiss Alps. These models will be data driven, i.e. only existing data will be used for their development (e.g. maps, sections, boreholes, seismics).

After having achieved a high level of performance and knowledge in 3D geological modelling during the past few years, the NGM also serves to shift the focus from data production to integrated data dissemination and utilization. Therefore, and in parallel to data production, an internet-based 3D viewer available to the public will be established that allows the visualization, analysis and processing of geological data of different sources. Online geological 3D modelling is under consideration and remains reserved. For our organization, three-dimensional models will be the enablers and drivers of the digital transformation. Maps and models will still be our main activities. However, in the near future, data-driven or IT services requested by our partners based on both these products will catch up with them in terms of importance for SGS. Therefore, the SGS actively advances the transition from “maps to models to services”.

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# Chapter 25: 3D Geoscience for the UK and Beyond

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## Introduction

With over 20 years of development in 3D capability, geological modelling is now becoming the primary tool for geoscience investigation by the British Geological Survey (BGS). 3D modelling underpins a broad range of research activities, and geological models are being developed at all scales from sites, to cities, to the UK landmass and continental shelf using a range of different software tools and methodological approaches.

3D modelling is advancing our understanding of geological systems by allowing us to integrate more diverse data sources, attribute a range of different properties, and assess the limitations of our data and knowledge. Recent advances in volumetric and geostatistical modelling are also enabling new integrated process modelling and supporting pioneering subsurface environmental monitoring initiatives.

The increasing availability of 3D models is transforming the way in which we view the subsurface and creating new opportunities for delivering knowledge to our stakeholders—through development of new resources and services, by enabling new approaches to knowledge exchange and engagement, and by supporting our many international partnerships.

This paper presents an overview of recent geological modelling within the BGS, and highlights critical issues arising from the growing influence of modelling across a range of BGS ac-

tivities. The rise of modelling is providing many opportunities, but also brings a range of challenges for managing data, keeping pace with the rapid rate of technological change, maintaining geoscience skills, and developing new delivery methods. Making the most of the opportunities that modelling provides is therefore not just the role of the geological modeller, it also requires the wider evolution of geological survey functions.

## Organizational Structure and Business Model

The BGS is the UK's public sector research institute tasked with the development, curation, and communication of geological data, information, and knowledge. Alongside the provision of up-to-date understanding of UK geology for government, industry, and wider UK society, the BGS undertakes geoscience research to address societal challenges in decarbonisation, environmental adaptation, and Earth hazard mitigation both in the UK and globally through international research partnerships (British Geological Survey, 2019).

The BGS is operated under the newly formed body UK Research and Innovation (UKRI), which supports the UK's research councils and research institutes and provides independent administration of UK research funding. The BGS is overseen by an independent Board on behalf of UKRI and the National Environment Research Council (NERC).

The BGS operates a mixed funding model, with an annual turnover of approximately £50 Million, of which just over 50% is from NERC through our national capability allocation and competitively won NERC research income, and the other half comes from commercial contracts, research grants (e.g. Horizon 2020), and data licencing.

## Overview of 3D Modelling Activities

Geological modelling is now used widely across BGS activities as a key tool for applied geoscience research.

Our modelling capability is underpinned by the in-house development of explicit modelling tools (GSI3D and Groundhog<sup>®</sup> Desktop; e.g. Kessler et al., 2009), and the use of proprietary software such as Petrel E&P<sup>™</sup>, DecisionSpace<sup>®</sup> and SKUA-GOCAD<sup>™</sup> (e.g. Aldiss et al., 2012; Campbell et al., 2010; Kearsley et al., 2018).

The BGS-developed Groundhog Desktop GIS (desktop geoscientific information system) is a graphical software tool designed for the display of geological and geospatial information, and the construction of cross-sections through stratigraphic correlations. The software facilitates the collation, display, filtering, and editing of a range of data including borehole data, geological map linework, interpreted cross sections and faults, as well as elevation models and images (including seismic sections).



Groundhog Desktop is being developed to succeed the earlier GSI3D platform.

Over the past 15 years, geological models including fence diagrams of intersecting cross-sections, surface and volumetric models have been developed for many different parts of the UK. Many of the models produced by the BGS are held in the national GeoModel Store, a repository containing c. 160 models, some of which are available for licencing by external users. These models have been produced through centrally funded ‘national-capability’ geoscience programmes, and were developed as part of commercial contract work.

The models developed by the BGS cover different geological settings in the UK and overseas at scales ranging from development sites, transport corridors and urban regions, to sedimentary basins and national coverage. Whilst many models are developed and designed for application to industry, strategic planning and regulation, targeted geological modelling is also undertaken by the BGS to advance geoscience research in areas as diverse as geological processes and structures (e.g., Newell et al., 2018), aquifer systems (e.g., Jackson et al., 2011), and coastal evolution modelling (e.g., Payo et al., 2018). Geological models are also being developed to underpin the new UKGEOS research platform for subsurface environmental monitoring, in which the integration of real-time telemetry data from new subsurface sensor systems will transition 3D models to 4D.

The National Geological Model project has recently been repositioned as the focus of the BGS’s national geoscience programme and will aim to develop surface and volumetric geological models for the UK’s deep and shallow subsurface. These models will provide a new generation of geological resources for the UK and support process and scenario model-

ling for environmental and energy resource applications. A current project benefiting from early developments in volumetric modelling for the UK is the Hydro-JULES project, a multi-disciplinary collaboration to develop the UK ‘water model’ through integration of climate, hydrological, and hydrogeological process models (Hydro-JULES, 2018).

## Resources Allocated to 3D Modelling Activities

The diversity and ubiquity of geological modelling within the BGS’s research and commercial activities precludes detailed assessment of the resources and staff allocated to 3D modelling tasks. The BGS operates a project-based system where staff work on research activities across a number of programmes, thus some degree of 3D geological modelling capability is increasingly being required of all geoscience staff within the BGS. The development of modelling skills is being encouraged through active training programmes and collaboration between geologists and advanced geological modellers, in addition to targeted recruitment of geological modellers, data scientists, and statisticians. Cross-disciplinary projects are also stimulating innovation in our 3D geological modelling community by linking geophysicists, geologists, petrophysicists, fluid modellers, and data scientists.

The National Geological Model project (NGM) coordinates the UK’s national geological modelling programme. The development of the current UK3D national fence diagram under the NGM (cf. Mathers et al., 2014), was supported financially by national capability funding covering the equivalent of 6 – 7 full time staff with additional commercial income. This funding supported work by a team of c. 10 – 15 regional geologists working part time on the project. Since the completion of the UK3D model in 2016, the national capability funding for the NGM programme has

decreased to the equivalent of 2 – 4 full time staff per year. The new NGM programme commencing in 2019 will be predominantly supported as a core national capability task with projected funding equating to c. 3 – 4 full time roles.

Geological modelling will also be a key component of new ‘Regional Corridor’ projects, designed to deliver applied geoscience for key socio-economic investment areas in northeastern England and to enhance groundwater management of the chalk aquifer in the London area.

## Overview of Regional Geological Setting

Located to the northwest of continental Europe, the UK now lies on the stable passive margin of the North Atlantic Ocean. However, it preserves a complex geological collage including rocks and sediments that range in age from the Archean to the present, and reflect repeated Wilson cycles and a large range of palaeoclimatic and palaeogeographic regimes. There are strong regional contrasts in landscape and geological environment, with Mesozoic and Cenozoic rocks generally exposed at the surface in the south and east of Britain while Precambrian and Palaeozoic rocks are more widely exposed in the north and west (Figure 1). In northern and western Britain and in Ireland multiple cycles of ice sheet development and decay during the Quaternary period conditioned the current landscape through glacial erosion of uplands and the deposition of heterogeneous glacial and glacio-marine deposits of variable thickness both onshore, and across the UK’s continental shelf.

Key areas for geological model development include the Carboniferous basins of northern and eastern Britain (including the continental shelf), and the broader Mesozoic basins of south-eastern Britain and the North Sea. The former are characterised by complex sedimentary fill comprising cy-

clic sequences of sandstone and mudstone with variable quantities of limestone, coal and oil shale, and are economically important for energy and mineral resources. The latter are significant for the extent and quality of major aquifers including the Sherwood Sandstone (Triassic) and Chalk (Cretaceous) that provide groundwater reserves for highly populated areas of southern Britain. Methods for basin modelling, including characterisation of normal and reverse faults, stratigraphic surfaces and volumes using both explicit and implicit methods have been applied widely in these areas at local, regional, and basin scales.

Demands for geological modelling in the upland terrains of southwestern England, central and north Wales, northern England, and Scotland are more limited because of their low population and relatively limited resource potential. However, future applications of geological modelling in these areas, including the development of national coverage models, must accommodate complex structural elements including folding and thrusting, and the diverse igneous intrusions that form key features of these terrains.

The shallow subsurface environment (0 – 200 m depth) includes the bedrock erosion surface, a weathering zone, and overlying glacial and post-glacial sediment deposits. This zone is of particular interest in the development of geological models for urban areas, transport corridors, and catchments (groundwater and surface hydrology). The properties of materials within this zone are typically highly heterogeneous as a result of Cenozoic

(particularly Quaternary) environmental processes and the impact of recent anthropogenic activities associated with industrial and urban development. Methods used for modelling the shallow subsurface include the development of explicit fence diagram, surface (and shell) models, and stochastic modelling where sufficient data is available.

The diversity of geological environments within the UK highlight the importance of a robust scientific understanding as an essential basis for geological modelling. Sound geological knowledge and reasoning are critical for the selection of appropriate methodologies, defining model specifications (including the stratigraphic framework used), integrating diverse input data (e.g. assigning the relative weight of different information sources), and model evaluation.

## Data Sources

A diverse range of data sources are available for UK geological modelling, including geological maps, onshore and offshore seismic data, borehole and well records, digital terrain models, and remote sensing data. Shallow geophysics and airborne geophysical survey data are also available for parts of the UK (Figure 1).

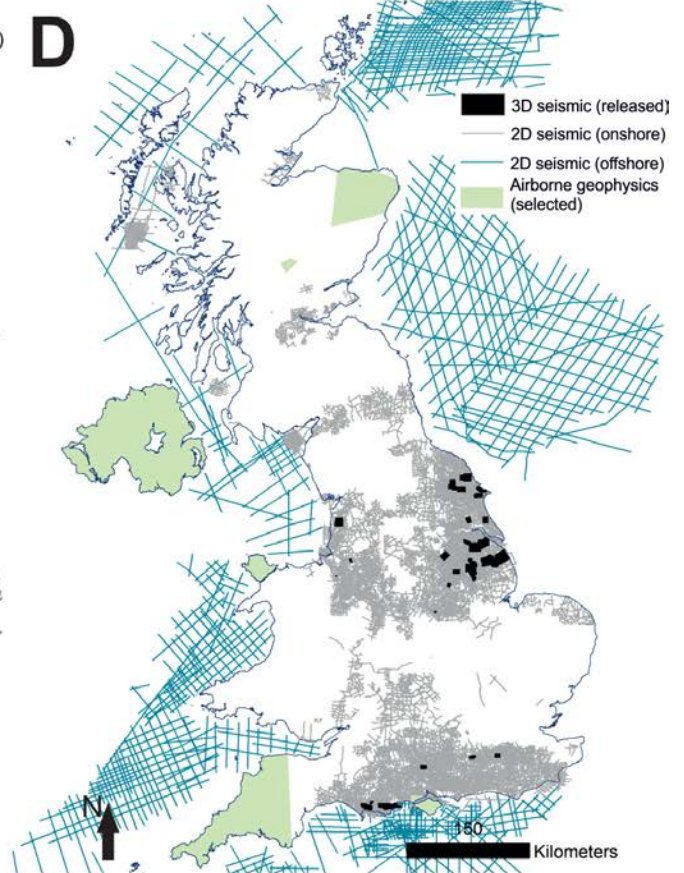
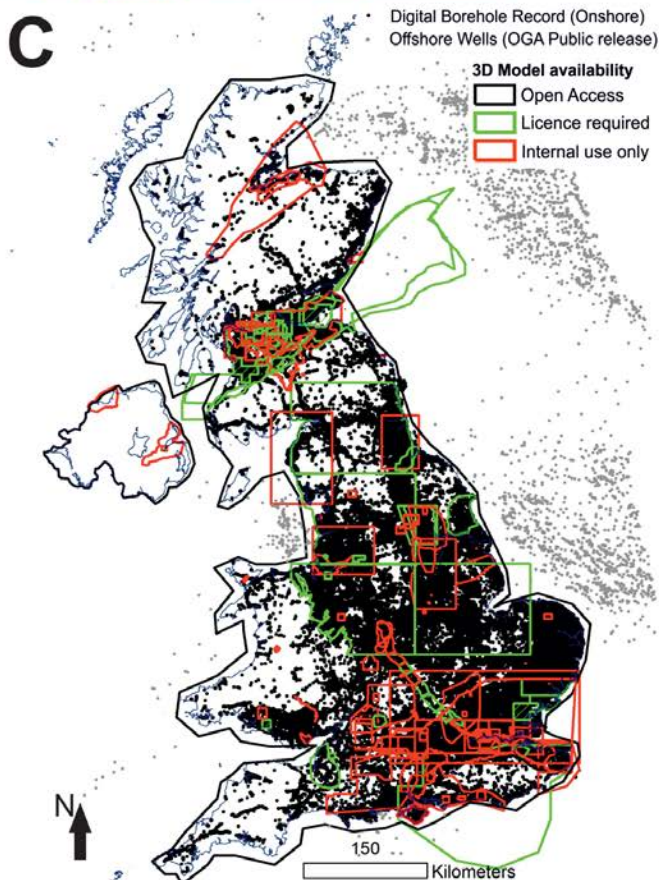
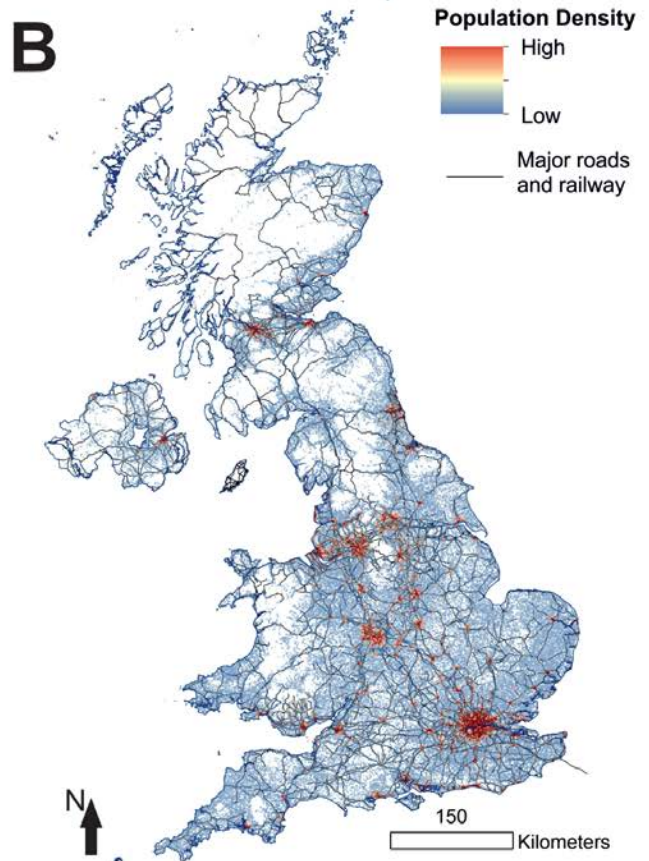
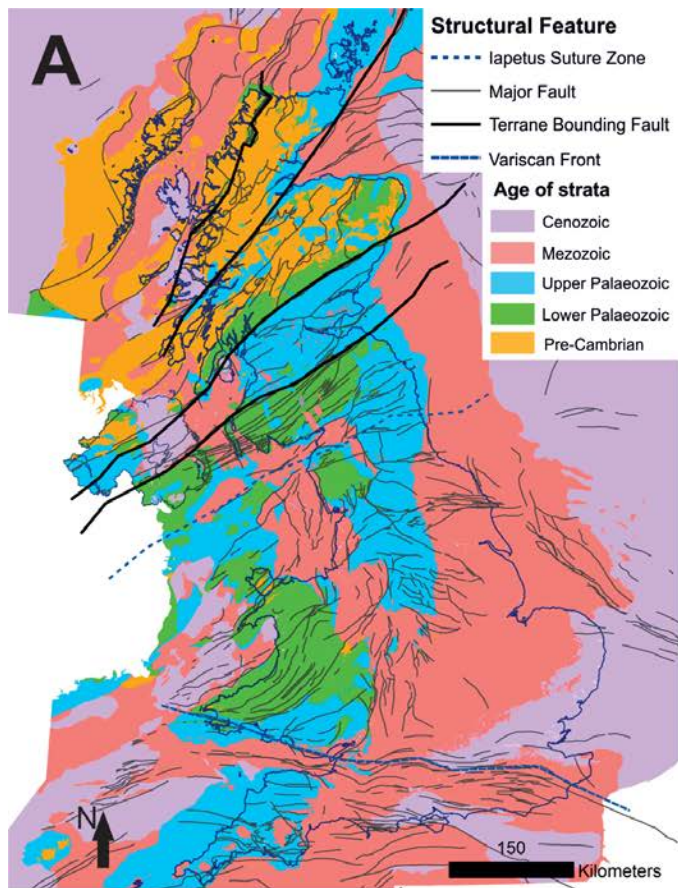
The BGS' National Geoscience Data Centre hosts the UK's national onshore borehole archive, containing over 3 million scanned records. These include water wells, hydrocarbon exploration wells, and BGS stratigraphic boreholes, however records of geotechnical site investigations donated by third-parties comprise the bulk of the dataset. Borehole records

available for modelling are thus highly variable in age and quality, and are typically focused in urban areas and along transport corridors (Figure 1). Digitisation of legacy borehole records is undertaken largely on an *ad hoc* basis through BGS research activities, although some systematic programmes for targeted borehole coding have been undertaken. The BGS currently holds digitised records for over a million onshore boreholes. Many of these are open access records, and increasing numbers of restricted-access legacy records are being made open access as time-limited confidentiality clauses expire.

Seismic data (2D and 3D) and deep well data, including downhole geophysical logs, are available for the UK landmass and continental shelf from the UK's Oil and Gas Authority (the OGA). Offshore data in particular are typically high quality, but have historically been subject to commercial restrictions on usage. However, released offshore well and seismic data is increasingly being made openly available via the OGA's Open Data Portal. Onshore seismic data and deep wells are available for many of the UK's major Carboniferous and Permo-Triassic basins, although the distribution and quality is highly variable. Data coverage within pre-Carboniferous terrains in Scotland, Wales, and southwestern England is limited (Figure 1).

Detailed mine plan data from historical coal extraction, is available for regions in Central Scotland, northern England, and South Wales. Mine plans provide valuable sources of structural data, but are time-consuming and costly to digitise. Long-term

**Figure 1.** Overview maps of the UK: **A)** Geology of the UK landmass and continental shelf derived from the BGS onshore 1:625,000 bedrock geology map and 1:250,000 marine bedrock geology map; **B)** UK gridded population density for areas classed as urban and suburban (Reis et al., 2017; contains National Statistics data © Crown copyright and database rights) and major transport corridors; **C)** The distribution of BGS-held onshore digital borehole records and publically released offshore wells supplied by the UK Oil and Gas Authority (Open Data), overlain by the distribution of geological models currently held by BGS; **D)** The distribution of released geophysical datasets for the UK landmass and continental shelf, includes UK Oil and Gas Authority Open Data. The UK coastline is shown by the blue outline in all images. Contains Ordnance Survey Data © Crown copyright and database rights 2018. Ordnance Survey Licence No. 100021290. Created using ArcGIS © ESRI. All rights reserved.



investment by the BGS in mine plan digitisation in Central Scotland has yielded a key dataset for geological modelling in this region, which is helping to support new research into geothermal potential from mine-waters (Monaghan et al., 2017).

A range of Digital Terrain Models (DTMs) derived from LIDAR, radar, and photogrammetry are available for the UK at resolutions of 1 – 5 m (e.g., NextMap and Bluesky). Remote sensing data are also available at a range of scales for most of the UK, although their use may be limited by cloud cover and vegetation/urban effects. Increasingly, these datasets are enhancing our capability in modelling of near-surface geological systems through the use of geomorphometric and data analytical techniques. Similarly, bathymetric data such as DigBath and GEBCO, together with offshore seismic data are enabling modelling of the near-surface geology offshore with relevance to windfarm development and large-scale modelling/mapping of the UK's continental shelf (e.g., rock at sea bed).

The capture of shallow geophysical data using shallow and passive seismic, electrical resistivity tomography, and ground penetrating radar is a growing focus for new data collection. Although limited in coverage, these data are increasingly being integrated into modelling workflows as constraining datasets for targeted local models, and will be used as test datasets for validation of regional and national-scale models.

High-resolution airborne geophysical data is also available for parts of the UK. The value of these data for advancing geological understanding and generating new opportunities for mineral exploration is highlighted by the TELLUS project in Northern Ireland (Young and Donald, 2013; Figure 1), where geological maps and models, including the UK3D fence diagram, are being updated through interpretation of new high-resolution airborne

gravity and magnetic datasets (e.g., Leslie et al., 2013).

### 3D Modelling Approach

The complex geology of the UK provides both opportunities and challenges for the development and application of geological models. A range of different approaches are employed within BGS geological modelling activities, with methods selected according to the research need, available data sources, and geological context. In some cases different modelling methods are combined within integrated workflows.

The in-house GSI3D and Groundhog Desktop software tools are based on an explicit modelling methodology, using fence-diagrams constructed by geologists to constrain the 3D structures of the subsurface and interpolation algorithms to project surfaces (e.g., Kessler et al., 2009). The fence-diagram approach is most effective for the shallow subsurface where borehole data and digital mapping comprise the main data sources. It is also valuable for regions where data is sparse or the distribution is highly variable. However, the ability of these tools to calculate faulted structures is limited.

Explicit modelling of faulted bedrock (surfaces and structures) in more complex onshore structural terranes is typically undertaken using GOCAD, which allows integration of data from a range of sources including borehole, mine plan, seismic data, and digital map information (e.g., Gillespie et al., 2013; Kearsley et al., 2018; Monaghan, 2014). Explicit modelling approaches using either GSI3D/ Groundhog Desktop or GOCAD, or indeed both, are also commonly employed by the BGS in commercial projects due to well-defined explicit modelling workflows. Geological modelling for 'deep' geology utilising seismic data in both onshore and offshore areas is undertaken using the industry standard software King-

dom™ and Petrel, with previous usage of DecisionSpace, GeoGraphix® and Vulcan™.

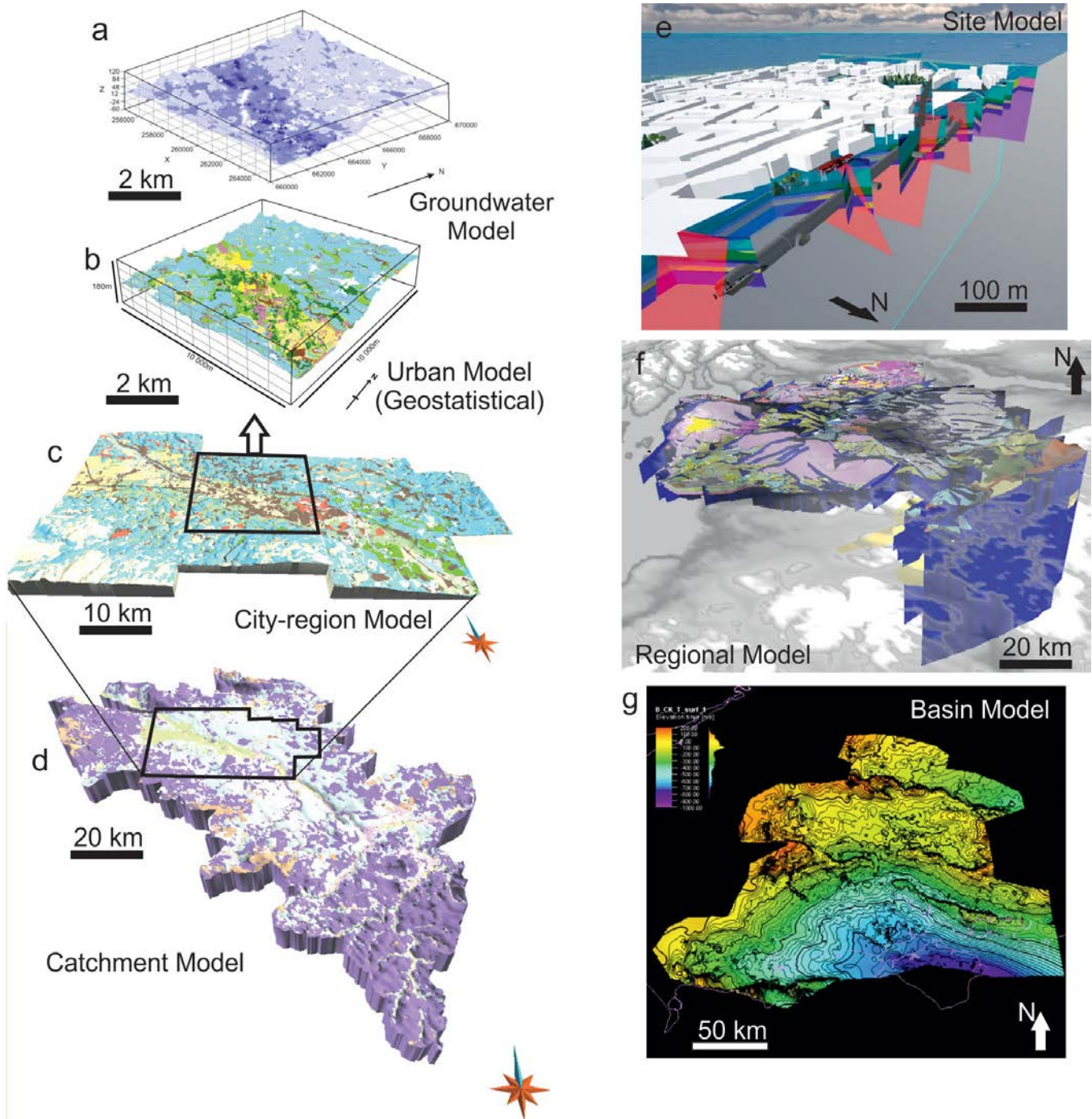
Implicit and geostatistical modelling approaches are also being developed through targeted research projects. Geostatistical (stochastic) modelling of the central Glasgow area, using GOCAD in conjunction with additional geostatistical tools, has been trialled as an approach for modelling heterogeneous Quaternary deposits in the shallow surface using a large borehole dataset (Figure 2; Bianchi et al., 2015; Kearsley et al., 2015; Williams et al., 2018). Implicit modelling using SKUA-GOCAD has also been used to develop regional, property-attributed models (Newell, 2018; Newell et al., 2018) and in the construction of a prototype national-scale gridded bedrock model for the UK designed for advanced groundwater modelling applications.

Current trends in geological modelling innovation within the BGS are seeing increased integration of geophysical data into 3D geological modelling methods, growing use of implicit methodologies, and convergence of geostatistics and data analytical methods with geological modelling, particularly in the characterisation of shallow subsurface systems.

### Clients

Bespoke model development for commercial clients in the UK and overseas represents a substantial component of BGS modelling activities. Primary commercial clients for targeted or bespoke modelling in the BGS include the Environment Agency (England), and companies in the construction and geotechnical sectors.

The BGS has developed strong relationships with a range of clients and stakeholders in planning, construction and infrastructure development, and has delivered geological models to in-



**Figure 2.** Examples of geological models produced by the BGS: **a)** Groundwater flow attributed geostatistical model (based on (b) adapted after Williams et al., 2018); **b)** Urban geostatistical model of superficial deposits for central Glasgow (adapted after Kearsley et al., 2018); **c)** City-region superficial deposits model of the Glasgow conurbation; **d)** Catchment-scale superficial deposits model of the Clyde catchment; **e)** Site-scale bedrock model for Farrington Station, central London; **f)** Regional bedrock model for the Glasgow area; **g)** Basin-scale model showing the base of the Chalk (two-way travel time) in the Wessex Basin (southern UK).

form development projects. Recent examples include the award-winning Farrington Station project (Aldiss et al., 2012), modelling the HS2 rail corridor for Rayleigh Wave Assessment

(e.g., Gunn et al., 2015), and geological models to inform surface and subsurface infrastructure development in Singapore (Building and Construction Agency; Kearsley et al., 2018)

and the United Arab Emirates (e.g., Ministry of Energy (Abu Dhabi); Farrant et al., 2018). In the example of the Farrington Station project, undertaken for the Dr Sauer Group and

CrossRail, geological model development was iterated in real-time during the construction phase of a new underground station in the city of London. Through efficient production of pertinent geological information and data flow, and strong partnership working between the BGS and the clients, the evolving geological model informed decision making during the construction process, resulting in reduced construction cost and ahead-of-schedule project delivery (Aldiss et al., 2012; Gakis et al., 2016).

Geological modelling is also undertaken by the BGS to support the UK's national and local government, and regulatory organisations. Commissioned urban, catchment and aquifer models developed by the BGS for the Environment Agency (England) are used to understand aquifer systems, and inform environmental regulation (e.g., Whitbread et al., 2013). Basin models have also been developed by the BGS as part of a series of shale gas resource assessments commissioned by the UK's Oil and Gas Authority (OGA) (e.g., Greenhalgh, 2016; Monaghan, 2014).

Geological modelling undertaken through the BGS' national-capability Regional Geology programmes, particularly the development of urban-region models, have been important in supporting and stimulating engagement with stakeholders through associated knowledge-exchange fellowships and the development of the ASK (Accessing Subsurface Knowledge) Network. The ASK Network is a knowledge-exchange consortium linking the BGS with a range of geoscience actors in industry and academia, including water companies, construction and geotechnical firms, environmental regulators, and universities. It enables dialogue over the use and applications of geological models and has also helped to promote new digital data sharing initiatives and standards for onshore borehole data in the UK (Bonsor et al., 2013). Originally established in Glasgow, the net-

work has now extended to Wales and Northern Ireland, and is linked to a number of knowledge sharing networks in England. The development of the ASK Network has aligned with the SubUrban COST programme, a wider European collaboration focused on enhancing geoscience data sharing, application, and integration within policy and decision making at city and regional levels (e.g., van der Meulen et al., 2016).

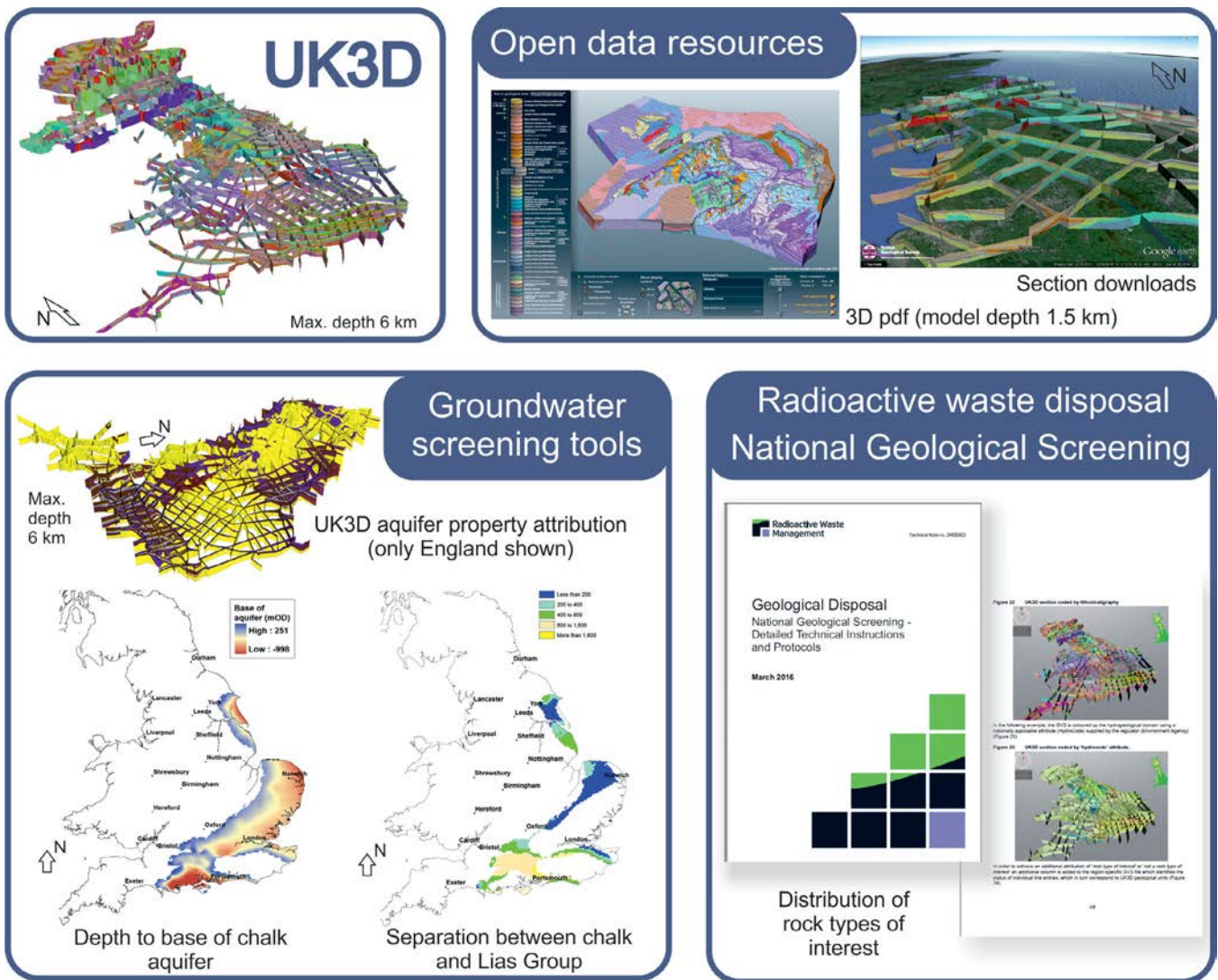
The BGS delivers a range of publically-accessible resources and services from our national-capability funded 3D geological models and selected commissioned models. These include open data access to our national-scale bedrock model UK3D, open-access models, and associated documentation designed for use in education, and licenced model data for selected regional models (e.g., London). The BGS geological models at a range of scales are also important in supporting the wider UK research sector through collaborations such as the NERC-funded Hydro-JULES project (Hydro-JULES, 2018), and the development of the UKGEOS research infrastructure for energy systems and applied environmental monitoring (e.g., Monaghan et al., 2018).

### **Recent Jurisdictional-Scale Case Study Showcasing Application of 3D Models**

The initial development of the UK's national-scale fence diagram was undertaken by the BGS to provide a coherent national 3D understanding to inform groundwater management by the Environment Agency, culminating in the release of "GB3D" in 2012 (Mathers et al., 2014). The GB3D model has been used to assess the distribution of key UK aquifers (Figure 3), and their spatial proximity to geological units that may host potential shale-gas resources (Bloomfield et al., 2014).

During a second phase of development, the GB3D model was 'densified' to increase the number of sections, and extended to include Northern Ireland and offshore areas up to 20 km from the coast, leading to the release of "UK3D" in 2015. This model upgrade was prompted by a need for full UK coverage and offshore extension of the sections to inform the National Geological Screening process undertaken by Radioactive Waste Management Limited (RWM Ltd.). This screening process represents a major UK research activity commissioned by the UK Government to identify potential areas that may be geologically suitable for hosting a geological disposal facility for radioactive waste. The UK3D model has formed a key input dataset for the screening's analysis of the distribution of rock types of interest and tectonic structure (Radioactive Waste Management Ltd., 2016).

The UK3D model is also available to the public as an open data resource via the BGS website, providing a coherent overview of the major structural and stratigraphic elements of the UK geological system. To enhance the delivery of 3D model data for non-specialist users, a new set of Regional Geological Visualisation Models (GV Models), has been developed from UK3D. These GV Models, for 14 regions of England, Wales and Northern Ireland, are constructed in a 3D pdf format and were released as open-access resources in January 2019. The models are designed to encourage user interaction with 3D data and provide essential contextual information for understanding the geological system and interpreting the model (Whitbread and Ritchie, 2018). The availability of these tools will also facilitate stakeholder engagement and consultation activities undertaken by the BGS and by external parties such as RWM Ltd.



**Figure 3.** The UK3D national fence diagram (v2015) and its applications. UK3Dv2015 has formed a key input dataset for several national-scale screening evaluations, including identification of potential sites for geological disposal of radioactive waste, and assessment of aquifer-shale separation for management of groundwater risk associated with potential energy extraction. Contains Ordnance Survey Data © Crown copyright and database rights 2018. Ordnance Survey Licence No. 100021290. Created using ArcGIS © ESRI. All rights reserved.

## Current Challenges

Advances in modelling capability are creating a wealth of new opportunities across BGS research, commercial, and national capability programmes. The growth of modelling, coupled with a move towards more diverse property attribution, is increasing demand for high-quality digital data. In the BGS the two main pathways for increasing digital data availability are the digitisation of legacy datasets and investment in new data acquisition.

Current BGS modelling activities depend heavily on datasets developed through long-term (>20 years) investment in digitisation of analogue data assets, including borehole records, mine plans, and geophysical interpretations (e.g., Kearsy et al., 2018). In order to continue to increase model resolution and reduce uncertainty, advances in data quality and methods for integration of diverse data sets are required. To enhance the quality of data available for modelling, methods for using machine learning to select high-quality data, and to recognise

patterns within datasets of differing qualities, are being trialled. For example, the former approach is being used in selecting borehole records for development of a new version of the UK's Superficial Thickness model (equivalent to depth-to-bedrock).

Developments in “text mining” are now making a wealth of textual (narrative) information available for 2D interrogation and semantic analysis. The BGS is engaged with initiatives such as GeoDeepDive, Geobiodiversity Database (GBDB), and Loop in which knowledge extraction from un-

structured resources supports wider academic research efforts. Harnessing the potential of knowledge extraction and resource linkages to inform geological interpretation in 3D modelling workflows and enrich model delivery is an important short to medium-term innovation challenge for the BGS.

New data capture is increasingly predicated on the need to validate and test geological models. Recent years have seen a dramatic increase in the BGS capture of shallow geophysical data such as passive seismic, ground penetrating radar, and tomography, particularly for constraining and validating shallow subsurface models. This is requiring ongoing development of relevant skills and expertise amongst BGS geoscientists and modellers.

The use of increasingly rich data sources, not all of them quantitative, brings a range of challenges for understanding the uncertainty of geological models. Improving the quantification of uncertainty is widely recognised as a key requirement for the geological modelling community, and is a vibrant area of current research. Arguably, the greatest value for uncertainty information is in helping to direct and prioritise new data collection. Within the BGS, a significant impact of improvements in quantifying uncertainty would be to stimulate new programmes of data capture potentially including mapping, geophysical surveys, and borehole drilling.

Despite much dialogue within the research community, the value of quantitative uncertainty information for many of our stakeholders remains less clear. Dialogue with clients and model users over the value of uncertainty metrics, and relevance of the language used to discuss them, is needed to better understand how we can effectively communicate the limitations of a model's interpretation as relevant to the user's needs.

The number and diversity of geological models being generated through BGS research and commercial activities poses a significant challenge for the management of geological models as a UK resource. Model design is influenced by a number of factors, including the geological context, the nature of the available data, and the intended use. Models must be optimised to be of value for research and decision making, and as such, models intended for investigation of, for example, the behaviour and impact of potential energy technologies, radioactive waste disposal, or aquifer system characterisation, may differ in their scope, scale, and the stratigraphy or properties that are represented. Thus, in addition to practical implications for data management and maintenance (i.e., versioning) of models, the question of appropriate contexts for model reuse is also significant. As a recent UK government review of computational modelling notes: "Modellers need to be guided by a clear articulation of the model's analysis, and a model designed for one purpose may not always be suitable for another" (Government Office for Science, 2018). Our model management approaches must evolve to reflect the dynamic world of modelling at the BGS, establishing robust decision making processes, and ensuring appropriate information capture related to model design, geological content, and limitations.

## Lessons Learned

Digital data capture from historic records, although time-intensive and expensive, has been critical for unlocking the power of modelling technology to transform our understanding of the UK's subsurface. Alongside long-term investment in digitisation of analogue records, the BGS has developed a fully digital data management workflow - from supply to delivery, including a digital records management system, and a new UK digital data deposit portal.

However, creating our digital data infrastructure is only part of the story. Ensuring our future modelling capability relies on sustained data supply from industry, including the geotechnical/construction, energy, and water sectors. To secure future supply and encourage digital data flow, the BGS has developed new consortium-based approaches for stakeholder engagement (including the ASK network), encouraged the pioneering use of contractual agreements to embed digital data standards within industry (e.g., Whitbread et al., 2016), and worked to develop innovative partnerships with industry to facilitate digital data sharing (e.g., Dig to Share). The digital revolution in geoscience does not just mean a change to the practise of geological research - it also requires the geological survey to encourage and facilitate behavioural change across industry.

Since the initiation of geological modelling programmes at the BGS, the development of modelling capability has gone hand-in-hand with investment in stakeholder dialogue and knowledge exchange. As well as ensuring that our modelling programme delivers quality geoscience and value for stakeholders, this partnership focus has increased commercial interest in our modelling 'services' and encouraged commissioned work. These commissioned programmes have provided a critical stimulus in the development of our modelling capability, driving innovation in software design, modelling approaches, property attribution, and delivery methods and formats. Thus, working closely with stakeholders and engaging in constructive dialogue has been fundamental for simulating both demand and innovation in the BGS's 3D geoscience.

Geological models have significant value as communication tools, providing 3D visualisations of the structures and systems of the subsurface, however delivery of 3D-format geoscience data to users is not

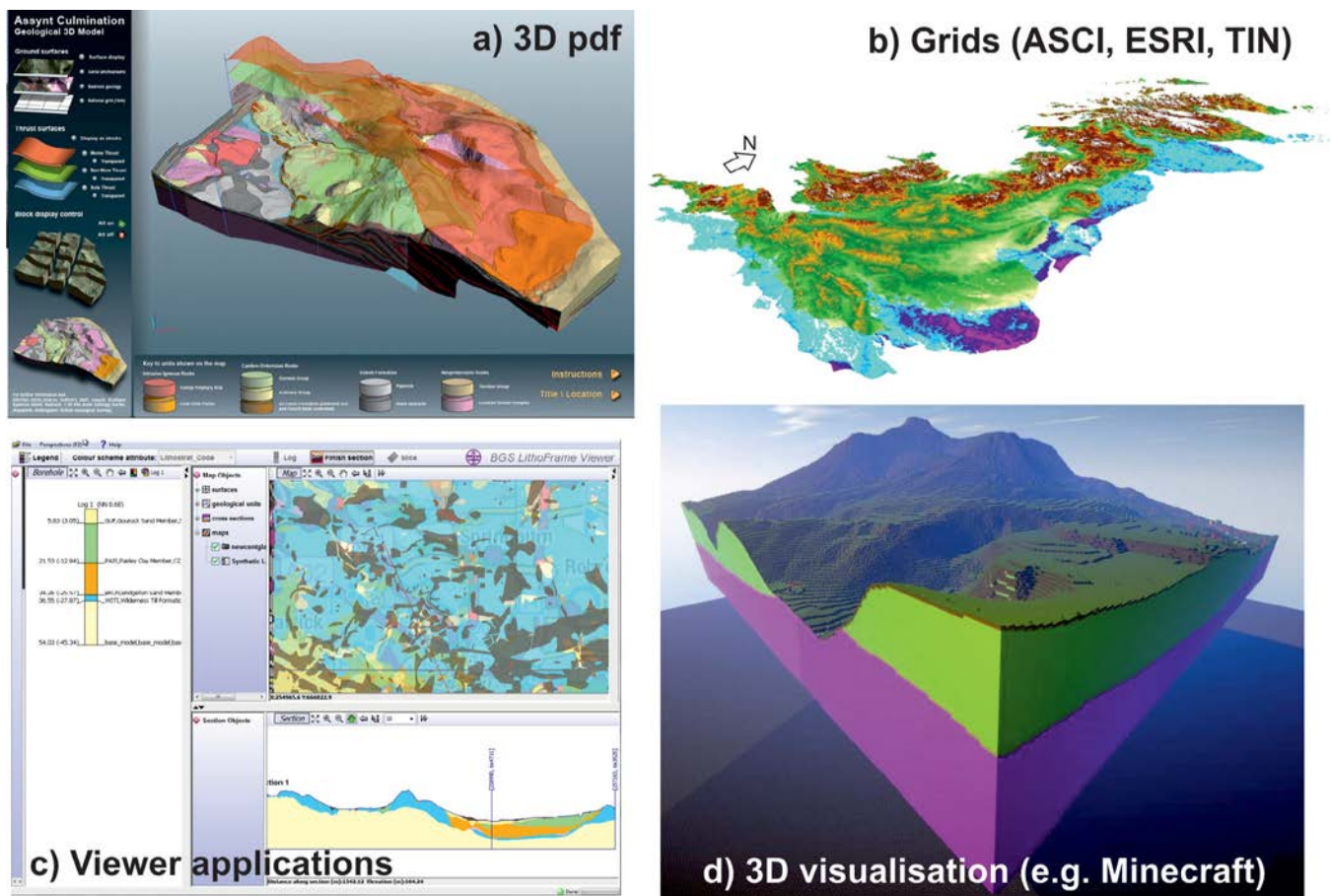


straightforward. In addition to delivering data grids and Shapefiles, for example for integration within Building Information Management (BIM) workflows, a range of interactive visualisation tools for 3D data have been developed, including 3D pdfs, interactive viewers and web-based applications, and integration within Geovisionary software and Minecraft (Figure 4). These methods enable visualisation of 3D data and have varying degrees of interactive capability. The development of the 3D pdf has proved to be a valuable tool for communication of 3D geology with a wide range of users including the

general public (e.g., Whitbread and Ritchie, 2018), as well as education and industrial sectors. The value of the 3D pdf is enhanced by the ability to integrate important contextual information about the model content, data inputs and limitations, directly within the delivery format. Developed through collaboration between geologists, geological modellers, and cartographers, the success of the 3D pdf delivery format is rooted in the attention paid to communicating the rich scientific content, *and* to the crafting of a user-orientated design.

## Next Steps

From 2019, the BGS will be implementing a new Science Strategy, providing renewed focus for the UK's regional and national geoscience programmes. Our national programme will focus on the development of a new generation of volumetric models for the UK, including the construction of a UK onshore-offshore gridded bedrock model, and new property-attributed models for key structures of the shallow subsurface (e.g., the bedrock erosion surface). The national bedrock model will involve the construction of a 3D structural 'basins



**Figure 4.** Styles and formats for delivery of BGS models: **a)** the 3D pdf format illustrated by the Assynt Culmination model – cross-sections and the geological map are displayed in a ‘block’ format with modelled thrust planes (orange and green surfaces) projected above ground; **b)** Grids for various modelling and visualisation applications, here displayed in ArcScene – the upper surface is the UK rockhead model (low elevation is pale green, high elevation is brown to white), the lower surface is the superficial thickness model (thin deposits are pale blue, thick are pink) – note the surfaces have been vertically offset for display purposes (developed using NEXTMap Britain elevation data from Intermap Technologies); **c)** The BGS-developed Lithoframe Viewer is an example of 3D model viewer applications – this image shows part of the superficial deposits model for the city of Glasgow (a glacial till unit is blue, a glaciofluvial unit is orange, and a glaciolacustrine unit is green), **d)** 3D visualisation software and applications, illustrated by a Minecraft build of the Ingleborough model (model depth is c. 1 km). Contains data from Minecraft © Mojang 2009-2019. Images a) and b) created using ArcGIS © ESRI. All rights reserved.

and terranes' framework for the UK landmass and continental shelf as part of a 3D digital research infrastructure. These models will support the development of new geological information resources, underpin new applied research such as integrated climate-groundwater-surface water modelling and energy resource assessments, and provide a platform for the development of predictive (4D) 'reservoir engineering' type modelling approaches.

Geological modelling activities will also form core elements of our regional work programmes designed to advance our understanding of the influence of heterogeneous ground conditions on groundwater flow; to test the behaviour and impact of potential energy technologies such as underground deep thermal storage, geothermal systems performance, and hydrogen storage in porous media; and to deliver 3D characterisation of ground conditions to inform infrastructure development. The pioneering UK Geoenergy Observatories project (UKGEOS) to monitor environmental change in the subsurface environment will also supply new telemetry data to transition site-scale 3D geological models into 4D sub-surface monitoring platforms.

The significance of computational modelling for informing strategic planning and policy in fields as diverse as health, infrastructure, manufacturing, and economics, has been recognised in a recent UK Government review (Government Office for Science, 2018). With critical relevance for energy, water, mineral resources, waste disposal, and infrastructure development, geoscience plays an important role in the UK's future socio-economic development. To ensure the impact of BGS geoscience is not just felt in the spheres of research, environmental regulation, and industry, but reaches critical areas of strategic planning and policy in Government, our geological modelling must progress from 3D characterisation towards the delivery

of advanced subsurface environmental process and scenario modelling. Investment in innovative 4D environmental monitoring and development of predictive modelling capabilities will ensure that the BGS geoscience delivers for decision makers in the UK, and for our global partners.

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# Chapter 26: Status of Three-Dimensional Geological Mapping and Modelling Activities in the U.S. Geological Survey

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## Introduction

The U.S. Geological Survey (USGS), created in 1879, is the national geological survey for the United States and the sole science agency within its cabinet-level bureau, the Department of the Interior. The USGS has a broad mission, including: serving the Nation by providing reliable scientific information to describe and understand the Earth; minimize loss of life and property from natural disasters; manage water, biological, energy, and mineral resources; and enhance and protect quality of life. USGS scientific activities are organized around major topics, or Mission Areas, aligned with distinct science themes; three-dimensional (3D) modelling typically supports research and project work within a specific Mission Area. The vastness, diversity, and complexity of the geological landscape of the United States has resulted in the creation of 3D geological framework models that are local or regional in scale; a National-scale 3D model is only beginning to evolve. This paper summarizes 3D geological modelling at the USGS and does not discuss 3D modelling that is conducted by other Federal agencies, state geological surveys, academia, or industry within the U.S. This paper updates and expands

upon a similar status report of USGS 3D modelling activities of Jacobsen et al. (2011).

## Organizational Structure and Business Model

In 2010, the USGS was organized into major topics, or Mission Areas, that were aligned with the broad science themes outlined in a 10-year Bureau-level Science Strategy (U.S. Geological Survey, 2007): Land Resources, Core Science Systems (which includes the National Cooperative Geologic Mapping Program), Ecosystems, Energy and Minerals, Environmental Health, Natural Hazards, and Water Resources. At the same time, 10-year science strategies were created for each of the USGS Mission Areas and for the programs focused on those topics (e.g., Evenson et al. 2013; Ferrero et al. 2013).

The annual USGS budget is approximately US\$1 billion from federal appropriations. The bureau also receives about US\$500 million from outside entities such as other federal agencies, foreign governments, international agencies, U.S. states, and local government sources. More than half of the outside funding supports collabora-

tive work in the Water Mission Area, and the balance of the funding supports work in the geological, biological, and geographic sciences and information delivery. The USGS workforce is approximately 9,000 distributed in three large centers (Reston, Virginia; Denver, Colorado; San Francisco Bay area, California) and in numerous smaller science centers across the 50 states (Jacobsen et al. 2011).

Scientific work is organized into “projects” run by principal investigators (PIs) who have significant latitude in planning and conducting research in accordance with Program-level guidance, including acquisition of the resources (e.g., equipment, computers, software, and data) needed to carry out their studies. USGS 3D geological mapping efforts typically occur on a project-by-project basis, and 3D modelling activities are decentralized and spread across USGS Mission Areas. The USGS uses a myriad of 3D modelling and visualization programs (Jacobsen et al. 2011) due to the variety of 3D applications, the distributed nature of scientific projects throughout USGS, and differences in scientific focus between Mission Areas. As a result, implementing a single organization-wide

software platform is challenging and perhaps not even desirable.

## Overview of 3D Modelling Activities

Within the Energy and Minerals Mission Area, a wide variety of 3D data management, modelling, and visualization tools are applied as part of resource assessments. In Energy, 3D geologic models are built as stand-alone research projects for reservoir characterization and as geologic input to 4D pressure, volume, temperature models that are used in petroleum geology assessments to understand and delineate areas that are thermally mature for oil and gas generation, evaluate timing of generation and migration relative to tectonic events and trap formation, and determine volumes of generated hydrocarbons for each modelled petroleum source rock. 3D data are released as grid files of elevation and thickness, and 3D model files with model-viewing capability (Higley et al. 2006; Higley, 2014; Hosford Schierer, 2007). Geothermal energy assessments increasingly use 3D geologic models in developing the structural framework to locate intersections of faults at geothermal prospects. In Minerals, 3D modelling includes 3D representation of geophysically derived surfaces and forward modelling of geophysical data to create 3D geologic models to support mineral-resources assessments and research. Recent emphasis on mineral commodities considered critical to the economic and national security of the United States (Schulz et al. 2017), particularly in areas buried beneath glacial or Phanerozoic cover, require extrapolating geological mapping from the surface to depths greater than 1 km over large areas where little borehole information exists. To extrapolate below ground, various geophysical datasets are integrated with surface geologic and borehole data to develop a 3D geologic model of the region (e.g., Drenth et al. 2015; Finn et al. 2015).

In areas of thick cover where borehole data are sparse, much of the region's geology and mineral potential is poorly constrained and geophysical methods are a primary means of developing a 3D subsurface representation.

Within the Water Resources Mission Area, the USGS has conducted regional hydrologic studies of principal aquifer systems (Figure 1) under the Groundwater Resources Program (Reilly et al. 2008) and currently as part of the USGS National Water Availability and Use Program (Evenson et al. 2018). Regional groundwater availability studies typically include a conceptualization of the hydrogeologic system, inventory of hydrologic data sets, and construction of a numerical simulation (e.g., Faunt, 2009; Feinstein et al. 2010; Heilweil and Brooks, 2011; Brooks et al. 2014). Understanding of groundwater flow systems is enhanced through the development of 3D hydrogeologic framework models produced as part of the regional study (e.g., Burns et al. 2011; Feinstein et al. 2010) or created by the USGS National Cooperative Geologic Mapping Program or state geological surveys. These 3D framework models are produced for regional water-availability assessments and are not intended to be components of a national geological model, yet are comparable in areal size to national-scale models produced by other national geological agencies (Figure 1; Table 1). At the groundwater basin scale, 3D modelling activities focus on the thickness and extent of specific aquifers, the configuration of the basin, and the geometry of faults that affect the aquifers (Pantea et al. 2011; Sweetkind, 2017; Page et al. 2018).

Within the Hazards Mission Area, 3D geologic modelling activities include building geologically realistic fault-block models used for incorporating geology into hazard scenarios (e.g., Phelps et al. 2008) and the development of crustal-scale 3D fault sur-

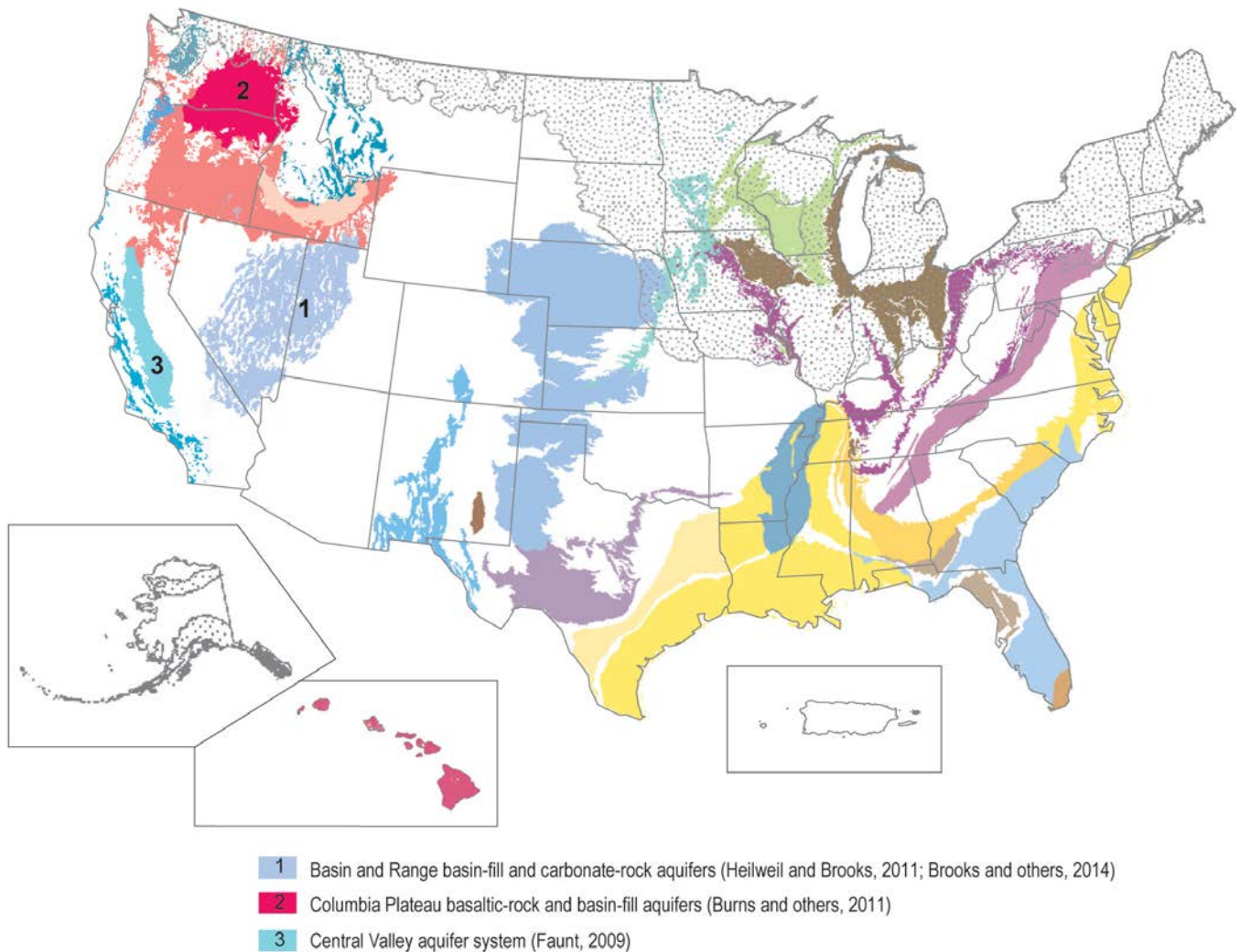
faces to help characterize complex patterns of fault interactions and 3D deformation (e.g., Plesch et al. 2007; Nicholson et al. 2014). Crustal-scale models for seismic hazard analysis incorporate geology-based 3D seismic velocity models that are used to model the propagation of seismic energy through the upper to middle crust (e.g., McPhee et al. 2007, Aagard et al. 2010). National scale three-dimensional geophysical structure based on knowledge of surface and subsurface geologic variations will assist with earthquake hazard risk assessment by supporting estimates of ground shaking in response to an earthquake (Boyd and Shah, 2018; Shah and Boyd, 2018). For assessment of volcanic hazards, 3D models of hydrothermal alteration and water content derived from airborne geophysical data delineate zones susceptible to sector collapse of Cascade arc volcanoes and subsequent destructive lahars (Finn et al. 2007; 2018) in addition to mapping structure and volume of volcanic products (Langenheim et al. 2016) and the magmatic system beneath Mono Basin (Peacock et al. 2015).

## Resources Allocated to 3D Modelling Activities

An estimated 50 to 100 people within the USGS routinely or occasionally conduct geological 3D modelling activities. These scientists are dispersed across the organization and 3D geological mapping efforts occur on a project-by-project basis. A far greater number of staff are able to visualize data in 3D, including the analysis and use of airborne and ground-based LiDAR and using animations, fly-throughs, and data-discovery tools to help researchers conduct science and communicate results.

## Overview of Regional Geological Setting

The United States has a large variety of geological terranes that record more than 2 billion years of geologi-



**Figure 1.** Principal aquifers of the United States (after Reilly et al. 2008). Colored regions represent separate regional aquifer systems as described by Reilly et al. 2008; only aquifers discussed in text are labeled.

**Table 1.** Area of selected 3D hydrogeologic framework models, USGS Water Mission Area compared to the area of the UK National model

3-D Model	Area, in mi <sup>2</sup> (km <sup>2</sup> )	Reference
USGS California Central Valley <sup>1</sup>	20,000 mi <sup>2</sup> (52,000 km <sup>2</sup> )	Faunt, 2009
USGS Columbia Plateau <sup>1</sup>	44,000 mi <sup>2</sup> (114,000 km <sup>2</sup> )	Burns et al. 2011
USGS Great Basin carbonate and alluvial aquifer system <sup>1</sup>	110,000 mi <sup>2</sup> (285,000 km <sup>2</sup> )	Heilweil and Brooks, 2011
British Geological Survey UK framework model	93,600 mi <sup>2</sup> (242,500 km <sup>2</sup> )	Mathers et al. 2014

<sup>1</sup>Shown in Figure 1.

cal history. The complexity of U.S. geology ranges from horizontal stacking of sedimentary rocks in the Great Plains, Colorado Plateau, and Coastal Plain Physiographic Provinces to compressional orogens of the Appalachians and Rocky Mountains Provinces to the complex overprinting of compressional, extensional, and transform tectonics of the Pacific Border Province of the western United States and Alaska (King and Beikman, 1974; Schruben et al. 1994; Reed et al. 2005a, b; Horton et al. 2017). These varied geological terranes present a challenge to 3D modelling of numerous stratigraphic units in divergent, convergent, transform, and stable cratonic settings. Surficial geological processes of the last several million years have left variable unconsolidated deposits, including the voluminous deposition of glacial materials in New England and the northern conterminous United States (Soller et al. 2012; Soller and Garrity, 2018).

## Data Sources

Construction of 3D geologic framework models typically involves the use of data from geologic maps, cross sections, water well and oil and gas wells, and surfaces developed from geophysical data (typically a depth-to-pre-Cenozoic basement surface). Because of the expense in acquiring or obtaining data, seismic data are less typically used, except where societal need demands specific knowledge of the subsurface, such as in seismic hazard studies (e.g., Wentworth et al. 2015). Geophysical data are generally developed in-house and integrate existing datasets with collection of new data.

Challenges faced by the USGS in creating 3D models, particularly at the regional scale, include: (1) lack of seamless and consistent geologic map portrayal across different states at scales needed for model creation; (2) differences in regional naming conventions for geologic formations; and

(3) differences in the digital and layout formats that are present in various State-managed collections of oil and gas and water-well drillers' records and the need for hand entry of scanned records into numerical format. More general 3D modelling challenges include how to translate physical properties into meaningful geologic units (and vice versa), how to incorporate uncertainty, and how to incorporate results of multiple realizations and alternate models.

## 3D Modelling Approach

Most USGS 3D geologic framework models are deterministic models of geologic surfaces (Belcher and Sweetkind, 2010; Burns et al. 2011; Sweetkind, 2017) or surfaces and bounding faults (Pantea et al. 2011; Page et al. 2018; Phelps et al. 2008). Some models use lithologic information from driller's logs or are interpreted from downhole electric logs to develop 3D textural models of grain-size variability (Faunt, 2009, Sweetkind et al. 2013; Wentworth et al. 2015). A few stochastic geologic models have been created through geostatistical modelling of geologic and geophysical data (Phelps, 2016).

USGS 3D gravity models use gravity inversion and geologic constraints from boreholes or seismic data to create a structural elevation grid that has geologic meaning (e.g., Grauch and Connell, 2013). 3D geologic framework models can be especially tightly constrained when multiple geophysical techniques (gravity, magnetic, MT) are combined with borehole and rock property measurements (e.g., Finn et al. 2015; Langenheim et al. 2016)

## Clients

Because of collection of long-term monitoring data, resource assessments, and the national and international scope of its science, resource and land management agencies use USGS science in developing policies

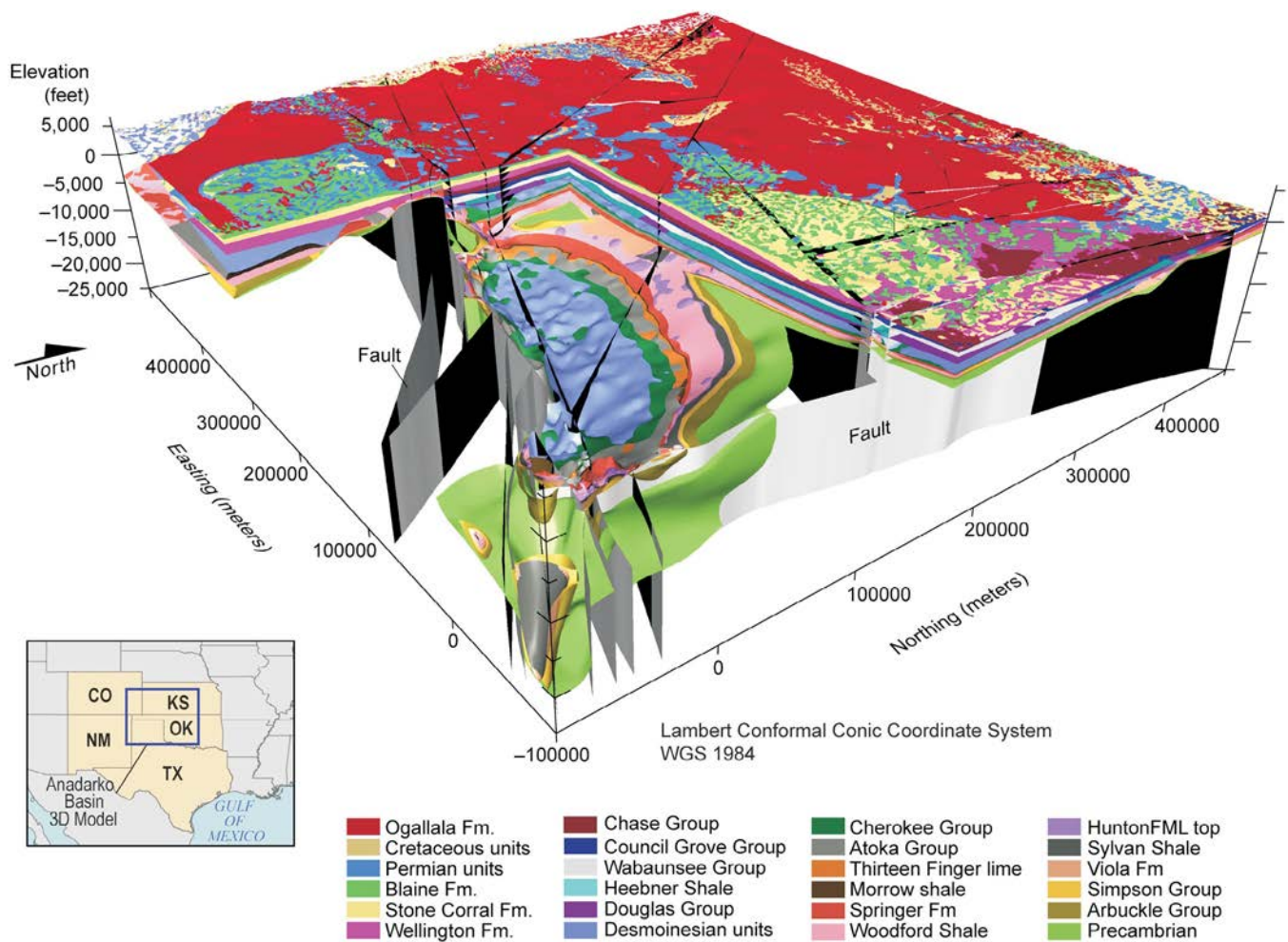
that help them meet their stewardship responsibilities. Most USGS 3D geologic framework models are used within the organization to support process and predictive models. Where models are built for outside entities, model extent and level of detail are closely coordinated to meet the needs of cooperators. The USGS takes advantage of cooperative research and development agreements to collaborate with research institutions both within and outside the United States (e.g., Berbesi et al. 2012).

## Recent Jurisdictional-Scale Case Studies Showcasing Application of 3D Models

### *Case study 1: 3D framework in Anadarko Basin petroleum assessment*

In 2010, the U.S. Geological Survey (USGS) completed an assessment of the undiscovered oil and gas resource potential of the Anadarko Basin Province of western Oklahoma and Kansas, northern Texas, and southeastern Colorado, covering an area of approximately 58,000 mi<sup>2</sup> (150,200 km<sup>2</sup>) (Higley, 2014). The assessment is based on analysis and modelling of geologic elements including: hydrocarbon source rocks; reservoir rock type, distribution, and quality; types and distribution of reservoir traps and seals; and timing of petroleum generation and migration and defining migration pathways (Higley, 2014). Stratigraphic units range in age from Precambrian to present; petroleum is produced from Cambrian through Permian strata. Much of the production is reported as being commingled from numerous formations that were deposited over broad age ranges; this requires modelling at the basin scale of the full thickness of geologic formations (Higley, 2014).

To support the assessment, a 26-layer 3D geologic framework model was constructed that serves as the geometric basis for petroleum system models



**Figure 2.** Perspective view from the southeast of a cutaway block model showing the 26 structural surfaces and vertical fault traces present in the 3-D geologic framework model of the Anadarko basin province (model of Higley, 2014). Fault plane colors range from light gray to black because of directional lighting of the model.

(Higley et al. 2014; Figure 2). Elevation, thickness, and fault data sources for the 2D grids and 3D model include formation tops from wells, contoured formation tops from proprietary and published sources, and outcrop/subcrop data from surface geologic maps. Data files were edited using 2-D GIS and 3D geologic modeling software to remove anomalies such as location errors and incorrect formation-top elevations. 3D grids were compared to published cross sections and maps, and anomalous surfaces were edited and regridded. A 3D geologic framework model was created by stacking the 26 stratigraphic surface grids and including Precambrian fault surfaces from the

province (Figure 2; Higley et al. 2014). Model grid spacing was 1-km with 601 cells in X-dimension and 576 in Y-dimension. Volumes of units are defined and shown in Figure 2 as the space between (1) two geologic surfaces, (2) geologic surfaces and fault planes, or (3) geologic surfaces and model extents. Faults in the 3D model were subdivided based upon whether they extended from Precambrian basement to the ground surface or crossed only some of the model layers. Due to modeling and time constraints, faults were designated as vertical.

Much of the petroleum assessment-related modelling was conducted in 4D

modelling software that supports analysis petroleum migration pathways, time-temperature maturation pathways in the basin, and modelling of hydrocarbon generation, migration, and accumulation through time (Higley et al. 2006; Higley, 2014). However, formation tops grids and associated data were used for other assessment purposes including 1D burial history models and 2D cross sectional models, such that it was more efficient to generate and edit layers in 2D GIS and 3D geologic modelling software and import the resulting grids or the 3D geologic framework model into the 4D modelling platform (Higley et al. 2006; Higley, 2014).



## **Case study 2: 3D geological models for regional groundwater availability studies**

The USGS conducted a regional assessment of groundwater availability of the Great Basin carbonate and alluvial aquifer system (GBCAAS) as part of a U.S. Geological Survey National Water Census Initiative to evaluate the nation's groundwater availability (Heilweil and Brooks, 2011; Brooks et al. 2014). Located within the Basin and Range Physiographic Province, the aquifer system covers an area of approximately 110,000 mi<sup>2</sup> (285,000 km<sup>2</sup>) across five states, predominantly in eastern Nevada and western Utah (Figure 1) and includes the Basin and Range carbonate-rock aquifers, the southern Nevada volcanic-rock aquifers and much of the Basin and Range basin-fill aquifers (Reilly et al. 2008). Diverse sedimentary units of the GBCAAS study area are grouped into hydrogeologic units (HGUs) that are inferred to have reasonably distinct hydrologic properties due to their physical characteristics. These HGUs are commonly disrupted by thrust, strike-slip, and normal faults with large displacement, and locally affected by caldera formation.

A three-dimensional hydrogeologic framework (3D HFM; Figure 3) was constructed that defines the physical geometry and rock types through which groundwater moves (Heilweil and Brooks, 2011). The 3D HFM consists of nine HGUs with distinct physical and hydraulic properties: three units representing Cenozoic basin-filling sedimentary and volcanic rocks and six units representing consolidated Mesozoic and Paleozoic bedrock and intrusive rocks (Figure 3). The framework was built by extracting and combining a variety of data, including:

- Land-surface elevation from seamless 1:24,000-scale National Elevation Data (NED) digital elevation models (DEM);

- Geologic data from five state geologic maps integrated into a seamless 1:500,000-scale geologic map database. Geologic contacts were sampled at regularly spaced points within a GIS and then assigned coordinate locations from the map base and elevations from a digital elevation model. The geologic map also provided location of faults and caldera boundaries.
- Stratigraphic log data from 441 wells compiled from oil and gas, mining, water-well, and other records;
- Geologic contacts digitized from 245 cross sections compiled from 99 separate sources;
- Elevation data of geologic surfaces from an existing 27-layer 3D-hydrogeologic framework for part of the study area; and
- A gridded surface defining depth to top of consolidated rock created by combining the results of five regional and subregional gravity-based surveys. The resulting surface defines both the top of pre-Cenozoic rocks and the base of the Cenozoic sedimentary basin-fill deposits and volcanic rocks.

The top elevations of the HGU surfaces were modelled from the input data using a 1 mi<sup>2</sup> (2.59 km<sup>2</sup>) grid cell size. In the hydrogeologic framework, individual HGUs are represented by an interpolated gridded surface of the top altitude of each HGU. The HGU surfaces were combined and stacked, resulting in the 3D-hydrogeologic framework (Figure 3). Major fault zones and caldera margins were incorporated as vertical boundaries to define abrupt changes in unit elevation and as structural control on the hydrogeology. Interpolation of spatial data points into grids representing the HGU surfaces was processed using 3D modelling software, and further modification and interpretation of the gridded HGU surfaces was completed using geographic information system (GIS) software. The model was released as a series of GIS raster files

that represent the modelled top surface altitude and extent for each of the hydrogeologic units within the study area (Heilweil and Brooks, 2011).

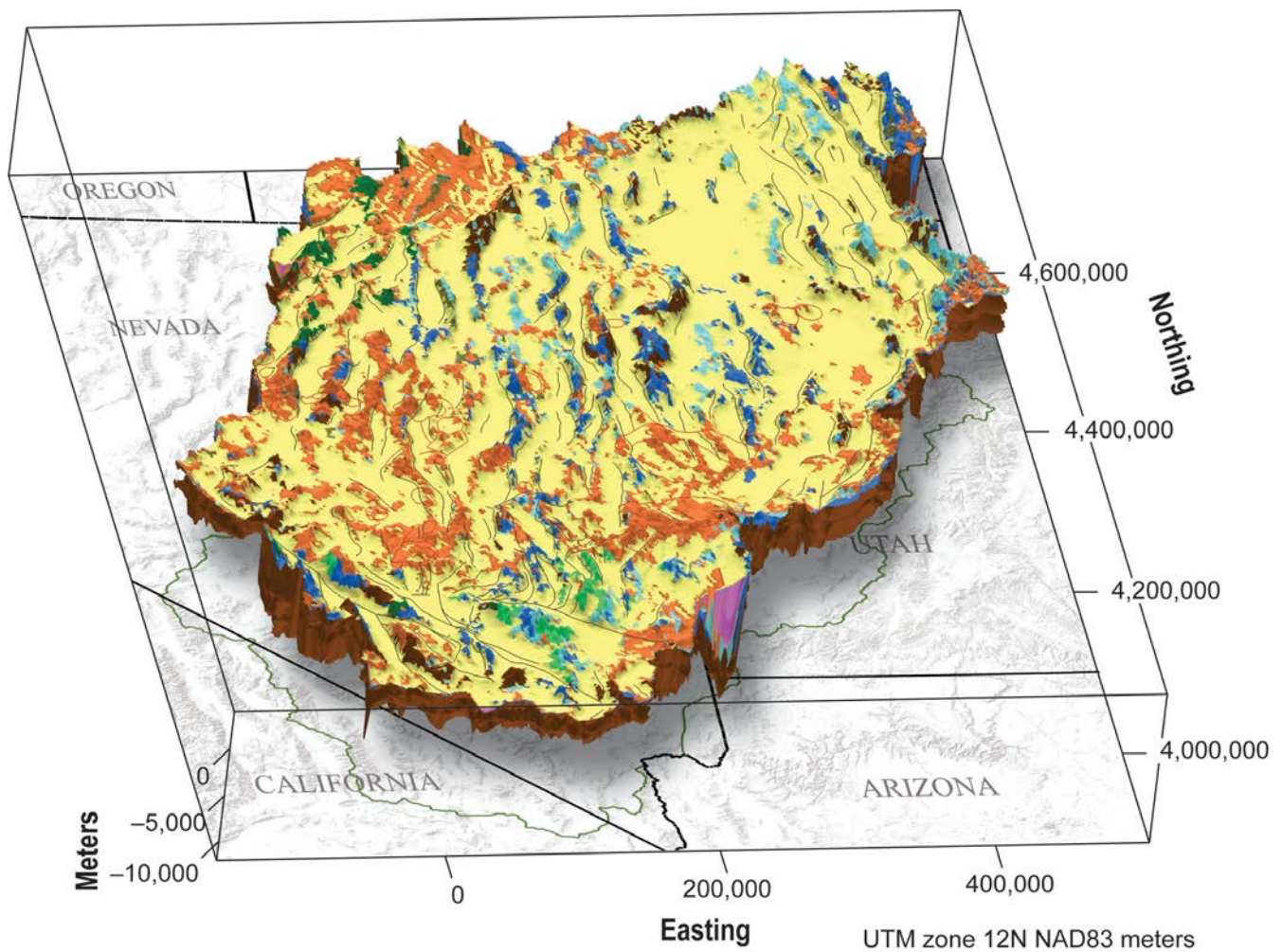
The 3D geologic framework was the primary geologic input into a steady-state numerical groundwater flow model of the aquifer system (Brooks et al. 2014). Explicit incorporation of a detailed three-dimensional hydrogeologic framework into the numerical simulation allowed evaluation and calibration of complex hydrogeologic and hydrologic elements, incorporated a conceptual understanding of an interconnected groundwater system throughout the region, and allowed an evaluation of inter-basin bedrock hydraulic connectivity and regional groundwater flow directions.

## **Case study 3: 3D models for seismic hazard analysis, from local to National scale**

Starting in 2007, the USGS developed a 3D fault framework model of the San Francisco Bay area, California (Figure 4) as a part of the larger effort to develop a statewide fault model as a primary data set for the Uniform California Earthquake Rupture Forecast, version 3 (UCERF3; Field et al. 2014), which "...provides authoritative estimates of the magnitude, location, and time-averaged frequency of potentially damaging earthquakes in California." UCERF3 is used widely in California for seismic hazard analyses, including by the California Earthquake Authority in setting insurance rates to reflect localized actual risk.

The San Francisco Bay Area 3D fault model was built using the following steps:

- 1) The regionally most important faults were selected, and their traces were simplified from geologic maps of the region (Graymer et al. 2006a; 2006b).



EXPLANATION	
<span style="display:inline-block; width:15px; height:15px; background-color:yellow;"></span>	Upper Cenozoic basin-fill aquifer unit
<span style="display:inline-block; width:15px; height:15px; background-color:purple;"></span>	Lower Cenozoic basin-fill aquifer unit
<span style="display:inline-block; width:15px; height:15px; background-color:orange;"></span>	Volcanic unit
<span style="display:inline-block; width:15px; height:15px; background-color:green;"></span>	Thrusted carbonate aquifer unit
<span style="display:inline-block; width:15px; height:15px; background-color:darkgreen;"></span>	Thrusted siliciclastic confining unit
<span style="display:inline-block; width:15px; height:15px; background-color:lightblue;"></span>	Upper Paleozoic carbonate aquifer unit
<span style="display:inline-block; width:15px; height:15px; background-color:olive;"></span>	Middle Paleozoic siliciclastic confining unit
<span style="display:inline-block; width:15px; height:15px; background-color:blue;"></span>	Lower Paleozoic carbonate aquifer unit
<span style="display:inline-block; width:15px; height:15px; background-color:brown;"></span>	Proterozoic siliciclastic confining unit
<span style="display:inline-block; width:15px; height:15px; border:1px solid black;"></span>	Caldera complex
<span style="display:inline-block; width:15px; height:15px; border-bottom:1px solid black;"></span>	Major fault

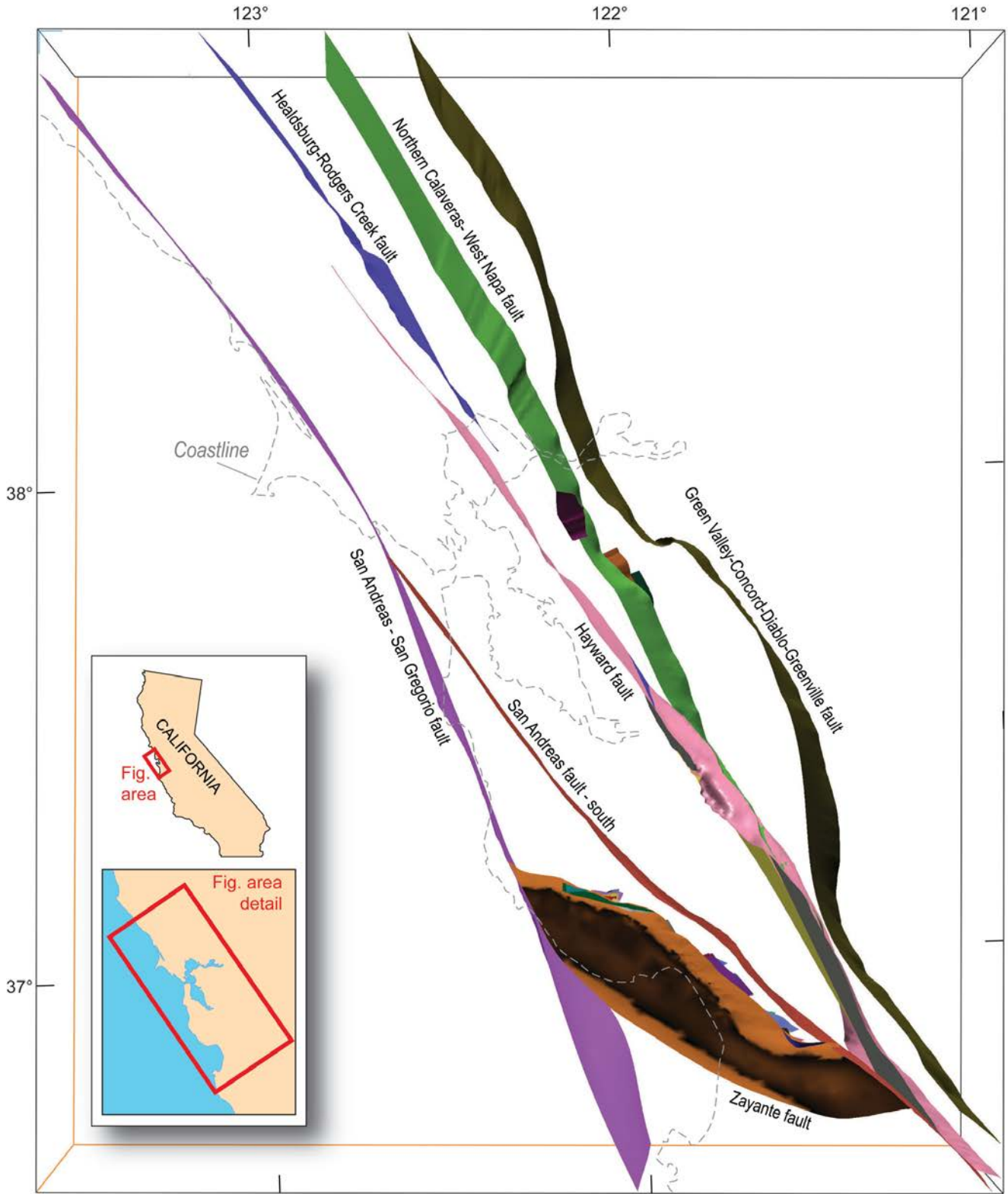
**Figure 3.** Perspective view of the upper surface of the 3D geologic framework model for the Great Basin carbonate and alluvial aquifer system (from Heilweil and Brooks, 2011). The colored units are nine hydrogeologic units that are stacked in 3D space.

- 2) Surface traces were projected onto a digital elevation model (Figure 4).
- 3) Subsurface projection of faults was constrained by, in order of preference: (a) double-difference

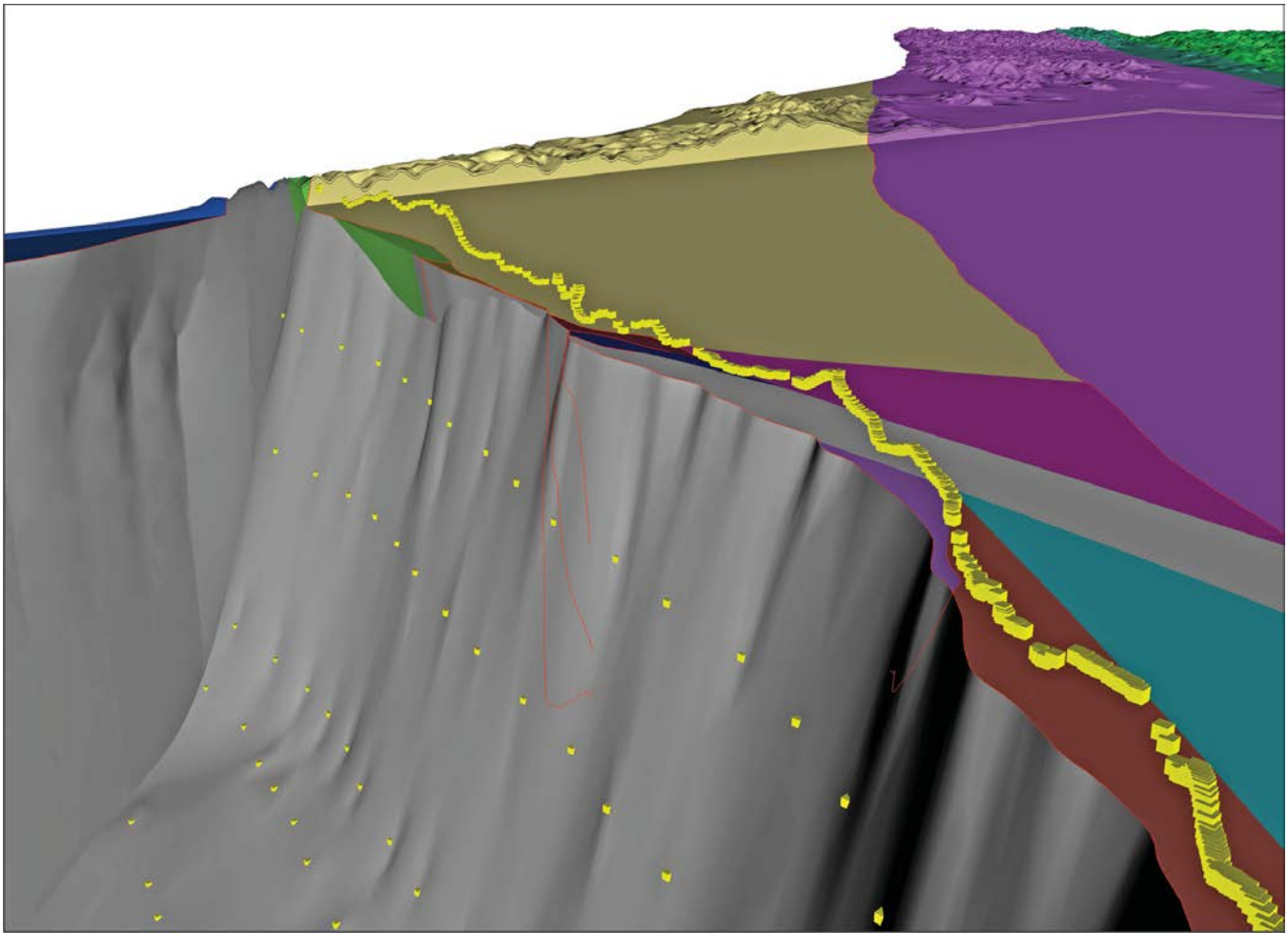
relocated hypocenters; (b) gravity and aeromagnetic data; (c) fault dip as reflected by the effect of topography on the fault trace; and (d) generic fault dip assigned based on relative fault offset (e.g.

pure strike-slip, vertical; pure reverse slip, 60° dip; oblique reverse slip, 75° dip).

These data sets and interpretations were converted into a suite of 3D points reflecting the surface trace and



**Figure 4.** View from above of the San Francisco Bay region 3D fault framework. Various colors represent individual modelled fault planes, of which only the major faults are labeled.



**Figure 5.** Perspective view from the southwest of a cutaway block model showing the 3D data points (yellow cubes) associated with the Zayante fault. The regularly spaced points are from structure contour data, the closely spaced points in the undulating trend represent the surface trace projected onto the Earth's surface, represented by a digital elevation model.

structure contours at depth (Figure 5). The 3D fault surface was generated using a least tension algorithm to fit the fault to the 3D points. A spatial hierarchy was defined to allow the various faults to be combined into a fault framework model.

A 3D fault framework is important to earthquake studies in a number of ways. In general, the 3D geometry of a fault network affects how the faults slip as a result of the regional tectonic stress, and thus the 3D geometry is incorporated into source characterization as well as geodetic models of slip rates. The 3D fault framework in the San Francisco Bay region also reveals faults without apparent surface connection that are directly connected in

the subsurface, and therefore can accommodate longer fault ruptures and potentially larger earthquakes.

Seismic hazard assessments also depend on an accurate prediction of earthquake ground shaking, which in turn depends on knowledge of three-dimensional variations in density, seismic velocity, and attenuation. Examples from the San Bernardino basin in southern California (Graves and Wald, 2004) and the Santa Rosa plain in the northern San Francisco Bay area (McPhee et al. 2007) highlight the importance of 3D basin geometry in producing damaging ground motions. Local to regional 3D geologic models have been constructed as the foundation to seismic velocity models

and numerical earthquake simulations (Aagaard et al, 2010; Stephenson et al, 2017). Nationally, the USGS is building a crustal-scale model that includes development of a multi-layered 3D geologic framework model, application of a physical theoretical foundation to couple geology and geophysical parameters and use of measured geophysical data for calibration (Boyd and Shah, 2018). The framework model is intended to be internally consistent and seamless on a national scale, defined on a 1-km grid, and integrate results of previous studies including maps of surficial porosity, surface and subsurface lithology (Horton et al. 2017), and the depths to bedrock (Shah and Boyd,

2018), crystalline basement or seismic equivalent, lower crust, and Moho.

A calibrated national crustal model can be used to assess and apply parameters currently used to predict earthquake ground motions including shear-wave velocity parameters that roughly correlate to the depths to bedrock and basement (Shah and Boyd, 2018). The model could also be used to develop new parameters with greater predictive power that can be applied in national seismic hazard assessments (Petersen et al. 2015).

## Current Challenges

Current challenges are in part related to the broad overall mission of the USGS and the focused nature of individual Mission Areas within the organization, which lead to decentralized 3D modelling activities. Pockets of 3D modelling expertise develop on a project-by-project basis, but there may not be enough knowledge transfer between projects. Across the USGS individual researchers and teams acquire 3D technologies with little to no knowledge or bureau-level coordination of other similar efforts. Although projects and Mission Areas add 3D applications as analysis tools, there are few forums for sharing ideas, data, products, and knowledge of emerging technologies. Although cost efficiencies could perhaps be realized using a standardized, organization-wide modelling platform, the use of multiple software platforms in general supports the diverse needs of the Mission Areas and, in and of itself, is not a major challenge. The bigger challenge is in developing datasets that are accessible, transferrable and importable into multiple software platforms.

At the National level, no Bureau-level guidance or infrastructure supports the following: (1) development of regional or National-scale drill-hole databases in a standard format; (2) development of national databases of gravity, magnetic, or seismic observa-

tions that could support framework model development; (3) guidance on database standards for 3D data; (4) guidance on archiving procedures for developed 3D models; and (5) National-scale efforts to catalog and maintain already-developed 3D framework models, beyond releasing models in publications.

## Lessons Learned

The USGS ScienceBase repository (<https://www.sciencebase.gov/catalog/>) is being used as a catalog and data store to track projects and their deliverables including publications, models, and datasets. Many of the model and data outcomes of focus area and topical studies are available directly from ScienceBase, whereas reports and data stored elsewhere are available through links cataloged in ScienceBase.

## Next Steps

The continued need for national-scale research and assessment of energy, minerals, geologic hazards, and water resources will continue to drive the development of 3D geologic framework models and their link to numerical process models. Energy resource assessments will continue to develop capabilities to understand basin stratigraphic, structural, and thermal development and use developed frameworks as part of hydrocarbon maturation and stratigraphic backstripping analyses as part of basin-scale petroleum assessments. In the Minerals realm, recent emphasis on availability of critical minerals for the Nation requires the evaluation of undiscovered resources, particularly beneath Quaternary and Phanerozoic cover. Such evaluations rely on the use of geophysical methods, both to map subsurface features in 3D and to forward-model geophysical anomalies in terms of geology. In the Water Mission Area, numerical groundwater models will continue to increase in sophistication as software platforms and computing power evolve, allow-

ing for the inclusion of increasingly complex 3D geologic frameworks in regional and local-scale numerical models of hydrologic processes. Development of 3D geologic frameworks will increasingly become needed at the energy-water nexus, both as a means of evaluating potential interactions between aquifer systems and shallow producing regions of oil and gas fields, and to evaluate possible interaction between groundwater aquifers and injection of fracking liquids and produced waters. Societal pressure for accurate and precise hazard and risk assessment in populated areas will continue to demand higher-resolution 3D framework models and closer integration with physical properties modelling.

The National Cooperative Geologic Mapping Program has recently updated its strategic vision to focus on the accelerated development of regional-scale geologic maps and the development of 3D geologic frameworks. To this end, the Program has started several new projects that are regional in scope and explicitly include 3D frameworks, for example, a planned regional mapping transect in the US Southwest and merging of multiple 3D models in central and northern California. Knowledge gained from these projects will inform strategies for resolving current challenges as various USGS science centers look to this Program and the Core System Science mission area for continued guidance.

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# Chapter 27: Communicating 3D Geology to Stakeholders

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## Introduction

Multi-dimensional geological models are widely used to provide decision support for multi-disciplinary geoscience investigations. The way that people are searching for geoscience information is changing rapidly, in large part due to advances in the computational power of IT hardware, the increased functionality of software, and the increased storage capacity and functionality of mobile devices. The majority of geological survey organizations (GSOs) that contributed to this synopsis indicated that improving and increasing the accessibility and communication of their 3D science to stakeholders is a near-term objective.

The Swiss Federal Office of Topography has indicated that approximately 80% of political decisions are related to spatial data (Baumberger, 2015). Therefore, it is incredibly important that the geoscience organizations responsible for analyzing and producing products and making predictions using geospatial data to support decision making are in a format that stakeholders can easily interpret and understand (Government Office for Science, 2018). Many GSOs referred to the value and effectiveness of using 3D geological models for communicating complex geological information to stakeholders with varying levels of background knowledge (Alberta, UK, Illinois). Current models are both consuming and producing

more data than ever before, and ensuring that this information is effectively communicated (including model uncertainty) to stakeholders has become increasingly more important. Recent technological developments have significantly increased the options available to communicate 3D geoscience information to stakeholders. This includes 3D web viewers, 3D printers, virtual reality (VR), augmented reality (AR), and the ability to modify gaming platforms to incorporate and represent real geological information (e.g., Minecraft, Unity).

## 3D Web Viewers and Data Accessibility

Many GSOs that contributed to this synopsis indicated that they are using 3D web-viewers to allow stakeholders to visualize their 3D models and data, and the majority of those mentioned that they are currently working to increase the functionality of their web-viewers. Currently, the web-viewers offered by most GSOs are able to allow users to rotate, zoom in and out, and turn layers on and off. However, the more advanced viewers allow users to slice through the models, create virtual boreholes, and import external data to be visualized within the 3D model (Alberta, Netherland, Poland, Switzerland, UK).

Some surveys allow stakeholders to not only visualize the models online, but also allow the users to download

the models, grids, and data online, which allows the web-viewer to also serve as an online data catalogue and dissemination platform.

Many GSOs indicated that the majority of their users are using the models to support learning and/or decision-making, and are not looking to download the models or grids. However, a number of them indicated that their models are built specifically for technical clients (for commercial use; Denmark, Netherlands, UK), and/or their models are used by technical stakeholders to support scientific investigations (Germany, Illinois, Poland, Saskatchewan). Thus, many GSOs are looking for open-access online tools that will allow users to query the models and download model data. This has also increased the need for the development and adoption of 3D model standards to ensure consistency and common understanding with regard to the information and models that are being shared. This especially is the case considering that many countries are working collaboratively to build seamless cross-border models (Bavaria, Germany, Netherlands, Poland, UK).

The British Geological Survey has been leveraging the use of 3D PDFs to allow users to download and interact with a number of their 3D geological models (British Geological Survey, 2019a). Although the functionality of 3D PDFs is limited to



zooming in and out of the model, rotating, and turning layers on and off, this is often sufficient to help non-technical users conceptualize the 3D form and geometry of the subsurface geological units within a free and easily accessible format.

## 3D Printing

GSOs have begun using 3D printers to produce physical reproductions of their 3D models (Alberta, Austria, Sweden) to allow stakeholders of all ages to interact and explore the models, and learn about the physical relationship of the geological units or geonities. The 3D prints can be constructed such that geological units can be printed individually, which allows stakeholders to take the model apart and rebuild to learn about the geological relationships and geometry of the subsurface (Figure 1A). A dual-extruder printer can be used to print with multiple filaments at one time, which can be helpful in representing integrated and intertwined relationships within the subsurface (Figure 1B).

Creating 3D prints is quite an easy and cost-effective method for engaging with stakeholders and sharing information about the subsurface. 3D printers are now widely accessible and can be purchased with a relatively large print-bed (12 inches) for as little as Can\$1000 (US\$700). The filament (plastic composite) that is

used to create the prints is very inexpensive especially if purchased in bulk. For example the 3D print shown in Figure 1A requires approximately US\$22 worth of filament.

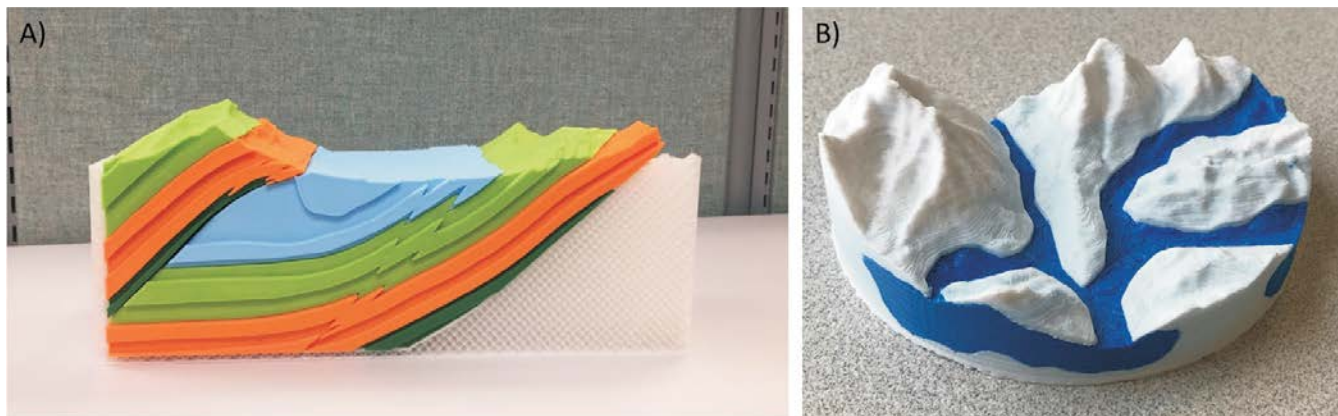
Other examples of physical 3D models that have been created by GSOs include models engraved by lasers into glass blocks (Austria), and cross-sections built using Lego blocks (UK).

## Serious Gaming

Providing extended communication and educational outreach is an objective of many GSOs. A continual challenge is to engage the public beyond the technical client. Conversion of 3D geological models into gaming platform formats with tangible geological scenarios provides an enormous opportunity to engage with a large audience. Minecraft is a software game distributed by Microsoft, that allows users to explore and interact with a surface and subsurface environment constructed entirely of cubes. The game has been incredibly popular with over 91 million users globally every month (Business Insider, 2018). It is a tremendous opportunity to leverage the popular platform to allow users to explore digital representations of the actual geology, environmental conditions, and resources of specific areas. Minecraft models can provide geoscientific information within a gaming platform. It allows

people to explore and learn about a region's geology and natural resources in a fun and interactive way. The typical Minecraft worlds that users explore are created using random geology and environmental conditions. Although it would appear that the majority of Minecraft users are children, the average age of people playing Minecraft is 24 years old (Xbox, 2018).

The British Geological Survey has created a number of Minecraft worlds that users can explore to learn about local geology, and has a high resolution model that incorporates buildings and roads on top of their model (British Geological Survey, 2019b). The German Federal Institute for Geosciences and Natural Resources is in the process of collaborating with the British Geological Survey to transfer some of their 3D models into Minecraft for stakeholders to explore (Germany). The Alberta Geological Survey has created Minecraft models that are available on their website and showcased as exhibits in science centers throughout the province (Alberta Geological Survey, 2019). The Minecraft models have been designed to allow users to explore the subsurface geology and resources, and is also using the models as educational tools to teach people about geological concepts such as erosion, unconformities, and the nature and distribution of select resources (Alberta).



**Figure 1. A)** 3D model representing complex faulted terrain, **B)** 3D model printed using a dual extruder printer which allows two colours of filament to be used at the same time.

## Virtual Reality, Augmented Reality, and 360-Videos

Many GSOs are experimenting with the application of emerging technologies to help engage stakeholders and facilitate communication and transfer of geoscience information. This section will discuss the use of 360-videos, virtual reality (VR), and augmented reality (AR) applications at GSOs.

**360-videos:** The difference between a 360-video and a regular video is that the users are able to control what they look at with a 360-degree range of motion. These videos have been used by GSOs to take users on a tour of a model (Alberta, Canada). 360-videos can be created from real environments with a 360-degree camera, or can be created for digital environments (i.e., through a model) using a variety of available software. When ready, the 360-videos can be posted on YouTube (via a link from the GSOs website) for easy access to users, which provides the necessary program to view 360-videos free of charge.

**Virtual reality:** Virtual reality (VR) is a fully immersive 3D experience projected within a headset. The use of VR applications can be done using a) a phone and an inexpensive headset (i.e., google cardboard - US\$2/pair), or b) using a computer or laptop with a powerful graphics card, and a VR

headset (Figure 2). The Alberta Geological Survey has created VR applications that allow users to interactively explore and take tours through their Minecraft models, which are used to engage a diverse range of stakeholders (Alberta Geological Survey, 2019).

**Augmented reality:** Augmented reality (AR) supports 3D projection, commonly using a headset; however, in contrast to virtual reality, AR allows the user to continue to see the local setting that is surrounding them. The AR and mixed-reality applications are steadily gaining in popularity as they allow users to interact and explore geoscience information within their current environment. AR applications can be accessed using a) an AR headset (i.e., Hololens), which can be quite pricey, or b) using an AR application that is easily downloaded on any mobile device or computer with a camera (Figure 3). GSOs that are developing AR applications to communicate their information are typically building applications that can be used on a mobile device to ensure that the applications are accessible to the greatest number of users. Augmented reality applications can be used to share information with stakeholders by georeferencing 3D geological models so users can visualize and interact with the geological units from the model wherever they are, and by visualizing spatially-defined, georeferenced objects (i.e., pipelines,

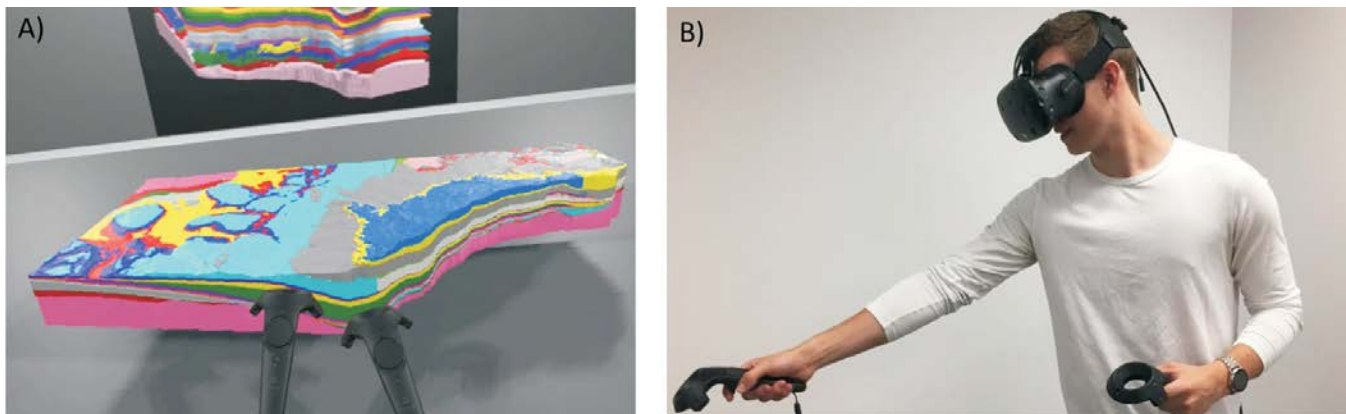
aquifers, etc.) within the immediate area. An AR app provides the effect of allowing users to have x-ray vision into the subsurface.

## Uncertainty

With an increasing number of decisions being made using 3D geological models, decision makers and stakeholders are now more accepting that these models are simply versions of reality that contain a certain amount of error and uncertainty (Government Office for Science, 2018). More important has been the recognition that error and uncertainty are not bad, and should be quantified and understood rather than ignored (Canada, Germany). Many GSOs mentioned that they are currently sharing information with stakeholders on model uncertainty (Alberta, Denmark, Netherlands, New Zealand), although most of these groups mentioned that they are still working on methods to improve communication of model uncertainty.

## Summary

Communication of 3D geological models used to be limited to a technical audience capable of using either modelling or 3D visualization software. In the last ten years, four important communication opportunities have emerged: 1) web delivery using browser plug-ins, 2) 3D printing of models, 3) model conversion to gam-



**Figure 2. A)** Image of 3D geological model within a virtual reality environment, **B)** user wearing a virtual reality headset and interacting with the 3D model using the hand controls.



**Figure 3.** Person using an augmented reality application on a mobile device that is designed to produce a 3D representation of Alberta's bedrock geology when it recognizes the 2D bedrock geology map.

ing platforms, and 4) virtual and augmented reality. Each approach provides opportunities to expand and broaden the communication opportunities and experience of users. The opportunities to greatly increase the communication of geological concepts and knowledge to the public will increase the broader geoscience knowledge from children to adults. This GSO activity will hopefully increase the level of public awareness of geoscience and engagement by the public.

A well-built geomodel may cost a million dollars, but producing a model that stakeholders actually understand and can use, is priceless!

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# Chapter 28: Global 3D Mapping and Modelling Coordination Initiatives

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Kessler, H., Turner, K., Berg, R.C., and Russell, H.A.J. 2019. Global 3D mapping and modelling coordination initiatives; Chapter 28 in 2019 Synopsis of Current Three-Dimensional Geological Mapping and Modelling in Geological Survey Organizations, K.E. MacCormack, R.C. Berg, H. Kessler, H.A.J. Russell, and L.H. Thorleifson (ed.), Alberta Energy Regulator / Alberta Geological Survey, AER/AGS Special Report 112, p. 294–301.

## Introduction

The focus of this Synopsis is on the activities and methodologies of geological survey organisations within their jurisdictions. As described in Part 2 of this volume, the approaches and outputs vary in each GSO for multiple reasons including political and economical drivers, geological survey evolution, their place in government, complexity of the geological environment, and availability and type of baseline data. This chapter presents initiatives that cross boundaries. Despite their justified inward looking focus, GSOs and their staff have been working across boundaries for several decades often in conjunction with staff from academic and professional associations. This chapter aims to give an inventory of these projects and initiatives to demonstrate that science and geology does not stop at political and continental boundaries and that honest knowledge exchange is crucial to advance our understanding of our planet and the processes acting within and upon it.

International projects and initiatives fall into three broad categories:

- Advancement of science and technology through knowledge exchange and research projects
- Solving a particular cross-border scientific, resource, or regulatory issue

- Development of regional or international standards and best practice

## Advancement of Science and Technology

In the late 1980s, the Deutsche Forschungsgemeinschaft (German Research Foundation) sponsored an extensive research program entitled “Digital Geoscientific Mapping” (Vinken, 1986) which involved many German research teams and supported two International Colloquia – the first at Dinkelsbühl in 1985 (Vinken, 1988), and the second at Würzburg in 1986 (Vinken, 1992). These colloquia included participants from the USA, the UK, and several western European countries, but the knowledge of this project was not widespread. After recognizing that much 3D modelling research was being undertaken in parallel by small groups without the benefit of any forum for exchanging ideas, Raper (1989) published a small collection of 3D modelling topics that had been presented in 1988 at multiple North American and European conferences.

The first international conference devoted to applications of 3D geological modelling was held at Santa Barbara, California on 10-15 December 1989 (Turner, 1991). The NATO Science Committee and the USGS financially

supported this conference; it also received significant logistical support from software and hardware suppliers and from the National Center for Geographical Information Analysis located at the University of California at Santa Barbara. About 60 participants representing the majority of the NATO countries attended.

The Santa Barbara conference initiated a long history of successful cooperation amongst geologists and technologists to advance methodologies related to geological mapping and modelling. Several participants modified the focus of their planned October 1990 conference in Freiburg, Germany to emphasize geological modelling topics (Pflug and Harbaugh, 1992). This became the first venue to further explore 3D research and technical advances. The European Science Foundation agreed to sponsor a series of three workshops; these were held in Italy in 1992, the UK in 1996, and The Netherlands in 1997. Each workshop focused on different aspects of a common modelling theme (European Science Foundation, 1992, 1996, 1997). While they served as valuable sources of communication among members of the geological modelling community, there were no published records of their deliberations.

By the mid-1990s, the role of 3D models as a part of groundwater resource modelling became an important research topic. The International Commission on Groundwater of the International Association of Hydrological Sciences (IAHS), with support from the United Nations Educational, Scientific and Cultural Organization (UNESCO) organized two international conferences held in Vienna, Austria. Proceedings for both these conferences were subsequently published (Kovar and. Nachtnebel, 1993, 1996).

In 2001, the European Science Foundation agreed to sponsor one additional workshop which addressed the importance of modelling the shallow subsurface for developing subsurface infrastructure and environmental assessment (European Science Foundation, 2001). The proceedings of this workshop were formally published (Rosenbaum and Turner, 2003).

Dedicated workshops and sessions on 3D geological modelling are part of three prominent international geoscience conferences 1) Geological Society of America annual meetings ([https://www.geosociety.org/GSA/Events/Future\\_Annual\\_Meetings/GSA/Events/Annual\\_Meeting.aspx](https://www.geosociety.org/GSA/Events/Future_Annual_Meetings/GSA/Events/Annual_Meeting.aspx)), 2) annual European Geoscience Union meetings (<https://www.egu.eu/meetings/>) and, 3) annual American Geophysical Union meetings (<https://meetings.agu.org/>).

The latter two have a slightly more academic focus, whereas the GSA meetings offer more opportunities on applied aspects of geology and therefore are the usual home of Three-Dimensional Geological Mapping Workshops (<http://isgs.illinois.edu/three-dimensional-geological-mapping>). Since 2001, North American and European geologists have attended, on a biennial schedule, this series of special workshops (a total of 10) which provide a unique international forum for exchange of best practices and innovation of 3D geo-

logical modelling methodologies and applications. The Illinois State Geological Survey maintains an online resource for all of the presentations at these workshops (<https://www.isgs.illinois.edu/three-dimensional-geological-mapping>). These workshops allow the 3D community to present and exchange ideas. This has not only assured the continued improvement of processes in the individual GSOs, but also has led to countless bi-lateral research projects and ultimately to the publication of this Synopsis and its previous version (Berg et al., 2011).

In 2011, a group of European participants at the Geological Society of America meeting in Minneapolis (<http://www.geosociety.org/>) decided to establish an equivalent European 3D geological modelling community to help coordinate and exchange information among the geological surveys of Europe. Its mission is to “exchange progress, problems and solutions in our common quest to understand and communicate the 3D composition and properties of the subsurface to support science-based decision making”. Meetings have been held at Utrecht in 2013, Edinburgh in 2014, Wiesbaden in 2016, Orléans in 2018, and Bern in 2019. A website contains the presentations, abstracts, and some images from those meetings (<http://www.3dgeology.org/>).

Together the members of these groups make up a highly innovative, collabo-



rative, technically diverse, strategic, and inspiring group of geoscientists from around the world working together and motivating each other to push the boundaries of multi-dimensional geospatial modelling (K. MacCormack, pers. comm., 2019).

## Cross-Border Cooperation to Solve a Particular Resource, Regulatory or Geoscience Question

In the 2011 Synopsis there were numerous mentions that cross-border collaborative 3D modelling projects would be beneficial. As of 2019 many of these projects that were at the concept phase in 2011 have been successfully completed, are proving to have a positive impact, and are positively resonating

One of the first cross-border initiatives, with a particular focus on the need to understand the Quaternary deposits for groundwater management is the **Central Great Lakes Geologic Mapping Coalition** (Berg et al., 2016). It was formed in the late 1990s by the state geological surveys of Illinois, Indiana, Michigan, and Ohio and the U.S. Geological Survey. In 2008, the Coalition expanded to include four additional states bordering the Great Lakes (Minnesota, New York, Pennsylvania, and Wisconsin), and it changed its name to the Great Lakes Geologic Mapping Coalition. It expanded again in 2012 by adding the Ontario Geological Survey. These eight U.S. states and one Canadian province have similar geologic conditions and common societal issues about land and water resources, the environment, and geologic hazards that required immediate attention with a focus on 3D mapping and modelling. By integrating their expertise and resources, geological surveys are addressing these issues more effectively than could any one agency. The Great Lakes Geological Mapping Co-

alition was a seed corn for the establishment of the Three-Dimensional Geological Mapping Workshops mentioned above.

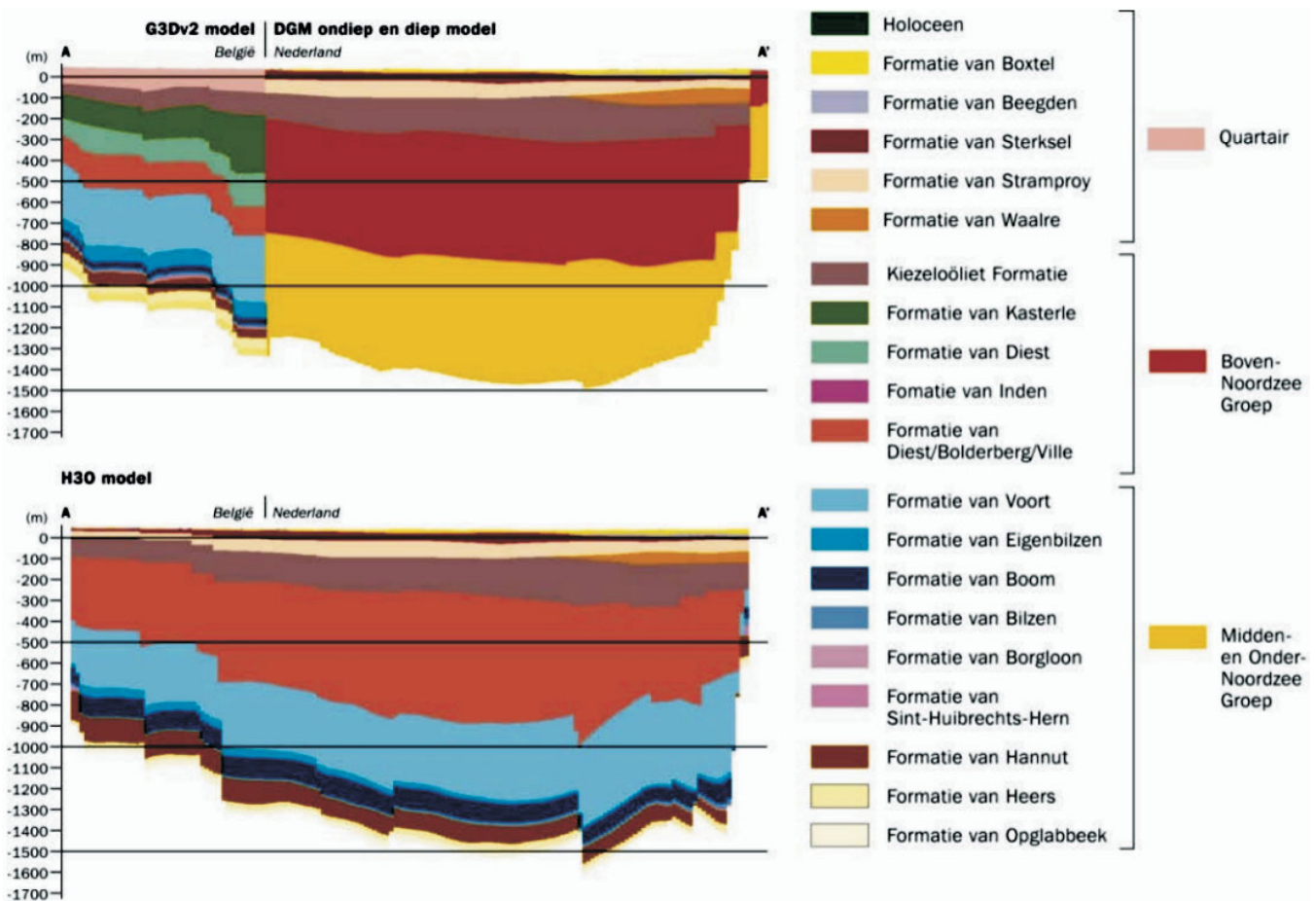
The Geological Survey of Canada (GSC) has developed a national 3D mapping initiative in collaboration with provincial and territorial surveys through the National Geological Surveys Committee (NGSC). The national committee provides guidance and coordination between the 10 provincial and three territorial geological surveys and the GSC. A recent project initiated by the GSC called **Canada-3D** aims to develop a 3D geological model and associated knowledge-base for the approximately 17,000,000 km<sup>2</sup> of the Canadian onshore and offshore subsurface. It is anticipated that Canada-3D will become the authoritative state of knowledge for the geology of

Canada at a national scale. It is a response to shifting scientific methods and emerging opportunities that favour digital techniques, as well as a response to the demands of a Canadian government open data strategy as well as global open data concerns. Canada-3D is also developing collaborative trans-boundary initiatives with the United States to provide as seamless coverage as possible between the two nations along their common very lengthy border. Such rationalization and synchronization already have been initiated through a variety of project scale initiatives, in part to support groundwater and surface water management of transboundary aquifers (Canada). Initial national scale modelling is focused on a three-layer model of the surficial, bedrock, and mantle layers along with

consolidation of surface bedrock and surficial geological mapping.

Several initiatives in Europe are worth highlighting as they show how the beginnings of a promising collaborative work-driven initiative that is directed by user needs and requirements.

Various stakeholders in the Netherlands, Flanders (northern Belgium), and north-west Germany expressed the need to harmonize the (hydro) geological models in the shared border region. Accordingly, the **H3O project** was initiated in March 2012 with the aim to produce cross-border, up-to-date, three-dimensional geological and hydrogeological models of Cenozoic deposits. Details are published by Heyvaert et al. (2016) and Vernes et al. (2016). Figure 1 shows



**Figure 1.** Cross-border section showing geological edge matches that were corrected during the H30 project from Vernes, R. et al., 2016.

the geological edge match issue at the border and the resulting harmonised model. Similar transboundary stratigraphic reconciliations between Alberta (Canada) and Montana (USA) have supported numerical groundwater modelling and an improved understanding of transboundary aquifers and it has supported water resource management.

**Project GEORG** was co-financed by the European Union European Regional Development Fund. It developed a cross-border geological and geo-thermal model of the Upper Rhine Graben, which has a high potential for geothermal energy exploitation. The data and model are delivered in a web-based viewer (Figure 2).

The **Geomol project** ([http://www.geomol.eu/home/index\\_html](http://www.geomol.eu/home/index_html)) was established to assess the subsurface potential of the Alpine Foreland Basins for sustainable planning and use of natural resources, in particular geothermal energy. The results of the initiative are not only an openly accessible 3D geological model of the northern and southern Molasse Basins, but the collaboration has led to significant progress on the harmonisation of differing stratigraphic frameworks and an improved capability and development of standards for the interpretation and modelling of geological horizons from historic seismic data (GeoMol Team, 2015).

A generalised tectonic crustal-scale model has been developed for the **British Isles** (Ireland, Northern Ire-



land, Scotland, England and Wales). This conceptual model comprises cross-sections down to 15 km depth and major fault surfaces (see Figure 3). It was developed through collaboration between the Geological Survey of Northern Ireland (GSNI), the Geological Survey of Ireland (GSI) and the British Geological Survey (BGS)

Early pan-European initiatives resulting in 3D data were the **Millennium Basin Atlas** and the **Southern Permian Basin Atlas (SPBA)** These were developed to present a comprehensive and

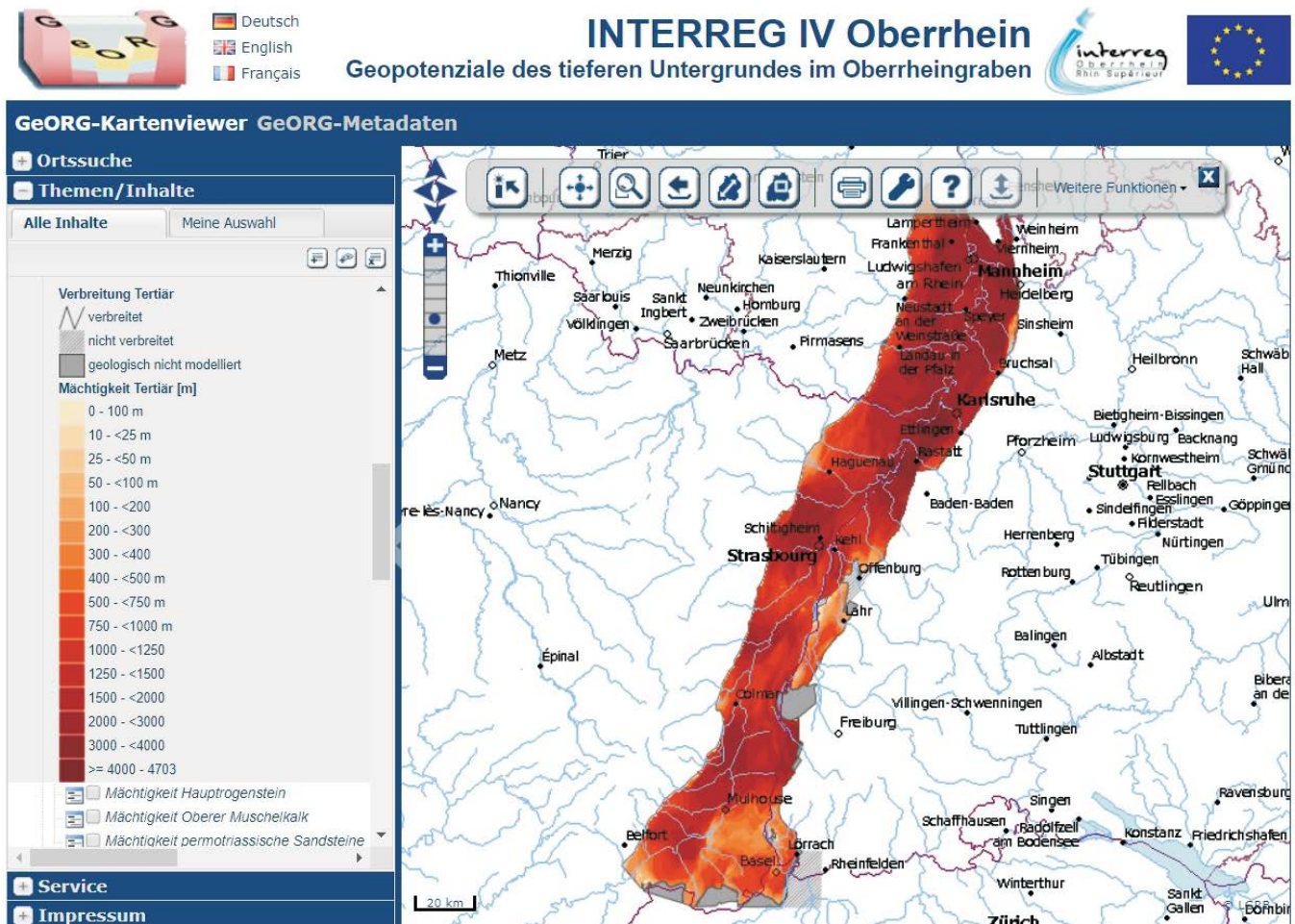
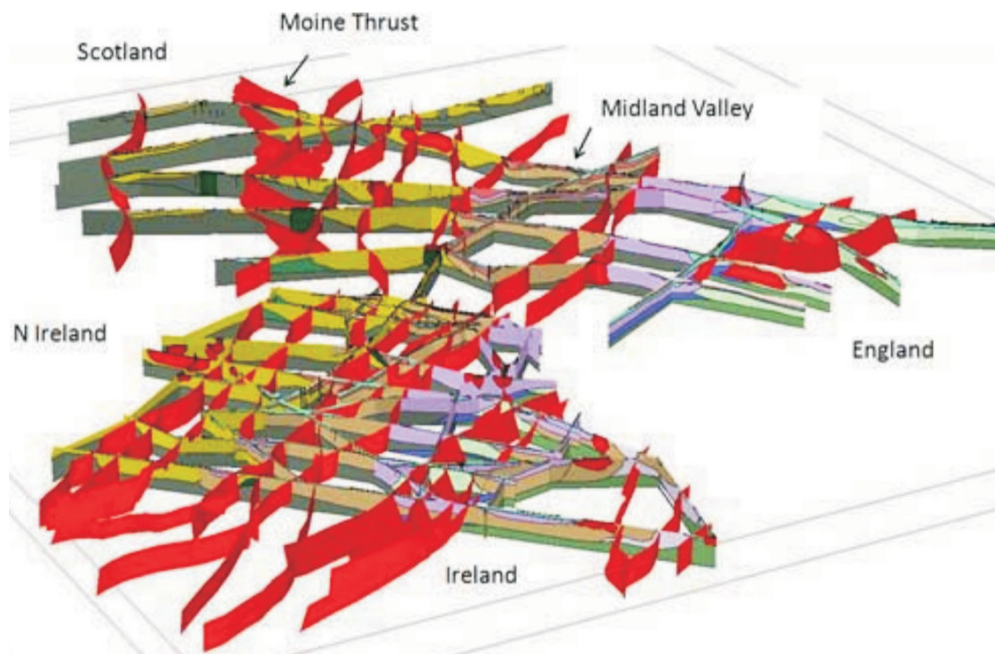


Figure 2. GEORG web viewer (<http://www.geopotenziale.org/geopotenziale/geothermal?lang=2>).



**Figure 3.** Crustal-scale model of Caledonian tectonic terranes bounded by major faults viewed from the south-west (from <https://www.bgs.ac.uk/research/ukgeology/nationalGeologicalModel/home.html>).

systematic overview of the results of over 150 years of petroleum exploration and research in the North Sea and Southern Permian Basin area and to stimulate the petroleum exploration and production industry to continue their activities in this mature basin. The initiatives were funded by the Geological Surveys of the United Kingdom, Norway, Belgium, Denmark, the Netherlands, Germany, and Poland (<https://www.tno.nl/en/focus-areas/ecn-part-of-tno/roadmaps/geological-survey-of-the-netherlands/geological-survey-of-the-netherlands/petroleum-geological-atlas-of-the-southern-permian-basin/>).

In addition, several cross-border projects are ongoing across national borders to understand groundwater resources, geothermal energy potential and ground conditions for tunnelling between Germany, Poland, and the Czech Republic (Krentz and Zander, 2016). Figure 4 shows their extent.

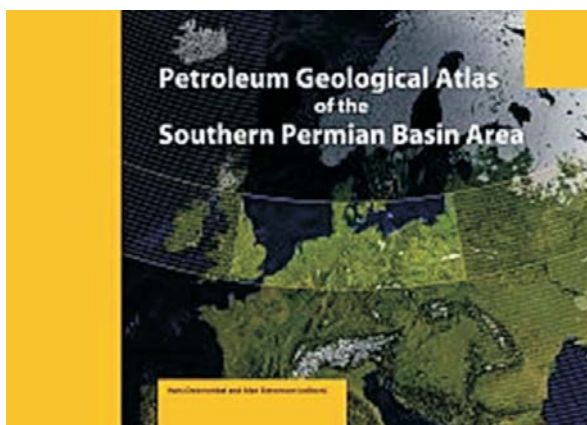
### International Initiatives to Set Best Practice and Standards

One of the most prolific and influential global projects is the OneGeology initiative (<http://www.onegeology.org/>) which was initiated in the mid 2000s

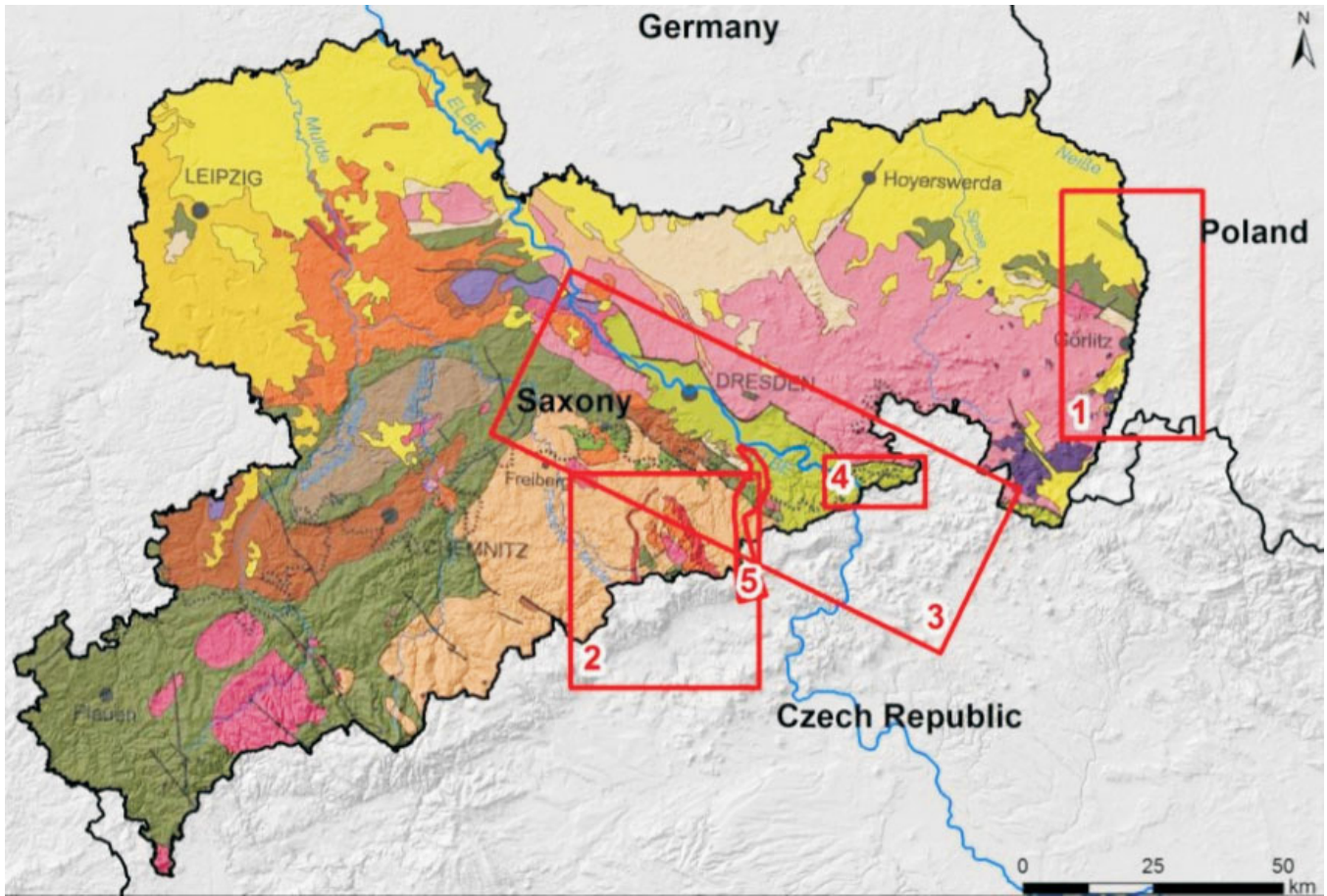
to deliver the world's geological data in a seamless, interoperable, and interactive manner via the OneGeology portal. In recent years, the interest in



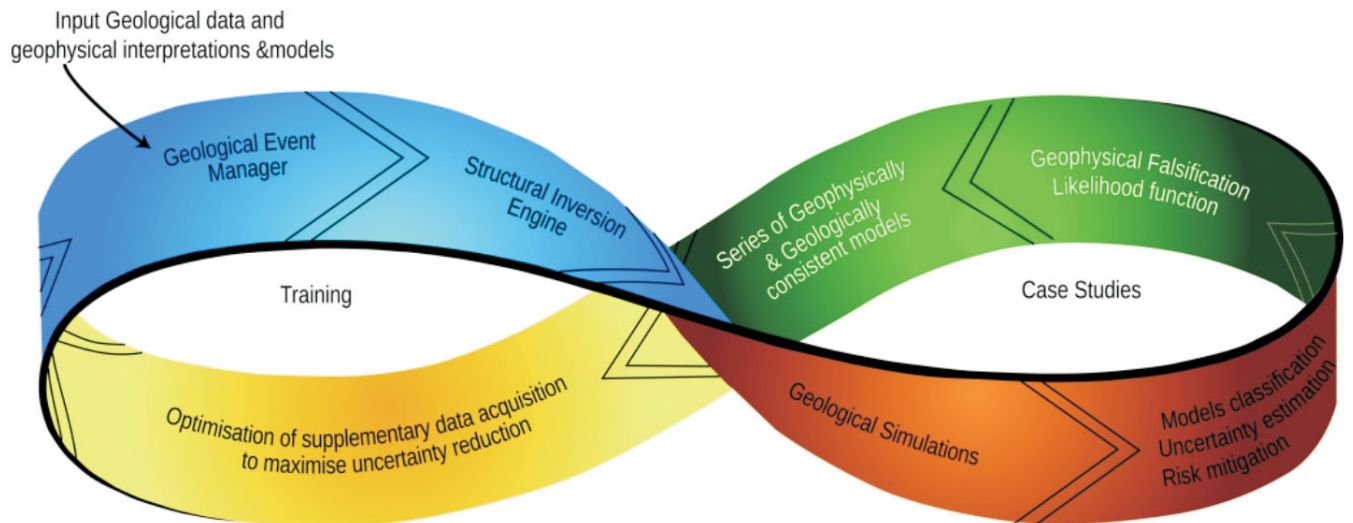
3D geology has grown and as a result, an Australian led initiative called “Loop - enabling 3D stochastic geological modelling” (Figure 5; <https://loop3d.org/>) has been established bringing a range of international GSOs and researchers together to develop open source modelling solutions to mitigate 3D geological risk in resources management. It aims to do so by integrating mathematical methods, structural geology concepts, and probabilistic programming to create new approaches to 3D geological modelling. The expected outcomes are an enhanced capability to model the subsurface, characterize model







**Figure 4.** Geological map of Saxony showing study areas of five transboundary projects: 1, Transgeotherm; 2, Caldera of Altenberg Teplice; 3, Elbe Zone; 4, GRACE; 5, NBS Dresden-Prag. (from: Krentz and Zander, 2016).



**Figure 5.** The concept behind the Loop project (from <https://loop3d.org/>).

uncertainty, and test multiple geological scenarios.

Sub-Urban (<http://sub-urban.squarespace.com/>) is a recently concluded 5-year pan-European project with a focus on improved modelling and management of the subsurface beneath cities. It was initiated by the British and Norwegian Geological Surveys, and funded by the European Union's COST action programme. Its final reports contain a large number of case studies from across Europe, as well as a series of recommendations and discussions on how to better integrate subsurface characterization into regional and city building planning, as well as for use by the construction industry.



The development of international standards for 3D geological model data and related in/outputs is still in its infancy. However, a Geoscience Domain Working Group has been established by the Open Geospatial Consortium which lists relevant initiatives and attempts to bring together various strands of standards development on its website (<https://www.opengeospatial.org/projects/groups/geosciencedwg>).



The European Union and EuroGeoSurveys (<http://www.eurogeosurveys.org>) are beginning to join forces in to establish a European Geological Data Infrastructure (EGDI) initiative to provide access to pan-European and national geological datasets including 3D geological models (more detail is given in Chapter 3). Early attempts are emerging through the GeoEra

3DGEO-EU project (<http://geoera.eu/projects/3dgeo-eu/>), where components of the Permian Atlas mentioned above are published on-line.



The Geological Surveys of Europe

## Conclusions

Geology and science in general does not recognise borders, and knowledge sharing and technology transfer is essential in order to avoid repeating mistakes, progressing our science, saving time and resources, and ultimately making better predictions about the subsurface so keenly needed for a range of societal challenges. The authors hope that, by the next edition of this Synopsis, the above initiatives have continued to flourish and we will be closer to a unified model and a more thorough understanding of the solid earth.

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# Chapter 29: Future of 3D Geological Mapping and Modelling at Geological Survey Organizations

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## Introduction

The “Next Steps” section contained within each of the 22 geological survey organization (GSO) submissions provided useful insights on directions and significant impacts of 3D geological modelling both in the short and long term. Highlighted is the positive global impact of these modelling projects and initiatives at multiple scales, the result of which will continue to prove essential for addressing a myriad of societal and research issues related to water and mineral resources, natural hazards and risk mitigation, the environment, and infrastructure development. Major emphasis of future work include (1) expanding the use and diversity of 3D geomodelling activities within GSOs, (2) improving data management strategies, (3) better understanding and improving work force and work flow issues, and (4) enhancing the dissemination of 3D models and associated data to users and stakeholders.

## Expansion of 3D Geomodelling Scales and Applications

An overarching theme of future plans by the GSOs emphasizes expansion

of 3D geomodelling activities within their jurisdictions, and this includes:

- 1) Infilling coverage gaps (enhancing regional coverage).
- 2) Shifting 3D geomodelling emphases from small scale to large scale and vice versa.
- 3) Flexibility and adaptability to incorporate models and geological interpretations (point data, maps, grids) created by external organizations.
- 4) Leveraging a variety of geomodelling methods to include specific geologic units and structural features of interest.
- 5) Geomodelling to support multi-disciplinary themes and scientific investigations.
- 6) Ensuring that models are adaptable and can include very complex and detailed geomodels that are required for assessing the subsurface of urban areas.
- 7) Interoperability for data description and exchange, as well as the ability to access models online within a sharable structure.

All of the above are dependent on the various geomodelling capabilities of the GSOs, levels of known subsurface information, and needs of constituents and stakeholders. Constituent and stakeholder needs will drive the prior-

itization for enhancing geological characterization in areas of strategic importance (e.g., urban regions, groundwater and mineral resource areas, transportation corridors, recreation areas, environmentally sensitive regions, as well as for attracting external investment opportunities).

The 3D modelling priorities for the 22 jurisdictions, and whether they are transitioning to larger scaled or smaller scaled 3D models, vary depending on where and how they began their modelling activities. Some jurisdictions started building models at a small (nation, state, or provincial) scale and are now in the process of infilling and transitioning to more detailed models of specific counties or regions, while others started by modelling counties and regions and are now working to integrate these localized models into large jurisdiction-wide models. The advantage to initiating geomodelling activities with large jurisdiction-wide models is that it provides a framework and context for construction of the more detailed large-scale models. The advantage of developing numerous local-scale geomodels is that it allows modelling teams to focus their efforts on developing 3D models in high-priority regions more quickly. Many organiza-

tions that have taken this approach to building models are now in the process of integrating these models into a single jurisdictional-scale model, thus creating a much desired single-source of geological information at various scales that can be updated with relative ease as new data becomes available.

Geomodelling of specific geologic units and structural features are GSO goals that address several thematic and scientific issues, including resource-scaled models that can be embedded into jurisdictional-scale models. They include modelling of:

- Bedrock structures beneath sedimentary basins to assess potential for thermal groundwater and geothermal energy.
- Deep tectonic structures to provide scientific insight on the general geologic framework.
- Onshore-offshore bedrock for energy potential.
- Nearshore bottom sediments to assess littoral transport and shore protection effectiveness.
- Structural basins and terranes for energy potential and development of predictive flow models for reservoir engineering and hydrocarbon maturation.
- Deep bedrock to assess the subsurface for deep thermal storage, geothermal systems performance, critical minerals, and carbon storage.
- Shallow bedrock and Quaternary/Holocene deposits to evaluate groundwater availability and its contamination potential, develop numerical models of hydrologic processes, monitor potential environmental changes associated with climate change, and for infrastructure development and hazard assessments. This also includes incorporating high resolution seismic profiling, ground penetrating radar, electrical earth resistivity, airborne electromagnetics, and other geophysical methods into the 3D modelling exercise.

- Shallow and deep bedrock to assess the energy-water nexus, including potential interactions between aquifers and producing regions of oil and gas fields, and potential interactions between aquifers and injection of fracking liquids and other produced waters.
- Mineral resource deposits assessment.
- Physical parameters of the subsurface in urban and infrastructure corridors.

Some survey organizations provided very specific future plans that elaborated on the need for increased 3D geological modelling of urban settings where infrastructure, near-surface geohazards, contaminant migration, and evaluation/conjunctive delineation of groundwater and surface water interactions at a detailed scale is essential for optimal land-use planning and decision making. In this dynamic setting of large and shifting populations and constantly changing land uses, high resolution, up-to-date, and easily updatable and accessible 3D geological modelling (including physical property modelling) of the upper ~100m is a priority, followed by integrating the subsurface data with man-made deposits, detailed topographic data (preferably LiDAR), and above-ground information. It is a goal of GSOs to ensure that resources and features (human and natural) at land surface and in the subsurface are integrated.

Many survey organizations indicated that they are striving to provide easily understandable and accessible 3D geological models so that land-use decision makers and economic developers can mitigate future risks (and therefore future liabilities), identify opportunities for cost-savings to government, increase public awareness, and take advantage of land areas posing less risk, as well as avoid conflicting land-use activities. This information directly feeds into the need for quantitative subsurface information for infrastructure development and

supplementing Building Information Models (BIM) in subsurface urban planning. There must also be better integration of geological information with the engineering community as shallow geological material character, thickness, and variability directly affects infrastructure design, maintenance and longevity of constructed facilities, and industry bidding on excavation projects.

## Data Management

An issue that still faces the global GSO 3D modelling community is dealing with large and diverse data sets, and their standardization, utilization, and dissemination. While some GSOs have this issue “well under control”, for most it looms as a major obstacle that must be overcome for fully implemented 3D geomodelling to proceed effectively and efficiently. It should also be noted that there are still many GSOs not included in this publication that lack the necessary subsurface data to even initiate a 3D geomodelling program.

Even for well-established programs, future plans call for the need to improve data management and the associated metadata that provides for its discovery and roots, and also for databases to incorporate information on, for example, mineral resources, rock properties, formation temperatures, and hydrogeological and other fluid flow data. Planning, administering, and implementing a central data storage and management system for 3D data and models is emphasized by several GSOs, followed by standardizing the creation of 3D geomodels, maintaining quality assurance processes, and sharing of modelling results. In particular, quite sophisticated 3D model databases and database management programs have been accomplished by, for example, the British, Netherlands, and Danish geological surveys.

It is essential that model validation, as well as the need to establish a time ta-

ble for quality control, be conducted at various steps throughout the modelling workflow, and also that various parameters for quality assessments be defined. Finally, newly emerging machine learning and deep learning methods are aimed to assist with the above mentioned issues as they can optimize data, as well as enhance 3D geomodelling products and data interpretation efficiencies.

## Availability of Technical Experts and Work Flow Issues

Two issues of immediate concern for future 3D modelling endeavors are (1) the availability of technical staff with modelling expertise to build models due to the increased rate of demand, and (2) the ability to build high quality models consistently and efficiently. Unfortunately, a general lack of 3D geomodelling training at many universities has resulted in a paucity of qualified practitioners. Currently, the majority of staff receive training on how to build 3D geological models on-the-job at the GSOs. It is critical that both current and future geomodellers have an understanding of computer programming, geostatistics, and most importantly a strong background in geological principles achieved through field based training, to ensure the models they develop are as accurate as possible. In addition, succession planning to insure that trainers/educators can train new staff in 3D geomodelling will be a challenge for academic institutions in the near future.

Some GSOs are indeed increasing the number of geologists involved in 3D geological models (Alberta, Netherlands). After all, geology is a multi-dimensional science and it makes sense that GSOs would train their geologists to properly characterize and categorize their data, and then be able to construct their 3D models with a working knowledge of their geology and its complexities.

For jurisdictions that have noticed an increased demand to build multiple geomodels as quickly as possible, there is an increased reliance on the use of workflows to allow them to build and update their models more efficiently. Many jurisdictions have indicated their intent to allocate time and resources to developing, improving, and/or standardizing workflows within their geomodelling teams. Workflows can range from being generic to very specific and highly detailed. Generic workflows serve the purpose of informing model users and stakeholders with a general overview of the modelling process that is used within a GSO. Very detailed and specific workflows (modelling scripts) can be constructed within a modelling software package to allow modellers to efficiently rerun and generate a new 3D model using an identical workflow after alterations or updates to the model dataset have been made. These modelling workflows are particularly important in areas where geological models need to be updated frequently, often to incorporate new data (Netherlands), and have been shown to significantly decrease the amount of time needed to rebuild the model (Alberta).

## Data and Model Dissemination

The final major goal for the future identified by most GSOs, is improving mechanisms for disseminating 3D geomodels, and their associated databases, and doing so in formats that are understandable and can be leveraged by researchers, educators, decision makers, developers, and others with an interest in a region's surface and/or subsurface geology. Since the early 1990s there has been a transition from data discovery, organization and production, to dissemination of integrated data. The steps in between include production of maps, the construction of individual surfaces and volumes of subsurface units, and 3D geomodels, followed by the full ser-

ving of all information, including keeping 3D geological models dynamic and up-to-date, as well as delivering earth and environmental process data and modelling associated with various scenarios including climate change. These transitional steps are needed to ensure that the complexity of the subsurface is understandable to the public, and that the data and models are properly utilized. When building 3D models that will likely be used for many purposes, it is important to make sure that the model metadata, including measures of model uncertainty, are properly documented and made available to all users.

A basic problem has been that GSOs who construct 3D geomodels generally have access to high-end computer hardware and software, and this far exceeds the capabilities of most users, and particularly those at more local and regional levels of government as well as the general public. It is a challenge to ensure that users have easy and low-cost access to compatible software programs, and/or can manipulate online applications using a web viewer to (1) retrieve relevant input data from a central database, (2) integrate, visualize, and evaluate the data within 3D geological models, and (3) create new custom-made models and a variety of derivative products. Open-source 3D viewers will be an important tool of the future for GSOs to leverage, and this will ensure that their models can be accessed and used by as many stakeholders as possible.

Emerging technology for augmented reality, virtual reality, serious-gaming, various visualization technologies, and 3D printing are allowing stakeholders to view and interact with 3D geomodel information in previously unimaginable ways. Many GSOs are leveraging these technologies to enhance communication of their geoscience information and products to all stakeholders, and also promoting knowledge sharing through various national and international exchange

sites. An example of knowledge sharing is the OneGeology initiative called Loop (<https://loop3d.org>). It consists of a consortium comprised of geological surveys and research institutions in Australia, Canada, France, Germany and the UK, with a specific intent to provide Open Source information to help construct future 3D geological modelling tools. It will allow users to better define their subsurface geology, assess data needs at various scales, and address geological problems and resource evaluations (Ailleres et al. 2018).

The role of 3D mapping and modelling in advancing understanding of the complexity of the geology that underpins many of society's needs appears to be well positioned. GSO contributions are highlighting this from the perspective of individual organizations and collaborative groups.

Thorleifson et al. (2010) highlighted the role and responsibility of GSOs to tackle 3D geological mapping as a continuum of their nearly 200 year evolution. This message is being reinforced and championed by both national (e.g. Boyd and Thorleifson, 2018) and international groups (EuroGeoSureys 2014). It is also being recognized more broadly by geoscience NGO's with an educational, regulatory, and policy orientation (e.g., Geoscientists Canada 2018).

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# Chapter 30: Conclusions and Recommendations

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In recent years, there has been a growing recognition of the societal value of geoscience data management, geological mapping, visualization, and modelling applications to support science-based decision making to support sustainable resource development and public safety. This volume provides an overview of how geological survey organizations (GSOs) from around the world have initiated programs to build 3D geological models, how the models are being used, program funding, current challenges, and future plans.

Approximately 80% of political decisions are related to spatial data

(Baumberger, 2015), and with so many GSOs using 3D models to facilitate communication of complex geospatial relationships, developing robust 3D geomodels is more important than ever (Government Office for Science, 2018). From an economic perspective, the geospatial analytics market is currently valued between \$35-\$40 billion and is projected to reach \$95 billion by 2023 (Market Research Future, 2019). Therefore it is not surprising that many GSOs are working quickly to develop and augment their 3D modelling programs. That being said, the information provided by each jurisdiction highlights that there is not one optimal approach

to building a geological model or geological modelling program. However, there have been some notable updates and new developments in 3D modelling efforts since the 2011 synopsis release, many of which will be discussed in the sections below. Table 1 provides a comparison of conclusions and recommendations chapter from the first edition of this synopsis (2011) provided versus a summary of the current state of GSO 3D modelling activities.

Many GSOs are transitioning from ‘many fit for purpose models’ to creating a ‘model fit for many purposes’. This transition seems to correlate with

**Table 1.** Comparison of information presented in 2011 and 2019 Synopsis volumes on 3D mapping and modelling at geological survey organizations.

2011 Synopsis	2019 Synopsis
Groups are exploring large numbers of tools and techniques	Many GSOs now have 3D modelling teams that leverage multiple software programs and tools to perform the required data analysis and 3D modelling.
Approaches to geological modelling are different to suit the needs of individual GSOs	Most GSOs use a multitude of modelling workflows depending on the amount, quality and distribution of the available data, and model output requirements.
Communication among the 3D mapping and modelling community must be maintained and formalized	The 3D mapping and modelling community is thriving and the number of organizations participating in yearly 3D modelling workshops and conferences seems to grow year after year.
International cross-boundary modelling efforts are rare	Many GSOs are currently involved in international, cross-border, collaborative 3D modelling projects
It would be worthwhile to initiate an international dialogue on the value of standards for 3D geological mapping and modelling	There is broad recognition and acceptance of the need for 3D modelling standards, and while many groups are working to develop an international standard, no single standard has emerged and been adopted internationally.



GSOs needing to update their models more frequently and efficiently as new data becomes available, and with the development of multi-disciplinary (integrated resource) models. It is common for GSOs to build numerous local and/or regional scale models, however, at a certain point it can become an administrative burden to keep all the models up-to-date as new data becomes available with many GSOs having a limited number of staff available to build and update models. Thus many GSOs are integrating and consolidating their 3D models so they have fewer models to update as new data becomes available. Some GSOs have developed semi-automated workflows to allow them to update their models even more efficiently and also reduce the chance of introducing user error when updating the model.

There has also been an increasing recognition of the need for multi-dimensional (2D, 2.5D, 3D, 4D, etc.) products to support information communication and decision-making (Catalonia, UK, Netherlands, Alberta).

Scientists, decision makers, and stakeholders are increasingly aware that the decisions related to the use or protection of one resource or region often impact the neighbouring resources or areas. Therefore, the trend towards integrated modelling will likely continue into the future as more and more decision-makers look toward having timely access to a current, single-source of credible information to support holistic decision making related to the safe, sustainable development, and protection of multiple resources.

This transition towards creating multi-disciplinary integrated models has been augmented by the increased capacity for big data analytics and machine learning approaches, which are allowing scientists to evaluate information and assess relationships between datasets extremely quickly.

Getting access to these large datasets has been facilitated by the increasing trend towards open-data portals. Many jurisdictions have acknowledged the value of providing and sharing data via open-data portals (i.e. GeoDeepDive; UK) and providing data that is FAIR (Findable, Accessible, Interoperable, and Re-usable; Wilkinson et al., 2016; Bavaria).

There has also been an increasing recognition for the importance of communicating uncertainty related to 3D model predictions and results (Czech Republic, Netherlands, Alberta). Decision makers and stakeholders are now more accepting that these models are simply versions of reality that contain a certain amount of error and uncertainty (Government Office for Science, 2018). A number of GSOs are testing methods of quantifying uncertainty within their model predictions and communicating this information to stakeholders (Netherlands, Alberta, Italy).

Since 2011 there have been numerous successful examples of GSOs working collaboratively with neighboring jurisdictions to develop 3D models beyond their borders (Netherlands, Bavaria, Switzerland, Poland, Germany) and on collaborative projects with other GSOs (GeoERA, HotLime, GeoMol, Canada 3D). These multi-jurisdictional studies will likely become more common in the future as GSOs work collaboratively to enhance their understanding and characterization of cross-boundary resources.

To facilitate collaboration on 3D modelling products between GSOs, the development of model standards are required. While many groups are working collaboratively to develop 3D model standards (i.e. Infra3D; Bavaria; Canada; Netherlands; OneGeology), there has not yet been broad adoption of a standard amongst GSOs. As GSOs continue to increase the number and frequency of models that they would like to share, it is likely that a common standard will

emerge amongst GSOs in the near future.

Some GSOs are looking for ways to increase support for their organizations by commercializing their geological models and results, or by contracting out their geologists and modellers to build models for other agencies or in other jurisdictions. It will be interesting to see in the future if more GSOs look to grow and develop their currently established 3D modelling programs through commercializing their 3D model products or geological and geomodelling expertise. While commercialization is not an option for many GSOs due to their mandates, the increasing demand for multi-dimensional and multi-disciplinary models and lack of available subject matter experts with modelling expertise, has created significant opportunities for collaborative projects within which 3D modelling expertise and knowledge can be shared and developed through either in-kind or direct financial support.

With the increasing number of GSOs being asked to provide multi-disciplinary models and information to support science-based decision making and enhance geoscience communication to the public, the future of 3D modelling within GSOs looks bright.

Just keeeeeeeep on modelling :-)

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