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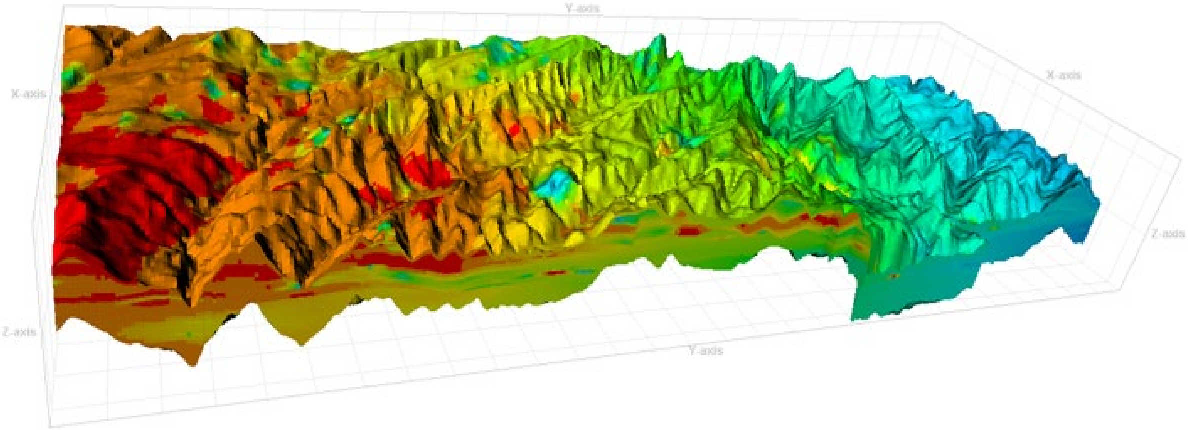
Three-Dimensional Geological Mapping: Workshop Extended Abstracts



Geological Society of America Annual Meeting
Anaheim, California
September 20–21, 2024

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AER/AGS Special Report 121

Three-Dimensional Geological Mapping: Workshop Extended Abstracts, Geological Society of America Annual Meeting, Anaheim, California, September 20–21, 2024

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Contents

3D GEOLOGICAL MAPPING – INTRODUCTION TO WORKSHOP 12

Thorleifson, L. Harvey[1], Richard C. Berg[2], and Kelsey E. MacCormack[3]

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The people of our planet invest in new geoscience, as well as findable, accessible, interoperable, and reusable (FAIR) geoscience information, to yield benefits in the form of energy, materials, water, safety, infrastructure design, and an understanding of Earth and its life. The work takes the form of research, which is conceptual, mapping, which is spatial, monitoring, which is temporal, and modeling, which assembles the foregoing, to facilitate management, which realizes societal benefits. Geoscience is done by geological surveys, academia, and industry. Whereas academics mainly balance research and teaching, survey geologists are committed to research and mapping.

Mapping is an essential service that is directly and indirectly required by all, as multiple resolution, and updated systematic mapping for a jurisdiction. We require ongoing meteorology and climatology, earth surface features, elevation, underground structures, bathymetry, soil mapping, and geological mapping of sediment and rock.

In 1815, William Smith produced the first geological map in the format that we know - depicting England and Wales. The map was accompanied by cross-sections, so Smith also created the first three-dimensional (3D) geological map content. Since then, geological mapping has remained a core function of geoscience.

However, geological mapping has evolved. The first century was about hand-colored wall maps, and the second century was about the printing press. The third century is a time of concurrent commitment to digital publications, as well as their assembly as evergreen seamless databases to support digital twins, which are indefinitely maintained dynamic models such as groundwater models that incorporate monitoring and support management.

The current revolution in geological mapping is a transition from the conceptual model paradigm to a machine-ready mesh paradigm. This is the essence of what 3D geological mapping, which depicts elevation and thickness, is all about. The transition has been driven since the 1980s by societal needs, accumulating data, and new technology.

Three-dimensional geologic mapping has been the norm in petroleum, minerals, and site-scale groundwater modeling for some time, but it has taken a while to implement this approach in the public sector, in part due to the need to assemble large databases of inconsistent public-domain data, benchmarked by adequate high-quality data.

To facilitate this new approach to geological mapping, a series of workshops was initiated in 2001, to support those who are: (1) engaged in 3D geological mapping of their jurisdiction, (2) just getting into 3D, and seeking guidance on where to start, and (3) interested in initiating a 3D mapping program within their institution, and thus seeking insights regarding not only best practices, but also ideas on how to promote the need for the program within their agency.

The workshops thus have addressed: (1) program rationale, (2) methods for model construction and validation, (3) managing large diverse data of variable quality that are required for 3D geological maps, (4) ensuring the interoperability of geologic maps and data, (5) developing visualization tools, (6) facilitating appropriate interaction between geological mappers and users, and (7) delivering 3D mapping and modeling products to users.

Within all this, a focus of the workshops has been to bring together geoscientists and technical staff who deal with large datasets, and who need to integrate data of variable quality with crucial high-quality data to construct 3D geology of appropriate detail that can be used for applications such as hydrogeologic modeling.

This is the 12th workshop in a series held with Geological Society of America, Geological Association of Canada, and Resources for Future Generations meetings. Participants have been from Australia, Canada, China, Denmark, Finland, France, Germany, Italy, Netherlands, New Zealand, Poland, Switzerland, the UK, and USA.

Eleven previous workshops have been held in Normal, Illinois; Denver, Colorado; St. Catharines, Ontario; Salt Lake City, Utah; Denver, Colorado; Portland, Oregon; Minneapolis, Minnesota; Denver, Colorado; Baltimore, Maryland; Vancouver, British Columbia; and Denver, Colorado. The 12th workshop is now at GSA in Anaheim, California.

The North American 3D workshops have been coordinated with counterparts in Europe and Australia. The European 3D Community has met since 2013 in Utrecht, Edinburgh, Wiesbaden, Orléans, Bern, and Copenhagen.

The growth of these workshops over 23 years began with the mere discovery that we were not alone. This progressed to developing workflows and products, to jurisdiction–wide strategies, for example to address increasing alarm regarding the ‘national groundwater crisis’. Hope to see you in Anaheim!

THE LOOP PROJECT: STATUS AND NEW DEVELOPMENTS

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Abstract

Developing digital-twins of our subsurface is essential to better manage our natural resources - metals, water, and waste disposal. By digital twins, we mean a realistic representation of the subsurface including the estimation of relevant physical and geochemical properties at an appropriate scale - in other words: a useful series of models. We present the current state of the Loop project, an open-source interoperable, integrative, probabilistic 3D geological modelling platform. The platform is built essentially on 3 python libraries (github.com/Loop3D)

1. map2loop is a library that automatically extracts geological information from maps and generates parameters for the modelling library.
2. LoopStructural allows the building of structurally consistent 3D geological models based on a time-aware parameterisation of a series of structural events. Each event is modelled sequentially and is associated with a structural frame which is defining a curvilinear coordinate system within each event-related geological object. Each structural frame consists of three perpendicular scalar fields that loosely represent the finite-strain ellipsoid directions of each object. The frames are fitted to structural data in 3D and then combined according to the geological history.
3. LoopResources utilises the curvilinear coordinate systems to enable geostatistical estimation of properties throughout the entire model.

We present the concept behind the structural frames for faults, intrusions and folding events, a simplistic proof of concept of enhanced property estimation within a Loop implicit formulation of 3D geology. We will also discuss the future of the project including the development of a user-friendly web-based interface.

LOOP Projects

Sub-surface resources management is far from being optimised because we do not have the tools (and sometimes the data) to properly characterise the physical properties in the subsurface, as well as their spatial variation and distribution. From the first day of exploration and maybe from the first drill-hole intersection of a resource, we should be able to predict and optimise where to drill next and in which orientation keeping in mind the need to optimise the amount of drilling required. Such a continued exploration approach will (1) continually test the exploration model, (2) continuously test our understanding of the system while assimilating newly acquired data in the model, and (3) continuously optimise the amount of resources (water and energy) required to define and extract the mineral resource. Similarly, at the mine scale, the ability to model the mine and the orebody knowledge (structural framework, lithology, mineralogy, grades, assays, alteration, …) in high detail will help optimise (1) the amount of drilling for resource definition, (2) the extraction efficiencies and (3) the processing pathways of varying ore types while minimizing dilution. This mine of the future will require less energy for crushing because we will know the metallurgical properties of each mine block, less drilling, less transport of waste, less water for drilling and processing, and it will generate a reduction of tailings volume. The mine of the future will have a reduced footprint and economic, socially-accepted mineral resource discoveries will depend on how well we are able to characterise the complex subsurface geology. In addition, under our cities, we need to predict urban subsurface geology for improved infrastructure development and waste management. All of these activities require the ability to probabilistically forecast sub-surface geology, allowing for rapid model updates when new information becomes available. This new type of geological model (Ailleres et al. 2018, 2020) will support rapid & testable decision-making and will be:

1. Interoperable: in addition to dealing with multiple sources of input data and knowledge, the platform will be compatible with a wide range of existing predictive tools;
2. Integrated: all data and knowledge available will be integrated in a series of best-fitting probabilistic 3D models. For example, geophysical data sets will be integrated in the geological modelling phase to reduce the parameter space, rather than only at the end of the modelling loop as a rejection criterion;

3. Probabilistic: geological and geophysical data will be inverted within a Bayesian framework to infer and predict 3D geology.

For the last three decades, building 3D geological models has required expert knowledge in 3D modelling, not geosciences. The complex process of building 3D models took the geologist out of the process and made 3D modelling a non-reproducible exercise. In the last six years, we have empowered geologists to automatically build 3D models (Ailleres et al. 2018, 2020; Jessell et.al. 2021; Grose et al. 2021a,b, Alvarado-Neves et al., 2024) and tackle difficult yet interesting geological questions rather than the technical decisions as to which button to press next. The map2loop library provides an automated analysis of geological maps and extracts geometrical modelling parameters such as formations thicknesses, structural information (strike and dip of strata), topological information related to faults, faults and formations, and the stratigraphy. This information is visualized in the Loop WebApp (Figure 1) and fed into the LoopStructural library to generate implicit formulation of a geological model.

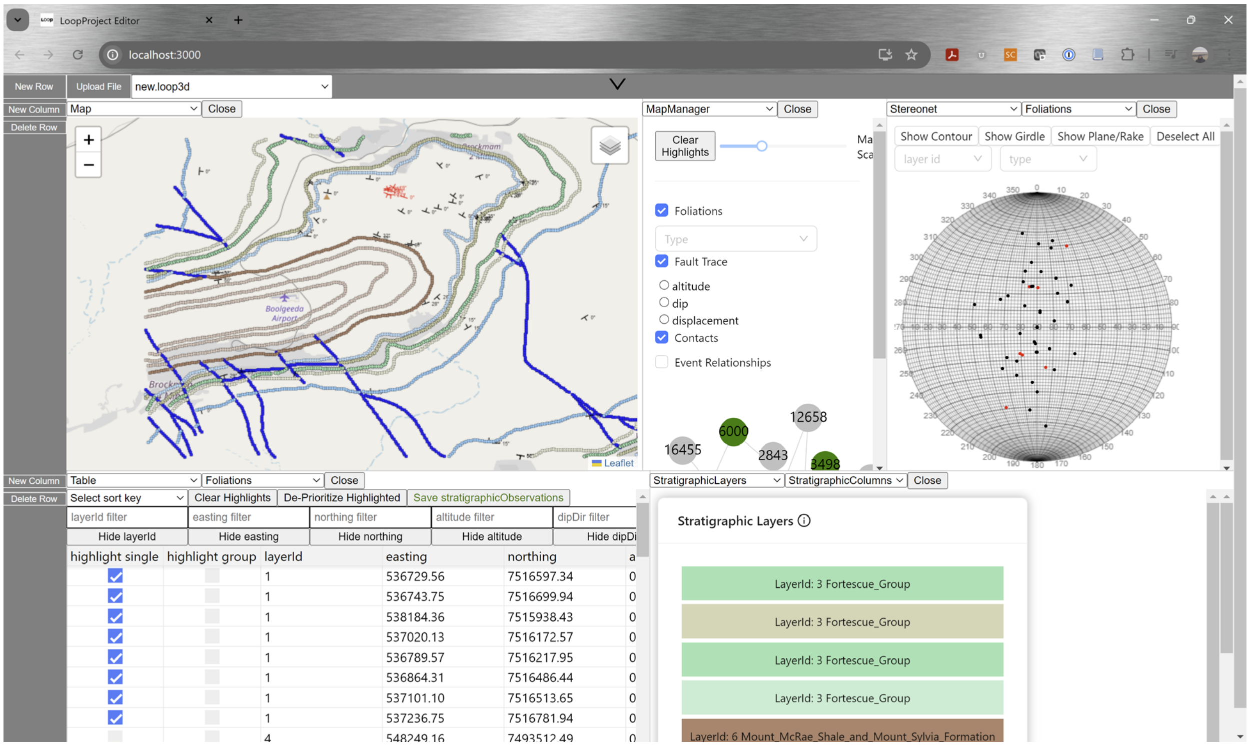

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Figure 1. The Loop WebApp allows for the visualization of the map2loop output process, allowing the user to assess the data and information to be fed to LoopStructural for model building. The WebApp is highly customable and allows editing of the augmented dataset prior to modelling.

In LoopStructural, we have defined a parameterisation of 3D geological models in a forward modelling sense. We now frame model building as a Bayesian inference throughout the entire workflow (Figure 1) including for input data and knowledge estimation and structural modelling. This novel approach allows us to investigate the parameter space and estimates of conceptual uncertainties. For example, one of the main limitations of the map2loop process is that structural information related to dip, shape, orientation, and amplitude of offset of faults are usually not provided. Similarly, structural information is usually only provided as strike/dip of bedding while multiple deformation events are poorly documented and supporting data are lacking. We propose to estimate these parameters using a Bayesian inference and feed the posteriori distribution to the modelling engine.

LoopStructural is based on the concept of the structural frame: a coordinate system defined for each object (faults, intrusions) or geological events (folding). These coordinate systems consist of three perpendicular scalar fields that are interpolated and fitted to data in 3D and then combined according to the geological history. This differentiates Loop from any other commercial or open-source 3D modelling package as we have enabled structurally constrained 3D modelling. This parameterisation of 3D geological model building reduces the modelling time 100 fold. These structural frames allow the definition of a curvilinear and conformable to layering, rectangular coordinate system throughout the models. We present the concept for LoopResources, our proposed property modelling library. Using this deformed cartesian coordinate system, we propose to adapt geostatistical and interpolation methods to curvilinear coordinate systems using classical XYZ-UVW transformations. This will ensure that lithological anisotropies are enforced during resource estimation and property modelling (Figure 2).

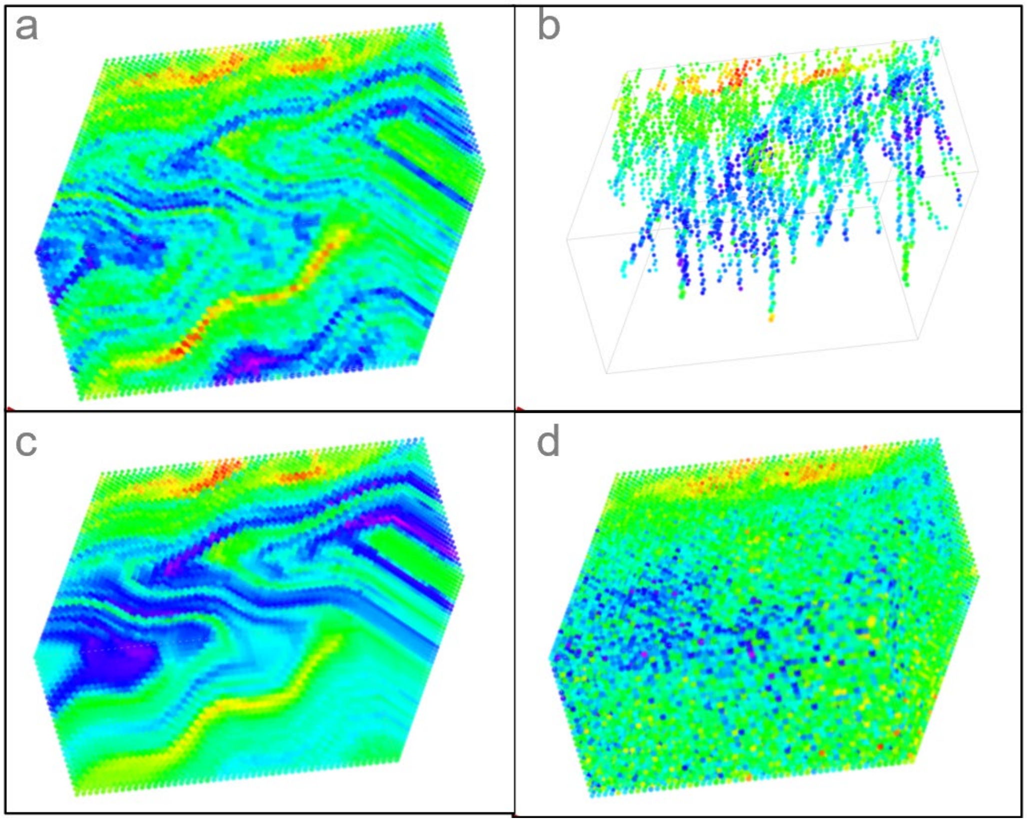

Figure 2: LoopResources: (a) synthetic property model generated within the Laurent et al., 2016 refolded model. Each layer has its own randomly generated property model. (b) Sampling the synthetic model with random drill holes to generate the dataset to be interpolated. Drill holes are roughly perpendicular to the main structural trend (axial surface of early folds); (c) Using the lithological model (pre-built from Laurent et al., 2016) and fold structural frames to apply geostatistics to the sampled properties allows for the recovery of a (too?) smooth model of the property; (d) Cartesian interpolation fitting a semi-variogram in x, y, z without using the inherited lithological anisotropy.

Conclusions

We are developing the next generation 3D integrative geological and geophysical modelling platform that will help build better - reproducible, inclusive, adaptable, updateable – models of the subsurface, including ore bodies and other natural resource reservoirs. We strongly believe that using Loop in the future will help reduce the mining footprint and the footprint of any extractive industry by reducing the amount of drilling required to define these resources and optimising the ore body and sub-surface knowledge in view to optimise the processing chain. This will in turn contribute to a large reduction of water and energy required to extract more metals out of a known resource.

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BACKGROUND, METHODS, AND PROGRESS WITH A 3D GEOFRAMEWORK DATABASE AT THE KENTUCKY GEOLOGICAL SURVEY

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By using a best-available-data approach, the Kentucky Geological Survey (KGS) has rapidly developed a robust and cost-effective digital database of three-dimensional geologic framework elements for research and visualization. Currently available 3D products (August 2024) include a preliminary statewide detailed fault model, a database of 227 partial or complete stratigraphic surfaces, and web tools for visualization and basic analysis. Future work will involve integrating detailed lithologic data and carrying this database forward into specific audience-driven applied models for groundwater, carbon management, hazard assessment, or other 3D research.

Best practices learned from established 3D programs at other geological survey organizations (compiled in MacCormack and others, 2019; Berg and others, 2022) include an analysis of audience needs, development of comprehensive subsurface databases, establishment of formal stratigraphic hierarchy, extensive correlation and stratigraphic tagging of subsurface data, and informed interpolation of surfaces between data points. Development and full implementation of a best-practices 3D program requires a significant investment of time and resources. Until 2021, Kentucky did not have a recognized source of funding for 3D geoframework projects. With the establishment of the US Geoframework Initiative within the USGS National Cooperative Geologic Mapping Program (Shelton and others, 2002), Kentucky was able to access limited funds to establish a preliminary 3D program.

Kentucky does not have an existing vocal audience demanding 3D models or products for application or research. However, the KGS recognizes extensive needs and opportunities for application of three-dimensional. Different audiences and applications of 3D modeling (geophysics, carbon management, water, etc) have well-established communities of practice and specific associated software packages. In general terms, these specialized software packages have well developed capabilities for data import, but do not encourage cross-platform export of analytical products. Until a specific audience is developed, the KGS is utilizing an existing university enterprise site license for ESRI Arc products. This platform allows for effective 2D to 3D conversion, adequate data management, and exports to many other software platforms.

The KGS 3D program is building upon a deep legacy of trusted geoscience research, including statewide detailed 2D geological mapping, extensive digital databases of oil and gas well data, water well records, geotechnical borings, stratigraphic and structural studies, and numerous geophysical projects. Decades of geological studies in Kentucky have produced a large inventory of published contour maps of stratigraphic surfaces of varying scales across many parts of the state. Recent interstate collaborative projects focused on subsurface carbon management have produced regional consensus interpolated 2D contour maps of Paleozoic stratigraphic surfaces across much of the eastern US mid-continent (i.e., MRCI, https://www.midwestccus.org/). A 1960 to 1978 cooperative project between the USGS and KGS produced a complete set of 707 published paper USGS geological quadrangle maps at a scale of 1:24,000. This project also resulted in a comprehensive view of Kentucky stratigraphy. Subsequent studies in coal, limestone, oil, and gas produced numerous detailed refinements of applied stratigraphy. Funded by the USGS National Cooperative Geologic Mapping Program (Statemap), an effort from 1996 to 2011 digitized the USGS paper maps into ESRI GIS formats and compiled them for free delivery through the KGS website (https://kgs.uky.edu). These original 2D geological maps were generated using predominantly elevation-based data and provide a vast storehouse of 3D-compatible information of mapped faults and contacts.

A necessary early product for the 3D database was a preliminary fault model derived from the original 1:24,000 USGS geological mapping. The compiled digital fault data were modified to generate continuous linear topological segments. The few available data on fault orientation were integrated, and then a process using MATLAB and ArcGIS Pro were used to generate 3D fault panels. This fault model will be a critical element in future best-practices interpolation exercises. Future work will include compiling and incorporating improved orientation data derived from available geophysical profiles.

Stratigraphic surfaces have been generated for the 3D database using a variety of compilation methods. Published contours were converted to a raster using a TopoGrid function. The scale of the original published vector data was used to determine the resolution of resulting rasters. Rasters were then converted to a 3D multipatch for visualization. Because of the large volume of available contour data sets, a process of automation was established, and is being managed using Jupyter Notebooks. For each available stratigraphic surface, the automated system generates a vector contour file, a raster, and a multipatch, with associated metadata for each.

For near-surface interpolation of 3D surfaces from 2D geological contacts, we have used a linear sampling method based on vector contact arcs. The target contact arcs are identified and isolated, Elevations of the contacts are sampled from an available digital elevation model, and the resulting point cloud of elevations is interpolated to a surface using a TopoGrid function. This process effectively reverse engineers the cartographic methods used for much of the original 1960 to 1978 USGS geological mapping program in Kentucky, which relied heavily on altimeters and surveyed elevations to extrapolate and interpolate geological contacts across wide areas with minimal geological exposure and subtle geological structure. Detailed documentation for all methods is on file at KGS and is available upon request for users or colleagues.

Fault model	847 fault segments statewide
Stratigraphic surfaces	227 surfaces total 12 priority statewide surfaces
Igneous features	10 irregular bodies 135 dikes
Rock cores	3,255 cores in 3D
Mines	171 mine footprints
Sample points	894 mineral point locations 291 geochemical sample locations

Table 1. Current inventory summary of features in KGS 3D database (August 2024).

The KGS has produced visualizations of parts of the 3D database for different projects and purposes. A statewide viewer of priority surfaces is providing a necessary popular public-interest viewer to allow various audiences to understand the potential of the 3D database. Another viewer also illustrates the complete inventory of 227 stratigraphic surfaces. Focused viewers illustrate stratigraphic geometry in the Jackson Purchase region (Gulf Coastal Plain), near-surface outcrops of clay-shale bedrock units, and bedrock morphology in the Ohio River Valley. A detailed viewer provides a visualization of data compiled for a USGS-funded Earth MRI project examining rare-earth-element potential in the Illinois-Kentucky Mineral District. A custom web tool (https://kgs.uky.edu/3d/demo/) provides a 2D interface for users to interrogate the 3D data and produce custom synthetic borehole records or cross-sections from the priority statewide stratigraphic surfaces.

Figure 1. QR code for Kentucky statewide viewer of priority stratigraphic surfaces.

Figure 2. QR code for detailed 3D visualization of the Illinois-Kentucky Mineral District.

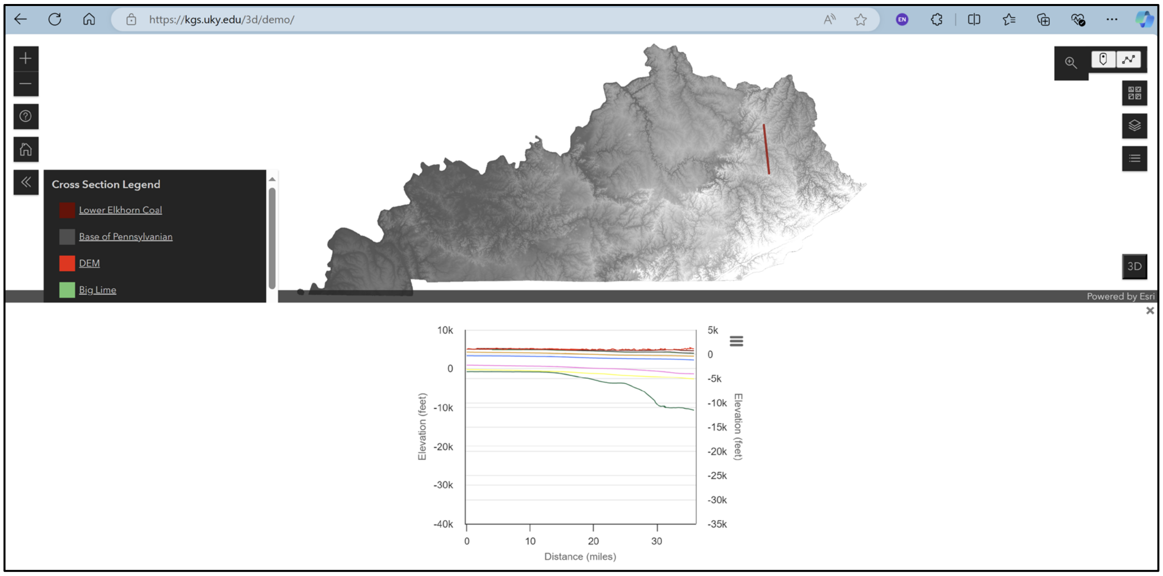

Figure 3. Screen capture of KGS 3D web tool (https://kgs.uky.edu/3d/demo/) for generating boreholes or cross-sections.

Through a deliberate cost-effective process of utilizing available published data, the Kentucky Geological Survey has successfully and rapidly generated a robust database of potential 3D-data inputs for future modeling and research. The data is available through online viewers and tools and can be delivered in a variety of formats on request from interested users. This preliminary effort has provided a body of usable data for pilot projects and proposal development and has developed detailed staff expertise in manipulating and managing 3D volume and point data.

KGS effort is now turning toward full implementation of best practices for a 3D program. An early sub-project developed a database of 140 reference wells for stratigraphic interpretation statewide. Active projects (August 2024) include detailed stratigraphic tagging of wells in areas of high priority identified by our state mapping advisory committee. Future funded work (2024-25, awarded by NCGMP Statemap) will be focused on developing automated methods for incorporating existing lithologic data from coal borehole, oil and gas, geotechnical, or water-well databases into the KGS 3D framework.

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ADVANCES IN SYSTEMATIC, COUNTRYWIDE GEOLOGICAL 3D MODELING OF SWITZERLAND: A WORK IN PROGRESS-REPORT

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Introduction

The work program “The National Geological Model of Switzerland” (NGM) aims at providing the first full and multi-dimensional geological survey of Switzerland by the end of 2030. This includes a countrywide, multi-resolution geological 3D model, systematically developed based on geological, technical, and methodological specifications. In addition, the modelling work is accompanied in parallel by other initiatives, e.g., the complete harmonization and update of the geological map vector dataset (1:25000).

After three years into the NGM program, the first projects have been completed and, following the presentation held at the 11th 3D geological mapping workshop (Baumberger et. al, 2022), we present the current state of work, the progress achieved, as well as lessons learned during the last two years.

Scope and use of NGM

The NGM is funded by the Swiss Government with CHF 22 Mio. for the period 2022 to 2029 and as of 2030 with annually CHF 1.8 Mio. for support, maintenance, and development of the work outcomes. It is a digitization, harmonization, standardization, and production program that includes, amongst other sub-tasks, the systematic geological 3D modelling of the entire Swiss territory.

The 3D modelling sub-task of the NGM concentrates on four independently treated models: The Swiss parts of Top-Bedrock, Jura fold-and-thrust belt, North Alpine Foreland Plateau, and the Alps. These models need to seamlessly fit together, eventually, regardless of e.g., their level of detail or resolution. Therefore, a common QC and risk assessment additionally is required.

This countrywide framework model serves as a basis for higher resolution geological 3D models to be used for infrastructure planning, groundwater studies, natural hazard assessment, education, and research purposes. Furthermore, it will provide access to strategic subsurface knowledge for geo-resource and geo-energy management and exploration.

Model 1 – Top-Bedrock

The first semi-automated geological 3D model of the rock head surface was established as an integrated part of the geological 3D model of the North Alpine Foreland Plateau (swisstopo, 2017). Today, its construction steps can no longer be traced, therefore, the methodology, the modeling approach or tools, respectively, and the data basis are currently being reviewed and restructured. As other regional providers also produce geological 3D models of the bedrock surface, these models need to be integrated into the Top-Bedrock model to produce a new nationwide geological 3D model of Top Bedrock in Switzerland. As a result, we have chosen to use two methods, one in which we integrate third party models and a separate method for updating model regions with new data. Currently, new data consists of well and outcrop data, but the method allows for any point data consisting of bedrock information (bedrock reached and not reached). The modelling itself (interpolation of data) is only a small part of the overall workflow, but it is important. Here we evaluate two approaches. One approach (A) basically models the difference between the current bedrock model and the new data using GRF (Gaussian Random Function) simulations and an isotropic variogram model. With this method we are not yet able to obtain a meaningful uncertainty. The second approach (B) uses GRF and an anisotropic variogram model and does not model the difference to the new data but all the data available in the region. This second approach allows us to incorporate data uncertainties into the model and also produces meaningful uncertainties as an end result. However, here the model quality is insufficient after qualitative and quantitative validation. Both of these approaches are still being developed and evaluated. Additionally, a methodology has been established to avoid boundary effects when integrating either third party models or updated regions into the nationwide model.

Results are promising. After running through several proof-of-concepts, the current modelling workflow (using approach A) supports the automatic update of any region of the existing national model with new data within a short amount of time as well as the thickness of the unconsolidated deposits, and it automatically validates the results (quantitatively). However, some challenges remain. The main focus and outlook are computational power for large numbers of simulations, uncertainty estimation for approach A, and improvement of interpolation results of approach B. We will also look into the incorporation of additional data types (e.g., geophysical data).

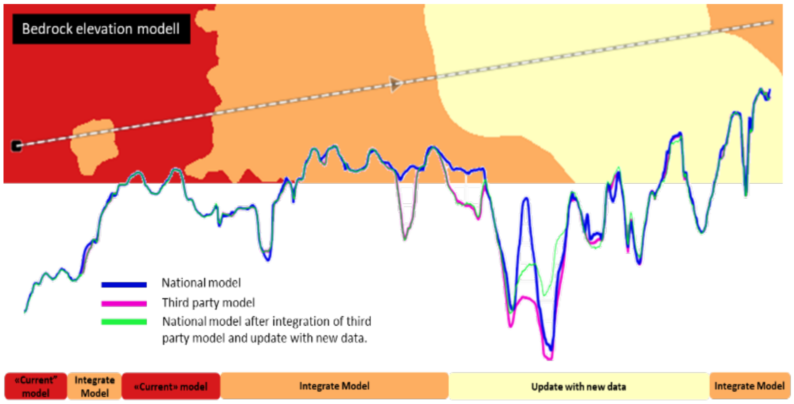

Figure 1: Comparison of the existing nation rock head model (red), after the partial integration of a third-party model (orange) and a partial, complete update with new data (yellow). Please note the absence of boundary effects in the new model (green line)

Model 2 – Jura fold-and-thrust belt

The Jura fold-and-thrust belt (JFTB) underwent intense tectonic deformation along its arc-shaped geometry, including folding and overthrusting that resulted in a complex structural pattern that significantly changes laterally from west to east. For the 3D geological modeling, the Swiss JFTB area was divided into eight different sub-areas, which were worked on by external contractors. This approach was chosen to meet the tight schedule of the NGM program by working in parallel and at the same time integrating the valuable regional knowledge of the local geological offices, which significantly enriched the model. The modelling team at the Swiss Geological Survey closely supports these mandates, is responsible for model management, and conducts quality controls in collaboration with external experts. To ensure a consistent tectonic interpretation by the external contractors and to receive a uniform and harmonized geological 3D model, they need to adhere to a set of guidelines addressing tectonic (Mosar & Jordan, 2022), stratigraphic, and methodological specifications.

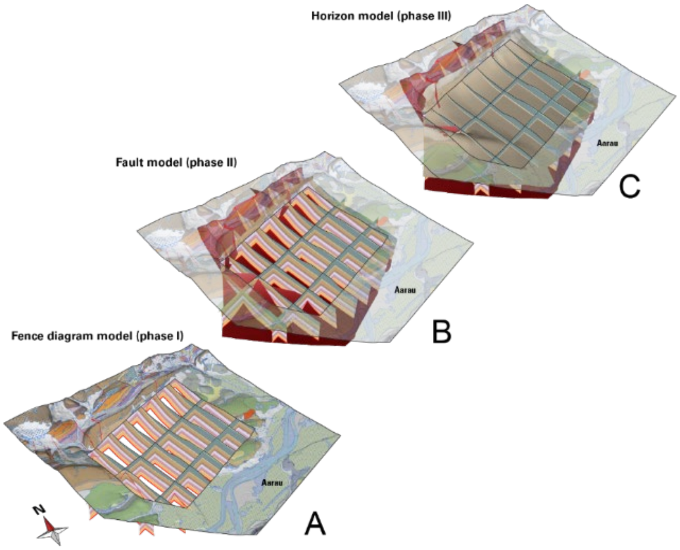

Figure 1: Schematic overview of the three phases of modelling the Jura fold-and-thrust belt: A) Fence diagram (phase I), B) Fault model (phase II) and C) Horizon model (phase III).

The modelling methodology follows the fence diagram model approach (Baumberger et. al, 2022). This is to (1) better control the interpretation and the modelling of the complex subsurface structures of the Swiss JFTB, (2) show a high level of detail of the structures and (3) allow for an easy adjustment or refinement of the model in the future.

After two years of intensive modeling work in the first model area, the project is expected to be concluded by the end of 2024. The modeling results are very promising and fulfil the expected quality requirements. For the first time, the subsurface of the Swiss JFTB has been comprehensively represented at a regional level by a consistent tectonic interpretation. However, experience from this project shows that, despite detailed guidelines and precise descriptions of the tasks, communication challenges were encountered that required more intensive support in order to achieve the desired result.

Model 3 – North Alpine Foreland Plateau

The Swiss North Alpine Foreland Plateau was modelled in the framework of the GeoMol project funded by the European Union (GeoMol Team, 2015). The Swiss Geological Survey invested an additional, significant amount of man-power to add more data to that first multi-national North Alpine Foreland Plateau model. The resulting 3D model for the Swiss part of the North Alpine Foreland Plateau supplies a much higher number of litho-stratigraphic horizons and faults as well as a higher level of detail interpretation of the subsurface of the central part of the Swiss Molasse Basin (swisstopo, 2017).

Since 2017, the model has been updated on a regular basis and it is regularly consulted by large projects dealing with e.g., new underground infrastructure, deep geothermal energy, and other exploration topics. At the same time, it also serves as the anchor point for the ongoing modelling projects (see this abstract), as they mandatorily need to provide reasonable, geologically correct transitions from their own modelling area to the GeoMol model, even though the modelling resolution might differ.

Model 4 – The Swiss Alps

The future Swiss Alps 3D geological model (SA3D) covers approximately 60% of the country and will provide a consistent large-scale underground 3D geological model of the main contacts and structures of the Central European Alps. Due to the sparse population and difficulties regarding accessibility (bad and/or at high cost), this region suffers from a lack of available subsurface data (seismic, boreholes, etc.). This represents a major challenge for any modelling project. However, it can be compensated for by the high relief, the sparse vegetation, which allows for excellent remote sensing data acquisition, and the large number of scientific studies already available. The new Tectonic Map of Switzerland 1:500’000 (swisstopo, 2024) serves as the main input data for the advanced surface-based 3D modelling applied in this model. Based on the paleogeographic origin and structural evolution pointed out on the new map, the model area is divided into eight modelling areas (Musso Piantelli et al., 2024). Within each of them, the target structural and lithostratigraphic contacts are modelled at the equivalent scale of 1:25’000. The workflow developed for SA3D shows similarities with the JFTB approach, which allows to benefit from and exchange on common experiences: (1) The necessary modelling work is performed by external contractors (here: universities); (2) The model is founded on a network of regularly spaced (1000 m) geological cross sections; (3) the contractors need to develop a scientific concept for their work area; and (4) the modelling team at the Swiss Geological Survey takes over the same roles as mentioned above for the JFTB.

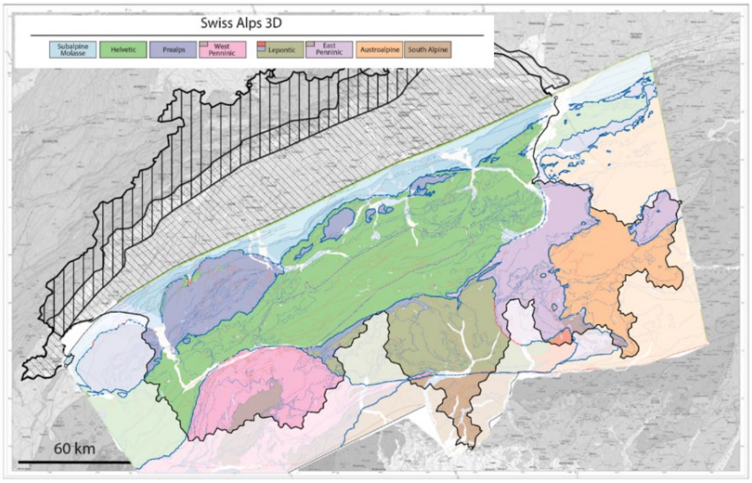

Figure 2: Division of SA3D work areas related to their paleogeographic origin and structural evolution

The workflow developed for SA3D offers the chance to gain validation approaches for domains only weakly constrained or with no subsurface data available, by generating a 3D model that integrates multiscale geological data unified by a common dataset provided by the Tectonic Map.

At present, work has only just begun in three areas (Subalpine Molasse, Helvetics and Pre-Alps). Therefore, no results can be presented yet. However, a large-scale 3D geological model of the Aar Massif has been constructed as a pilot study for the SA3D project (Musso Piantelli, 2022). This allows for a demonstration of the workflow and expected results.

Quality control, risk assessment, model access and workplan

Quality control is one of the connecting elements between the different modelling regions. Even though the modelling approaches, as well as the QC procedures per model may differ, each of the modelling areas can still benefit from the other ones. This perspective is currently being documented and integrated in a comprehensive 3D modelling QC system.

The main risk has moved from finding a sufficient number of valuable contractors (Baumberger et al., 2022) to the common understanding by external contractors of how to meet the requirements set by the Swiss Geological Surveys regarding the quality of the final results.

All of the model data will be available for search, query, and download in their correct spatial location at https://viewer.swissgeol.ch, the award-winning open-source 3D viewer of the SGS. They will be available to the public, as sub-model areas become available.

Outlook

The Swiss Geological Survey plans to complete the first full, multi-dimensional and multi-resolution geological survey of Switzerland by the end of 2030. At this time, digitally available data sets will be harmonized, nationwide, in both a geometric and semantic sense, too.

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THE VALUE OF GEOLOGICAL MAPPING: AN ECONOMIC ANALYSIS OF THE COSTS AND BENEFITS IN THE USA FOR THE 1994-2019 PERIOD

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Introduction

Geological mapping is a foundational activity and a core scientific function of all geological surveys. Geological maps (1) integrate multiple interpretations of stratigraphy, lithology, geological structures, unit correlations and ages, paleontology, and mineralogy, and (2) have interpretive outcomes that can have a profound influence on the national economy and the ability to sustain and protect natural resources. Notably, geological maps are viewed as a public good, are available and accessible to everyone, and they can be used by many at the same time without being “consumed”. However, despite their societal importance, there have been very few quantitative analyses of the actual costs and, most importantly, the resultant benefits of such geological maps.

This report provides a summary of an economic analysis of the costs and benefits of geological mapping across the entire United States of America (USA). Costs dedicated to geological mapping were gathered from State Geological Surveys (SGS) and the U.S. Geological Survey (USGS) for the 26-year 1994 to 2019 period. Estimates of the benefits of mapping were collected in a questionnaire sent out to more than 81,000 individuals in both the private and public sectors, and nearly 4,800 responses to the questionnaire were received. Globally, this is the largest and most comprehensive jurisdictional assessment on the value of geological mapping ever conducted. Included in costs and benefits were those few regions in the USA where 3D geological mapping and modeling had been accomplished. However, separate costs and associated benefits for the 3D mapping were not provided.

Geological Mapping Costs and Types

The publicly funded effort of geological mapping in the U.S. has been a major undertaking, as shown by the 10,200 individuals reported to be employed in 2020 by SGS and the USGS, with about half of them geoscientists and the rest supporting the effort (e.g., GIS analysts and cartographers). Total spending for geological mapping by SGS and the USGS during the project period was $1.99B in constant 2020 dollars, and there was a pronounced trend of declining annual expenditures for geological mapping from about $80M in 1994 to about $70M in 2019.

Geological maps can be large scale (at scales 1:62,500 or more detailed), medium scale (e.g., 1:100,000), or small scale (at 1:500,000 or less detailed). As reported by SGS and the USGS, and as expected, greater area mapping coverage has been accomplished at small scales than at other scales. Geological mapping coverages vary greatly between states depending on population, size, availability of funds, and economic activity. SGS also reported that 73 different kinds of derivative maps (maps prioritizing a specific natural resource, land use, or Earth hazard) have been generated by them.

Profile of Stakeholders

Stakeholder responses were received from all 50 states and the District of Columbia, and many stakeholders worked in multiple states. About 63% of them worked in the private sector, while 37% were employed in the public sector. Private sector responders represented the mineral and energy industries, water resource industry, construction, transportation, geotechnical industry, independent geologists, public utilities, environmental industry, education and research, tourism, real estate, and not-for-profit organizations. Stakeholders from the public sector included those from all levels of government and educational institutions. Stakeholders also represented all sizes of organizations, from those employing less than 5 to greater than 5,000 individuals. Small organizations and individuals working alone represented the largest group of stakeholders (~ 25%), with the remaining coming from larger organizations varying between 5% and 10% of the respondents.

Further breakdown of stakeholder responses shows that their derivative map preferences were for ground and surface water related issues (included in 40% of the responses), followed by hazards (e.g., earthquakes, tsunamis, floods, and landslides) (15%), and minerals and energy (13%). About 81% of respondents indicated a preference for large-scale maps, with 37% preferring maps of 1:24,000-scale and 35% favored more detailed maps.

Geological Map Value

Questionnaire responses on geological map value. The value of geological maps was assessed in several ways. The first assessment was based on stakeholder responses to queries about money and time that stakeholders perceived to have saved, because maps were available to them. Other questions asked what they would willingly pay for a map and to estimate the long-term value of geological maps. Table 1 summarizes the stakeholder assessment of the value of geological maps. Because of the wide range of data, particularly with some very high values representative of very large expenditures on major projects by large organizations, the median values were considered more representative than the mean values, and they are also the most conservative.

Table 1. Summary of Quantitative Evaluations by Respondents.

Time/Cost saved over 5 years	*Median project time saved — 20%* *Median project cost saved — 15%*
Project cost increase if maps unavailable; Responses included maximum and minimum budget statements.	*Median project cost increase — 30%, Median budget size of 776 projects-min. $250,000, max.$300,000* *Median number of maps used — 4* *Median value per map — $11,062-$18,375*
Willingness to pay (WTP) for a map if not available	*Median WTP — $3,000*
Long-term value of a map	*Median long-term value of a map — $10,000*
Expected payment for a map	*Median expected to pay — $2,883* *(Best data, least uncertainty, and consistency with WTP)*

The 1994 to 2019 project period was characterized by a rapid decline of sales of paper geological maps (primarily distributed at the cost of printing or copying), as these transactions were replaced by the increasing and mostly free availability of digital versions of geological maps that could be accessed, downloaded, or consulted online. Therefore, for this economic analysis, geological map demand was best represented by numbers of map downloads and online views. Therefore, SGS and the USGS provided data on direct downloads and online views of geological maps, and a few SGS also provided some data on geological maps sold.

A complicating factor affecting the reporting of geological map online view and download data was the interaction of robots, or “bots”, with web sites. Designed to perform specific and repetitive tasks automatically, faster, and often more effectively than if humans performed them, their downside is that they can skew web statistics and make websites appear more popular than reality. Nine SGS and the USGS were able to account for bot activity in their geological map web view and/or download numbers. All other SGS did not/could not report on their degree of bot activity. Therefore, their raw website view and download data were reduced to account for bots according to annually reported 2012–2019 industry data on bots versus human traffic. Bot data are not available prior to 2012. Therefore, between 2004 and 2011 (years for which SGS and USGS data were provided), web view and download data by SGS and the USGS were reduced by an average of 44.3% based on the 2012-2019 average of industry data on bot versus human traffic.

In addition to accounting for bot activity, marketing companies make estimates regarding the percentage of online web page views that result in transactions. This is called a conversion rate, and downloading geological maps from websites are considered transactions. Nine SGS were able to provide online view and download data for 33 cumulative years covering the latter portion (2012 to 2019) of the study period, and this yielded a conservative conversion rate of 3.32%. This conversion rate was applied to online visits reported by SGS and the USGS to arrive at a download number of 378,546, in addition to reported downloads of 4,360,736 and 86,673 paper maps that were reported sold, bringing the total of maps downloaded and sold to 4,825,955.

Additionally, 24 SGS were able to provide geological map view and/or download data, and that accounted for 65.14% of the total SGS costs. The other 24 SGS that did not provide these view and download data accounted for 34.86% of the total costs. It was assumed for the latter that they had a high likelihood of contributing to the overall download data, because they received federal funds for geological mapping and were required to 100% match those funds. Applying the 3.32% conversion rate of map views to downloads over the 1994–2019 project period and extrapolating map sales data resulted in an additional 2,275,768 downloads and 46,383 maps sold for a total of 7,148,106 downloads/maps sold.

Using the most conservative median amount that respondents expected to pay per map ($2,883) in response to an answered stakeholder question, the cumulative range of values between the actual maps downloaded and sold (4,825,955) with the extrapolated amounts (7,148,106) would be between $13.91B and $20.61B. Considering the $1.99B cost of producing the geological maps during the 1994–2019 period, the minimum value estimates range between 6.99 and 10.35 times the expenditure.

Mere viewing of geological maps, however, may provide adequate information to the user without downloading them. Again, using the $2,883 median amount that respondents expected to pay per map, the cumulative range of values between the actual maps viewed, downloaded, and sold (15,849,376) with the extrapolated amount, as discussed above (24,331,250), would be between $45.69B and $70.15B. Therefore, maximum value estimates range between 22.95 and 35.23 times the expenditure. Although maximum values are not realistic, it is safe to assume that value estimates would lie somewhere between the 6.99 and 10.35 values and the higher extrapolated values of 22.95 and 35.23.

Assessment using USEPA data. Benefits of geological maps also were assessed using data provided by the USEPA as part of their “SuperFund” program (established to clean up polluted industrial sites with funds from Congressional appropriations and the parties responsible for the sites). It was based on the rationale that future contamination mitigation costs, resulting primarily from waste disposal and industrial sites, could be minimized significantly or even avoided had geological information been available and used prior to the locating of these potentially detrimental sites.

USEPA data show their total expenditures for the years 1994 to 2019 in non-inflation adjusted dollars were $29,943,391,516. Adding private party commitments of $34,686,400,000 resulted in a total of $64,811,791,516 dedicated to SuperFund cleanup and associated activities. This $64.8B, once inflation adjusted to 2020 dollars, is $86,227,531,539. It is not known if and to what extent geology was considered when these waste disposal and/or industrial sites were located (often many years prior to being designated as SuperFund sites). However, it is reasonable to assume that at least some of the pollution could have been avoided, and some of the cost of clean-up saved had geological maps been available and used prior to the locating of these sites. The present study documents $1.99B of costs spent on geological mapping from 1994 to 2019. A 2.3% savings from the SuperFund expenditure of $86.23B would have paid for the entire 26 years of geological mapping in the U.S.

Regional variations in costs and benefits. An additional approach to evaluating the value of geological mapping is a review of questionnaire responses for six regions of the U.S., identified as Northeast, Southeast, Great Lakes/Great Plains, South-Central, Intermountain West, and Pacific Rim. Estimates from respondents on how much they would spend on a map were viewed as costs, while appraisals of long-term value were viewed as benefits. Calculations show that all regions showed a high percentage of positive long-term values (benefits), ranging from 71% to 87% for both public and private sectors.

In addition, expenditures on geological mapping reported by SGS and the USGS were compared to the number of maps produced annually for representative states from the six regions to determine the average cost of producing a relatively detailed geological map (1:24,000 to 1:100,000 scale), and this ranged from ~$42,000 to ~$123,000, with the lowest costs from the Southeast region (Tennessee) and highest costs from the Pacific Rim region (Washington State). Using 2019 as an example year, these values were verified by actual costs reported by the USGS and the Illinois State Geological Survey.

Conclusions

Despite using (1) the lowest geological map value number ($2,883), (2) underreported numbers of geological map views, downloads, and sales – all significantly lowering map demand numbers, and (3) the highest industry reported bot statistics that further lowered demand numbers by an average of 44.3%, all of these actions still resulted in a minimum value estimate of 6.99 times the expenditure, the most conservative estimate. Even when factoring in extrapolated view and download numbers from those SGS that did not provide any online web data, this action only increased the value estimate to 10.35 times the expenditure. This above approach, plus other approaches all derived significantly positive values for using geological maps. Results of these approaches underscore the vital significance of geological information as a foundational component of understanding Earth's complex infrastructure that supports society's most basic needs for clean drinking water, environmental protection, human health and safety through the mitigation of geological hazards, and sustainable development of all natural resources.

Moreover, and finally, this study assesses more than the value of geological maps. Geological maps reflect an "end product" of geological comprehension that is rooted in a deep understanding of the age, order, and distribution of geological materials, as well as the Earth processes responsible for their formation. Geological mapping may be one specific activity within the broad discipline of geology. However, because it has been possible to obtain specific mapping costs from all SGS and the USGS as well as measurable benefits from a wide range of geoscientists and other direct users of geological maps, the economic value of geological mapping stands as a surrogate for the discipline as well. As this national study shows, the value of geological mapping reflects a wide range of economic sectors that directly benefit from geological information. As we move forward, it is paramount that we truly understand the value of geological information, as it directly touches all of the above issues.

The final report on this economic analysis of the cost and benefits of geological mapping in the U.S. is planned for publication by the American Geosciences Institute in late 2024.

THREE-DIMENSIONAL MODELS IN THE REAL WORLD

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Ontario is a large and geologically diverse province located between the Great Lakes and Hudson Bay in central Canada. In the north, Precambrian igneous and metamorphic rocks contain much of the province's “critical mineral” wealth. In the south, sedimentary rocks are important industrial resources for aggregates, salt, and hydrocarbons, and support substantial groundwater supplies for potable drinking water, industry, and agricultural use.

Over 250 m of thick Quaternary-aged sediment deposited during successive glaciations cover the bedrock across much of southern Ontario. These sediments form vital aquifers, areas of groundwater recharge, and additional sources of aggregates. Our province is home to nearly 15 million people, and most of them live in what is referred to as the Greater Golden Horseshoe, in the area surrounding the City of Toronto. Here the competing demands of an expanding population, industry, agriculture, infrastructure, recreation, and the environment shift the focus from critical minerals, as found in northern Ontario, to hydrogeology, land-use planning, aggregate extraction, and geohazards.

Recognizing these demands, the Ontario Geological Survey (OGS) created a series of seamless GIS-based maps across Ontario to support water resource, environmental, and geotechnical projects. These maps include seamless surficial geology, physiography, Quaternary sedimentary and Paleozoic bedrock geology, and sediment thickness maps, all of which have remained flagship products after more than 20 years. However, these two-dimensional maps only tell a portion of Ontario's complex geological story. After a successful pilot project completed in 2007, three-dimensional (3D) Quaternary sediment mapping has become a core program area for the OGS Groundwater Initiative.

These 3D mapping projects have been designed to provide the public with a baseline understanding of the hydrostratigraphic units beneath urban and rural areas of southern Ontario. Each project follows a standardized, well-established workflow from project inception to delivery of final products while maintaining flexibility to address the specific needs and issues related to each geographical area. The goals of each project are to reconstruct the regional Quaternary-aged glacial and interglacial histories, assemble standardized subsurface databases of project-specific and legacy geological and geophysical information, develop implicit 3D hydrostratigraphic models of regional-scale sediment packages, and generate technical and non-technical products for a diverse set of clients. Over the years, ministries from all levels of government, conservation authorities, and consulting companies have been the primary users of the models and supporting datasets.

Despite the challenges of working with an abundance of low-quality lithologic descriptions available through water well records, and relatively scarce high quality cored boreholes drilled on roughly 5 to 10 km intervals, the OGS's 3D Quaternary mapping team has been justifiably proud of the models and related products that have been delivered to end users. As an increasing number of practitioners have used and analyzed the data contained within the hydrostratigraphic models and associated data delivery products, the strengths and the weaknesses of the models have become apparent. With continuous improvements in mind, the OGS 3D team and groundwater practitioners work together to learn more about the modelling process, how models are being used, and the effectiveness of the OGS's end products. This presentation identifies how public and private organizations use OGS products, provide feedback to the OGS modelling team, and work cooperatively to solve groundwater resource challenges on both regional and local scales.

Recently, OGS 3D Quaternary mappers joined a multi-ministry team developing scientifically defensible recommendations for extending Protected Countryside designation under Ontario's Greenbelt Act to include a high-profile moraine. The primary drivers for this were groundwater recharge and flood protection. The moraine was viewed by other ministry team members as homogeneous gravel-rich entity with a hummocky topographic surface expression, and something that should be easy to draw a line around. However, new lidar data revealed a varied landscape comprising the moraine core, as well as meltwater channels and outwash fans that coalesce into broad plains. Once the complexity of the moraine system (both landforms and sediments) was communicated to the team, the decision was made to develop two landform-derived boundaries. One boundary was restricted to the moraine core of hummocks and ridges, and a slightly larger boundary that encompassed contiguous ice marginal fans and other coarse-grained sediments. However, based on the stated goals of the team, there was a need to advocate for, and then define, a third, more expansive boundary which incorporated thick buried sand and gravels connecting groundwater recharge areas within the moraine system with discharge areas in adjacent streams as well as private and municipal water supply systems. This third boundary was defined using a combination of regional 3D sediment models in the northern and southern portions of the study area, and water well records in between. These efforts highlighted the importance of 3D models for supporting decision making but also the difficulties in communicating the complexities of buried landscapes to non-subject matter experts. Importantly, gaps in product delivery were identified by experiences of using older 3D models. This information is now being used to develop new products and maps such as summary stratigraphy maps (Figure 1).

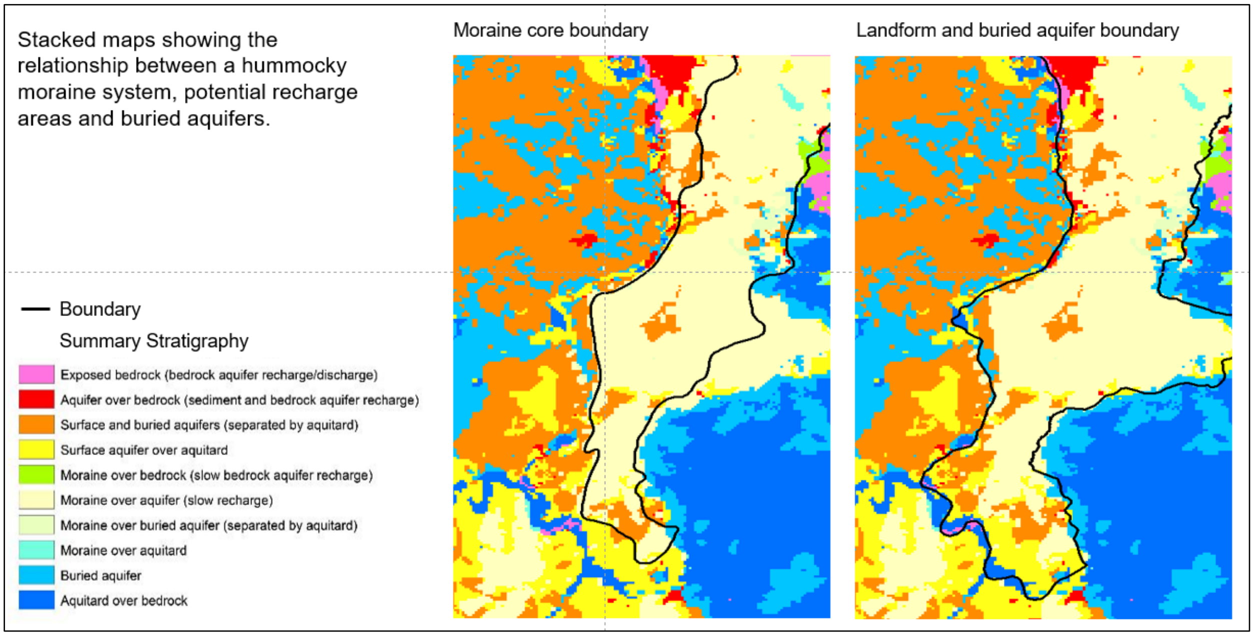

Figure 1: Example of a new derivative map product illustrating the relationship between aquifers, confining layers and a moraine system.

In Ontario, Conservation Authorities are watershed-based agencies responsible for programs which ‘protect people and property from flooding and other natural hazards, and to conserve natural resources for economic, social and environmental benefits’ (https://conservationontario.ca/). They are regulated under the Conservation Authorities Act. The Grand River Conservation Authority (GRCA), geographically the largest of the 36 Conservation Authorities across Ontario, has an approach to watershed-based resource management guided by the following principles:

- The watershed is the appropriate scale for managing water and the linkages between water and other natural resources.
- A well-managed river system is crucial for a healthy watershed, sustaining prosperity, growth, well-being, and climate change resiliency.
- Collaboration is essential, as the management of water and land is a shared responsibility among the conservation authority, municipalities, First Nations, government agencies, landowners, residents, and other interest holders.
- When making decisions, the GRCA considers the broad range of water uses and values, and the needs of natural and human communities.
- The GRCA’s programs adapt and respond to changing conditions, priorities, vulnerabilities, and pressures.

Hydrostratigraphic models have supported these management objectives through an increased understanding of Quaternary sediments across the watershed, 3D conceptualizations, and hydrostratigraphic models. For example, the Whitemans Creek subwatershed, a world-class cold-water fishery, contains cold-water dependent aquatic species at risk. The subwatershed is also an area of intense agriculture. The cold-water portions of Whitemans Creek and groundwater used for irrigation to support agriculture rely on an extensive shallow sand aquifer. The OGS developed a hydrostratigraphic model for the area which was used as the basis for a GSFLOW model and irrigation demand model for future water management in the subwatershed. In the Township of Centre Wellington, also within the Grand River watershed, the OGS 3D Quaternary hydrostratigraphic model was used to inform the development of a groundwater model in a municipality that is completely reliant on groundwater for municipal supply. This study involved both a private water bottling company and the local municipality who were interested in safeguarding future municipal groundwater sources in the face of a rapidly expanding population.

Other collaborative efforts have focused on augmenting baseline data. The GRCA maintains a long-term monitoring well network consisting of 60 wells across the watershed. Seventeen of these wells have been converted from OGS investigative boreholes into long-term monitoring wells. The wells are commonly situated in areas of high-water demand, or areas subject to drought management, and away from local pumping influences. Monitoring data from these wells informs local programs such as Low Water Response during times of drought.

In addition to GRCA's watershed-based resource management approach, Conservation Authority's across Ontario work with the Province and local municipalities to deliver the Source Protection Program under Ontario's Clean Water Act (2006). As part of the program, each municipality has developed local groundwater flow models to map quality-based Wellhead Protection Areas for their municipal water supply wells, and in areas under moderate to significant water quantity stress, have assessed the long-term sustainability of their municipal supplies through detailed groundwater flow models.

Consulting hydrogeologists and hydrogeological engineers have used the 3D hydrostratigraphic units created by the OGS to form the backbone of their Conceptual Site Models for these groundwater studies. The 3D hydrostratigraphic layers provide drillers, and geoscientists with early interpretations of the hydrostratigraphic layers that may be encountered when drilling new wells, with the understanding that the OGS layers are created at a regional scale, and local variations are expected. The reports and data that are included in the 3D sediment mapping products alongside the 3D hydrostratigraphic surfaces describe the interpreted depositional environment under which each unit is laid down. These interpretations are invaluable as they provide insight into how continuous or discontinuous certain aquifers or aquitards may be in the subsurface. In the Region of Waterloo, the Town of Orangeville, and the Town of Erin, OGS hydrostratigraphic units were refined using groundwater levels and chemistry data. The locally refined hydrostratigraphic units were then used as surfaces to create groundwater flow models of the area and these models were used to evaluate the source of water for municipal drinking water wells (i.e., Wellhead Protection Areas) and evaluate the long-term sustainability of the supply wells when considering drought, future land use, and future municipal pumping rates. The impact of groundwater-surface water interactions and how future municipal pumping may impact sensitive surface water features have also been evaluated. Other uses are to better understand contaminant transport through the subsurface.

Hydrogeologists and hydrogeological engineers working on groundwater studies across Ontario require improved visualization tools and so the OGS is working with Aqua Insight Inc. to create cross-section tools for several 3D sediment mapping areas. The cross-section tools are designed to run on any computer with an internet browser, and they allow the users to draw a polyline on a plan view map and immediately see a cross-section that illustrates the OGS's 3D hydrostratigraphic surfaces. Figure 2 provides a sample of the cross-section tool that will be available free of charge, and accessible to all those who have a computer with an internet connection. Other feedback has focused on the impacts of adopting a clip-and-merge modelling technique as well as how highly discontinuous units were modeled. Being open to suggestions for improvements will ensure future models meet client needs well into the future.

Publicly accessible baseline geological interpretations and 3D hydrostratigraphic models streamline the efforts of practitioners across the Province. The OGS provides regional scale interpretations of not only plan view maps of geology and geological features, but they also have worked hard to provide 3D sediment mapping products that have saved municipalities and private industry thousands of dollars. The OGS has advanced the bar to create cross-section tools that will enhance the accessibility of the data for end users and bring the OGS's interpretations to an even broader audience. While there are ever more pressures to reduce Provincial funding, publicly accessible and unbiased, baseline geoscience data and expert knowledge to help support local decision making is more important now than ever before.

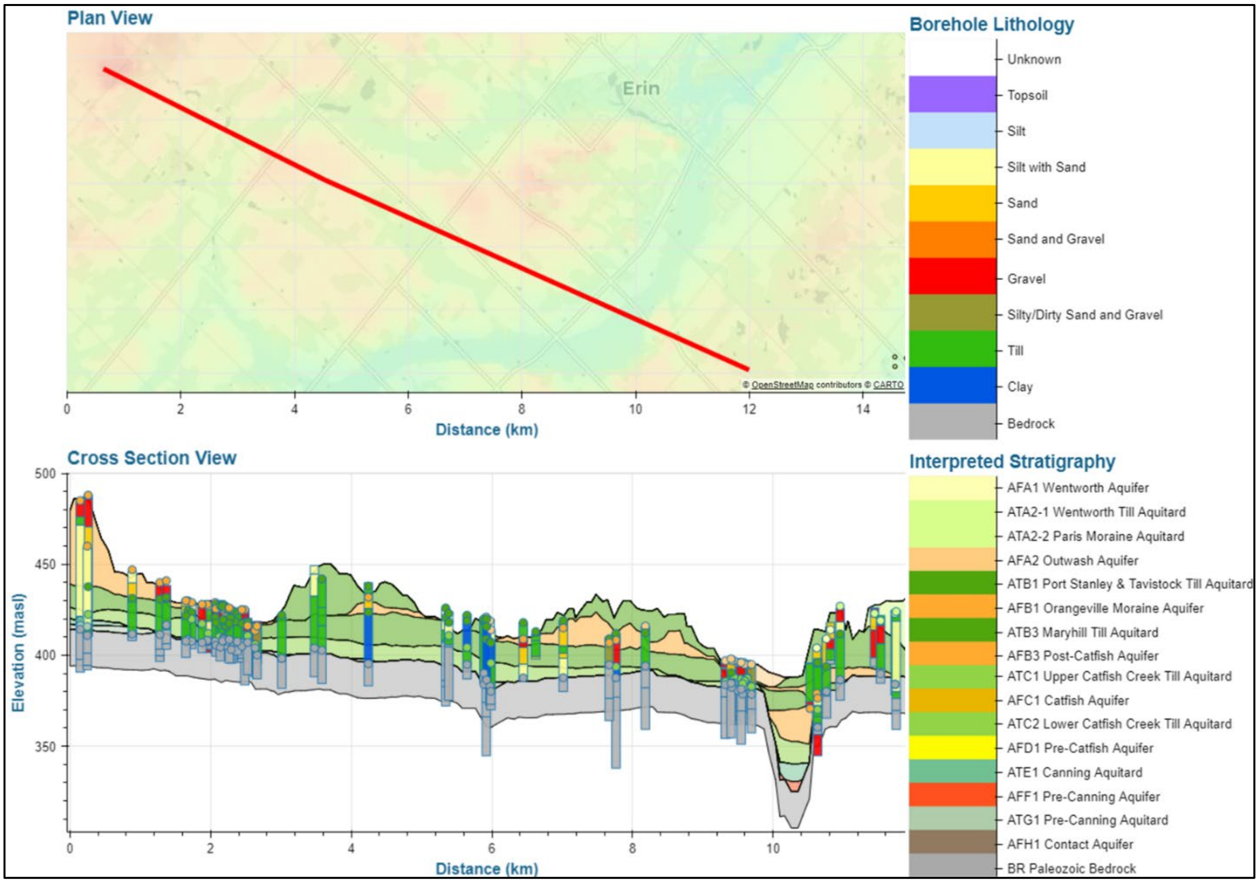

Figure 2: Sample of OGS Cross-section Tool in the Orangeville-Fergus Area.

3D GEOMODELLING EXPERIENCE AT THE BRGM (FRENCH GEOLOGICAL SURVEY)

Calcagno, Philippe and the 3D geomodelling team

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Introduction

BRGM, the French geological survey, is France's leading public institution for Earth Science applications in the management of surface and sub-surface resources towards sustainable development. Under partnerships with numerous public and private stakeholders, BRGM focuses on scientific research, expertise and innovation. Its activity meets four objectives:

- Understanding geological phenomena and related risks,
- Developing new techniques and methodologies,
- Producing and distributing data for surface, subsurface, and resource management,
- Providing the tools required to manage the surface, subsurface, and its resources, prevent risks and pollution, and manage policies in response to climate change.

Our missions as a Geological Survey benefit from fifty years of experience from field mapping to quantitative and predictive geosciences. One of BRGM's main roles is to produce and disseminate 3D geological information on the subsurface (Courrioux et al., 2016; Lopez et al., 2017). Outcrop and borehole observation data, geological maps, geophysical surveys, and any other data giving information on the geological structures are used to construct BRGM's geomodels. They are produced for various applications such as tectonostratigraphy (Maxelon and Mancktelow, 2005), urban planning (Bourgine et al., 2008), water resources (Lacquement et al., 2011, Figure 1; Pennequin et al., 2017), geothermal energy (Calcagno et al., 2022; Mas et al., 2022), and mineral resources (Pochon et al., 2023).

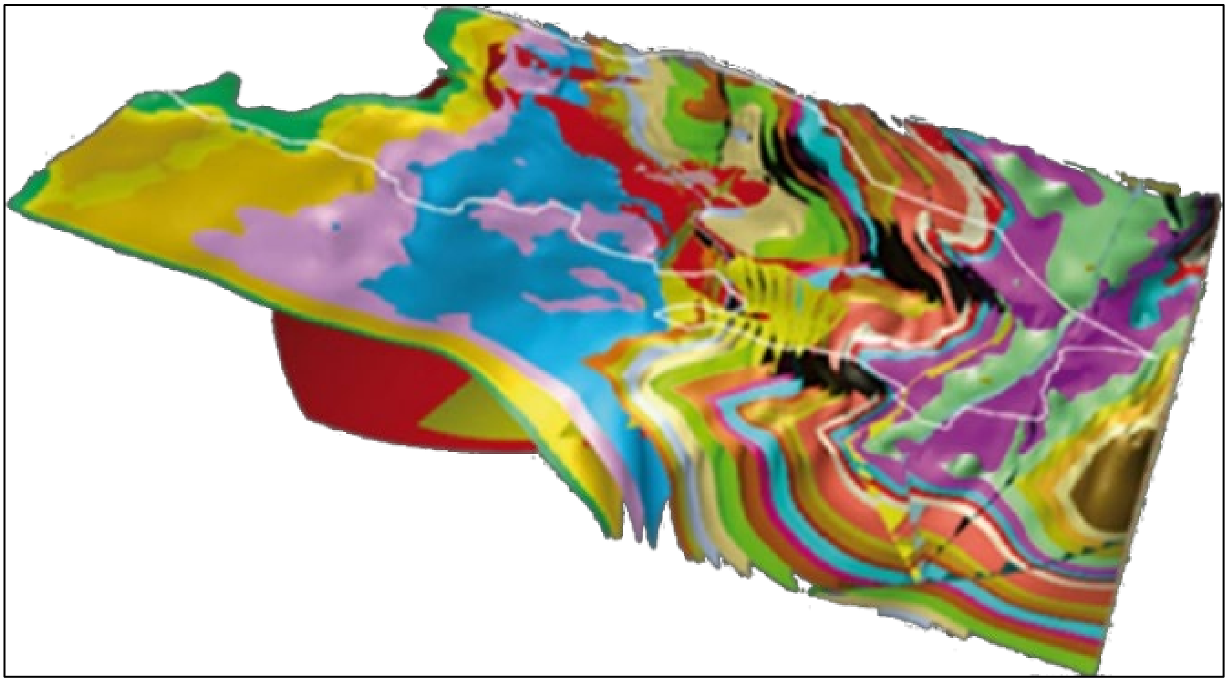


Figure 1: 3D geological model of the Givet zone (France) for water resources management (Lacquement et al., 2011).

BRGM is investing in the development of 3D geological modelling methods as well. The goal is to produce models as realistic and accurate as needed for the final applications. We need to take into account as much as possible the full range of available data and information to improve our geomodels, but also the geological processes driving the underground. In addition, we pay close attention in making interdisciplinary 3D geological interpretations.

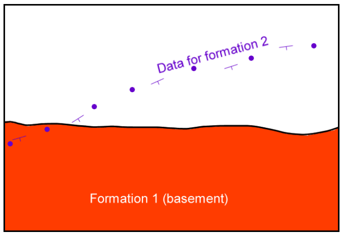
Original methodologies and packages for 3D modelling

Georges Matheron, who spent part of his carrier at BRGM, was a pioneer in geostatistics in the 1960's. His work (Matheron, 1989) has deeply driven the setup of geological modelling techniques (Chilès and Delfiner, 1999), and often co-constructed with MINES Paris Tech (Renard et al., 2019). Based on these techniques, BRGM was the first geological survey organisation to develop in-house geological modelling tools that are still in use in various countries.

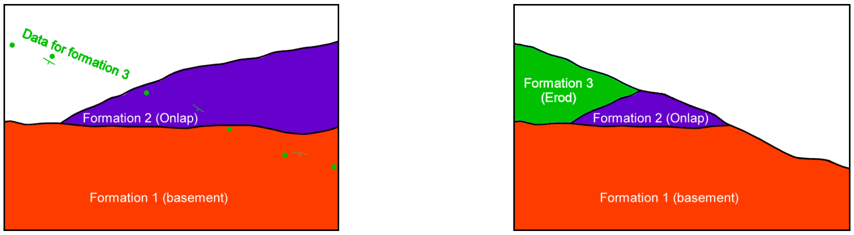
One of the most famous software in that lineage is GDM (Geological Data Management). It served in the middle of the 1980's to optimise the geological reconnaissance campaigns of the Channel Tunnel and helped the design of its route. GDM is based on a powerful geostatistical toolbox dedicated to the interpolation of elevation surfaces and thicknesses in an explicit way. It produces 2.5D models especially efficient in multilayer geological contexts. GDM is also a powerful tool to manage borehole data and to cross-validate them.

Another emblematic software developed by BRGM is GeoModeller. In the 1990's, it was born from the will to transpose geologist's classical representation tools into the numerical world. The goal was to work with geological maps, cross-sections, and boreholes in a computer environment and to interpolate all of these data in an implicit 3D model. The process is based on a potential field interpolation, initially developed in 2D (Lajaunie et al., 1997). It was generalised a few years later in 3D and improved with a geological pile concept to manage various potential fields (Calcagno et al., 2008, Figure 2). The potential field interpolation method allows the estimation of uncertainties in theoretical (Aug, 2004) and empirical (Courrioux et al., 2015) ways. In addition, capabilities for gravimetric and magnetic susceptibility forward and inverse computations were added to GeoModeller (Guillen et al., 2008).

Figure 2: Taken from Calcagno et al. (2008). Complex geology is modelled using different potential-field functions for different geological series. These multiple potential fields are managed using Onlap and Erode relations between series. In this example, each series comprises a single formation.



(a) Interpolated Formation 1 (basement) and data for potential field of Formation 2.



(b) Formation 2 interpolated using an Onlap relation and data for potential field of formation 3.

(c) Formation 3 interpolated using an Erode relation.

Interdisciplinary approach

The way in which geomodelling tools are used plays a role in the validity and robustness of the geomodels. Particularly, the integration of data and information coming from various scientific fields, enabled by geomodelling is crucial to produce quality models. Using these data in an interdisciplinary approach is powerful to set up a common interpretation (Hollis et al., 2024). If the construction of the model is interactive and allows on-the-fly adjustments, the process can be used as a collaborative platform to exchange and debate among the specialists of the disciplines feeding the model.

Usually, data are aggregated in a workflow process (Maxelon et al., 2009). For instance, data and information from geology, gravimetry, magnetotellurics, and geochemistry can be combined to construct a geomodel. Typically, in a workflow, the contributions from each of these four scientific fields are added one after the other in a sequential way. Associating data in a workflow methodology satisfies the forecasted objective of combining multi-discipline data. However, these disciplines are used chronologically and independently, making difficult common and crossed reasoning.

Merging the contributions from the scientific fields instead of simply aggregating them is a step forward. The interpretation of a given discipline may benefit from the input of another discipline, with no chronological preference in the process. For instance, the geological interpretation could benefit from the magnetotellurics interpretation or vice versa. In that case, the geomodel is no longer the only final result of a sequential data integration, but rather, it is the main and central object of the interpretation process (Calcagno, 2015; Figure 3).

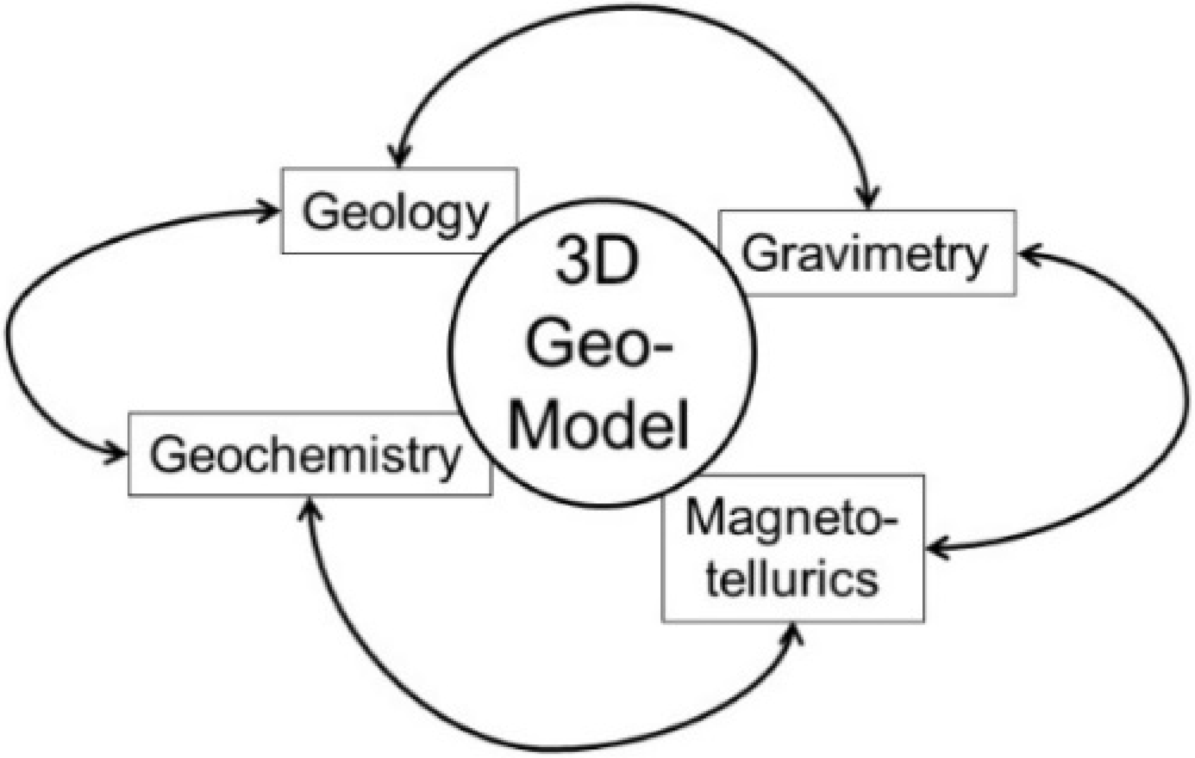


Figure 3: The 3D geomodel is the central part of the interpretation. Scientific fields cooperate and interact to produce a common interpretation.

Tackling the next challenges

Producing 3D geomodels better adapted to the final application (e.g., mineral resources exploration or risk mitigation) is one of the main challenges at BRGM. It requires taking into account of the geological context specificities and an increasing number and types of data and information. We need to keep R&D capacities to propose new solutions that are able to overcome the obstacles we encounter in the geomodelling process. Our in-house historical tools were the place to develop new methodologies and turn them into operational functionalities. However, these packages were designed as monolithic tools offering few options for combining capacities from one to the other. On top of that, their technological debt has increased and they have become increasingly difficult to maintain.

Consequently, we have started a transition phase to move from our historical packages to codes that are more versatile. The first step is to make the original methodologies that we have developed over the years, independent and combinable via an integrative platform. This modular approach allows for the mix with other codes (e.g., open source) to construct a 3D geomodel. As an example, geological surfaces, each one interpolated by the most appropriated algorithm depending on the nature of the surface, can be assembled to complete the model. We have developed a set of modules embedded in QGIS plugins. This brings the GIS, commonly used by geologists, and 3D modelling ways of working closer together (Figure 4).

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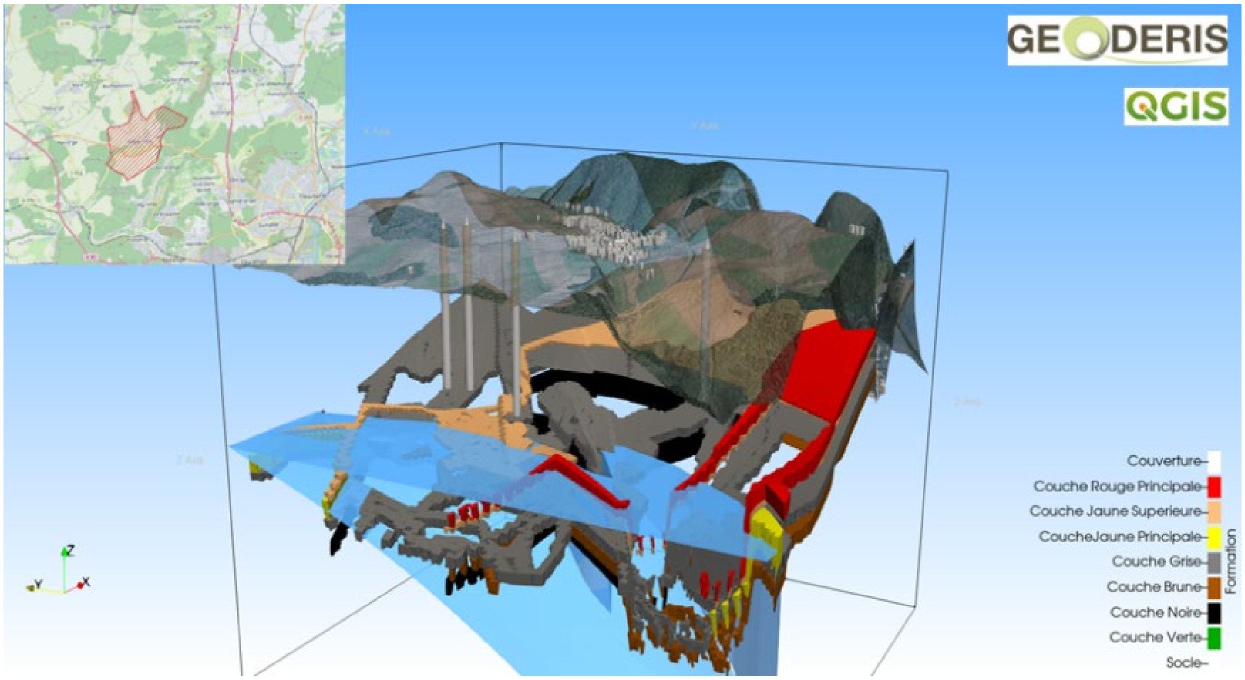

Figure 4: 3D scene plugin in QGIS combining geology and anthropic tunnels (Janvier, 2023).

In a second step, we intend to go further in leading edge R&D to better fulfil the needs of the final application, but also to improve the computational performance in the modelling process. New methodologies to tackle fault offset or to consider geophysical inversion remains to be set up. The ability to operate in 3D when integrating data and working on the interpretation, beyond classical 2D maps and cross-sections, would improve the user experience. On top of that, being able to perform 3D modelling in the field would be a step forward in the interaction with outcrops during fieldwork.

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APPLICATIONS OF 3D MODELING TO GEOTHERMAL RESOURCE EVALUTION, GREAT BASIN REGION, WESTERN USA: LESSONS LEARNED IN STUCTURALLY COMPLEX VOLCANIC TERRANES

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The Great Basin region of the western U.S. is one of the largest geothermal provinces on Earth, thanks to crustal thinning, high geothermal gradients, and abundant active faults in this extensional to transtensional region. This region has been subjected to multiple orogenic events, which have included large magnitude folding and thrusting in late Paleozoic-Mesozoic time followed by regional extension-transtension in the Cenozoic. Voluminous volcanism associated with arcs and the Ignimbrite flare up have also swept across the region. Although beset with challenges due to complex structures and stratigraphy, with multiple overprinting events, detailed 3D modeling is possible given availability of well and geophysical data to provide subsurface control.

Detailed 3D models (Figure 1) have been completed for several geothermal areas in the region, including Bradys, Soda Lake, Granite Springs Valley, Fallon FORGE, SE Gabbs Valley, Astor Pass, Neal Hot Springs, Steptoe Valley, and Tuscarora. Most 3D modeling was carried out by Dr. Drew Siler while with the Nevada Bureau of Mines and Geology and the USGS. Datasets incorporated in the models included geological mapping, well logs generally after review of cuttings and/or core, fault kinematic data, slip rates and age of ruptures on Quaternary faults, regional stress field, gravity, magnetics, MT, and seismic reflection profiles (if available). The 3D models provided insight into fault geometries, structural controls on fluid flow, geothermal reservoirs, and conceptual models. In some cases, it resulted in the first firm estimate of which units contained geothermal reservoirs for operating plants. The models also elucidated subsurface structure by modeling density of fault intersections and slip/dilation tendency, both crucial in controlling fluid flow. Three-dimensional geophysical inversions were employed at some sites to test results. The size of the 3D models varies, but generally do not exceed ~ 200 km^3, with depths from ~2-3 km. Considering that such modeling is relatively low cost, it is worthy of investment, as the process of making the model refines the 3D perspective, which leads to more informed selection of drill sites and reduces risks. These efforts show that 3D modeling is alive and well in a complex terrane like Nevada, but by necessity is generally finer in scale and focused more locally, as compared to 3D modeling in some other parts of the country.

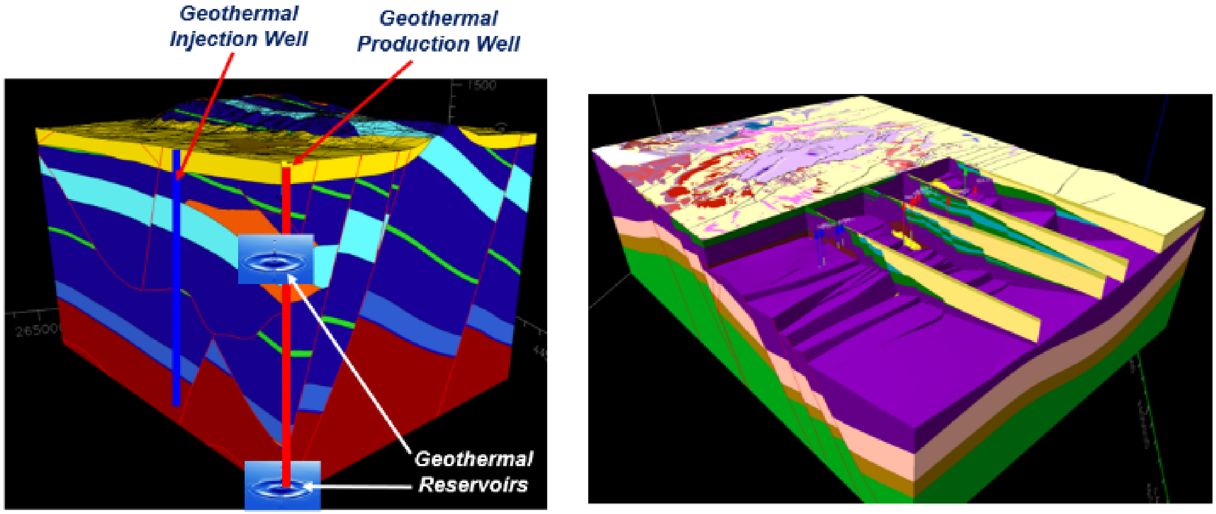

Figure 1. Representative 3D models of structurally complex geothermal systems in Nevada. The 3D models are based on detailed geological mapping, abundant well data, detailed gravity surveys, and seismic reflection profiles. Models were constructed by Drew Siler.

FUTURE OF URBAN 3D MODELLING IN THE UK

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Urban Geological Modelling is increasingly becoming a unique subset of 3D geological modelling and is distinct from those geological models created to aid Geothermal, Groundwater, Carbon Capture and Storage, Radioactive Waste disposal, and conventional and unconventional hydrocarbons because it focuses on shallower depths, typically the top 50m (Figure 1). Three-dimensional geological models characterise the changes in depth and spatial distribution of rocks and sediments in the subsurface, providing sophisticated tools for enhanced geological understanding. These models are increasingly at the core of decision making and support advanced analysis for ground conditions, groundwater systems, geothermal assessments, and subsurface storage. Urban contexts provide specific drivers that influence the design and content of the geological model. Urban models need to:

1. Make predictions relevant to urban scales of interest (e.g., development and infrastructure sites).
2. Be efficient to develop and be easily updateable, to suit the more local-scale, higher turnover of urban projects.
3. Capture the lithological variability within geological units as relevant to engineering, geological, and hydrogeological considerations using methods like lithological property modelling (c.f. Kearsey *et al.* 2015).
4. Enable model outputs to be delivered in a range of formats and be interoperable with other urban and built environment data management and decision-making tools (e.g., Building Information Management (BIM) compatible)/
5. Have an automatic/semi-automatic calculation of the accuracy/uncertainty of the model in the workflow for integration within risk management workflows in ground models.

Three-dimensional geological modelling is increasingly becoming common practise in geotechnical and groundwater consultancy. The development of embedded 3D modelling capability within industry raises the prospect that the British Geological Survey's (BGS) role may need to shift from *informing* users through the provision of models and associated knowledge, to *enabling* users to create relevant knowledge themselves. The latter will require the delivery of QA'd baseline data, as well as services to review models and interpretations created by consultants. This shift will require a renewed emphasis on BGS geological expertise, and a new approach to the provision of data services (Bricker et al. 2021).

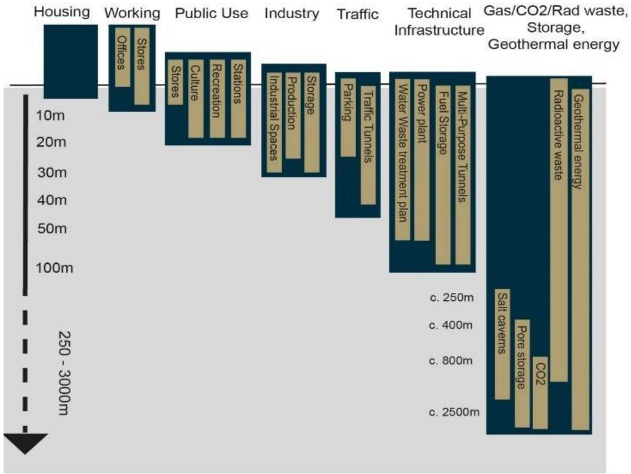

Figure 1. Depth ranges of underground activities (adapted from Evans et al. 2009).

Building urban models is particularly challenging in countries with diverse geology. In the UK, the BGS assessed the geology under 42 of the largest towns and cities. The ages of bedrock units that underlie the selected towns and cities are shown in Figure 2. Carboniferous, Jurassic, Triassic, and Palaeogene rocks collectively underlie 84% of these towns and cities by geographical area. The high proportion of Carboniferous rocks beneath the towns and cities is due to the proximity to coal, iron, and limestone resources, which controlled the growth of industrial centres in the 19th and 20th centuries.

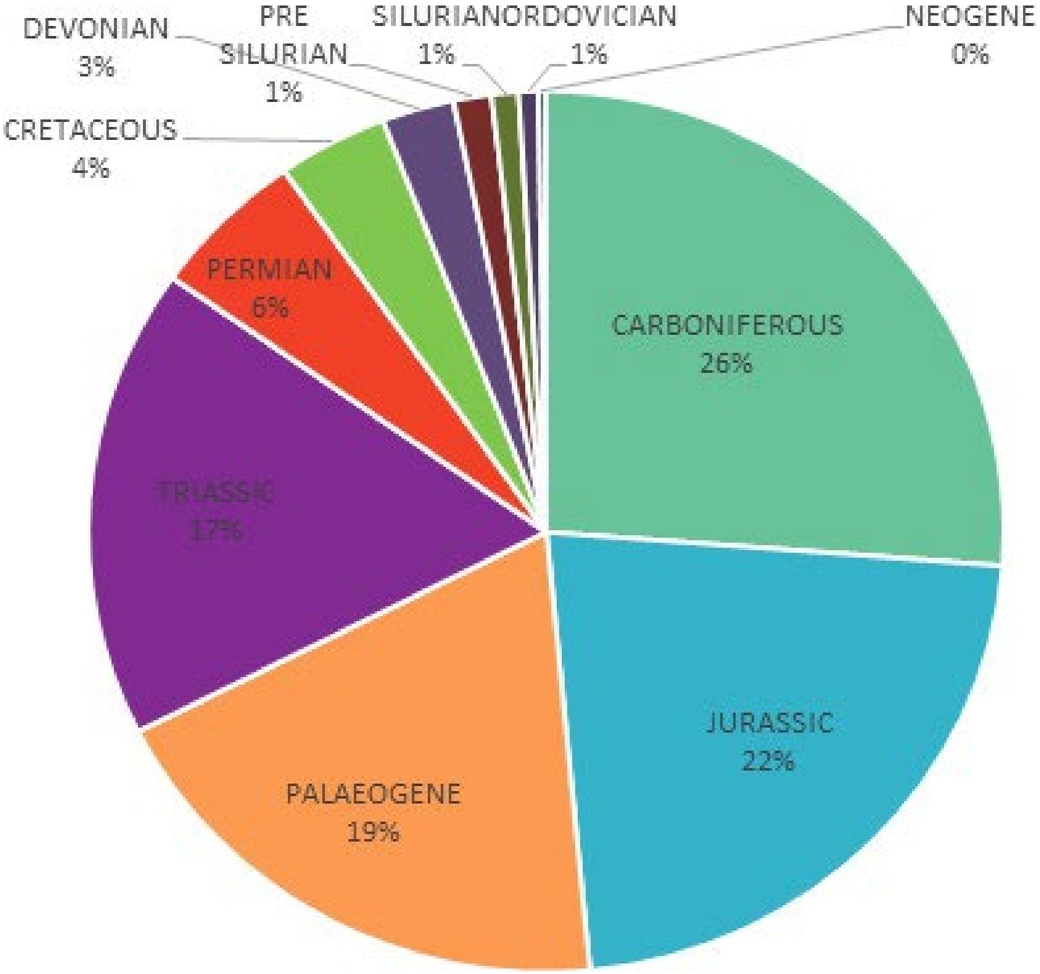

Figure 2. Ages of bedrock units underlying towns & cities by area of coverage.

Furthermore, the superficial deposits under the studied cities are variable and complex. They represent between 0.1% and 5% of the volume of the top 100 metres under the study cities (Figure 3). However, these deposits often account for the most complicated ground conditions (Terrington *et al.,* 2021). The average thickness of superficial deposits under the studied cities is 8.07m, yet the maximum is 108m (Four towns and cities have maximum thicknesses of superficial deposits that locally exceed 100m: Glasgow, Greater Manchester, Liverpool, and Barrow-in- Furness). Widespread glacial deposits are present in these areas and the exceptional superficial deposit thicknesses are likely to be associated with buried valleys, deep sediment filled channel-like features with no surface expression that are only revealed through boreholes/geological models.

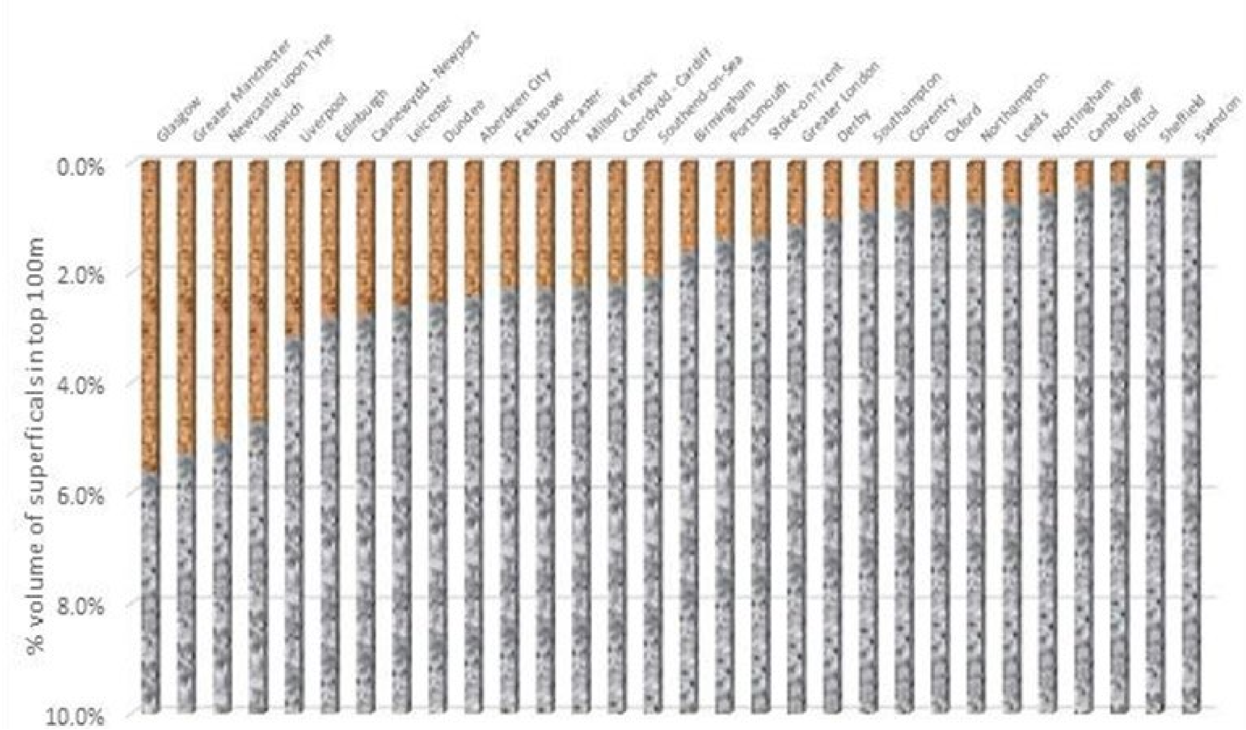

Figure 3. Percent volume of the top 100m under the study cities comprised of superficial deposits.

BGS geological maps are predominantly constructed using outcrops and geomorphology (feature mapping). Both are scarce in urban settings; instead, boreholes provide one of the main sources of information on the subsurface in these areas. Boreholes are used to inform geological maps in cities, but typically only 10-50 boreholes would be used on a 1:50 000 scale bedrock map sheet. This is a fraction of the subsurface information now available under most cities, which represents a step-change in our observations of the subsurface. The BGS is developing new methods to help speed up the ingestion and interpretation of data workflows for visualizing and interpreting clouds of boreholes, 3D interpretation borehole and rules-based interpretation semi-automated interpretation borehole into the model building process to limit the time spent creating fences of cross-sections.

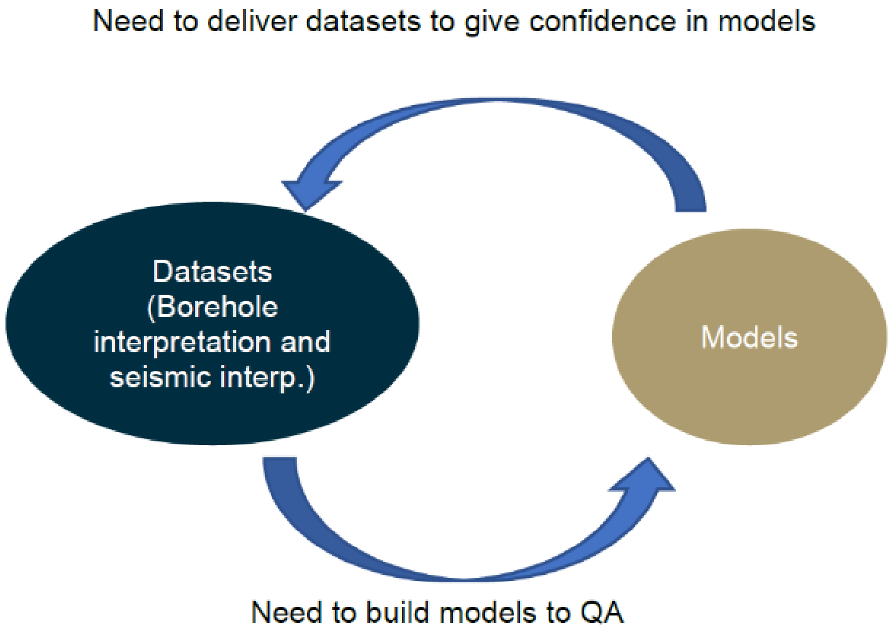

Figure 4. The circular link between models and between models and borehole datasets.

Finally, within the ground investigation community, we are seeing the role of Urban Geological models changing. The 3D model itself is not being viewed as the end point, as is the case with a traditional geological map. Stakeholders increasingly want the interpreted datasets that sit behind the model, such a stratigraphic interpretation of boreholes. This is so they can integrate the regional understanding into their site scale models. As a result, the role of an urban geological model shifts to demonstrating the regional interpretation of the borehole data.

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3D STRATIGRAPHIC AND STRUCTURAL MODELLING OF THE NORTHERN INTERIOR PLAINS AND PROTEROZOIC BASEMENT IN THE REGION OF COLVILLE HILLS, NORTHWEST TERRITORIES, CANADA

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Over the last few decades, the Mackenzie Corridor located along the Mackenzie River in Canada's Northwest Territories (NT) (Figure 1) has been intensively studied and has become a region of major hydrocarbon exploration and production (Hannigan et al. 2011), especially in the Mackenzie Mountains foothills (Norman Wells area) where hydrocarbons have been identified and exploited in the Devonian Horn River Group. More recently, the shift in priorities of the Canadian government and the growing interests of local communities for the characterization of sustainable regional georesources (with a focus on regional geothermal, groundwater, CCS, natural hydrogen and storage potential) and critical minerals (Cu, Zn, P, He, Li, K), have raised the need to further investigate the regional geology in the northern Interior Plains. Previous research (Grasby et al., 2012) identified significant geothermal potential overlapping the study area, which is of interest to the isolated communities (Norman Wells, Colville Lake, Fort Good Hope, Paulatuk) of this remote region.

The northern Interior Plains located north of the Cordilleran Foreland Belt (Mackenzie Mountains and Franklin Mountains), east of the Mackenzie River and west of the Canadian Shield, encompass deformed and undeformed Proterozoic to Paleogene sedimentary strata (Figure 1). Cretaceous to Paleogene siliciclastic Cordilleran foreland deposits (Fallas et al. 2021) overlie carbonate, clastic, and evaporitic Cambrian to Devonian sediments. The latter rest unconformably on a thick and deformed Proterozoic sedimentary strata deposited on the NW margin of the crystalline Canadian Shield (Cook and MacLean. 2004). This thick Proterozoic to Paleogene sedimentary succession recorded the complex regional deformation history, marked by multiple geodynamic events including the Paleoproterozoic Racklan and Forward Orogeny, Proterozoic and Cambrian rifting and the Cretaceous-Paleogene Cordilleran orogeny. Those events alternated with periods of relative tectonic hiatus and erosion evidenced by major regional unconformities.

In this general context, the current research project aims to refine our 4D understanding of the Proterozoic to Paleogene structural and stratigraphic evolution in the Mackenzie Corridor. It is based on the 3D geological modelling of the regional scale stratigraphy and structure of the northern Interior Plains and the Proterozoic basement in the region of Colville Hills, using the 3D SKUA-Gocad geomodelling software. This new 3D perspective was produced by integrating and interpreting legacy surface geological data (geological maps, 450 planar and linear structural measurements) and subsurface geophysical data (296 seismic reflection profiles, 50 wells and associated logs) acquired in the region over the last few decades (Figure 1). Use of seismic-reflection data and available interpretations (Cook and MacLean. 2004; MacLean, 2012) required revision and time-depth conversion. Prior to the time-depth conversion, a velocity model was built using average velocities computed from well markers and calibrated seismic horizons in time and interpolated in 3D. 3D modelling progressed from the data-rich region of Colville Hills to data-sparse surrounding areas (Brock Inlier). First, regionally continuous, stratigraphic marker horizons were identified and interpreted; the stratigraphy was then expanded depending on the data available for each unit. A total of 20 stratigraphic units were modelled in 3D.

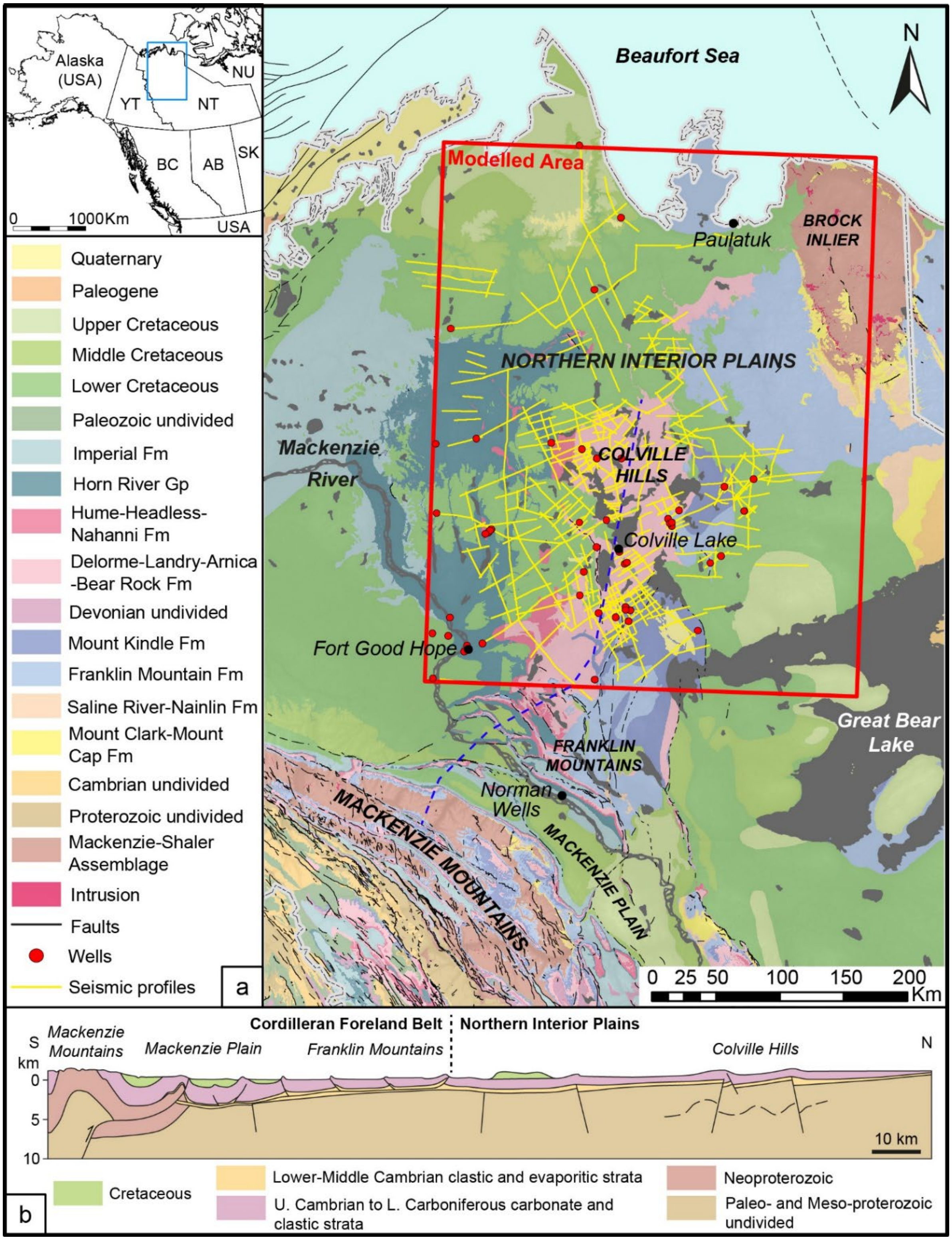

Figure 1: a. Harmonized geological map of the Mackenzie Corridor in the Northwest Territories, Canada reporting the location of the seismic reflection profiles and wells integrated in the 3D Model. Compilation of Canadian Geoscience. Maps and existing geological compilation (Okulitch and Irwin. 2014). b. Structural cross-section from the Mackenzie Mountains to the Colville Hills. Modified from Fallas et al. (2021) and Hannigan et al. (2011). The location of the cross-section is represented by a blue dashed line on the geological map.

Besides characterizing the 3D geometry of the Proterozoic (Figure 2) to Paleogene strata and mapping Cordilleran and basement structures (thrust faults, steeply dipping reverse and normal faults, relay faults, flower structures) in the northern Interior Plains (Figure 3), this 3D interpretation allows us to discuss the deformation history in the region and the influence of inherited Proterozoic basement structures on the Phanerozoic deformation dynamics. Results show a concentration of Cretaceous to Paleogene Cordilleran deformation (folding, faulting) above the preexisting Proterozoic structures, and single or multiple reactivations and/or inversions of basement faults during regional tectonic events in the Proterozoic (Forward Orogeny) and the Paleozoic (Cambrian rifting).

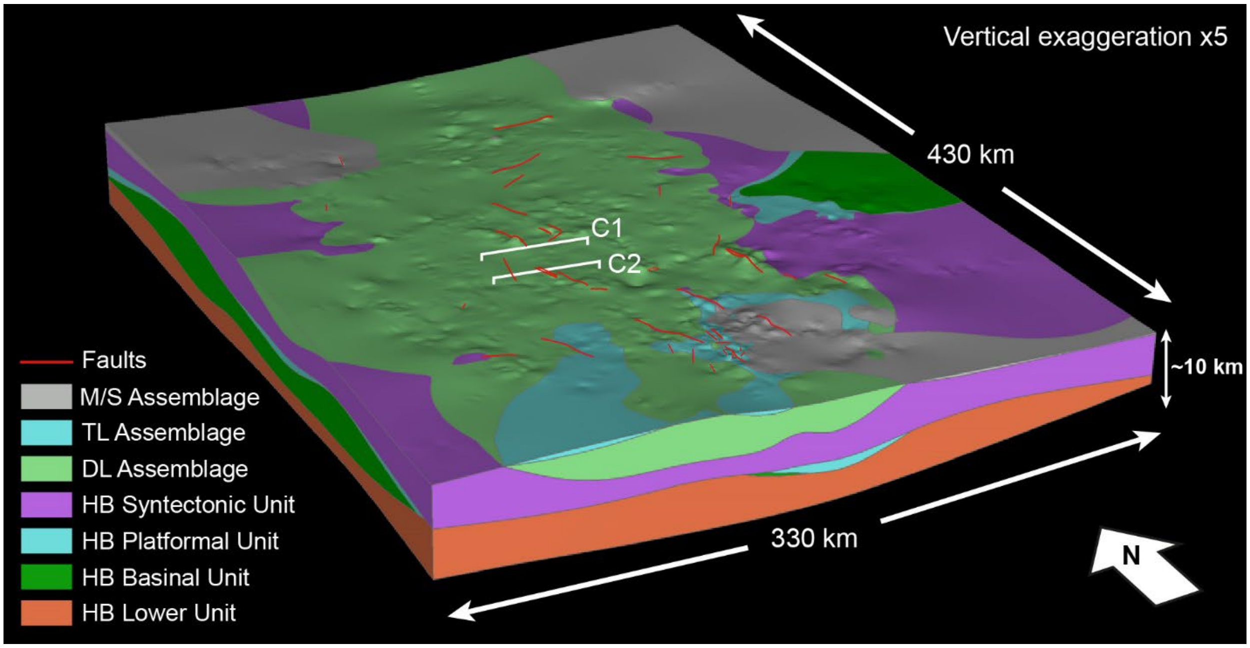

Figure 2: 3D structural model of the Proterozoic basement in the region of Colville Hills. This preliminary version of the model was computed in time domain, using the SKUA-Gocad geomodelling software. M/S: Mackenzie/Shaler Assemblage; TL: Tweed Lake Assemblage; DL: Dismal Lake Assemblage; HB: Horny Bay Assemblage. The cross-sections C1 and C2 are illustrated in Figure 3.

By providing an up-to-date geological framework, this study represents the first steps towards assessing georesource potentials (geothermal energy, CCS, hydrogen mining and storage, critical minerals) in the region. It contributes essential constraints for future environmental assessments (groundwater) and georesource potential evaluation, including (1) mapping of faults for locating ore bodies or identifying potential drains or seals within groundwater, hydrocarbon, hydrogen, and geothermal systems; (2) characterization of reservoir and cap-rock geometry (extension, depth, thickness, deformation); and (3) production of 2D and 3D materials to support future coupled hydrodynamic and/or geothermal systems modelling.

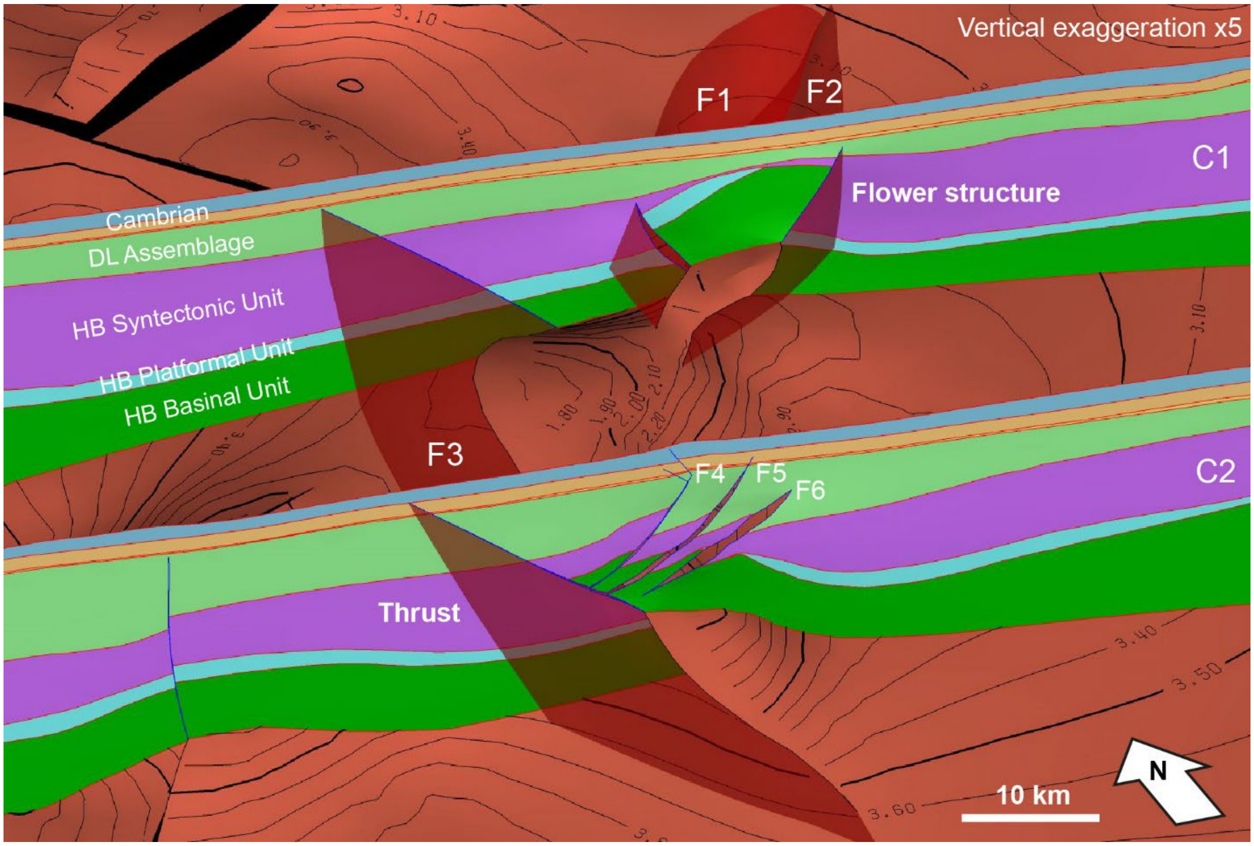

Figure 3: 3D view of the top of Horny Bay Assemblage Lower Unit (Proterozoic) modelled in the time domain (unit in seconds TWT), showing a flower structure (F1 and F2), a major thrust fault (F3), and a thrust-related anticline crosscut by younger reverse faults (F4, F5 and F6). Location of cross-sections C1 and C2 in Figure 2.

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UTILIZING OPEN-SOURCE DATA AND MODELING METHODS TO CREATE 3D HYDROGEOLOGIC MODELS ACROSS NEW MEXICO

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The Aquifer Mapping Program at the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) has been investigating the use of 3D geologic models to better quantify groundwater resources across New Mexico and to date have mapped a quarter of the state (Figure 1). This important work has been funded primarily by philanthropy (Healy Foundation) and the oil / gas regulatory agency (Energy, Minerals and Natural Resources Department (NM EMNRD)). Our initial goals for these maps were to better understand the extent and thickness of local aquifers, but more recently this work has been funded by the USGS as part of their 3D GeoFramework initiative. Historically, our funding been insufficient for any new large-scale data collection, and so the models are created from carefully curated public datasets. Typical datasets include surface geological mapping, formation contours, digitized cross-sections, water well drilling logs, and geophysical logs from oil and gas wells. The exact methods for developing these hydrogeologic models have varied for each region but the focus has remained on utilizing readily available tools such as ArcGIS, Python, and others to create our models in platforms that will provide the widest access to the final results. The pros and cons of these modeling approaches are presented here, along with potential new modeling techniques for future study areas.

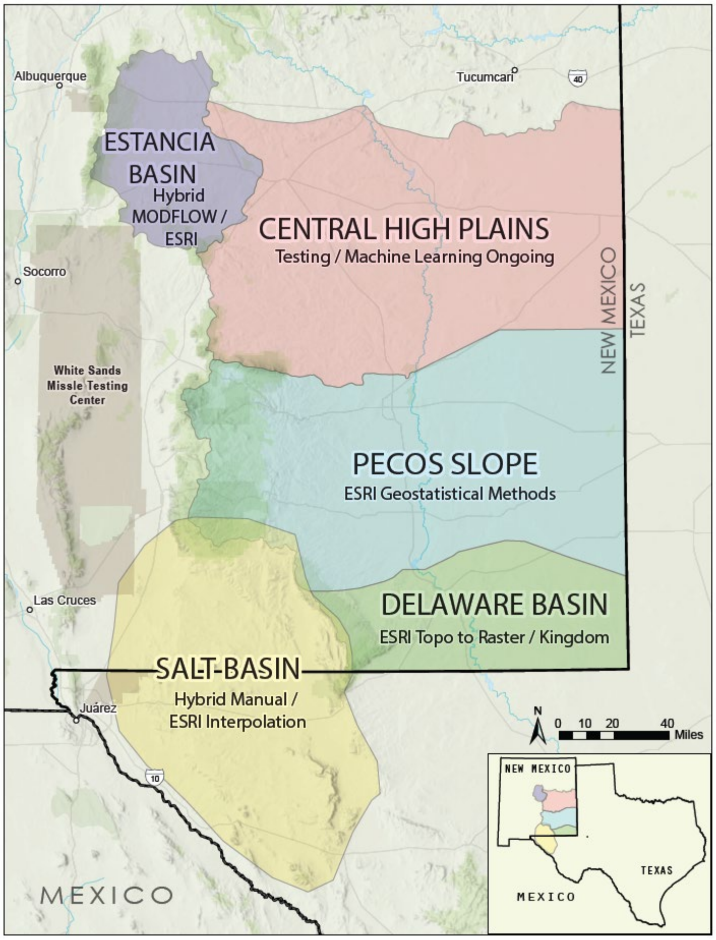

Figure 1: Location and extent of 3D hydrogeologic models completed by the NMBGMR.

The NMBGMR's first attempt at a regional 3D model focused on the Estancia Basin, a structurally, hydrologically, and administratively closed basin with limited groundwater. These dwindling water supplies led to the creation of a MODFLOW model by the New Mexico Office of the State Engineer (Shafike and Flanigan, 1999) for groundwater administration purposes. This model relied primarily on water well drilling records to develop hydrological zones within the basin. NMBGMR adapted this model into GIS by creating a series of Triangulated Irregular Network (TIN) datasets for the tops and bottoms of all hydrostratigraphic units (Newton et al., 2020). The extent of each unit was identified by delimiting where the model thickness was greater than 0 feet and then this footprint was extruded between the TIN surfaces in ArcGIS to create a 3D model volume (Cikoski, 2018, unpublished). While this modeling method was fairly straightforward, the overall result is constrained in accuracy by the limited original input data. Water well drilling logs, while often the only dataset available, can be overly general in geological unit description, and tend to focus on the shallowest hydrological unit at each site as drilling frequently only penetrates the top of a given aquifer.

Upon completion of the Estancia Basin model, the NMBGMR team focused efforts on the data-rich Permian Basin oil and gas fields of southeastern NM. This region of the state is geologically complex, containing shelf and reef deposits from Permian and late Ordovician seaways. Surface and groundwater sources are in high demand for both agricultural uses and oilfield development. In particular, the NM EMNRD was interested in using 3D modeling to issue more informed drilling permits and to prepare quicker and more educated responses to spills. The NMBGMR team approached this region by modeling it in two steps. The northern portion is referred to as the Pecos Slope (Figure 2), (Cikoski et al., 2020), and the southern portion is the Delaware Basin model (Fichera et al., 2024). Funding in these combined regions was sufficient to analyze and extract geologic picks from approximately 5,000 geophysical logs from oil and gas wells, which greatly enhanced the model accuracy. The data for this geophysical analysis required the effort of several staff over multiple years to process. This wealth of data allowed us to experiment with different interpolation techniques and the ability to create uncertainty maps for these typically deeper formations, however, processing such a large dataset did slow down the overall modeling timeframe.

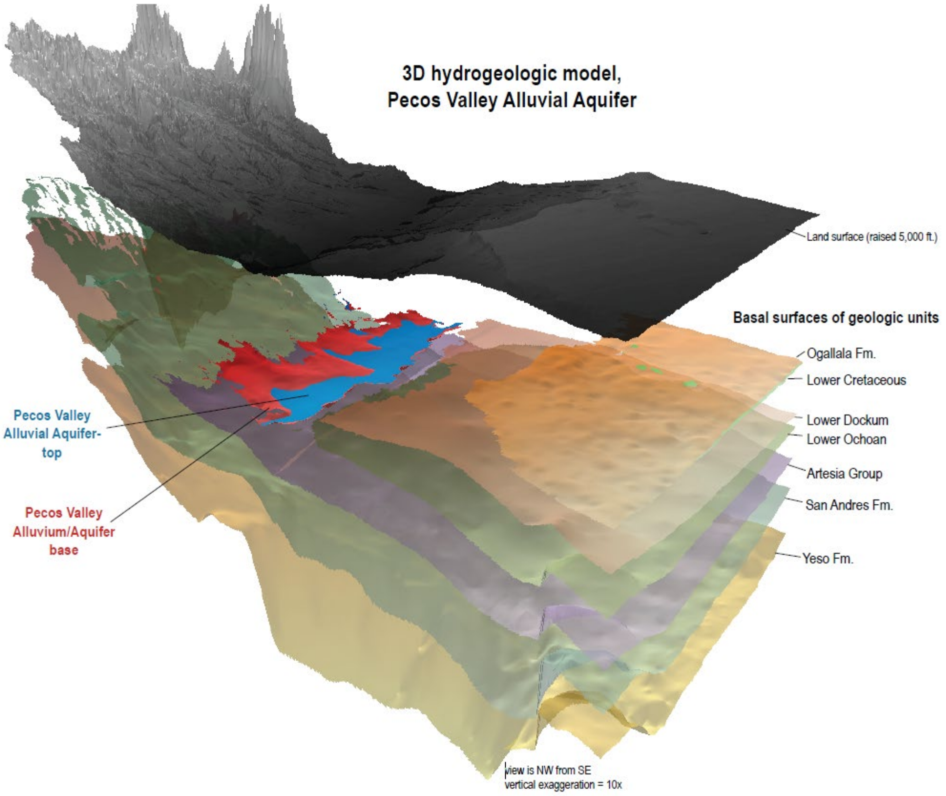

Figure 2: Exploded diagram of the Pecos Slope model showing the top elevation (blue) and bottom elevation of the alluvial aquifer in the region.

Interpolation of model surfaces for both the Pecos Slope and Delaware Basin were undertaken by combining the deep geologic picks from geophysical logs with the data for shallower surfaces through ArcGIS geostatistical algorithms. For the Pecos Slope region, a local polynomial interpolation was applied iteratively to identify and remove influential outliers that exceeded an ever-refining threshold. In the first iteration, points with a residual > 500 ft were removed, while in the second iteration, points with a residual >400 ft were removed, etc. These filtered datasets were interpolated using ESRI's Kernel Interpolation with Barriers algorithm which allows a user to define a series of fault traces along which the algorithm can accommodate fault displacement. Testing has shown that interpolation of some datasets produces nearly identical fits both with and without faults as input barriers. This suggests that the magnitude of displacement calculated by the algorithm is partly influenced by the density of available data. Additionally, the algorithm may not predict elevations in some locations with no or little data bounded by nearby faults. This can incorrectly predict the extent of a model unit and makes it difficult to assemble model units if the predicted model unit extents are different.

A distinction with the Delaware Basin model was the use of Kingdom ™ Geoscience Software to aid in the processing of regional geophysical logs. The Kingdom software proved to be a robust and time saving tool in this endeavor, allowing the team to process more logs in a smaller amount of time. The subsurface Delaware Basin model was created using the ESRI Topo-to-Raster algorithm, which is based on the ANUDEM algorithm (Hutchinson, 2011) and can also approximate fault offset from user-defined fault traces. The outliers for the Delaware Basin model were removed via a refined iterative process (compared to the Pecos Slope region) where points exceeding a constant threshold residual (100 ft) were removed. The Topo-to-Raster algorithm is prone to overfitting, so a Monte Carlo-style method was performed after the interpolation in which 10 randomly-sampled subsets of each model formation's dataset was interpolated and then compiled to develop a surface describing the uncertainty in the elevation of the model surface across the study area. This method is fairly robust, but has a few drawbacks. The outlier removal methodology is sensitive to the fault traces. Model testing identified a case where a poorly-constrained fault was not included in the interpolation, which resulted in nearby high-quality data points being automatically filtered out in the outlier removal module as the interpolation did not match these data points well enough without the modeler introducing fault offset. A large amount of subsurface data and interpretations were available for use in the Delaware Basin study area, which enabled precise analysis of the model surfaces. In data-poor regions, this level of analysis and strict outlier removal would not be appropriate.

Aquifer surface elevations and subsurface extent were developed for the Pecos Slope and Delaware Basin model by compiling many different data sources, including oil spill monitoring reports from NM EMRD that noted depth to groundwater. Data from domestic and livestock well drilling logs continues to be the most abundant source of data in the state regarding depth to water. However, gathering this drilling data typically requires sorting through hand-written drilling notes, and if the well is old, the location may not be accurate. Fortunately, there was an abundance of water quality data from oil and gas wells in these regions. While these oil and gas well data points are typically focused on much deeper brines and production zones, and not the shallow aquifers used for municipal and livestock, they do provide valuable insight into variations in water quality with depth.

With the completion of the Delaware Basin model, the NMBGMR team is currently developing a model of the NM Central High Plains, a sparsely populated and less-studied region of the state. This region contains the western most edges of the Ogallala aquifer, where cities such as Clovis and Portales are facing water shortages. The geology of the Central High Plains includes the northwest shelf of the Permian Basin and most formations follow a gradual easterly tilt to the NM-TX border (Kelley, 1971). Because of the relative structural simplicity of the subsurface, this model area was selected as an adequate setting to test machine learning as a method of interpolation. The open source Python Scikit-Learn package is currently being used to investigate machine learning models. Unpublished maps of the Precambrian basement were available from previous NMBGMR research and are being used in the training and implementation of the machine learning models. Initial results show that machine learning-interpolated surfaces matched subsurface structural features for several Permian formations better than surfaces interpolated using the ESRI Topo-to-Raster algorithm (R. Broadhead, personal communication, June 12, 2024). While these findings are promising, the potential drawbacks to this method include a poor ability to handle faults and an increased degree of randomness in the model training compared to other methods. The machine learning algorithm trains itself by taking several (~100) randomized datasets and learning the patterns in those subsets before applying what it learned to the rest of the dataset. As such, if you have a highly heterogenous dataset you might find that different patterns were being learned based on the subset of data used. Machine learning will continue to be tested for 3D subsurface mapping, but initial feedback indicates this is a feasible model method for future work. Water quality and groundwater extent mapping will be limited to water well drilling records, as the oil and gas well data is not available in this region.

The final goal for this research conducted at the NMBGMR is free and easily accessible maps and models. ESRI map packages and Google Earth KMZ files are available on the NMBGMR website, containing both the geological and hydrological surface elevations and extent for each model region. Open-File Reports are also provided for each region which document the modeling techniques used and provide 2D contours and maps of aquifer thickness and elevation. The use of ESRI or open-source software such as Python has proven useful for the regions modeled thus far. Sensitivity to faults and displacement has been observed in all methods so far, requiring detailed geological understanding by the model team to prevent error in the final interpreted surfaces. An additional observed drawback to software not designed for geologic or 3D modeling is the limited visualization options for the final model, with significant time and energy required to post process the results into publication-ready graphics. Future modeling efforts by the NMBGMR will include the Salt Basin, a closed surface-water basin that covers parts of southern New Mexico and western Texas, and the alluvial basin along the Rio Grande Rift valley. These geologically complex regions will test the limits of our current modeling methods and may require exploring new and more sophisticated software.

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3D GEOLOGICAL FRAMEWORK OF ALBERTA: DELIVERING MODELS AND DERIVATIVE PRODUCTS TO FACILITATE STAKEHOLDER COMMUNICATION AND SUPPORT DATA-DRIVEN DECISION MAKING

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The Alberta Geological Survey (AGS) is responsible for providing information and advice about geology and resources to the Government of Alberta, the 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), disposal and storage potential, and geological hazards. We also are responsible for providing geoscience outreach to stakeholders ranging from professional colleagues and academia to the general public.

To support these efforts, we have developed a multi-scalar, multi-dimensional, geostatistically optimized, and probabilistically parameterized 3D geological model of Alberta. This serves as the single-source of geological truth, providing a reliable 3D geospatial context to facilitate the integration and evaluation of surface and subsurface properties and interactions ensuring that risk-based strategic and operational decisions are based on sound science and credible evidence. The current version (v4) of our 3D Geological Framework of Alberta (GFA) model delineates 90+ geological units and covers 602,825 km2. Our strategy for updating the GFA has transitioned from adding geological units and/or refining the model where new data becomes available, to taking a strategic approach to focusing our efforts in areas of interest (Figure 1). The reasons for this are twofold, 1) we only have a few geomodellers within the AGS and they are often required to support geomodelling efforts for our other projects or to support regulatory needs, and 2) the GFA is already very large (computationally) and becoming difficult to use by many software programs. However, due to significant interest in the basal Cambrian units, version 5 of the GFA will likely increase to 110-115 geological units this year.

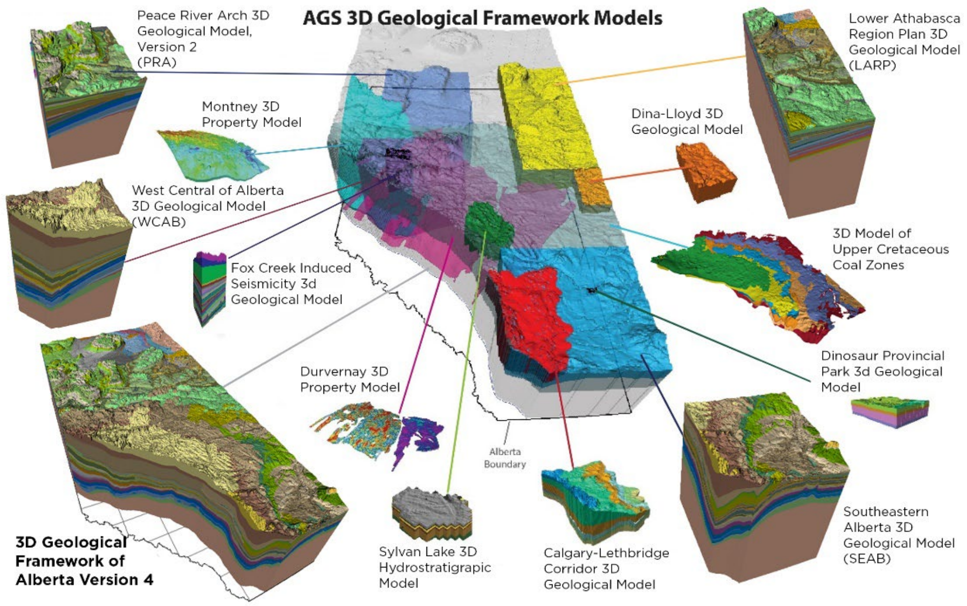

Figure 1: Overview of the many sub-models that were derived from the provincial scale 3D Geological Framework of Alberta model, and which in turn have been re-integrated within the GFA to increase its detail and resolution.

Current Activities and New Developments

We are making the 3D Geological Framework (including sub-models) accessible to our external stakeholders 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, and environmental protection, to support economic diversification and public safety. This has become increasingly important as there has been a significant expansion of interest in Alberta resources and resource potential including;

- Groundwater quality and quality (Figure 2a)
- Oil, gas, and condensates
- Critical minerals
- Geothermal energy
- Cavern storage capacity
- Carbon capture storage capacity (Figure 2b)

Many of these resources are either co-located or occur in proximity to potential geological hazards, therefore we need to not only be looking at the opportunities associated with these resources but the potential risks as well including;

- Seismic susceptibility and induced seismicity (Figure 2c)
- Potential interference
- Containment
- Sterilization and/or conservation of resources

As such we have seen a significant increase in the use of the GFA to support AGS projects and support requests from the Alberta Energy Regulator and Government of Alberta. In 2020-21, the GFA was used to support 28% of our projects and in only 3 years time that has increased to 73% of projects in 2023-24. Components of the GFA were used to support projects and activities related to carbon capture storage and sequestration, aquifer characterization, commingled well abandonment and requirements for zone segregation, transboundary aquifer delineation, investigations of induced seismic activity, and many others.

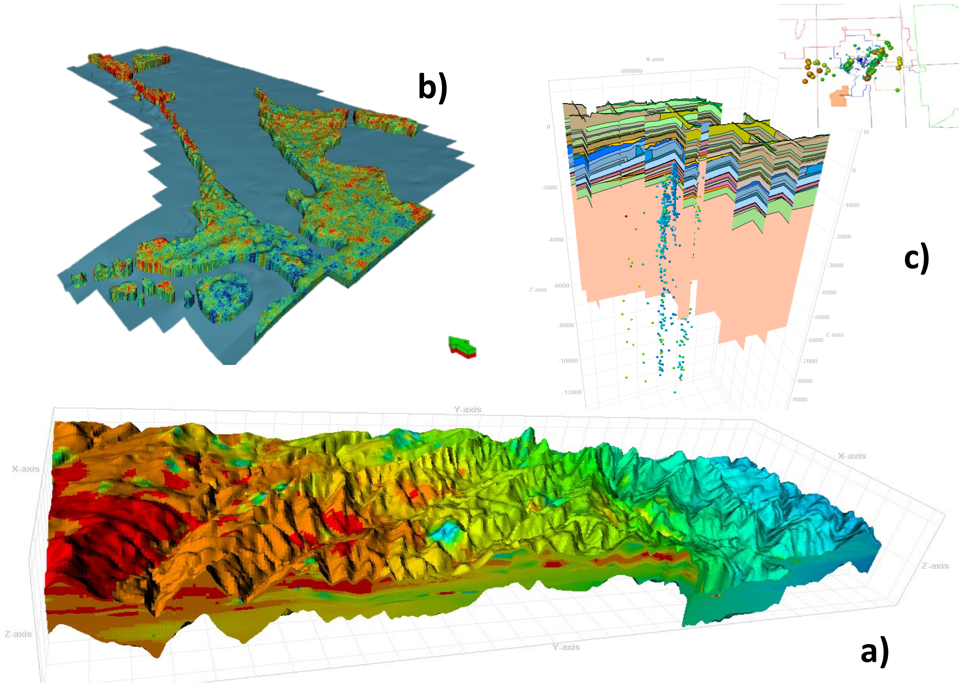

Figure 2: Examples of how our provincial GFA model has been used to support projects and investigations into a) groundwater quantity and quality, b) carbon capture storage potential, and c) induced seismicity.

The success of our 3D Geological Framework is contingent on properly documented and transparent processes to generate reproducible and scientifically credible predictions, as well as ensure that users are properly informed as to the model limitations and uncertainties.

Ongoing and Emerging Challenges

Although building 3D geological models in any jurisdiction comes with its own set of unique challenges, the 3 main challenges we are facing are;

1) Finding efficient ways to publish and share our 3D models online
2) Modeling the deformed geology of the Rocky Mountains and Foothills region with little to no data
3) Dealing with the size and computational requirements to continue to build such a large and detailed model……even with cloud computing options.

The AGS has received lots of positive feedback regarding our enhanced approach to outreach and stakeholder engagement by leveraging the 3D Geological Framework models to develop interactive and educational applications such as Minecraft models (https://ags.aer.ca/public-geoscience/minecraft), narrated virtual reality tours of the subsurface (https://ags.aer.ca/public-geoscience/minecraft-model-video-tours), 3D prints of the subsurface (https://ags.aer.ca/public-geoscience/3d-printing-files), and augmented reality applications that allow users to interact with our 3D models in a mixed reality environment (Figure 3).

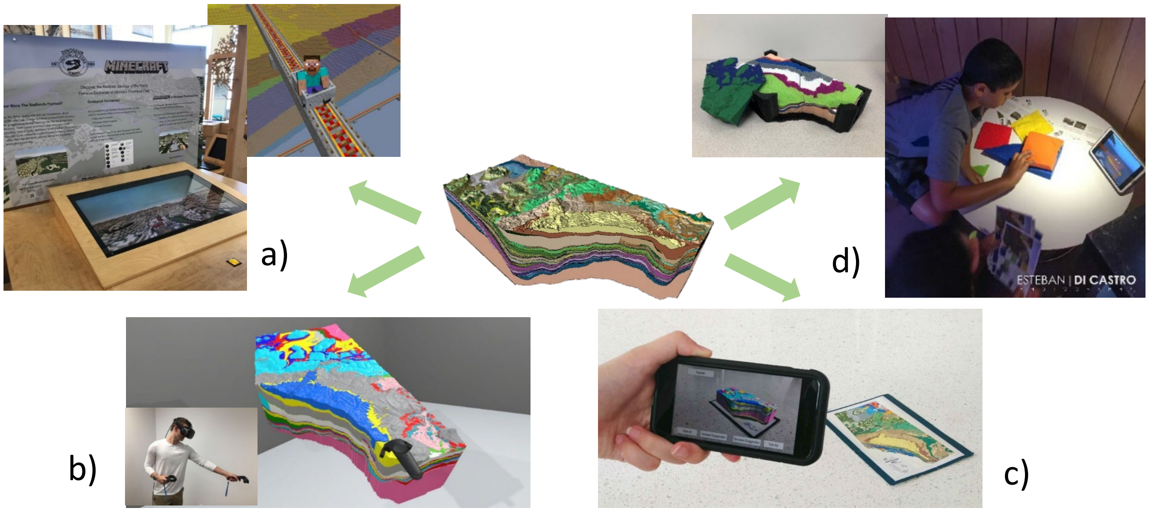

Figure 3: Examples of how the Geological Framework model has been used to create unique applications for people to learn about and interact with Alberta's subsurface geology via a) Minecraft models, b) virtual reality tours, c) augmented reality applications, and d) tangible 3D prints

We continue to struggle to find a platform to share the many components of our full high-resolution 3D geological model. Our team has been testing a number of interactive online platforms to share and make our models more accessible and has recently published version 3 of our Geological Framework Model via ESRI ArcGIS Online (Figure 4; https://gfa-v3-ags-aer.hub.arcgis.com). The benefits are that our ESRI portal site provides a one-stop shop to access, visualize, download, and even allow users to integrate their own data within our grids and models. Unfortunately this platform is not able to visualize the model in a 3D environment or allow users to visualize multiple geospatial entities (I.e. surfaces, geobodies, wells, etc.) at the same time. Our team is looking for online platform options that are allow users to visualize and manipulate large models and geospatial entities, so if you have suggestions or recommendations, please send them to (kelsey.maccormack@aer.ca) so I can share them with our team.

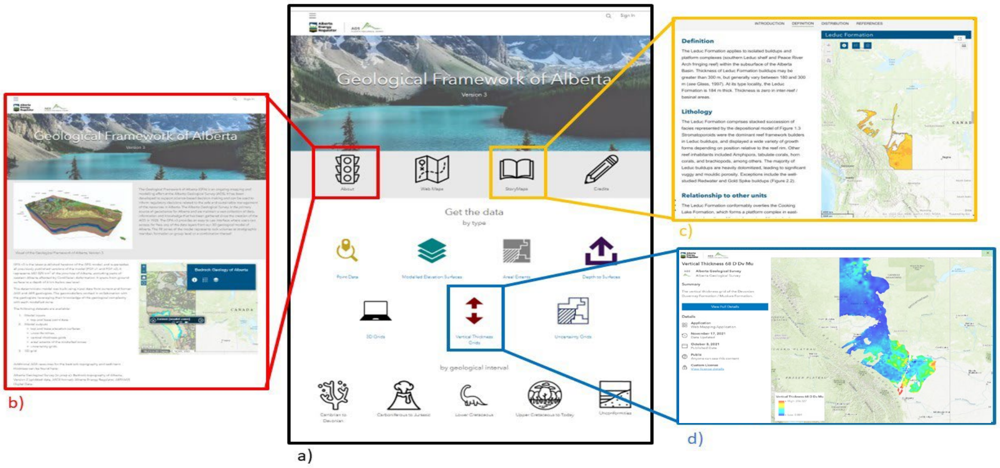

Figure 4: Geological Framework of Alberta homepage (a) showing an overview of the ‘About’ page (b), StoryMaps (c), and an example of a vertical thickness map (d) available for any of the 91 layers in the model.

The second major challenge is dealing with the complicated structure of the Rocky Mountains and Foothills region (RMF). We will need a completely different modeling approach from what is being used across most of the province. We have maps of the geological units exposed at surface, and several interpreted cross-sections, but overall, the data available to model this region of the province is severely limited. Due to the significant differences in variability between the RMF and plains regions of Alberta, we are planning to model this region separately. We are interested to learn what modelling approaches have worked for other jurisdictions that modelled similar mountainous terrain with limited data.

Our third challenge is dealing with the size, both extent and resolution, of our GFA model. It has become too large to model using a desktop computer and now needs to be done using software that supports cloud computing. Fortunately, we have been able to transition the GFA from Petrel, which is desktop software, to Dephi which is Schlumberger’s cloud-based version of Petrel. Using cloud-based software allows the team to access additional computational power to build the increasingly large and complex GFA, however it has increased the IT costs associated with this program.

This presentation will focus on recent opportunities and challenges we are encountering as we leverage our 3D Geological Framework models and derivative products to build trust and confidence with stakeholders, government, and the general public by facilitating transparent communication of complex geological and environmental issues using tangible graphics and visualizations, which are easy to understand and are based on scientific data.

GETTING READY FOR CHANGING SOCIETAL NEEDS – RENEWING OUR 3D MODELING EFFORTS

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Introduction

Since the turn of the 21st century, geomodeling, i.e., mapping the subsurface three-dimensionally, has been taken up by several geological survey organizations worldwide as an addition to, and in few cases replacement of, surface geological mapping. The models that they are constructing differ considerably. Modeling methods used can for example be explicit, implicit or process-based; scale and resolution range from local to national; and the models are used and parameterized for different applications, e.g., geotechnical, hydrogeological and geo-energy. Depending on the combination of geological setting and application, rock types and structural complexity vary as well.

Subsurface models are finding their way to a growing group of users, each having their own set of needs. The Geological Survey of the Netherlands (TNO-GDN) produces and maintains a suite of four nationwide models that describe the subsurface down to depths of ~5 km. Three of these modes, the geological framework model DGM, the hydrogeological model REGIS II, and the lithological voxel model GeoTOP (Figure 1), are part of the Key Registry of the Subsurface (BRO: Basisregistratie Ondergrond). The BRO is part of the Dutch framework of key registries, a set of vital public national databases that governmental organizations are obliged to use.

Becoming part of the BRO has a significant impact on GDN's modeling effort. Most importantly, making the application of the models obligatory has resulted in more use by more users. This did not only increase the overall impact of the models as such, but also raised the awareness of the need to consider the subsurface as an important part of the physical environment. The obligations also come with stringent standards for quality and quality control, as well as higher expectations of being up-to-date. Subsurface data that are delivered to the BRO are expected to become incorporated in the models as soon as possible, preferably on-the-fly. In addition to the momentum brought about by the BRO itself, developments in spatial planning, resource planning, and climate adaptation challenge us to keep improving and developing the portfolio of BRO subsurface models.

The fourth model (DGM-deep) serves the geo-energy domain and is not yet part of the BRO. Originally developed as a framework model for the exploration of oil and gas, it now faces new user needs related to the energy transition and new use of the subsurface. For example, it lacks the geological detail of individual reservoirs and their properties that are needed for the assessment of geothermal energy and geological storage potential.

All in all, the entire model portfolio of the GDN is in transition, driven by new technical possibilities, socio-economic trends, and environmental and societal change. The GDN therefore initiated a program to renew its subsurface modeling efforts, which not only considers the individual models, but also their combination.

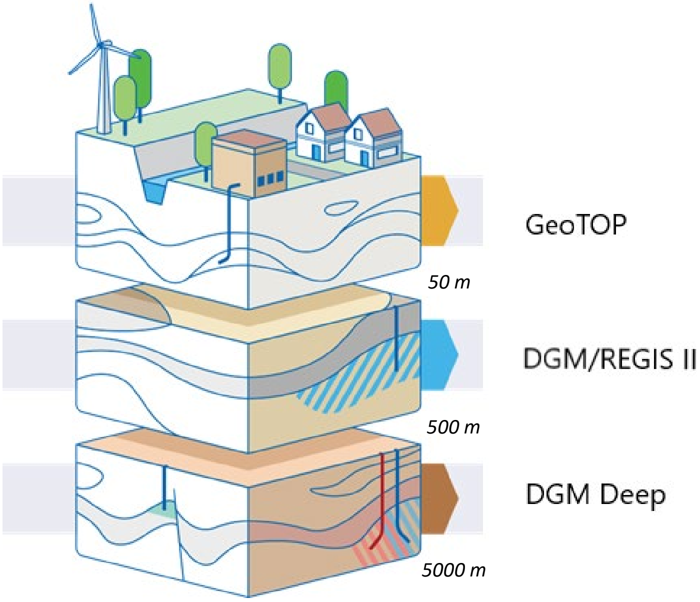

Figure 1 The Dutch suite of four subsurface models shown and their application domains; GeoTOP: built environment, DGM/REGIS II: groundwater, DGM Deep: geo-energy.

Renewal of subsurface modeling

We develop our geomodeling efforts according to several guiding principles. Input, specifications, workflows, and dissemination are to be designed within the context of an information chain that connects data sources to end use. Models should be based on all publicly available data and information, as well as interpreted data and semi-products from (subsurface modeling) projects of the GDN and third parties. Using third-party interpretations presents an additional challenge to model the quality control system that we have in place. Furthermore, we need to develop ways to combine data representing a wide variety of measured properties (seismic, EM, cone penetration test, well logs) at different scales. In many cases, substantial preprocessing is needed before subsurface data can be used in the construction of our models.

Modeling within information chains

A key learning of developing the BRO has been to combine the collection, storage, interpretation, modeling, dissemination, and use of data and information in an information chain (Figure 2). Such chain considers workflows, formats, transactions and standards, and thereby facilitates the cooperation and coordination between agencies, including geological surveys, that traditionally work in relative isolation. The GDN is currently elaborating the information chain for geothermal energy, which will ultimately combine subsurface, built environment, and energy transport network data. In that context, we developed ThermoGIS, a public, web-based geographic information system supporting companies and the government in developing geothermal energy in the Netherlands by showing geothermal potential. The subsurface model within ThermoGIS is a derivative of DGM-deep, which is augmented with reservoir information used in the potential calculations.

We are also developing an information chain for land subsidence, which connects subsurface properties and the effects of human action, which allows us to better distinguish between, and manage the effects of mining, water abstraction, and water management. A completely new chain is evolving around critical raw materials. Pursuant to the EU Critical Raw Materials Act and the national Raw Materials Strategy, the GDN has been tasked to establish the Netherlands Materials Observatory, which will serve as the national Minerals Intelligence center and conduct an exploration program.

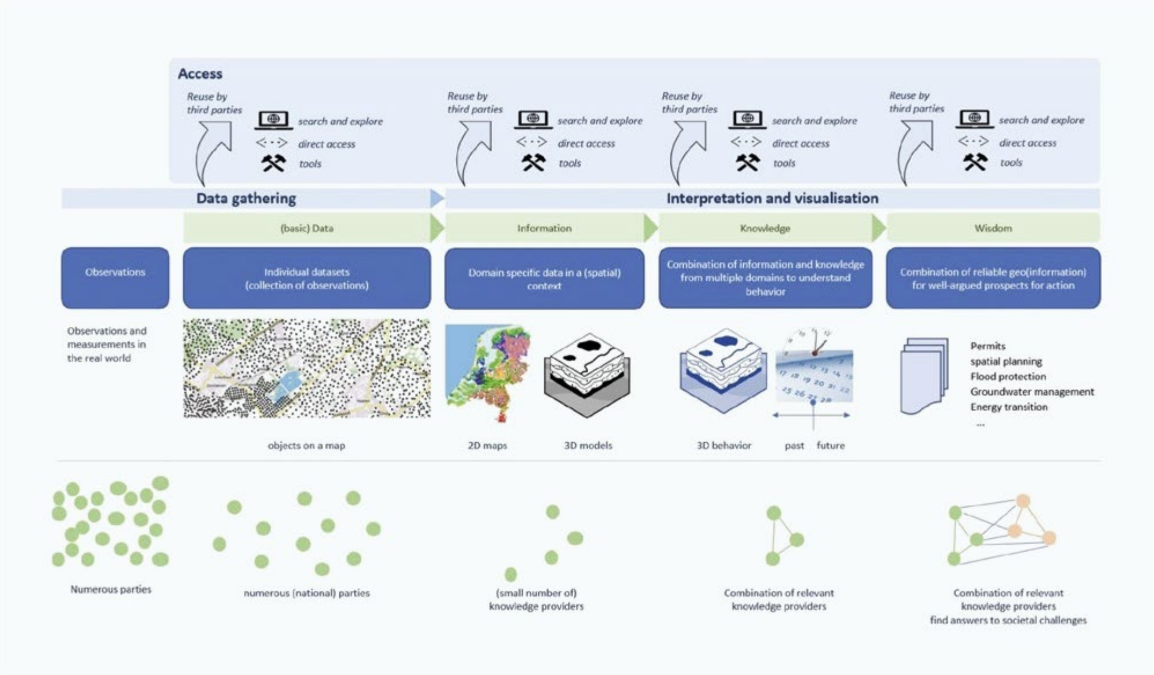

Figure 2 Data and information chain in the physical environment (Anonymous, 2023).

Data conditioning and interpretation

To include more data, strategies are developed to use more and other data sources, for example to scan paper reports to harvest their content using machine learning (ML) techniques, or to use such techniques to automatically extract fault and stratigraphic horizon interpretations from seismic data. In addition, we deploy ML techniques to translate cone penetration test data into lithology, which allows us to use that data in our 3D-modeling workflows. To maintain grip on existing and forthcoming data and information, we will further expand our national subsurface database to contain all relevant available data. The database currently holds a diverse array of data sets, however not all relevant data is served in a standardized way, for example, because it is data that has only been acquired recently, or has limited coverage. These new data sets include (airborne) electromagnetic (EM) data, but also versioned model results, including their litho-, chrono, bio-, and seismo-stratigraphic interpretations.

Stratigraphic forward modeling and sequence stratigraphy

The end result of our modeling efforts are, or are to be, lithostratigraphic and seismostratigraphic geological models parameterized with, for example, lithology, hydraulic conductivity, porosity, permeability, and temperature. Understanding sedimentary facies distribution is key in predicting the 3D distribution of properties within the lithostratigraphic or seismostratigraphic units. Generally, data density for these units is too low to reliably use interpolation techniques, which is why we are now exploring the use of stratigraphic forward modeling. This process-based technique is based on sequence-stratigraphic concepts and simulates various geological processes, generating an estimated facies distribution that is directly tied to the internal architecture of the unit. Available litho-, chrono, bio-, and seismostratigraphic data and interpretations can be used to ground-truth the resulting models.

Implicit modeling

Most of our models are constructed using explicit modeling techniques in which stratigraphical bounding surfaces are explicitly modeled from tops and bases observed in boreholes or picked from seismic lines. These surfaces are then stacked to create a consistent 3D model (Turner et al, 2021). Explicit modeling is a labor intensive, iterative modeling workflow: getting results from the stratigraphical interpretation of boreholes to the final model can take several months. Implicit modeling techniques, in which stratigraphical boundaries are extracted as equipotential surfaces of a 3D scalar field computed from scattered data points, may considerably shorten computation times. In a pilot study, we are using Gempy software to compute a first-order 3D model within minutes, instantly aiding our geologists in understanding the impact of adjustments they make in their stratigraphical interpretations.

Filling the gaps

In addition to the new ways to approach modeling, we are also aiming at improving the way we handle data sparseness and uncertainties. For this purpose, we are looking into ways to include petrophysical and geological considerations into our interpolation workflows, identify outliers, and visualize uncertainties.

Summary

The Geological Survey of the Netherlands has a suite of four nation-wide models. Due to changing needs in our stakeholder and user communities, we have initiated a renewal of our modeling efforts and approaches. The focus is on data, interpretation and modeling techniques, and model use. Together with ongoing work these additional efforts will eventually result in a single unified geological layer model. This model will consist of geological units that are, within relevant stratigraphic or depth ranges, parameterized for geo-energy, groundwater, geotechnical, and other applications that we serve or will be serving. We have come to see our models and their workflows as parts of a bigger information chain, with the collection of data on one end, and the use of models in policy or decision-making processes on the other. It helps us to cooperate with both data suppliers and user organizations, in terms of data and information exchange and of better cooperation in general.

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FROM COMPLEXITY TO CLARITY: THE IMPACT OF GEO3D VIEWER ON GEOLOGICAL VISUALIZATION

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The development of 3-D geological mapping, including 3-D geological modeling, over the past three decades presents challenges for the proper presentation of results. It is natural to present the final outcome to the user, which is a three-dimensional object in the form of a 3-D grid or a set of layers or geobodies. Modeling software often, but not always, offers free viewers to display the results, but these are often complex programs akin to the modeling software itself. Their complexity and the necessity of installation on a computer often pose a barrier to a wider audience. Therefore, there is a need for lightweight, free software accessible via a web browser that allows for the presentation of 3-D geological mapping/modeling results to both specialists and the general public.

Is it worthwhile to create a tool that meets the needs of both specialists and the general public? The answer to this question is not straightforward. In the following description of the Geo3D web viewer, various aspects of visualizing geological structures and the data used for modeling will be presented. Hopefully, the answer will become apparent.

Early Attempts at 3-D Geological Web-Visualization

The first attempts to visualize 3-D geological models on the web appeared at the turn of the 21st century, utilizing the then-popular VRML format used to save 3-D objects. These technologies garnered interest and enthusiasm among geologists seeking innovative solutions for sharing their work. The development of 3-D web visualization technologies led to the emergence of new technologies like X3D, which replaced earlier 3-D visualization web services. Eventually, in the mid-2000s, WebGL technology took the lead for many years and is still used today in libraries such as X3DOM and the most common Three.js. Progress continues as WebGL and this is gradually being supplanted by WebGPU, and we must be prepared for significant changes in the world of geological model visualization in web browsers.

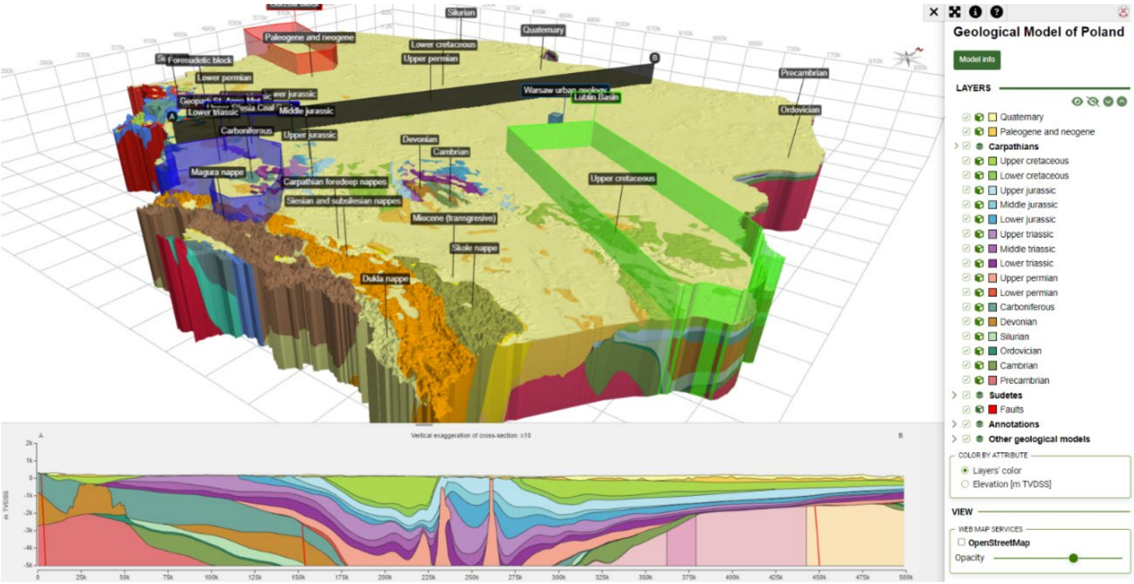

Figure 1. Geo3D web viewer showing 3-D geological model of Poland (Malolepszy et al. 2023). https://geo3d.pgi.gov.pl/model_Poland/index.html

Evolution of the Geo3D Viewer

From 2015 to 2020, many organizations and geological surveys undertook various efforts to create their own geological model viewers, leveraging available technology. At a meeting of the 3-D modeling group in Wiesbaden, Germany in 2016, there was a spontaneous “beauty contest" where geological survey organizations from many countries showcased their achievements. One of the applications participating in this contest was the Geo3D viewer from the Polish Geological Institute. The viewer originally created in 2007 (Malolepszy et al. 2008) reached PGI in early 2015 and was presented that same year at the GSA 3-D mapping workshop in Baltimore. The interest of geologists in this tool ensured its longevity, and after nearly ten years, Geo3D is thriving and expanding into new areas of geological structure and data visualization, which will be described below.

The Idea Behind the Geo3D Viewer

The Geo3D Viewer is conceived as a tool for intuitive exploration of geological models, aiming to bridge the gap between complex modeling software and the ease of use associated with traditional paper maps. Our objective is to create a visual interface that facilitates rapid data extraction without overwhelming users with unnecessary complexity.

The viewer's design prioritizes simplicity, focusing on essential controls and minimizing clutter. We recognize the challenge of balancing interface clarity with the need for ongoing development and feature integration. To address this, we are committed to a user-centered approach, carefully considering the placement and interaction of interface elements to ensure optimal usability.

By adhering to these principles, we aim to create a geological visualization tool that is both accessible to novice users and efficient for experienced practitioners. The goal of Geo3D viewer is also to provide common visualization and a publishing platform for geologists, hydrogeologists, geophysicists, and geo-engineers working on various specialized 3D-modelling software packages, such as GoCAD, Leapfrog, Petrel, Geomodeller, etc. Geo3D has clear benefits for both the communication and distribution of models and accompanying reports. The innovative tools provided by Geo3D aid in communicating the modelling results in a very practical way, for instance to city planners, and particularly those with a responsibility for underground planning. Geo3D’s investigative tools enhance the explanation of the geology and distribution of geological properties.

Core Features of Geo3D Viewer

Basic and Obvious Functionalities:

- Toggle Layers and Model Objects: Clicking checkboxes to show or hide individual objects or entire groups within the model view, with additional buttons for expanding and collapsing all groups in the object tree.
- Model Color Scheme Selection: Changing object colors from default to height value or attributes defined in the model.
- Display Open Street Map WMTS overlay above the model: Regardless of the coordinate system, if it is defined in the EPSG system, it is possible to present a topographic map over the geological model, with adjustable transparency to facilitate visualization.
- Geological Cross-Sections: A basic tool for visualizing geological structures, allowing for slicing the model along the XY axis as well as Z on horizontal slice maps, and creating true cross-sections along any arbitrary line.
- Virtual Drilling: A basic function to show the profile of layers in a selected location.
- Layer dragging apart: An intuitive functionality allowing one or more layers to be lifted to see what is beneath, enabling the inspection of both sides of stratigraphic or erosional discontinuities.
- Picker: Sampling model parameters at any location by clicking on an object, which displays a popup with XYZ coordinates, dip, and azimuth, and the object’s name and parameters if defined in the model.
- Annotations: Attaching an informational bubble to a selected object or landmark, with the ability to add a broader description with graphics and links that appear in a popup window upon clicking.
- Isolines: layers can be contoured with isolines of various intervals and line thicknesses.

Beyond the project results themselves, Geo3D enables the presentation of borehole data in a 3-D view with interactive object selection, basic attribute previews, and linking to the borehole database. In a similar manner, seismic lines or other data can be displayed to enrich visualization of the 3-D geological models. Geo3D also visualizes properties of geological modes distributed in orthogonal voxet and stratigraphic grids, though the latter currently may only contain a single layer. Work on visualizing more complex grids is ongoing. Additionally, each layer or geobody can be painted with attributes like thickness or others.

Geographical Independence

Many available solutions present geological models embedded in the topographical realities of a given country. While interesting, we decided not to tie models to overarching areas. The Geo3D viewer is designed to provide a dynamic platform for visualizing standalone 3-D geological maps. Our viewer allows you to explore these maps in their own right, without the need for integration into larger 3-D or 2-D map overlays. These standalone 3-D maps are georeferenced using versatile coordinate systems, which operate independently. This unique feature empowers users to present geological models from diverse locations worldwide, offering a wide-ranging perspective and unparalleled global coverage. Our platform grants the flexibility to examine geological models at various scales, whether or not there is an interest in the geological makeup of an entire country or the intricate details of individual tectonic features. This adaptability opens doors for in-depth exploration and analysis, catering to the specific needs of researchers, geologists, and stakeholders.

We acknowledge that this standalone approach may be perceived as a limitation when the goal is to consider models within the broader context of a region or country. We understand that seamless integration into larger geospatial settings is important for comprehensive analysis and decision-making. To address this concern, we are actively working on innovative solutions to effortlessly embed our standalone models into various geospatial environments. Our ongoing efforts aim to ensure that our platform can seamlessly coexist with other geospatial tools and systems. In the meantime, we have taken steps to facilitate access to our models within the context of larger geospatial settings. Currently, we provide outlines of the models on the map, complete with direct links for easy access. As we continue to refine our capabilities, we are committed to improving the user experience and enhancing the integration of our standalone models into broader geospatial contexts.

Model Size Limitations – Moving Towards Streaming Big Data

The Geo3D viewer provides a powerful platform for the visualization of geological models, but we acknowledge that there are limitations when it comes to the size of the models, especially concerning web transfer and the capabilities of web browsers. Currently, to ensure a smooth web viewing experience, models need to be tailor-made for web visualization. This often involves downsampling the original model to a level that is convenient for efficient web rendering.

We recognize that there is a vast range of devices with varying graphic performances, from powerful desktop workstations to compact smartphones. To address this diversity, we are actively exploring solutions that will allow us to stream very large models, ensuring that they can be depicted at the required level of detail on various devices. This streaming approach will encompass both the geometry of the model/grid and the raster textures used to drape over modeled layers. However, it is important to note that we currently operate within specific size limitations for model/grid dimensions due to considerations related to web performance. These limitations are necessary to provide a seamless and responsive viewing experience. As we continue to innovate and enhance our platform, our goal is to expand these constraints, ensuring that our users can explore geological data with precision and clarity.

User Interface for Model Uploads

The autonomous user interface in the form of the web application, allowing registered users to upload their own models in the future, is a crucial part of the Geo3D viewer's development. We have already outlined necessary features of such a tool, including loading, converting, and displaying 3-D geological maps and models. Its development is ongoing and the app will be released early in 2025.

Summary

In an era of rapid advancements in digital geological mapping, it is evident that the next significant leap lies in the realm of 3-D geological mapping. However, the realization of this transformative shift is contingent upon the availability of straightforward and universally accessible tools for visualizing 3-D geological maps—tools as intuitive and effortless to use as traditional paper maps or 2-D displays for their two-dimensional counterparts. This is precisely why we are passionately committed to the creation and promotion of the Geo3D viewer. We firmly believe that simplifying the visualization of 3-D geological maps is a vital driver for making 3-D geological mapping more widespread. By providing a user-friendly and readily accessible platform, we aim to accelerate the adoption of 3-D geological mapping techniques and foster their widespread delivery.

Our investment in the development of the Geo3D viewer is driven by a vision of a future where 3-D geological maps are effortlessly shared, understood, and harnessed for scientific research, exploration, and decision-making across a spectrum of industries. We envision a world of geology where the complexity of 3-D geological data is tamed by intuitive visualization, opening doors to a new era of geological understanding and discovery.

Link to Geo3D web viewer:
https://geo3d.pgi.gov.pl

Link to GSA 3-D Mapping Workshop 2024 demo:
https://geo3d.pgi.gov.pl/GSA_3D_mapping/index.html

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GEOH5: A FRAMEWORK FOR GEOSCIENCE DATA AND MODEL PORTABILITY

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Abstract

We have developed a data structure called GEOH5 with the objective of general integration and storage of geoscientific models, data, and metadata where dissemination, general access, and persistence are required. It answers the needs of geoscientists who require a database structure that is compact, open, reasonably comprehensive in scope, and extensible. Although only a few years old, the GEOH5 data structure is already in use by thousands of users with increasing acceptance across the geosciences. This includes industry, academia, and geological survey organizations. The open format of GEOH5 makes it an ideal candidate for storing and disseminating models, data, and metadata.

GEOH5 is based on open-source HDF5 technology because of its many advantages: wide acceptance across numerous data-intensive industries, self-describing behavior through the integration of data and metadata, fast I/O, excellent compression, file merging, cross-platform capability, unlimited data size, and access to libraries in a variety of programming languages. It provides both professionals and researchers with a robust means of handling large quantities of diverse data.

An open-source Python API called GEOH5Py facilitates reading from and writing to the GEOH5 data structure. A free, powerful GEOH5 reader called Geoscience ANALYST has been created to display the contents of GEOH5 files as tables, charts, documents, maps, cross-sections, and 3D visualizations. The combination of GEOH5, GEOH5Py, and Geoscience ANALYST provides a convenient and free mechanism for creating and sharing projects as well as immediately visualizing the results of Python modelling and data processing routines in the context of other data and model elements. Among other benefits, this allows researchers to focus on development of new methods rather than the creation of data structures, user interfaces, and visualization systems to support their work.

Introduction

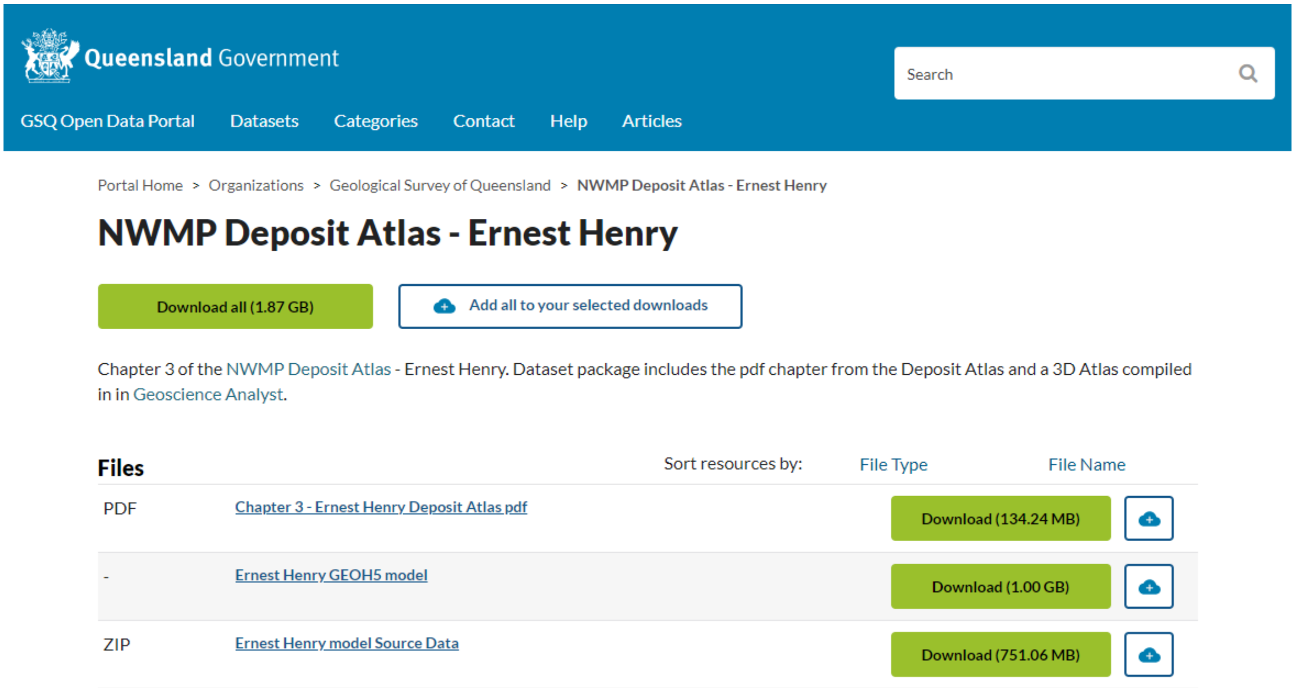
Barriers to interoperability, imposed by design or default by software vendors for commercial reasons, serve neither the interests of technology advancement nor the objectives of the data acquirers, interpreters, and researchers who need to disseminate their geoscientific data, metadata, and models. Geoscientists must often undertake complex and costly manual workarounds to share data and models among mutually non-interoperable systems. The result is lower productivity, poorer decision-making, potential data loss, and dissatisfaction with proprietary systems.

In this article, we introduce the GEOH5 open-format file structure as a solution to the interoperability problem. We also describe its open-source Python API, GEOH5Py, that provides a standard programmatic interface for reading from and writing to the GEOH5 format. Finally, we present Geoscience ANALYST - a free-to-use viewer of the content of GEOH5 files. The combination of the API and the free viewer makes a compelling case for the GEOH5 file structure as a potential “standard” for geoscientific data.

A useful analogy to GEOH5 is the ubiquitous Portable Document Format (PDF), an ISO standard that seeks to capture documents in a manner independent of application software, hardware, and operating system. In a broadly similar manner, GEOH5 provides an open, documented, extensible structure for storing and sharing geoscientific models, data, and metadata. The structure is aligned with the FAIR guiding principles for making data Findable, Accessible, Interoperable, and Reusable (Lightsom et al., 2022).

GEOH5: an open format for geoscience data and models

GEOH5 is a documented public, open, easy-to-use, vendor-neutral, and permanently accessible exchange format for geoscientific data storage. The power of GEOH5 lies in its capacity to handle geological data stored on various object types — points, curve, surfaces, drillholes, geophysical surveys, and 3D models. The format facilitates interoperability between different software, fostering a collaborative environment for geoscientists, researchers, analysts, and other stakeholders, including for public dissemination. GEOH5 has already been adopted by several governmental agencies as a delivery format for public data, as shown in Figure 1.



NWMP Deposit Atlas - Ernest Henry

Chapter 3 of the NWMP Deposit Atlas - Ernest Henry. Dataset package includes the pdf chapter from the Deposit Atlas and a 3D Atlas compiled in in Geoscience Analyst.

Files

PDF	Chapter 3 - Ernest Henry Deposit Atlas pdf	Download (134.24 MB)
-	Ernest Henry GEOH5 model	Download (1.00 GB)
ZIP	Ernest Henry model Source Data	Download (751.06 MB)

Figure 1. Example of a public geological model delivered in GEOH5 format by the Geological Survey of Queensland, Australia.

GEOH5 has its roots in the Hierarchical Data Format (HDF5), a universally accepted and widely used data model, library, and file format for storing and managing complex data. HDF5’s attributes make it an obvious choice as a foundation for an open geoscience data standard: wide acceptance across numerous data-intensive industries, self-describing behaviour through the integration of data and metadata, fast I/O, excellent compression, file merging, cross-platform capability, unlimited data size, and access to libraries in a variety of programming languages. It provides both professionals and researchers with a robust means of handling large quantities of diverse data. The content of GEOH5 files is readable and writeable by third-party software using scientific programming environments such as open-source HDFview, Python, MATLAB, Fortran, C, and C++.

The main structure of the GEOH5 format is shown in Figure 2, as displayed by the free HDFview program[1]. Groups, Objects and Data entities are stored in flat structures and indexed by a unique identifier as specified by the RFC 4122 standard[2]. Entities hold references to their own children for rapid navigation. Groups are simple containers for other groups and objects. They are often used to assign special meanings to a collection of entities or to create specialized software functionality. The current set of Objects implemented in GEOH5 supports a range of geological, geophysical, geotechnical, and mining data and model elements that can be attributed with properties. At the top level, the Root container contains pointers to the full hierarchy of the file, providing the complete linkage between all entities and their dependents, ensuring a seamless and organized structure for efficient access and retrieval of information.

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[1] https://www.hdfgroup.org/downloads/hdfview

[2] https://datatracker.ietf.org/doc/html/rfc4122

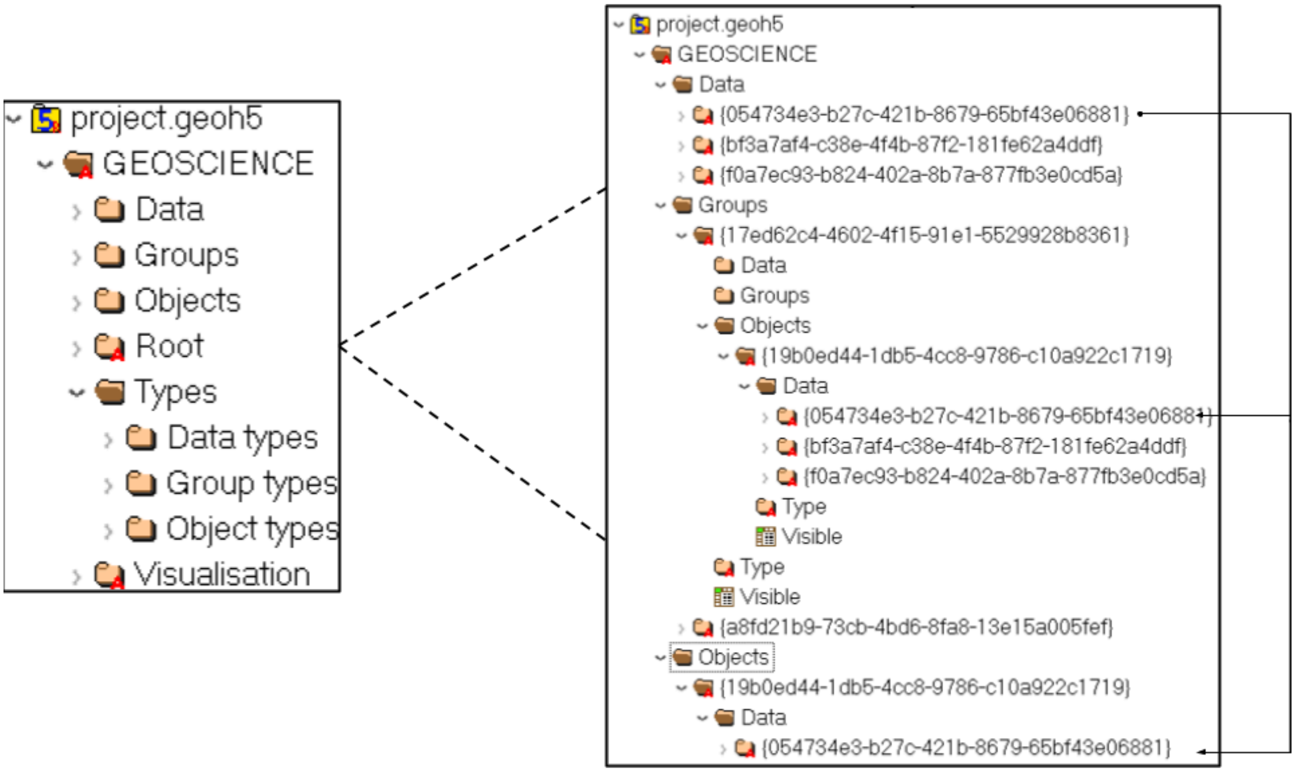

Figure 2. At left, main structure of the GEOH5 file format. At right, Data, Groups, and Objects entities are stored in flat HDF5 containers, each indexed by a unique identifier. Pointers to the child entities are given for rapid navigation through the tree structure.

Data are currently always stored as a 1D array, even in the case of single-value data. New data types can be created at will by software or users to describe object or group properties. Data of the same type can exist on any number of objects or groups of any type, and each instance can be associated with vertices, cells, or the Object/Group itself. Some data type identifiers can also be reserved as a means of identifying a specific kind of data. Data attributes include specification of the primitive type with optional descriptive metadata (e.g., units and text description) and display parameters to be used by a viewer. Primitive types include float, integer, text, referenced or categorical, date-time, filename (which must correspond to a stored binary file as a data instance), and blob (which must correspond to a binary dataset as a data instance).

GEOH5Py: An open-source API

We created an open-source Python API to facilitate reading from and writing to GEOH5 format. With GEOH5Py, it is simple to build an application to read and write GEOH5, or to conveniently add GEOH5 to the import and export types supported by other software platforms. For example, we have used GEOH5Py to provide a conversion between the Open-Mining Format (OMF)[3] and GEOH5.

With the help of the API, users can easily create, modify, and remove objects and data programmatically. The main component is the Workspace class. It handles all read/write operations performed on GEOH5 with simple function calls, as demonstrated in Figure 3. This high-level interaction with the GEOH5 storage format allows practitioners to easily leverage the rich Python ecosystem to build their own custom processing routines. GEOH5Py itself relies on the open-source NumPy and H5py packages. Full documentation describing the GEOH5 format[4], and its GEOH5Py API, are available online and updated with every release.

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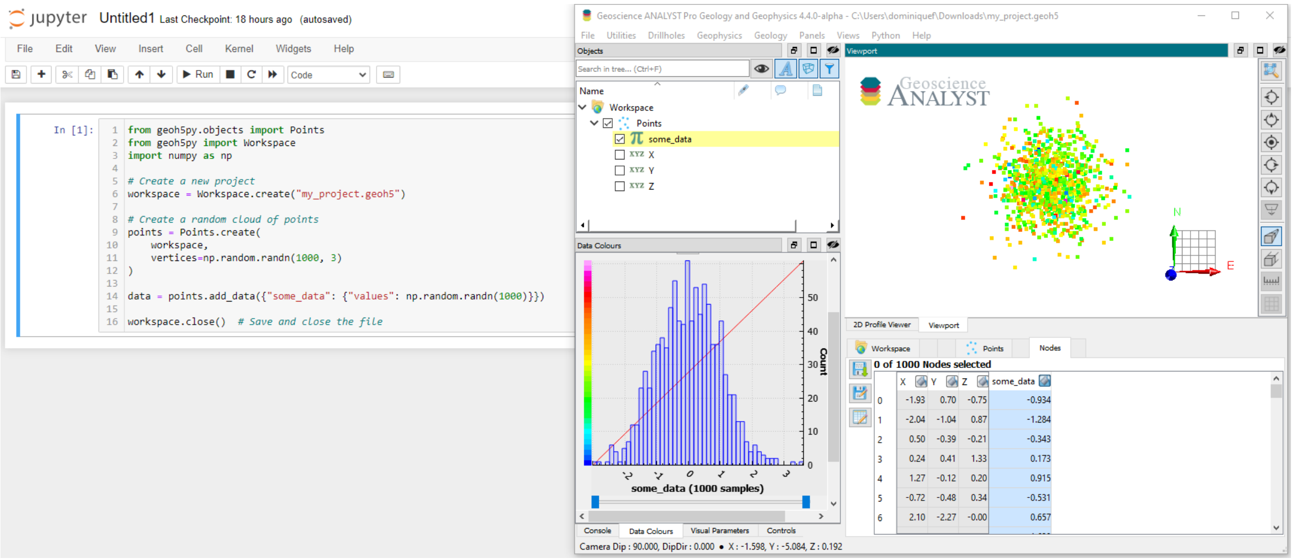
[3] https://gmggroup.org/projects/data-exchange-for-mine-software
[4] geoh5py.readthedocs.io



```python
from geoh5py.objects import Points
from geoh5py import Workspace
import numpy as np

# Create a new project
workspace = Workspace.create("my_project.geoh5")

# Create a random cloud of points
points = Points.create(
    workspace,
    vertices=np.random.randn(1000, 3)
)

data = points.add_data({"some_data": {"values": np.random.randn(1000)}})

workspace.close()  # Save and close the file
```

0 of 1000 Nodes selected

	X	Y	Z	some_data
0	-1.93	0.70	-0.75	-0.934
1	-2.04	-1.04	0.87	-1.284
2	0.50	-0.39	-0.21	-0.343
3	0.24	0.41	1.33	0.173
4	1.27	-0.12	0.20	0.915
5	-0.72	-0.48	0.34	-0.531
6	2.10	-2.27	-0.00	0.657

Camera Dip : 90.000, DipDir : 0.000 • X : -1.598, Y : -5.084, Z : 0.192

Figure 3. Example demonstrating the creation of a new GEOH5 file using the GEOH5Py-API, containing a Points object and associated random data and viewed by the Geoscience ANALYST reader.

Geoscience ANALYST: a free GEOH5 viewer

The utility of the freely downloadable[5] Geoscience ANALYST reader is a principal motivation for geoscientists to adopt GEOH5. It is a powerful viewer that displays GEOH5 file data and metadata in tables, charts, documents, maps, cross-sections, and 3D visualizations. In the PDF analogy to GEOH5, Geoscience ANALYST plays the role of the freely downloadable Adobe Acrobat reader—the existence of which is a principal motivation for users to adopt the PDF document standard. However, in contrast to the Acrobat reader, the Geoscience ANALYST reader can also import additional data and save them back to the GEOH5 file.

It is intended that Geoscience ANALYST preserves unsupported data (and generally be very tolerant with regards to missing information) when loading and saving GEOH5 files. This feature allows third-party applications to include additional information outside of the formal GEOH5 specification.

Conclusions

Although only a few years old, the GEOH5 data structure is already in use by many thousands of users with reasonably broad acceptance across the minerals industry. This includes geological survey organizations that are using GEOH5 as a convenient, compact, and permanently accessible means of disseminating models and data with embedded metadata. Anyone can build an application to read and write GEOH5, or conveniently add GEOH5 to the import and export types supported by modelling platforms.

In addition to portability, the freely available data structure, API, and visualization system provides significant benefits to open-source geoscience modelling initiatives, allowing modelling researchers to focus on modelling technology rather than the creation of data structures, user interfaces, and visualization systems to support their work. The Python API provides a convenient mechanism for immediately visualizing the results of Python modelling and data processing routines in the Geoscience ANALYST viewer at no cost, relieving Python application developers of the need to re-invent geoscience domain interfaces and visualization methods.

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[5] https://mirageoscience.com/mining-industry-software/geoscience-analyst

SYSTEM-SCALE AIRBORNE ELECTROMAGNETIC SURVEYS IN THE LOWER MISSISSIPPI RIVER VALLEY SUPPORT MULTIDISCIPLINARY APPLICATIONS

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Abstract

The lower Mississippi River Valley spans over 200,000 square kilometers in parts of seven states, encompassing areas of critical groundwater supplies, natural hazards, infrastructure, and low-lying coastal regions. From 2018 – 2022, the U.S. Geological Survey acquired over 82,000 line-kilometers of airborne electromagnetic, radiometric, and magnetic data over this region to provide comprehensive and systematic information about subsurface geological and hydrological properties that support multiple scientific and societal interests. Most of the data were acquired on a regional grid of west-east flight lines separated by 3 – 6 kilometers; however, several high-resolution inset grids with line spacing as close as 200 m were acquired in targeted areas of interest. Approximately 8,000 line-kilometers were acquired along streams and rivers to characterize the potential for surface water-groundwater connection, and another 6,000 line-kilometers were acquired along the Mississippi and Arkansas River levees to characterize this critical infrastructure. Here, we present a summary of the data along with several examples of how they are being used to inform regional groundwater model development, inferences of groundwater salinity, identification of faults in the New Madrid seismic zone, and levee infrastructure.

Introduction

The Mississippi Alluvial Plain (MAP) hosts one of the most prolific shallow aquifer systems in the United States but is experiencing chronic groundwater decline over much of its spatial extent. The Mississippi River Valley alluvial aquifer (MRVA), the surficial aquifer within the MAP region, was among the most heavily withdrawn aquifers for irrigation in the United States in 2015 (Lovelace et al. 2020). Furthermore, the Reelfoot rift and New Madrid seismic zone underlie the region and represent an important and poorly understood seismic hazard (Frankel et al. 2009). Despite its societal and economic importance, the shallow subsurface architecture has not been mapped with the spatial resolution needed for detailed scientific studies and prudent resource management.

Here, we present airborne electromagnetic (AEM), magnetic, and radiometric observations, measured over 82,000 flight-line-kilometers, which collectively provide a system-scale snapshot of the entire region of more than 270,000 square kilometers (Figure 1). This work nearly doubles the extent of regional airborne geophysical coverage originally completed in 2019 (Minsley et al. 2021), extending coverage south to the gulf coast of Louisiana as well as expanding laterally to cover recharge areas of the Mississippi Embayment and the Chicot aquifer system. Additional cooperator funding was leveraged to investigate the confining unit in Shelby County, Tennessee as well as improve coverage of the entire Mississippi River and Arkansas River levees within the study area.

We developed detailed maps of aquifer connectivity and shallow geologic structure, inferred relations between structure and groundwater age, identified previously unseen paleochannels and shallow fault structures, and characterized variability in the surficial fine-grained deposit on which the levee system is built. This work demonstrates how regional-scale airborne geophysics can close a scale gap in Earth observation by providing observational data at suitable scales and resolutions to improve our understanding of subsurface structures. In addition to supporting a range of applications today, comprehensive and foundational data collection efforts support a large ‘decision-space’ that will contribute to future studies with emergent sets of questions benefitting from expanded knowledge of regional geological and hydrological properties.

Data acquisition and processing

Airborne geophysical data were collected over multiple phases from 2018–2022. Data were collected with both the helicopter frequency-domain Resolve AEM instrument and the fixed-wing Tempest time-domain system. One-dimensional electrical resistivity models were recovered for the Resolve data using Aarhus Workbench (Auken et al. 2015) and for the Tempest data using GALEI (Brodie 2017). Both radiometric and magnetic data were acquired together with the AEM surveys (Figure 2A,C).

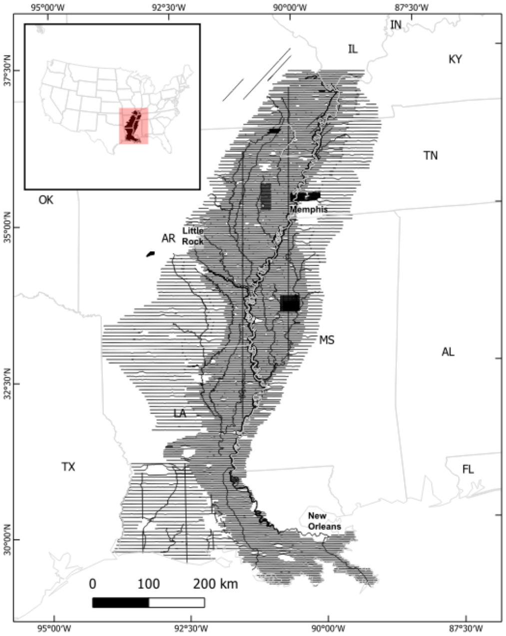

Figure 1. Airborne geophysical flight lines collected from 2018 - 2022.

Native-resolution models (~30 m spacing for Resolve and ~150 m spacing for Tempest) are investigated along flight lines in specific areas of interest. However, given the widely spaced (3–6 km) flight lines and regional nature of the investigation covering a large area, we also produced a coarse three-dimensional resistivity grid that combines data from both sensors (Figure 2B, Figure 3). Resistivity models from each AEM instrument were kriged separately onto a common 1 km by 1 km grid with 5 m vertical intervals. The two grids were then combined using a depth-weighting function that favors the Resolve models at shallow depths, transitioning to Tempest models towards the maximum depth of investigation for Resolve (Minsley et al. 2021).

Hydrogeology

Regional-scale resistivity models agree with known hydrogeological structures and areas of high groundwater salinity (Figure 2B, Figure 3), and provide additional detail needed to refine the geometry of hydrological structures and variability within units. Binned resistivity classes were the basis for several interpretive products derived from the AEM data; these include thickness and extent of shallow confining materials, connectivity between the surficial aquifer and deeper geological units, and connectivity between the aquifer and streams and rivers (Minsley et al. 2021).

The configuration of different resistivity classes, inferred to have different hydrological properties, were used to inform both regional and inset groundwater models in the study area. Resistivity classes were used to inform layering of the groundwater models during model construction, then to assign initial values to the aquifer properties, streambed conductance, and recharge zonation in the calibration process.

Resistivity models and their derived interpretive products, together with the radiometric data and in situ measurements of groundwater chemistry and water quality have been incorporated into machine learning algorithms to predict distributions of manganese and arsenic (Knierim et al. 2022) and groundwater salinity in the surficial aquifer. A separate multi-method machine learning model incorporates geophysical information along with hydrological and climatological variables to predict monthly groundwater levels with uncertainty bounds for the MRVA from 1980 through 2020 (Asquith and Killian 2022).

Hazards

In northeastern Arkansas and southeastern Missouri, west of the New Madrid Seismic zone, a previously un-documented fault was identified along multiple AEM profiles spanning an along-strike distance of more than 100 km. Fault offset of about 50–75 m is observed, clearly extending at least to the base of the shallow surficial aquifer (Minsley et al. 2021). Several shallow features attributed to sand boils caused during past earthquake liquefaction events are identified along several higher-resolution Resolve flight paths.

Infrastructure

Resistivity models from flight lines acquired along the Mississippi River and Arkansas River levees were classified into 10 groups using a k-means clustering algorithm. Individual clusters identify resistivity models that share similar layering structure and lithologic characteristics. Cluster numbers were mapped back to positions along the levees in order to identify regions of interest for follow-up investigation with drilling or other ground-based methods.

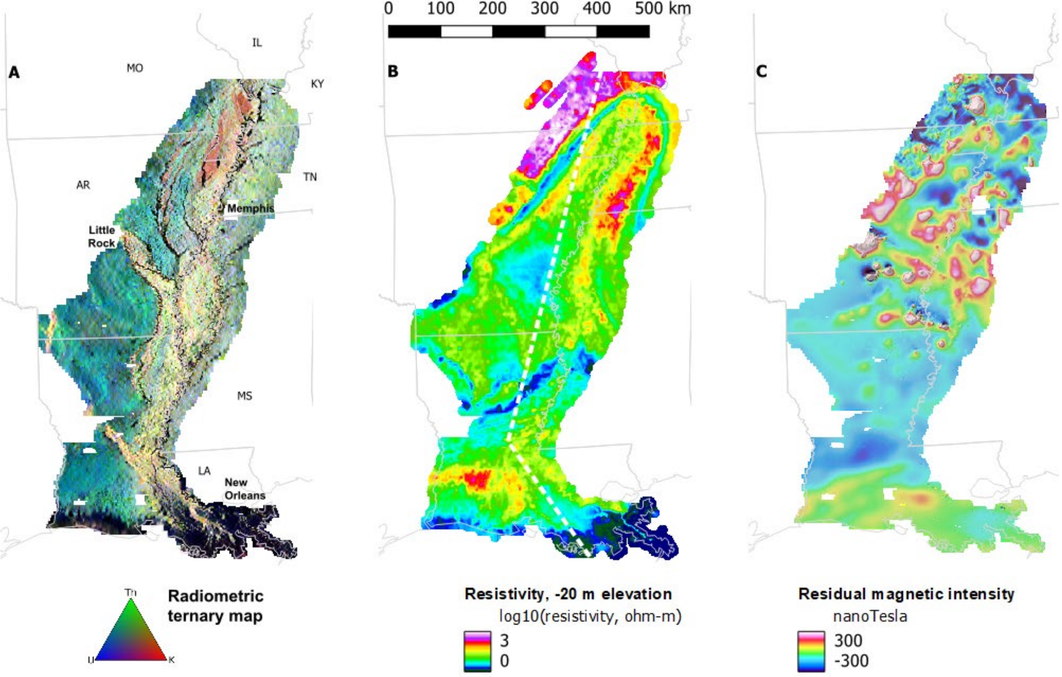

Figure 2. Gridded airborne geophysical results. (A) Ternary radiometric map showing relative abundance of Potassium (K), Thorium (Th), and Uranium (U). (B) Electrical resistivity at a constant elevation of 20 m below sea level. (C) Residual magnetic intensity.

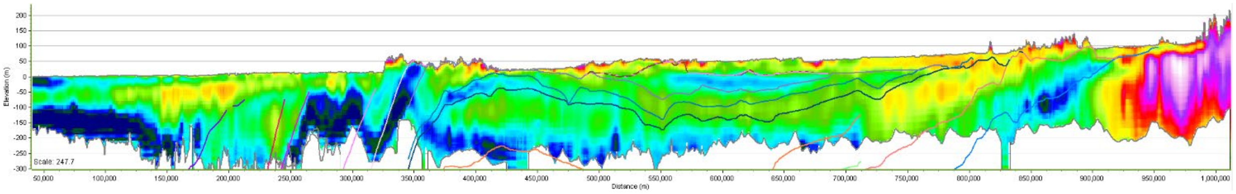

Figure 3. South-north resistivity cross-section. Gridded resistivity models are shown along a ~1,100 km cross-section from the Louisiana gulf coast on the left, where elevated groundwater salinity can be seen as a low-resistivity lens in the near surface, to the upland area outside the alluvial plain in southeastern Missouri (white dotted line, Figure 2b). The subsurface resistivity architecture closely corresponds with the top surfaces of hydrogeological units (colored lines, Mississippi Embayment Regional Aquifer Study (MERAS) model (Hart, Clark, and Bolyard 2008).

Outreach

We have focused on raising community awareness about airborne geophysical surveys and the value provided by these data throughout the project. Outreach efforts have included: multiple stakeholder and public events held during survey operations, presentation of data interpretations, and publication of online geonarratives that describe the results of the geophysical surveys for the general public. We developed a 3D-printed physical model interpreted from a subset of our AEM data for use as a communication tool and handout for cooperators and other officials (Figure 4).

Conclusions

Airborne geophysical data extend our view into the subsurface, transforming our ability to inform three-dimensional mapping from catchment to basin scales in a cost-effective and systematic approach. Here, we demonstrated that system-scale airborne geophysical data of the lower Mississippi River Valley provide a robust platform from which to address a host of subsurface questions with important scientific and societal applications.

Acknowledgements

This study was primarily funded by the U.S. Geological Survey (USGS) MAP project, as a federal appropriation to the USGS Water Availability and Use Science Program. Partial funding for airborne geophysical survey data came from the U.S. Army Corps of Engineers and the University of Memphis. Airborne geophysical data were acquired by Xcalibur Multiphysics and CGG Airborne through a competitive open solicitation. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government. Data acquired in this study are available online: https://www.sciencebase.gov/catalog/item/58a5d9c5e4b057081a24f3fd.

Figure 4. Outreach and communication examples. (top-right) Open-house events were held during survey operations to provide opportunities for media and the public to view the AEM survey equipment and learn about the project. Follow-on meeting sessions were held with cooperators to review datasets and discuss interpretations. Photo credits: Roland Tollett (USGS) and Randy Hunt (USGS). (top-left) A physical 3D-printed model of three layers interpreted from the AEM data collected over one of the high-resolution survey blocks in Mississippi is a useful communications tool and handout for cooperators. Photo credit: Department of the Interior. (bottom) Online geonarratives were created to present both regional and high-resolution inset AEM datasets in a simplified format to showcase the survey results to public audiences. The geonarratives can be found at:
https://apps.usgs.gov/lmg/map/regional_SM.html
https://apps.usgs.gov/lmg/map/shellmound_SM.html

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SUPPORTING HYDROGEOLOGICAL AND CONTAMINATION/REMEDIATION ASSESSMENTS IN ALBERTA THROUGH DATA SCIENCE MODELLING AND DATA DASHBOARDS

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Introduction

The Alberta Geological Survey (AGS) is responsible for conducting applied research across a wide range of geoscience disciplines, including the development of 3D geological models (MacCormack et al., 2019) to support groundwater availability and quality evaluation. As part of these initiatives, the AGS is leveraging data science to create new approaches for the 3D prediction of surficial deposits. These predictions, in turn, help to further our understanding of the distribution of shallow aquifers, hydraulic characteristics, recharge and discharge processes, and groundwater chemistry.

However, the dissemination and delivery of 3D geological information in a form that is suitable for a broad spectrum of users presents challenges, with users increasingly requiring analysis-ready solutions and decision support tools, in addition to access to raw data products that necessitate robust software requirements. Additionally, the iterative and dynamic nature of data science products requires agile forms of product delivery. To meet the needs of regulatory end users and the public in general, the AGS is developing end-to-end, data pipelines and workflows that automate the process of model development, prediction, and updating of web applications and interactive tools to explore complex geoscience datasets.

Here we describe an application of 3D geological modelling for Neogene to Quaternary aquifer delineation purposes using machine learning methods. The work was performed to support collaborative, hydrogeological research into the quality of shallow groundwater, and to inform the Alberta Energy Regulator’s contaminated sites team, who required a first-order, province-wide groundwater susceptibility map to evaluate oil and gas applications and to support remediation efforts. A modified DRASTIC approach (Aller et al., 1987) for groundwater susceptibility was selected as the methodology to synthesize different sources of geoscience information into a single index suitable for this purpose. However, the DRASTIC approach requires an estimation of aquifer media properties for surficial deposits, which had not been previously performed at the provincial scale. An additional issue with DRASTIC is that it can be difficult for users to understand how the governing geological and hydrogeological factors affect the susceptibility rating in any location.

Model Development

For surficial aquifer delineation, a machine learning spatial prediction workflow that incorporates information from traditional digital elevation model-derived estimates of terrain morphometry and satellite imagery, augmented with spatial feature engineering techniques, was used to predict sediment thickness and 3D lithological properties of sediments above bedrock across Alberta. Bedrock depth picks from >300,000 litholog and outcrop observations were used for sediment thickness modelling, employing several machine learning algorithms (XGBoost, Random forests, Cubist, deep learning neural networks), and with the use of spatial feature engineering techniques being shown to significantly improve predictive performances. Next, the properties of sediments above bedrock were estimated using a coarse/fine-grained 3D machine learning classification model trained on the binarized litholog interval data. The results, when evaluated in 3D as iso-surfaces (Figure 1a) or sliced at specific depth intervals, for example to show the probability of coarse-grained deposits occurring immediately above the bedrock contact (Figure 1b), successfully delineated the distribution of many major sand and gravel dominant geobodies at provincial and sub-regional scales.

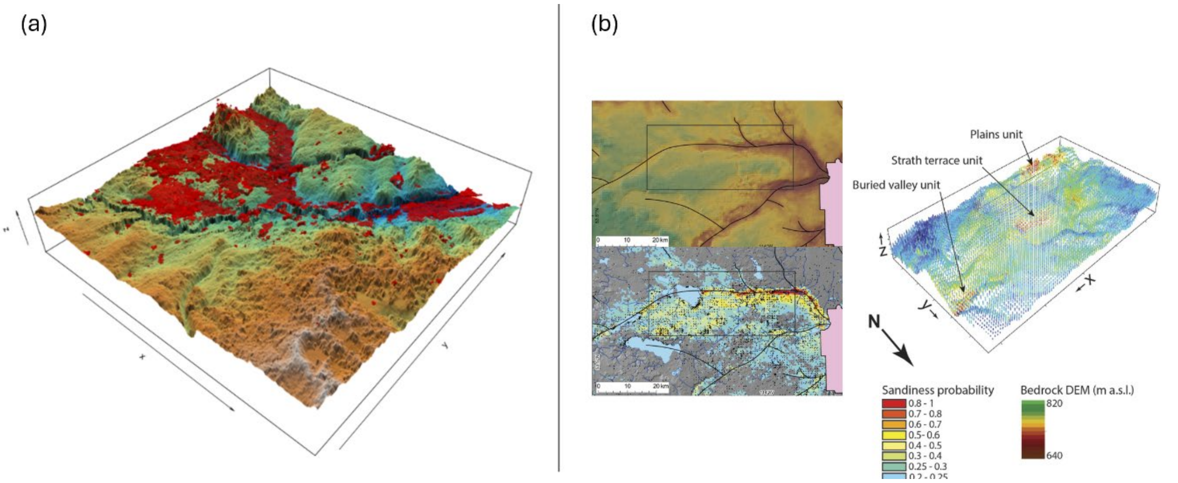
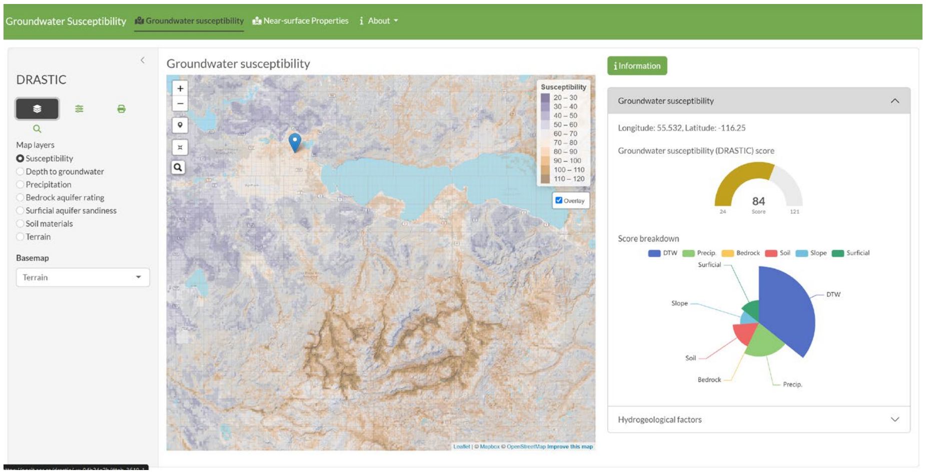


Figure 1. (a) Isosurface of voxelized 3D spatial prediction of the probability of coarse-grained deposits in the Edmonton region of Alberta, highlighting surficial deposits that have a high probability of contained coarse-grained, aquifer-hosting materials. (b) Bedrock elevation (top-left), the probability of coarse-grained deposits at 2.5 m above the bedrock surface (lower-left), and 3D point cloud of predicted 3D properties (right). Modified from Hartman et al. (2024).

Data Dashboard

The modelled thickness and composition of sediments above bedrock were used as input to the aquifer media parameter, which represents an important component of the DRASTIC approach, along with other input layers (depth to water, precipitation, soil type, and terrain slope). The predictions, which depict the probability of coarse-grained deposits in the subsurface in three dimensions, were used as a proxy for overall 'sandiness' and were assigned a relative rating within the DRASTIC formula. The workflow was setup as a data pipeline, using Azure and Posit data science platform components and data lake storage, so that model outputs can be used to update the DRASTIC index upon changes to the underlying datasets.

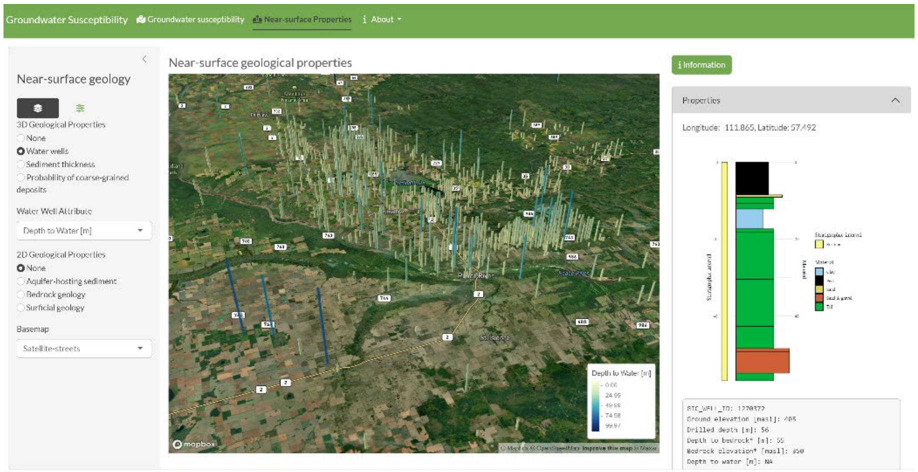
For results dissemination, a lightweight, open-source R Shiny web application was developed to combine the suite of geological layers with hydrogeological information (Figure 2). The application was designed to enable end users to identify locations where near surface aquifers have a higher susceptibility to surface contamination, and to explore the geological factors that influence these predictions within a simple and easy to use web-based tool.



Longitude: 55.532, Latitude: -116.25

Figure 2. The groundwater susceptibility data dashboard, providing a spatial visualization of DRASTIC scores and additional plots/tables to explain the influence of the underlying geological and hydrogeological parameters.

The data dashboard uses 2.5D components based on deck.gl to allow users to visualize massive datasets, for our example, comprising water well attributes, sediment thickness, surficial and bedrock geology maps, and slices through the surficial deposits at any modelled depth interval (Figure 3). Other commonly requested features, such as being able to visualize the lithologs of nearby water wells, create 2D geological cross-sections, and export the results to a PDF document, were also implemented. The overall user experience and interactivity of individual map layers is fast for typical operations of zooming/smoothing/selecting. Performance for re-rendering after switching layers is reasonable (within 5s). Further improvements could be made by offloading components to raster/vector tile services such as GeoServer or calling an external API (e.g., FastAPI) to serve the application with additional information based on user interaction.



3D Geological Properties
○ None
● Water wells
○ Sediment thickness
○ Probability of coarse-grained deposits

Water Well Attribute: Depth to Water [m]

2D Geological Properties
● None
○ Aquifer-hosting sediment
○ Bedrock geology
○ Surficial geology

Basemap: Satellite-streets

Longitude: 111.865, Latitude: 57.492

```
GIC_WELL_ID: 1270372
Ground elevation [masl]: 405
Drilled depth [m]: 56
Depth to bedrock* [m]: 55
Bedrock elevation* [masl]: 350
Depth to water [m]: NA
```

Figure 3. 2.5D visualization of hydrogeological properties (static water levels) and water well litholog viewer.

Ongoing Development

Increased water demands and widespread drought concerns have led to products such as sediment thickness and surficial deposit properties being frequently updated in support of regional hydrogeological investigations. Continued model development includes moving from specific machine learning models, to using model stacking/ensembling and AutoML techniques. The increased availability of high-resolution predictors has also provided iterative improvements to the results. Current work is looking to integrate collections of airborne electromagnetic survey data to generate more detailed, sub-regional 3D predictions in high priority areas.

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SYNOPSIS OF BASIN-SCALE 3D FRAMEWORK MODELING AT THE USGS MAPPING PROGRAM

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Introduction

Digital three-dimensional (3D) subsurface models are increasingly becoming a standard practice for Geological Survey Organizations (GSOs) to systematically investigate and document the geology within their jurisdictions (MacCormack et al., 2019). Demand for these products from GSOs is ever increasing, as competing pressures between societal demand, subsurface resource development, and the environment require quantitative and accurate geoscience information to be appropriately managed (Thorleifson and others, 2019).

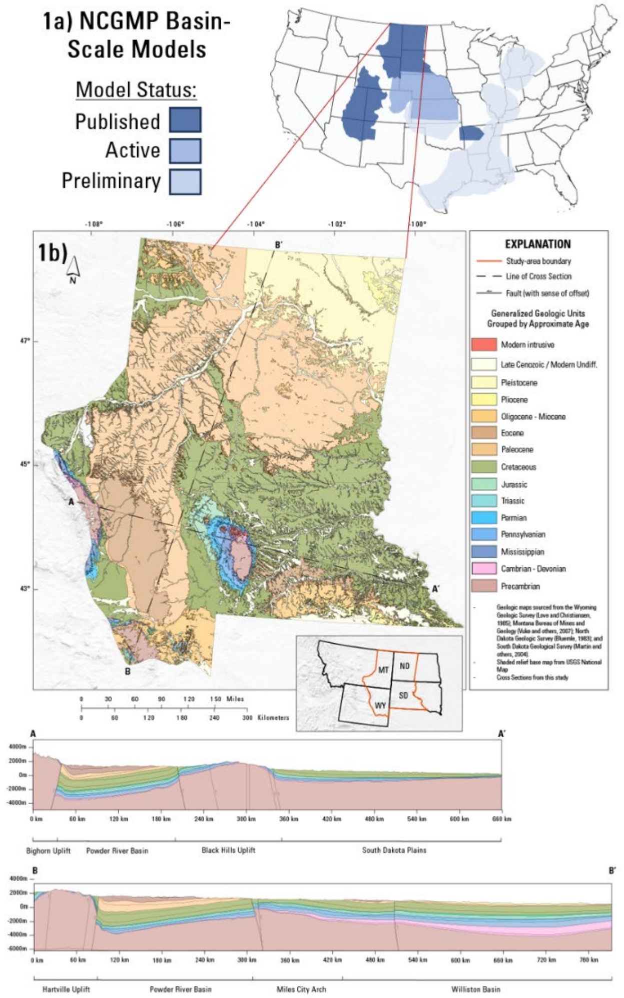

Figure 1. (a) Status map of current NCGMP basin-scale projects. (b) Zoomed-in view of the northern Great Plains study area, showing the generalized surface geology grouped by geological age, and highly simplified geological cross sections cut through the model highlighting structural basins and uplifts.

In a similar fashion to other GSOs, the U.S. Geological Survey (USGS) is engaged in numerous 3D modelling activities that address specific problems related to USGS Mission Areas, such as Energy and Minerals, Water Resources, Core Science Systems, and Natural Hazards (Sweetkind et al, 2019; Sweetkind and Zellman, 2023). The USGS National Cooperative Geologic Mapping Program (NCGMP) has invested in development of expansive basin-scale 3D framework models with the intent to integrate these together into a national-scale subsurface framework (U.S. Congress, 2019, p. 48–49; Brock et al., 2021). Framework models provide a regional interpretation of the subsurface by mapping the elevation, thickness, and extent of subsurface geological units, defining broad structural trends and faults, and modeling the interactions between these components in three dimensions (Turner and others, 2021). Similar to a 2D geological map, geological framework models are a fundamental starting point for a myriad of location or purpose-specific studies which may apply the broad interpretation as base data, boundary conditions outside of areas of interest, or consult the reference documentation to identify data sources for their own studies.

This extended abstract discusses the NCGMP's effort to serve a deterministic geological framework model of the conterminous United States from the crystalline Precambrian basement to Earth's surface to support subsurface conceptualization, resource assessments, and process models. While 3D subsurface modeling in and of itself is not a novel concept, we explore specific challenges, solutions, and future questions identified by the NCGMP pertaining to basin-scale subsurface modeling in the US onshore lower 48 states.

Current NCGMP Modeling Efforts

Similar to the methodology of GSO's such as the Alberta Geological Survey (MacCormack, 2019), a considerable portion of the NCGMP's effort to model the conterminous U.S. (over 8.08 million square-kilometers) is dedicated to producing basin-scale models which can eventually be merged into a larger national-scale product. Narrowing the scope of individual studies to the basin-scale allows for workers to draw on local expertise from state geological surveys, industry, and academic experts to capture geologic nuance more appropriately than might be achievable at the national scale. Currently the NCGMP has published over 435,000 square-kilometers of geological models including the Colorado Plateau (Sweetkind et al., 2023), Arkoma Basin (Lutz et al., 2024), and the greater northern Great Plains which includes the Powder River Basin region, the Williston Basin region, and western South Dakota (Spangler, 2024a, 2024b). Additionally, the NCGMP is actively working on basin-scale models which span an additional 1.17 million square-kilometers including the Denver-Julesburg Basin region, the states of Kansas and Nebraska, and the Michigan Basin region (Figure 1a).

The northern Great Plains region was selected as a pilot project to test the 3D modeling capabilities within the NCGMP. Here, multiple types and large quantities of publicly available data were integrated into a volumetric 3D subsurface model that includes regions of variable data density and quality. The northern Great Plains encompasses major hydrocarbon-producing basins with a well-defined Phanerozoic stratigraphy (the Powder River and Williston Basins), underexplored regions (Miles City Arch, South Dakota Plains), and major basement-cored uplifts with moderate structural complexity to the west of the study area (Bighorn, Hartville, and Black Hills Uplifts) (Figure 1b).

Geologic Data in the Conterminous U.S.

Geologic data across the conterminous U.S. is simultaneously an asset and a challenge for NCGMP basin-scale modelling efforts. Given the long-lived and extensive history of geological exploration and research in the lower 48 states, an abundant quantity of publicly available subsurface data, interpretations, and theoretical knowledge is available to NCGMP modelers to construct robust framework interpretations. Geospatial data and nonspatial studies produced by state GSO's, the USGS and other federal agencies, academic groups, and industrial partners are a significant asset to the program.

As an example of data available to the NCGMP 3D effort, the northern Great Plains study incorporated over 307,500 geospatial inputs from surface maps (Love and Christiansen, 1985; Martin et al., 2004; Vuke et al., 2007; Bluemle, 1983), hydrocarbon and water wells, and structure contour maps (e.g., McCormick, 2010; Spangler & Sweetkind, 2022; Thamke et al., 2014; Lichtner et al., 2020), with an additional 6 million datapoints from previously published geological models (Gelman & Johnson, 2023; Spangler et al., 2023) and USGS DEMs (USGS.gov). These data were extracted, standardized, and applied to construct a 42-layer framework model (Figure 2).

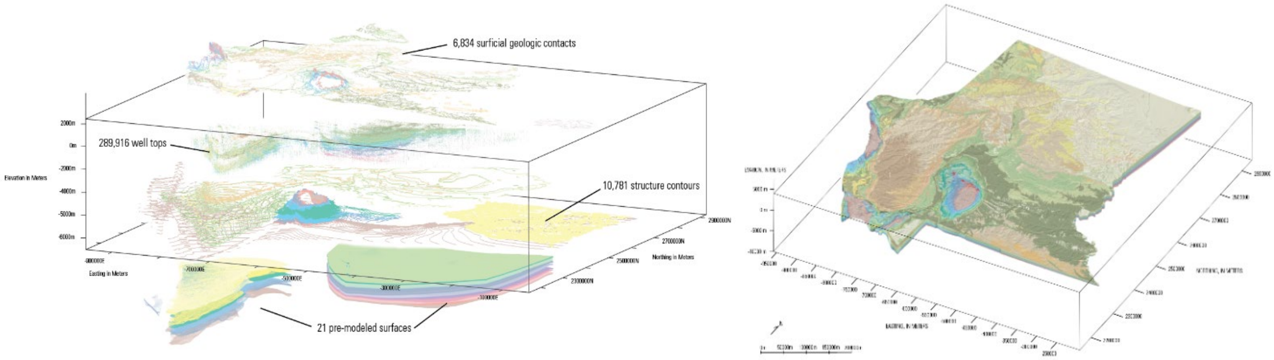

Figure 2. Examples of publicly available spatial data used in the northern Great Plains study, including ~1:500,000-scale surface mapping, hydrocarbon and water well stratigraphic tops, structure-contour datasets, and previously published model grids (left). The resulting framework (right) approximates 1:500,000-scale surfacer mapping where surfaces intersect the DEM.

While the volume of publicly available data is significant, the distribution of these data both laterally and vertically is generally clustered around hydrocarbon or groundwater producing basins and formations, with significant gaps in data availability outside of these areas. Further complicating this issue, data abundance, format, accessibility, and vintage are heavily dependent on the effort of individual states. This results in a disjointed collage of data across the conterminous U.S. ranging from professionally vetted and formatted databases available as a subscription service (North Dakota DMR), to simply no central repository existing for entire U.S. states at all (Georgia for example). Many of the highest-quality subsurface datasets are privately owned and limited in extent to areas of commercial resource exploration and production. This decentralized state of subsurface data requires that basin-scale modelers spend a significant amount of time finding, extracting, and formatting data before importing those data into a GIS for modeling. Furthermore, it underscores the need for ongoing USGS synthesis and compilation efforts (Smout et al., 2023).

Methods & Tools

The NCGMP employs a variety of methods and tools for efficiently constructing deterministic basin-scale models, aiming to incorporate diverse geological information, generate consistent volumetric models at approximately a 1:500,000 scale, and produce reproducible and useful results.

Initial modeling methods involved extruding grids into 3D shapes using a GIS (Figure 3a). Recent modeling studies such as the northern Great Plains or the state of Kansas examples, use a hybrid approach combining implicit modeling from geospatial data with explicit techniques where enough data is available (e.g., fence diagrams, cross sections) (Wang et al., 2024). With this approach, separate structural and stratigraphical models are constructed from available base data, and then integrated into a single volumetric faulted framework model. Multiple iterations of model refinement are then conducted to harmonize the two frameworks, to eliminate outliers and conflicting datapoints, and to add detail or enforce geological rules for gridding calculations.

Several tools are employed to construct these deterministic models, including ESRI ArcPro^{TM}, Seequent Leapfrog Geo^{TM}, Rock Ware's RockWorks^{TM}, and Petex MOVE^{TM} 3D modeling software. Each platform has strengths that support the program's efforts, and each basin-scale modeling project uses some combination of these tools depending on the needs of the specific study area. For example, work in the Arkoma Basin primarily utilized software with ordinary kreiging for detailed fault construction and analysis, followed by software with a radial basis function interpolant for stratigraphic refinement and data export, and a traditional GIS for preparation for dissemination (Figure 3b) (Lutz et al., 2024). Similarly, the northern Great Plains study primarily was conducted using a radial basis function followed by a traditional GIS (Figure 2). These tools were chosen because of the large amount of irregularly distributed input data, and the ability to modify gridding parameters based on conceptual controls on basin fill over such an expansive study area.

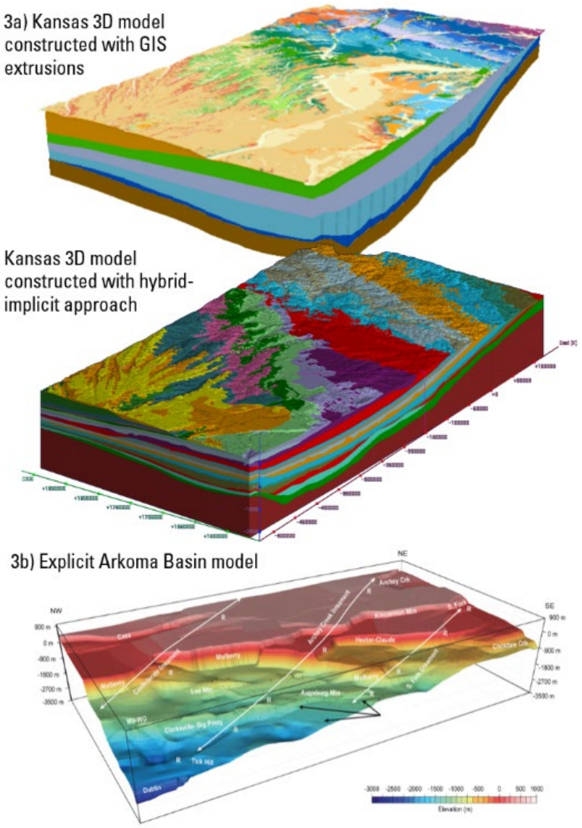

Figure 3. (a) Two 3D geological models of the state of Kansas constructed with extrusions and multipatches in a GIS (above), and a second model constructed using a hybrid-implicit approach (below). (b) Stratigraphic surface constructed with an explicit approach across multiple modelling platforms in the Arkoma Basin.

Validation and Communication of Uncertainty

Validation and communication of uncertainty are critical aspects of geological framework model development. Accuracy assessments help users make informed decisions based on model confidence and identify locations where future subsurface investigations or data collection efforts may provide significant value. Model validation is a standard practice amongst subsurface modelers (Wang, L., 2024) and the NCGMP is working to communicate accuracy of model results and uncertainty. Initial attempts at quantifying model accuracy involve simple goodness of fit tests which identify the difference between the input data and the model results (z-residuals). Plotting the spatial distribution of these values on a base map can be an easy-to-understand proxy for uncertainty, where one could infer that regions of low data density or poor model fit have a lower confidence. As more models are built and the complexity or user base for this work grows, these methods will certainly need to evolve.

Model Output and Dissemination

The USGS and the NCGMP have established standards for attribution and public dissemination of 2D geological data such as the GeMS data structure (USGS NCGMP, 2020). These standards ensure that products produced by the USGS are findable, accessible, interoperable, and reusable (FAIR). Fundamentally, 3D information produced by the NCGMP is similar enough to 2D data that model outputs are served in a geodatabase in GeMS-like format, adhering to FAIR data practices and maintaining structure. In the northern Great Plains, 42 stratigraphic surfaces are served in a geodatabase as separate 250 square-meter resolution single-band elevation rasters, with 64 faults served as point feature classes at a 500 square-meter resolution. Accompanying nonspatial tables include a glossary, description of model units, data dictionary, and reference list. A table of model inputs and their associated settings is included to ensure reproducibility. Results are published on the USGS's public-facing data repository ScienceBase, and are accompanied by a USGS report. This report discusses input data, model construction, and model limitations among other topics potentially of value to the end user.

To facilitate accessibility and usability, the NCGMP is exploring visualization tools and platforms that allow users to interact with 3D models in virtual environments. These tools include web-based applications that provide dynamic views of subsurface structures and features, enabling stakeholders to explore and analyze geological data in an intuitive and user-friendly manner. Furthermore, an interactive visualization tool will likely be an important component of reaching audiences who may not otherwise be aware of these products.

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VOXEL MODELS OF THE NETHERLANDS: CONSTRUCTION METHODS, RECENT DEVELOPMENTS AND NOVEL 3D VISUALIZATIONS

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Introduction

TNO – Geological Survey of the Netherlands (TNO-GDN) systematically produces 3D models of the subsurface of Netherlands. To date, we build and maintain two different types of models that have national coverage: (1) layer-based models in which the subsurface is represented as a series of tops and bases of geological or hydrogeological units, and (2) voxel models in which the subsurface is subdivided in a regular grid of voxels (3D grid cells) attributed with a number of geological properties. Layer-based models of the shallow subsurface include the national geological framework model DGM and the hydrogeological model REGIS II. A third layer-based model is DGM-deep with Carboniferous to Neogene seismostratigraphic units up to a depth of 7 km.

The three main voxel models are the aggregate resources model and the multi-purpose NL3D and GeoTOP models. The aggregate resources model is the oldest one, published in 2005. It is being replaced step by step by GeoTOP (Maljers et al., 2015). NL3D can be constructed rapidly but has less detail and is less accurate than the state-of-the-art voxel model GeoTOP. All voxel models schematize the near-surface in millions of voxels up to a depth of 50 m below Dutch ordnance datum (~ mean sea level). Each voxel contains multiple properties that describe the geometry of stratigraphic units (layers), the spatial variation of lithology within these units, as well as measures of model uncertainty. The addition of physical properties to the voxels enables the deployment of the model for a wide range of applications, including long-term predictions of land subsidence due to compaction of clay and oxidation of peat, aggregate resource assessments, groundwater flow studies, land-use planning, and site-response assessments of induced earthquakes.

In this extended abstract we discuss the NL3D and GeoTOP voxel models. Comparing the two models demonstrates the importance of putting as much geological knowledge as possible into the model. Next, we will look at recent developments in GeoTOP, including an update of the oldest part of the model, the latest extension and the acceleration initiated to model the remaining 30% of the country. Lastly, we will show the new 3D-webservices of GeoTOP and REGIS II.

Geotop – State-of-the-Art Voxel Model

GeoTOP models the shallow subsurface of the Netherlands in a regular 3D grid of voxels measuring 100 by 100 by 0.5 m (x ,y, z) up to a depth of 50 m below Dutch ordnance datum (Stafleu et al. 2021). Each voxel contains estimates of the lithostratigraphic unit that the voxel belongs to and the lithological class (including a sand grain-size class) that is representative for the voxel. GeoTOP is publicly available from the Survey's interactive online platform (https://www.dinoloket.nl/en/subsurface-models/map). At present, GeoTOP covers 29,000 km^2 (71%) of the surface area of the Netherlands (Figure 1). GeoTOP is constructed using c. 495,000 borehole descriptions from the national subsurface database operated by TNO-GDN (https://www.dinoloket.nl/en/subsurface-data), complemented with c. 125,000 auger holes from Utrecht University in the central Rhine-Meuse river area. The modelling procedure consists of four steps:

First, the borehole descriptions are interpreted into standardized lithostratigraphic units with uniform sediment characteristics. Because of the large number of boreholes, an automated workflow consisting of lithostratigraphic interpretation routines (Python scripts) is developed. These routines combine geological knowledge and model decisions in the form of digital stratigraphic distribution maps, stratigraphic rules (e.g. superposition), and lithological criteria (e.g. main lithology, admixtures, grainsize and shell content, amongst other criteria) to determine the depth of the top and base of the lithostratigraphic units in each of the borehole descriptions. Due to the extensive available borehole data, GeoTOP is highly detailed and distinguishes some 35 Holocene and 45 Pleistocene and older formations, layers, beds, and facies units such as channel systems.

Second, 2D interpolation techniques are used to construct surfaces bounding the bases of the lithostratigraphic units as observed in the boreholes. Subsequently, all surfaces are stacked according to their stratigraphical position, resulting in a consistent 3D layer-based model with estimates of top and base of each lithostratigraphic unit. Top surfaces are derived from the bases of the overlying units. The layer-based model is then used to place each voxel in the model within the correct lithostratigraphic unit.

Third, the borehole descriptions are classified in eight different lithological classes.

Fourth, in this last modelling step, lithological classes are estimated for each lithostratigraphic unit separately using a Monte Carlo approach. The estimation results in 100 equiprobable realizations of lithological and grain-size class for each voxel. Post-processing of the realizations results in probabilities of occurrence of each of the lithological classes as well as a 'most likely' estimate of lithological and grain-size class.

All four steps are repeated in several iterations, each time refining the distribution maps and automated procedures to honor both data and geological interpretations. Reviewing and rerunning the model multiple times makes the construction of GeoTOP a time-consuming effort.

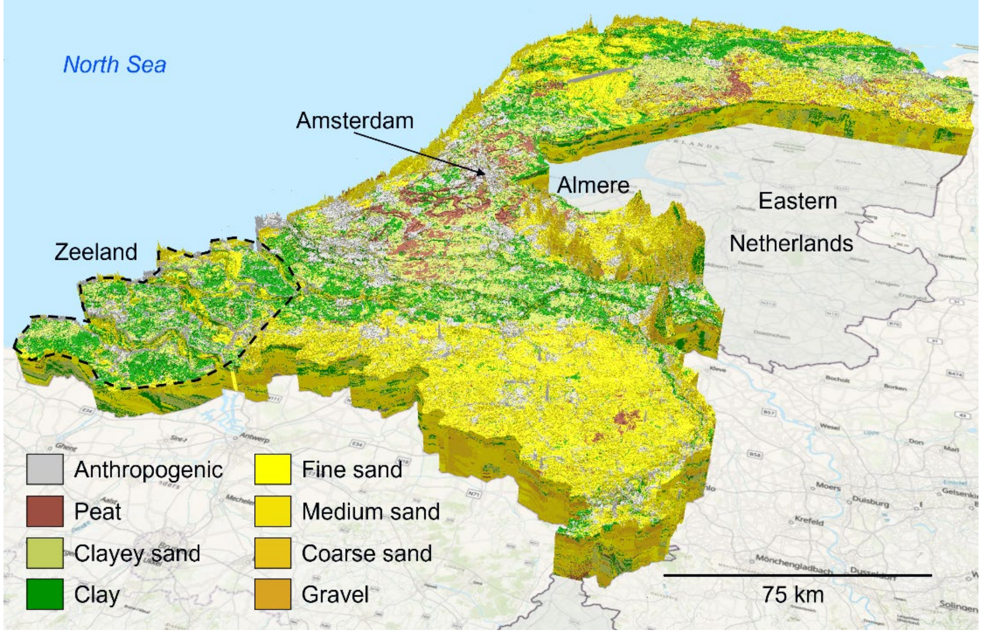

Figure 1. 3D view of lithological classes in GeoTOP, visualized as a multidimensional voxel layer in Esri's ArcGIS Pro. Vertical exaggeration 200x.

Nl3d – Rapid Voxel Model Construction

NL3D models lithology and sand grain-size classes in voxels measuring 250 by 250 by 1 m (x ,y, z) up to a depth of 50 m below Dutch ordnance datum. NL3D uses c. 640,000 borehole descriptions from the aforementioned databases which are interpreted stratigraphically by intersecting each borehole with the top and base raster layers from the DGM layer-based model (Gunnink et al., 2013). This is a simple procedure, resulting in stratigraphic interpretations that are geometrically consistent with the DGM model, but not necessarily consistent with the borehole descriptions. For example, a borehole interval describing 'peat' may erroneously fall within a DGM defined unit that is characterized by sand deposits. In GeoTOP, which uses advanced routines to assign stratigraphy based on the lithological characteristics observed in borehole descriptions, these issues are much less common.

Next, the surfaces of the DGM model are used to place each voxel in the model within the correct lithostratigraphic unit. DGM is a layer-based model built from a smaller dataset of c. 26,500 manually interpreted borehole descriptions from the national database. As a result, it is less refined than the layer-based model underpinning GeoTOP. For instance, DGM combines all Holocene formations in a single unit, whereas GeoTOP features 35 different Holocene formations, members, beds, and channel belt systems.

The third and fourth steps are identical to the ones described for GeoTOP, and result in a voxel model with the same set of attributes (Figure 2).

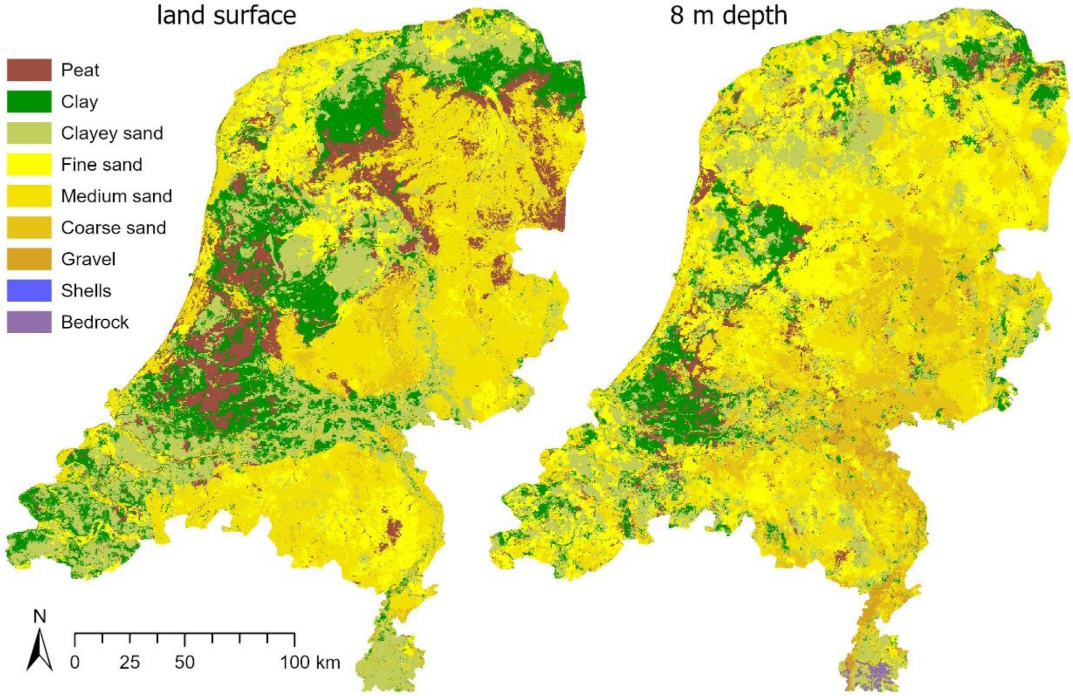

Figure 2. 2D raster maps derived from NL3D, showing lithological class distribution at land surface (left) and at 8 m below land surface (right). Cell size 250 m.

GeoTOP is clearly a better model than NL3D: the resolution of GeoTOP is higher, the layer-based model is more detailed and the stratigraphic interpretation routines are more advanced. The great advantage of NL3D, however, is that computation times are relatively short and the workflow is highly automated. When new borehole data becomes available, a new version of NL3D can be constructed and published in less than 200 hours of work. Another advantage is that the model has national coverage, whereas GeoTOP is still unfinished. NL3D is used in applications requiring full national coverage and in areas where GeoTOP is not yet available.

Geotop – Recent Developments

The GeoTOP modelling program started in 2006. In the first 16 years, modelling was conducted in twelve large model areas, roughly corresponding to the Dutch provinces, and each taking 2 – 3 years to complete. GeoTOP currently covers about 71% of the country. In 2020, GeoTOP became part of the Key Registry of the Subsurface (BRO), which led to an increase in the use of the model. In addition, there is a strong demand for GeoTOP in the areas that still have to be modelled.

Following the completion of the seventh model area in the south of the country, we re-modelled the existing model of Zeeland (outlined by the dashed line in Figure 1) in order to meet the new quality requirements of the BRO. The Province of Zeeland utilizes the updated model as a foundation for policy issues, such as studying the ongoing salinization of the area. In the freshwater-saltwater balance, the Holocene sandy tidal channels play a crucial role. Consequently, we focused on accurately modeling these channel systems.

In 2022 – 23, we took a different tack and created a relatively small GeoTOP model of the municipality of Almere. This city is currently planning the development of some 30,000 new homes as well as a new road and rail connection to Amsterdam. GeoTOP is key to successfully address Almere’s subsurface challenges such as soft soils and land subsidence, water management, and thermal storage systems. Special attention was paid to accurately model the anthropogenic deposits which are important in Almere’s man-made landscape. Because of the smaller area, we were able to build the model in a single year, responding much faster to the needs of the municipality.

Modelling the remaining 30% of the country in many small areas does not provide a faster route to national coverage. We therefore decided to model the remaining part in a single, large model area in only three years’ time. We can do this by focusing on the modelling of those stratigraphic units that are most important for the application of the model in the built environment (e.g. Holocene and upper Pleistocene deposits). Older deposits will be modelled using the rapid construction methods of NL3D and the existing national layer-based model DGM. After national coverage is reached, the lessons learned from Almere will be applied to update small areas incorporating new data and geological insights. These local updates may also have a higher resolution and additional properties to meet specific user requirements.

Another development in GeoTOP is the ever-increasing amount of subsurface data, as a consequence of the BRO. New data types in GeoTOP include cone penetration tests, now used for a better estimation of the base of the Holocene deposits, and pedological borehole descriptions, detailing the upper 1.5 m of the model. In the near future, airborne EM data, revealing the spatial distribution of lithology continuously, will become available in the northern provinces.

Novel 3D Visualizations

All models are disseminated free-of-charge via the Survey's interactive online platform (https://www.dinoloket.nl/en/subsurface-models/map) in a number of ways, including an online map viewer with the option to create virtual boreholes and vertical cross-sections through the models, and as a series of downloadable GIS products. Full 3D visualization is supported by the freely downloadable SubsurfaceViewer® software, which allows users to download and visualize the models on their personal computers.

A recent development in model visualization is the capability of Esri's GIS-software to visualize large voxel-models in 3D (the 'multidimensional voxel layer' in ArcGIS Pro). Following up on this development, we recently published 3D webservices of GeoTOP in two different ways: (1) as Voxel Scene Layers, in which voxels sharing the same attribute value (i.e. the same lithological class or stratigraphic unit) are represented as a 3D-layer; and (2) as 3D Object Scene Layers, in which each individual voxel is represented as a 3D-shape bounded by six rectangular faces. Object Scene Layers of the hydrogeological REGIS II hydrogeological model are also available. The 3D-webservices can be viewed directly in the browser, without the need of specialized or licensed software (Figure 3). Webservices may also be integrated in customized web applications created by, for instance, municipalities who want to inform citizens about the subsurface in their neighborhoods.

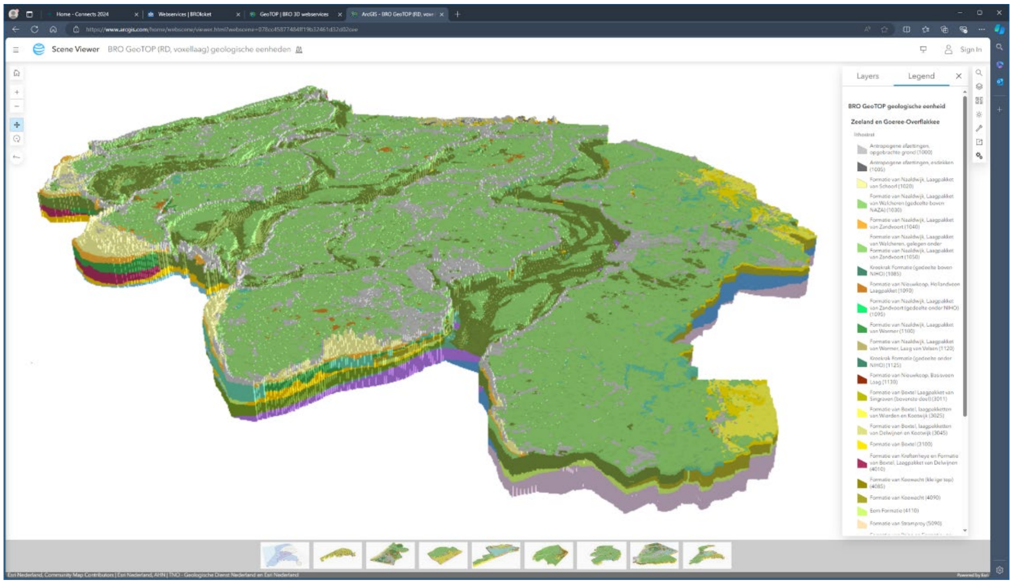

Figure 3. Interactive 3D visualization in a browser showing the GeoTOP model of Zeeland attributed with stratigraphy.

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3-D MAPPING OF THE CONTERMINOUS U.S. WITHIN THE USGS NATIONAL COOPERATIVE GEOLOGIC MAPPING PROGRAM: PROGRESS AND FUTURE PROSPECTS

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Abstract

The U.S. Geological Survey (USGS) National Cooperative Geological Mapping Program (NCGMP) is bringing together subsurface and three-dimensional (3-D) information at multiple scales throughout the conterminous United States from data produced throughout the USGS and by federal and state partners. Components of this work include data inventory and catalog development, data integration and database development, and construction of subregional and basin-scale 3-D geologic models. At smaller scales, the NCGMP is compiling subsurface data to create a limited number of subsurface layers that map the majority of the lower 48 States. At larger scales, 3-D models of stratigraphic units are intended to be the subsurface analog and extension of the surface geological maps made within the Program. The Mapping Program is developing methods of storing, visualizing, and distributing 3-D models and subsurface data from multiple sources in easily shareable, queryable, non-proprietary format(s). In this extended abstract, we report on progress in 3-D mapping of the conterminous U.S. and on future prospects.

Introduction

Water, energy, mineral resource, hazard, and land-use assessments are central to the U.S. Geological Survey mission and increasingly rely on subsurface information and 3-D geologic models. USGS science-planning documents and strategic plans for the USGS NCGMP (Brock et al. 2021) call for geological mapping across the Nation to become increasingly 3-D in nature. Increases in Congressional appropriations to the USGS NCGMP starting in Federal Fiscal Years 2020 and 2021 directed the NCGMP to initiate Phase Three of the National Geologic Map Database (NGMDB; Soller and Berg, 2002), “bringing together detailed national and continental-resolution two-dimensional (2-D) and three-dimensional (3-D) information produced throughout the Survey and by federal and state partners.” Based on the NCGMP’s strategic plan, vision documents from the Association of American State Geologists (Allison, 2014), and in response to Congressional direction and funding, the NCGMP launched the U.S. GeoFramework Initiative (USGI) to deliver a digital national geological map and 3-D geologic model of the United States (Shelton et al. 2022). As a part of the USGI, the NCGMP created a new project, the National Geologic Synthesis Project, to develop 2-D and 3-D geological information at National scales.

Data inventory and catalog development

Inventory and cataloging activities support the development of subsurface maps and models. The National Geologic Map Database <https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html> contains an extensive inventory of published geological maps; the inventory may be accessed through text-based queries of catalog entries or by a map viewer application. However, prior to the inception of the USGI, relatively little attention had been paid to cataloging 3-D-relevant subsurface data depicted on maps within the NGMDB catalog, and 3-D models were not inventoried at all, making the NGMDB unsuited to supporting the initial phases of subsurface mapping and 3-D geological modeling. Current work, conducted in partnership with the NGMDB, will expand the NGMDB catalog to include 3-D models and subsurface datasets and enhance the accessibility and findability of 3-D-relevent datasets.

Progress Data inventory activity has focused on (1) searching for and collecting past studies that mapped tops, bottoms, thicknesses of geological units; (2) making “paper” records digital and publicly available in standard format, and (3) putting data into a centralized, searchable catalog with records that are tagged and attributed. A concerted effort was made to find older USGS reports and maps that were focused on structure contours and isopachs, such as data from the Regional Aquifer System Analysis (RASA; Sweetkind and Masbruch, 2020; Sweetkind et al., 2023a) or from Energy or Water resource assessment studies. Data were digitized, attributed, and released to the USGS ScienceBase trusted digital data repository (e.g., Smout, 2023). A partial inventory of structure contour and isopach datasets was released on USGS ScienceBase (Smout et al., 2023). Previously published 3-D geological models from all USGS Mission Areas were inventoried; results were released as GIS data and a companion USGS report (Sweetkind and Zellman, 2022; 2023) and as a webapp <https://apps.usgs.gov/3d_geologic_model_inventory/>. Digital datasets from some previous 3-D models were revised to non-proprietary formats and released (Zellman and Sweetkind, 2023; Spangler et al. 2023). A companion project in the USGS Water Mission Area inventoried all USGS groundwater models (Ritchie et al. 2023); geology relevant datasets could potentially be extracted from model horizons within this inventory as a future activity.

Future Prospects It is anticipated that these inventories will be incrementally expanded to include, for example, geological models and subsurface data funded or produced by other federal agencies, State Geological Surveys, or academic institutions, and to become increasingly integrated with the NGMDB over time. Through the U.S. GeoFramework Initiative, an expanded set of opportunities was made available to State Geological Surveys within the STATEMAP component of the NCGMP; the initial successful projects have been recently completed and are being submitted to the Program for ingestion into the NGMDB and for use in subsurface mapping. The 3-D part of the NGMDB will become increasingly vector-based through digitization of maps with subsurface data, conversion of legacy data formats, and attribution of digital data. Through the expansion of scope and periodic updates of content, these inventories are intended to serve as a comprehensive and persistent record of 3-D models and subsurface data produced throughout the United States.

Construction of 3D geologic models

The USGS National Geologic Synthesis Project is creating basin-scale to regional-scale 3-D geological models that depict the extent, thickness, and elevation of geological units and the faults that intersect these units (See L. Spangler expanded abstract in this volume). 3-D models are constructed as topologically closed volumes that focus on stratigraphic bounding surfaces that can be linked to 2-D geological maps compiled within NCGMP.

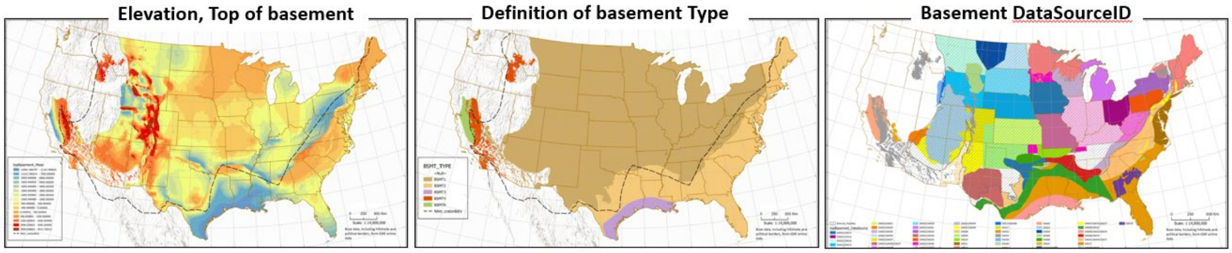
Progress Digital 3D models are created from a wide variety of geological input data including geological maps, borehole data, and various subsurface maps that show unit elevation and thickness; datasets are produced by both Federal and State Geologic Surveys. To date, a 3-D hydrogeological framework model of the entire Upper Colorado River Basin has been published (Sweetkind et al. 2023b) and several basin-to state-scale 3-D geological models of the northern and central Great Plains region are in peer review, or in preparation (See L. Spangler expanded abstract in this volume). In addition, the project has adapted a 3-D geological model constructed as part of a USGS Oil and Gas Assessment of the Williston Basin (Gelman and Johnson, 2023). These models have a total areal extent of almost 1,000,000 km^2 or about 1/8 the area of the conterminous US. USGS projects that produce 3D datasets deliver their data to the public through the ScienceBase trusted digital data repository (e.g., Gelman and Johnson, 2023; Sweetkind et al. 2023b) and through the release of traditional USGS information products. Visualization of the 3D model results is currently delivered in various ways, for example, some model renderings are posted on the Sketchfab 3D viewer <https://sketchfab.com/USGS3D>.

Future Prospects Regional-scale to detailed-scale 3D geological models are built initially as stand-alone models that differ in type, number, and identity of modeled units. Models are anticipated to evolve toward a more "seamless" depiction as regional stratigraphic correlation evolves. At present, the USGS does not have a purpose-built online platform capable of accessing or displaying 3D datasets. Future development for online 3D visualization capability is envisioned to meet the USGS's new and ongoing data visualization needs; integration with the USGS Model Catalog <https://data.usgs.gov/modelcatalog/> is also envisioned.

National scale surfaces and models

A USGI National-scale 3-D geological model synthesizes subsurface data to create a limited number of subsurface layers that map the majority of the lower 48 states.

Progress The initial model took on the initial challenge proposed by the Association of American State Geologists for "3D mapping at least of depth to bedrock and basement as well as subdivision of sediments and/or little-deformed rock strata" (Allison, 2014) creating a three-layer model at a cellular resolution of 2.5-km for the conterminous United States by mapping the altitude of three surfaces: land surface, top of bedrock, and top of basement. These surfaces are mapped through the compilation and synthesis of published stratigraphic horizons from numerous topical studies. The mapped surfaces create a 3-layer geological model with three geomaterials-based subdivisions: unconsolidated to weakly consolidated sediment; layered consolidated rock strata that constitute bedrock, and crystalline (either igneous or deformed), and metamorphosed basement (Figure 1). The digital dataset consists of a single polygon feature class which contains a mesh of square polygons that are 2.5 km in x and y dimensions. These polygonal cells contain multiple attributes including x-y location, altitude of the three mapped layers at each x-y location, the published data source from which each surface altitude was compiled, and an attribute that allows for spatially varying definitions of the bedrock and basement units (Figure 1).



(a) (b) (c)

Figure 1. Example of data from the “basement” layer of the 3-layer geological model of the conterminous United States. (a) elevation of the top of basement surface, (b) spatial varying definition of basement type, (c) source of information for basement elevation, colors show different data sources. Uncolored areas in western U.S. indicate areas where basement as not defined or not yet compiled.

This model is expected to increase in complexity and rigor through time as more geological layers and data from more detailed 3-D models are added. Selection of regional and national-scale model units can rely on the compilation units of a National-scale map, such as the Geologic Map of North America (Garrity and Soller, 2009), or on regional stratigraphic correlation charts such as COSUNA (Childs, 1985). Future 3-D geological modeling and subsurface mapping of the nation will likely involve multiple scales and types of models, will proceed using datasets of varying quality, and will occur in various regions based on data availability and the activities of various geological survey organizations. It is expected that National scale models like this might remain fundamentally a GIS-based product to support import-export capability and ability to ingest and merge datasets. It is understood that a GIS-based product will be problematic in areas of great structural complexity or where units are repeated vertically.

Two other National-scale subsurface mapping activities are occurring within other USGS Mission Areas. The USGS Water Mission Area is building the National Extent Hydrogeologic Framework (NEHF; Belitz, 2022), which will develop a 3-D hydrogeological framework for the nation’s groundwater resources based on previously mapped principal aquifers (Miller, 2000; U.S. Geological Survey, 2003) and secondary hydrogeologic regions (Belitz et al. 2019). The general approach is to add thickness to the previously mapped aquifers and hydrogeological regions and to identify within these modeled regions the depth zones of groundwater used for drinking water (Degnan et al, 2021). The USGS Hazards Mission Area has constructed a 3-D Geologic Framework for the National Crustal Model, a National-scale framework for Seismic Hazard Studies (Boyd and Shah, 2018; Boyd, 2019; 2020). The geological framework is created from geological maps and multiple subsurface geological unit boundaries including the base of the Miocene, Cenozoic, Phanerozoic, and the Moho. The geology at or near the Earth’s surface is based on published maps with modifications to remove discontinuities across state borders. Extrapolation of rock type and age in the subsurface is achieved by iterative stripping of units of a given age, nearest neighbor interpolation of the remaining units, and constraints on basement geology (Boyd and Shah, 2018; Boyd, 2019; 2020).

Future Prospects The USGI and the National Geologic Synthesis Project have taken initial steps to develop a database structure for 3-D model input and output datasets that are broadly derived from standards for 2-D geological maps (U.S. Geological Survey National Cooperative Geologic Mapping Program, 2020) and that facilitate data interoperability between STATEMAP and FEDMAP contributors and the USGI National 3-D synthesis. Ultimately, 3-D model data will be hosted and delivered digitally, with the ability to receive and accommodate updates and contributions from across the NCGMP. This digital infrastructure will facilitate regular updates at a variety of scales; subsurface data and 3-D model data will be stored and served in non-proprietary formats; and 3-D data will be able to be visualized and downloaded without specialized 3-D software platforms.

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MAPPING AN AQUIFER IN 3D FROM THE AIR

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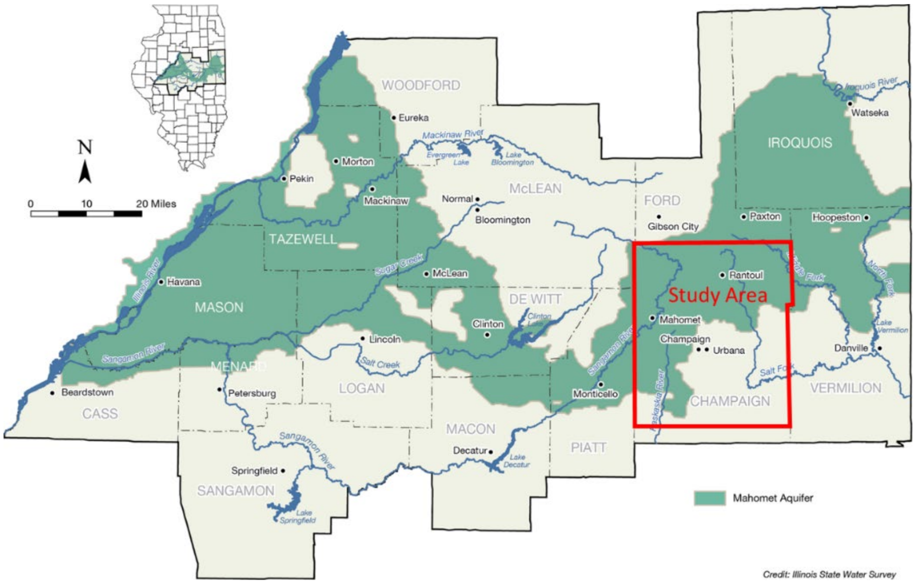
Introduction

Understanding the three-dimensional architecture of aquifer systems is vital to sustainable long-term planning and management. In east-central Illinois, the primary source water for consumption, irrigation, and industry is derived from the Mahomet aquifer (Figure 1). This aquifer is a complex succession of buried sand and gravel deposits within the Teays-Mahomet bedrock valley which extends through Illinois, Indiana, and Ohio. The Mahomet aquifer supplies water to nearly 1million people in east-central Illinois, and in 2015, the US EPA designated it as a federal Sole-Source Aquifer.



Credit: Illinois State Water Survey

Figure 1. Regional distribution of the Mahomet aquifer in east-central Illinois (modified from Brown et al., 2018).

Over the past several decades, scientists have invested millions of dollars and years of staff resources to study and improve our understanding of the Mahomet aquifer system sediments. These studies include maps of regional bedrock valleys and geology (Horberg, 1945; Visocky and Schicht, 1969), regional studies of aquifer character and groundwater flow (Kempton et al., 1991; Herzog et al., 1995), and more recent studies of detailed geology and predictive groundwater flow modeling (Roadcap et al., 2011; Stumpf and Atikinson, 2015). These studies have solidified the basic stratigraphic framework, the regional extent of the aquifer system, and the major flow patterns within the overall groundwater system. These studies have largely relied on traditional ground-based investigations such as drilling, geophysics, and groundwater-monitoring. Despite decades of research, there are still large regions of the aquifer system that have been unexplored, unmonitored, and poorly understood. Much more information is needed to clearly understand the key complexities of the aquifer characteristics, the nature of groundwater-surface water interactions, primary recharge pathways, and the impacts of long-term, high-capacity withdrawals. Thus, we have developed a 3D geological mapping program that deploys airborne geophysics to help map and delineate the detailed architecture of the Mahomet aquifer system more rapidly and effectively (Brown et al., 2018).

Methods

In the past two decades, helicopter time-domain electromagnetic (HTEM) technology has been rapidly developing as a means to gather high-resolution geophysical data quickly and effectively (Sattel, 2006). HTEM technology consists of a large EM transmitter and receiver that are suspended from a helicopter and flown over the study area. The transmitter generates a primary magnetic field in an on/off cycle, which creates (induces) a secondary field in the Earth below the transmitter loop. The receiver then measures the decay of this secondary field during the first ten milliseconds after the transmitter turns off. The strength of the secondary field is directly proportional to the average conductivity of the subsurface materials, a relationship that allows us to interpret resulting resistivity profiles in terms of the potential succession of geological materials. A 1D conductivity profile, called a sounding, is generated from measurements of the secondary field at multiple time intervals (microseconds to milliseconds) after the transmitter is turned off. These soundings are typically collected every 30-50 meters along a flight transect, and they penetrate the subsurface to nearly 300 meters (Christiansen and Auken, 2013; Sørensen and Auken, 2004), with high vertical resolution. After extensive processing and inversion of the measurements, the laterally-dense 1D soundings can be visualized as 2D profiles along a flightline transect (Figure 2). The depth of penetration depends on the size of the transmitter loop, the available power from the transmitter, and ambient electromagnetic noise. Additional surface geophysical data, including borehole geophysical logging, seismic, resistivity, and ground-based TEM systems, have all been used to ground-truth the HTEM data.

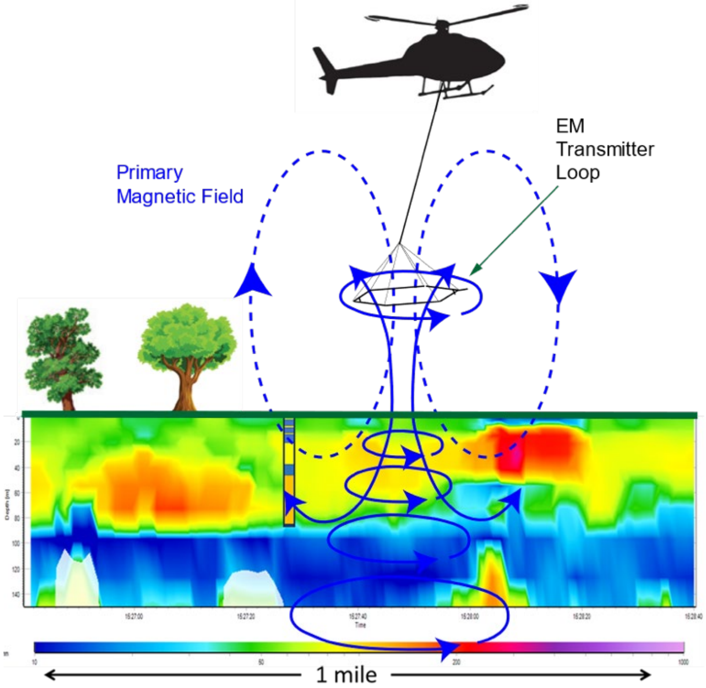


Figure 2. Schematic representation of the HTEM system and resulting profile of electrical resistivity data.

The raw HTEM data in the study area (Figure 1) were processed and inverted using Aarhus GeoSoftware's Workbench software. The 1D resistivity data were inverted in a pseudo-3D format by imposing simultaneous lateral constraints on individual 1-D measurements (Viezzoli, et al., 2008; Viezzoli, et al., 2009). From the pseudo-3D inversion, profiles and elevation slices of subsurface resistivity in any location can be generated and used for 3D geological interpretation and mapping (e.g. Jørgensen et al. 2013a).

Preliminary Results

HTEM data were collected in east-west profiles across Champaign County at 650-meter intervals (Figure 3). The data penetrated to depths of nearly 375 meters and resolution decreased substantially below a depth of 250 meters. Fortunately, the Mahomet Aquifer and the MABV do not extend below 150 meters depth, so those features were located within our highest-resolution HTEM data.

Resistivity values within the glacial sediments ranged from approximately 40-160 Ohm-m. Electrical resistivity of clay-rich diamicton units ranged between 40-60 Ohm-m, sandy diamicton units ranged between 60-80 Ohm-m, and sands of the Mahomet Aquifer ranged between 90-160 Ohm-m. No data were collected in dense urban areas or across large highways due to FAA limitations and/or excessive electrical disturbance.

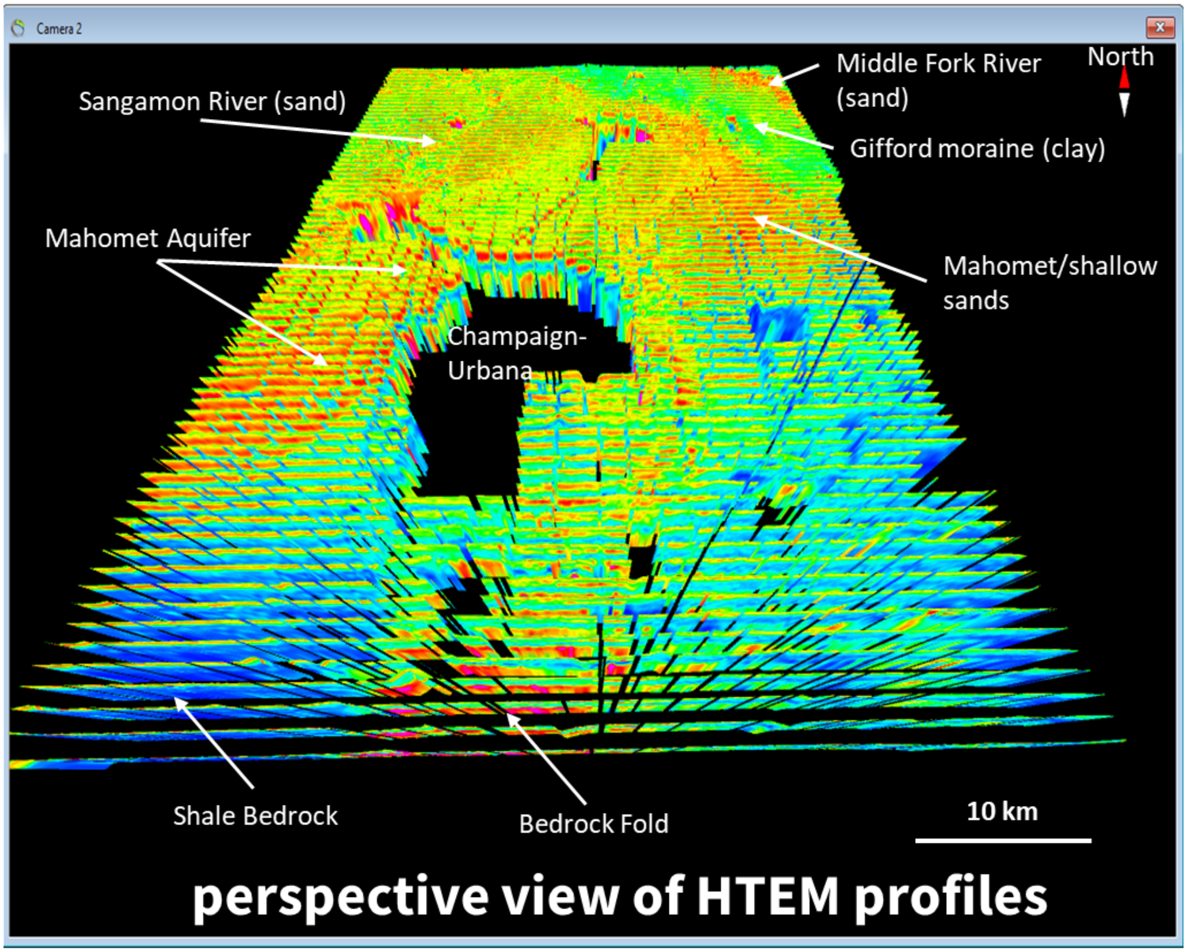


Figure 3. Perspective view of HTEM data in Champaign County, Illinois and generalized interpretations of geologic features.

3D Geologic Mapping Strategies

We have used GeoScene3D software for 3D geologic mapping and modeling. GeoScene3D is a versatile application that incorporates various data types (including HTEM data) and provides 2D and 3D visualization windows to support the mapping workflow (Figure 4.), including the ability to create geological interpretations in a 2D view while visualizing and navigating within the 3D view. GeoScene3D also includes modules for building layer-based and voxel-based geological models, and it includes user-assisted machine learning tools (i.e. smart-interpretation tools) for more efficient and consistent interpretation of HTEM data.

Our approach includes collective 2D and 3D visualizations of HTEM data, water-well records, downhole geophysical data, 2D electrical resistivity tomography data, and 2D seismic reflection data. By navigating those visualizations and using versatile “picking” tools in GeoScene3D, we create interpretations of geological contacts and structures rapidly and effectively. Additionally, the manual interpretations are used to train and refine the machine-learning tools in GeoScene3D (i.e. Smart Interpretation), which help to further expedite the interpretation process throughout the entire 3D model domain.

Ultimately, our plan is to generate several different geologically-plausible interpretations of the 3D geology by integrating the trained machine-learning processes in GeoScene3D and other user-guided AI approaches. These alternate distributions will be designed to better communicate what we know about the subsurface and to enable groundwater flow modelers to more effectively identify suitable parameterizations and to better evaluate the risk and sustainability of various management strategies.

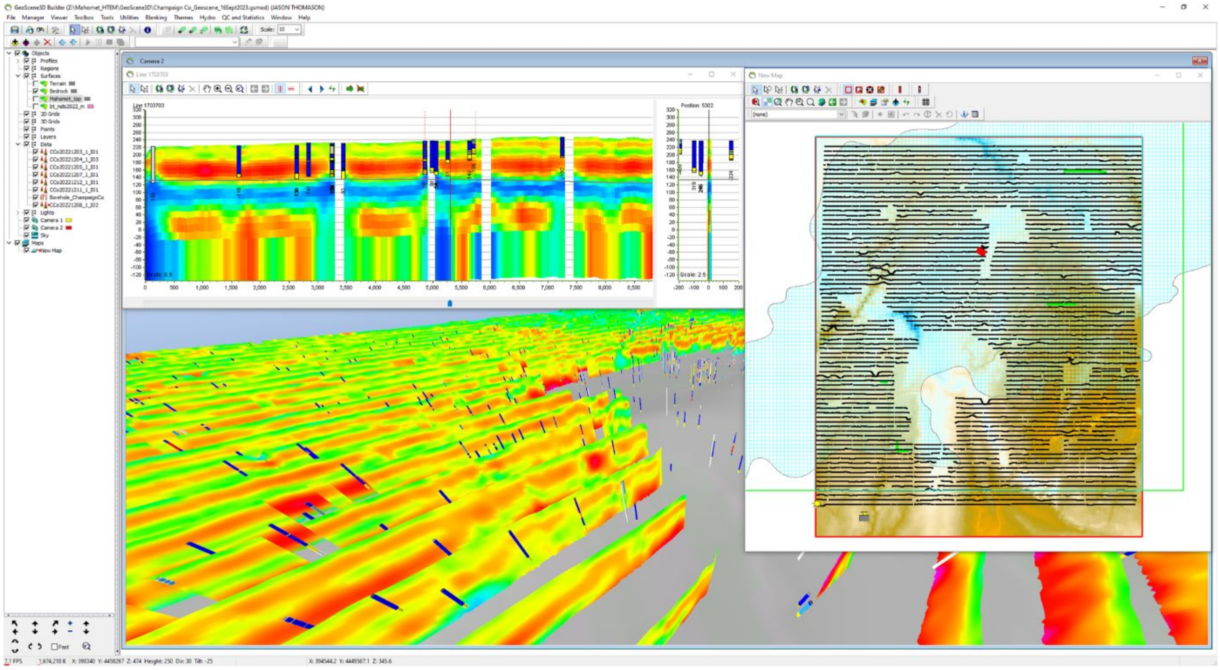


Figure 4. Multi-view user windows within GeoScene3D.

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RATIONALE AND METHODS FOR JURISDICTION-WIDE 3D GEOLOGICAL MAPPING

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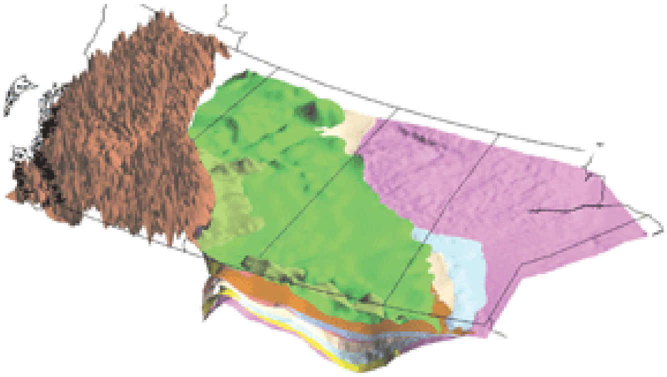
Abstract

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

Introduction

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

Rationale – Why do I need to do this?



Geological survey agencies are unique and essential services that maintain knowledge of subsurface conditions throughout a jurisdiction, thus allowing governments, economies, and societies to function in an informed manner and stimulating benefits related to resources, safety, public health, and natural heritage (Häggquist and Söderholm, 2015; Riddick et al., 2017; Hill et al., 2020; Brock et al., 2021). Geological mapping, along with jurisdiction- wide geophysical, geochemical, and other surveys, and underpinned by a comprehensive and influential grasp of geological research, is a core activity of these agencies and their partners. For two centuries, geological maps have utilized the printing press to communicate observations and predictions of the lithology and other attributes of sediments and rocks. Pressing societal needs and accelerating capabilities in the form of methods and data are causing an accelerating shift to queryable 3D mapping that is ready for application to modeling, where achievable (Turner, 1991; Rosenbaum et al., 2003; Culshaw, 2005; Turner, 2006; Turner et al., 2009; Thorleifson et al., 2010; Smith and Howard, 2012; Pavlis and Mason, 2017; Turner et al., 2021).

Geological mapping is a mature field (Varnes, 1974; Lisle et al., 2011), and analyses show that the activity returns large positive economic returns (Bernknopf et al., 1997; Bhagwat and Ipe, 2000). National, multi-resolution, updated 2D mapping remains needed. A cross section commonly accompanies a 2D map, while a 3D map can consist of a sufficient number of cross sections. All principles that apply to plan view apply to section view, so 3D mapping is thus an extension of well-established 2D mapping methods. In the context of these well-established roles for geological survey agencies, and well-developed methods for geological mapping, societal needs that rely on geological mapping are escalating in importance—in areas such as anticipation of ground conditions in engineering, groundwater capacity and vulnerability, assessment of sedimentary basins regarding energy and waste injection, mineral resources, hazards, and fundamental understanding of earth materials, processes, and history.

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

Background – What do I need to understand?

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

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

Geological mapping has been 3D since its inception, at least in the form of structure symbols, cross sections, structure contours, isopachs, and stack-units. Use of regularly spaced, orthogonal cross sections to build 3D geology was described by Mathers and Zalasiewicz (1985), while early principles of 3D GIS were outlined by Vinken (1988), Turner (1989), Raper (1989), and Vinken (1992). Bonham-Carter (1994) stressed that 2D GIS differs from 3D, in that 3D has x, y, and multiple z values, unlike plan view 2D, or perspective 2.5D methods based on a single z per site. A comprehensive conceptual structure for 3D GIS was presented by Houlding (1994), while Soller et al. (1998) worked out a method for regional 3D geological mapping based on geological maps, stratigraphic control points, and large public drillhole databases. Recent overviews have been published on 3D methods in the hydrocarbon industry (Zakrevsky, 2011; Tearpock et al., 2021) and in applied hydrogeology (Kresic and Mikszewski, 2012).

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

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

Data compilation – What do I need to compile?

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

Data acquisition – What field work is needed?

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

Model construction – How do I draw layers?

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

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

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

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

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

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

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

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

Adoption of appropriate formats, and provision of adequate accessibility, with needed guidance to users, will ensure discovery and application of the mapping to societal priorities (de Mulder and Kooijman, 2003; Giles, 2006; Mathers et al., 2011b), while protocols such as Building Information Modeling (BIM; Bhuskade, 2015; Kerosuo et al., 2015), RESQML (Legg et al., 2015), or Geo3DML (Li et al., 2015b; Wang et al., 2017) may facilitate delivery to user communities, as will strategies to address, for example, the needs of urban design (Schokker et al., 2017; Volchko et al., 2020; Kearsey et al., 2022).

Examples – What have other people done?

Many successful yet steadily evolving 3D geological mapping programs have been established (MacCormack et al., 2019). Examples include Australia (Gill et al., 2011; Martinez et al., 2017 ; Jessel et al., 2021; Alvarado Neves et al., 2024), Belgium (Hademenos et al., 2019), Canada (Matile et al., 2002; Ross et al., 2005; Sharpe et al., 2007; Tremblay et al., 2010; Burt and Dodge, 2011; Keller et al., 2011; Russell et al., 2011; Bajc et al., 2012; MacCormack and Banks, 2013; Frey et al., 2016; Carter et al., 2017 ; 2021; Crombez et al., 2017; Russell et al., 2017; Bajc et al., 2018; Burt, 2018 ; Frye et al., 2016; 2019 ; Hillier et al., 2021), China (Li et al., 2015a), Denmark (Thomsen et al., 2004; Møller et al., 2009; Jorgensen et al., 2012; Sandersen et al., 2016), Finland (Artimo et al., 2003), France (Castagnac et al., 2011; Mas et al., 2022), Germany (Pamer and Diepolder, 2010; Lehné et al., 2013; Diepolder and Lehné, 2016), Italy (De Donatis et al., 2009), Netherlands (Stafleu et al., 2011; Kombrink et al., 2012; Gunnink et al., 2013; Meulen et al., 2013; Maljers et al., 2015; Kruiver et al., 2017), New Zealand (Raiber et al., 2012; White et al., 2016), Poland (Małolepszy, 2005), UK (Kessler et al., 2009; Mathers et al., 2011a; 2014; Aldiss et al., 2012; Tame et al., 2013; Burke et al., 2015, 2017; Woods et al., 2015; Gakis et al., 2016; Bricker et al., 2022), and US (Thorleifson et al., 2005; Phelps et al., 2008; Faith et al., 2010; Jacobsen et al., 2011; Keefer et al., 2011; Pantea et al., 2011).

Strategies – What should I do next?

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

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SPATIAL GEOSCIENCE INFRASTRUCTURE

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Introduction

Geological mapping is of escalating importance. People strive for safety, health, wealth, and respect for our human and natural heritage. Geological knowledge is needed by society to fulfil all of these aspirations. Geologists provide this knowledge as research, mapping, monitoring, modeling, and management. Our efforts help clarify energy, minerals, water, hazards, infrastructure, and research. There is an urgent need for us to better enable management of these topics. Examples of applications that require complete, consistent, queryable, and model-ready geology include sedimentary basin analyses, mineral resource assessments, inclusion of groundwater in regional and national water resource management, hazards modeling such as for earthquake propagation and magnetic storm vulnerability, infrastructure design, and all research on our planet and its life. Therefore, governments are funding the multi-resolution, queryable 2D and 3D geological mapping that is required by the people of their Nations.

Mapping

Geological mapping is an activity that is familiar to us all, and we all know what a geological map is. All mapping is guided by a specification, and assessment of progress toward goals. We map the atmosphere, land surface, water depth, and subsurface/subbottom. The latter includes soil mapping, underground structures, and geology.

Soil mapping

Soil mapping and geological mapping are the same thing. Soil mappers think in cm, whereas geologic mappers think in m and km. Soil mapping has advanced to a dynamic, seamless database. Soil mapping is the best reference for geologic properties for the 1st m in sediment-covered areas on land.

Underground structures

There is a need for coordination between geology and mapping of underground structures such as pipes, wires, and tunnels.

Geology

Due to the sparsity of data and the need for interpretation, our maps are authored by researchers who can visualize the geology. Our research informs our mapping, and our mapping informs our research. Academics balance research, teaching, and service, whereas survey geologists balance research, mapping, and service.

Data

Observations enable our inferences that are meant to support applications. Our mapping in turn serves as a window on the data. Our data need to be findable, accessible, interoperable, and reusable (FAIR). Each database of observations, collections, or measurements requires ongoing assessment, under data stewardship programs.

Geological maps

In geological mapping, we have focused on 2D maps that are not necessarily positioned vertically, nor fully categorized, although each is seamless and includes some 3D. Paper-format 2D geological maps have distinct advantages, and in the future will be more important than ever. In resource, hazard, and engineering applications, geological maps commonly need to be translated and augmented as derivative maps. Geological mapping returns a very positive cost/benefit. All mapping has resolution levels, each with appropriate generalization. Resolution levels for geology are here described as urban (<24K), regional (24/250K), national (500K/2M), continental (5M), and global (~30M). Regional geological maps are based on fieldwork, analyses, topography, and geophysics, or on assembly of new and compiled data for covered geology. A simple definition of regional mapping is any new map more detailed than the current jurisdictional map. Our mapping is guided by an evolving stratigraphic model. Coordination with neighbors is an essential activity that leads to consistency needed by users. Compilations are based on assembly and reconciliation of multiple published maps. For generalized compilations, such as a jurisdictional geological map, gaps are infilled at consistent resolution as required.

Seamless 3D

New and unfamiliar forms of geological mapping have emerged, and we still lack consensus on our direction. Change is being driven by the realization that research, mapping, and monitoring are essential for the quantitative modeling and management that are needed to respond to societal expectations. In the digital era, compilations no longer have to be generalized to fit on a sheet of paper. Seamless, queryable, updatable databases therefore have emerged in all mapping fields. It seems likely that paper-format geologic maps will mainly be used as PDFs by eye, while GIS users will prefer seamless. It might not be possible, nor even desirable, to save the GIS files for every paper map, forever. Seamless is a standardized compilation, with reference to source of each tile, without generalization, and with ongoing harmonization and facilitation of query completed with authorship and review as for compilations. Seamless shows gaps, to ensure consistent resolution, to show where mapping is needed, and to attract funding. Lower resolution mapping can be used to infill gaps to make a best-available map for some users. The purpose of seamless is queryability. Interoperability is not enough. Ongoing maintenance of seamless requires standards to support interoperability, ongoing assessment of progress, synthesis in part to test harmonization, and iteration to incorporate ongoing updates.

In the past, 3D was done as sedimentary basin atlases. In 3D, vertical position and properties of surfaces, strata, and structures are specified as allowed by data. In 3D, a layer is a seamless 2D map polygon whose thickness can be mapped. To be queryable, seamless 3D has to be built from a mature 2D map. For layers, we map extent, vertical position, thickness, properties, heterogeneity, and uncertainty.

We need a 2D map, at multiple resolutions, for each unconformity, such as surficial, top of mineral sediment, bedrock, pre-Mesozoic, Precambrian, and basement. In some cases, due to data sparsity, we are unable to add resolution for covered geology, such as regional mapping of mineral sediment below peat, for Paleozoic beneath Mesozoic cover, or for basement under Precambrian cover.

The 2D mapping is vertically georeferenced by elevation grids – the top of mineral sediment surface is inferred from a peat thickness map and bathymetry. Surficial mapping in sediment-covered regions is positioned at -1m to accommodate soil mapping. Parsing of legends is using well-defined terminology to facilitate query and to support inference of properties as needed for modeling. With 3D, we subdivide between the unconformities.

Dominant lithology allows inference of properties such as hydraulic conductivity. To support a 3D program, jurisdiction-wide, onshore/offshore, and cross-border cross-sections are needed at the outset. This will help resolve stratigraphic issues and clarify surfaces to be mapped. 3D also requires long-term effort on data and geophysical surveys, especially drillhole data. 3D mapping can be expressed as a grid of synthetic drill holes. Below the layers is basement. In layers, we map strata, and in basement, we map structures, then discretized properties.

Modeling

These new forms of mapping are a transition from conceptual models to the mesh paradigm. Our work in research is conceptual, while mapping is spatial, monitoring is temporal, and modeling assembles the research, mapping, and monitoring. Management, which is enabled by modeling, is required, especially in fields such as groundwater. We thus can foresee that a future role for geological mapping will be to support nested dynamic models. Model- ready, machine-readable geology is best done primarily by geologists, with appropriate roles for modelers or machines methods. Modeling may be done on a one-time project basis, or as an indefinitely maintained digital twin. The first and most important step in modeling is the conceptual model, a qualitative depiction that guides subsequent quantification. Geological maps are conceptual models meant to primarily be used by eye, that are not necessarily positioned vertically, and that often are not fully categorized. Seamless and 3D function in the mesh paradigm – quantifiable, complete for all space of interest, varying in resolution if necessary, with structured resolution, and with uncertainty specified.

Roles

All information is most usable if standardized, and users demand standardization. Geological mapping therefore now involves: 1) maps, 2) standards, and 3) seamless and 3D. This three-fold approach was recognized two decades ago in the design of the US National Geologic Map Database (NGMDB). Geologic maps presented as research publications and conceptual models are NGMDB Phase One – the catalog. Protocols needed to make our geologic maps usable and interoperable are NGMDB Phase Two – the standards. Seamless and 3D are NGMDB Phase Three – the framework database. Paper maps are static, authored publications that undergo one-time peer-review. Standards are developed through consensus with guidance from standards organizations. Seamless undergoes recurring audits and is updated indefinitely as versioned databases. International agencies are considering alignment with these three functions. Multinational geological maps are published by the Commission for the Geological Map of the World (CGMW). Development of international geologic map standards is led by the

Commission for the Management and Application of Geoscience Information (CGI). Seamless 3D is a good task for OneGeology.

Evolution

We are evolving. From the 1980s to the 2020s, soil mapping has evolved from photomechanical, to digital, to web accessible, to seamless, to gridded, to raster, to dynamic. Geological mapping is entering the seamless phase. Geological mapping as we know it began with the 1815 William Smith geology of England and Wales. Our first century involved national surveys and hand-colored wall maps. Our second century involved the printing press. It can be foreseen that our third century will focus on enabling model-ready national 3D geology to support digital twins.

Geological survey leadership

We all will play a role in building the geological mapping that people require. In the U.S., Congress has directed, and funded, construction of regional, national, and continental-resolution seamless 2D and 3D. The U.S. National Cooperative Geologic Mapping Program (NCGMP) therefore is facilitating critical functions: program office, conference support, coordination, geospatial reporting, stratigraphic naming, NGMDB Catalog, NGMDB Standards, NGMDB Phase Three, international coordination, and cross-border harmonization. There are crucial federal roles: cross-border mapping, federal priorities, and mapping needed to optimize synthesis; stratigraphic, paleontological, structural, geochronological, and other research, especially as needed to support synthesis; and arrangements for national synthesis products, with arrangements for indefinite updating. Federal databases can largely be built from iterated State contributions: mapping, derivatives, catalog, training, digitizing and conversion, regional mapping, seamless, surfaces, correlation, strata, and geochronology. At regional, national, and continental resolution, as allowed by data, we require seamless for all pieces of the puzzle: bedrock geology, bedrock elevation, surficial geology, basement geology, basement elevation, 3D rock strata, 3D sedimentstrata, and 3D basement structures. We need a great acceleration in data compilation and geophysical surveys. We need to focus on an orderly progression of tasks. As in all mapping, completeness is first achieved at low resolution. Urban applications largely will be based on data.

Status

We need consensus on what we will do, and measures of our progress. Status mapping is required, to develop consensus on goals, to monitor and manage our progress, to identify priorities, to stimulate funding, and to cause us all to strive. A status map differs from a publication index, which indicates the spatial footprint of published maps, including obsolete, superseded maps. Status mapping requires local knowledge, judgement about needs, a composite index, and thus an indication of progress toward evolving goals. This nationally standardized, annually updated status procedure, implemented in stages, will require consideration of 2D mapping, depth to bedrock and basement or equivalent, subsurface data and mapping of sediment and rock layers, and basement mapping.