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

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Introduction

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

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

A noteworthy difference from the 2011 volume (Berg et al., 2011) is the greatly increased scope in this volume on implicit modelling and property modelling (i.e., physical rock properties: density, magnetic susceptibility, sedimentary facies, and flow parameters: porosity and permeability etc.) of geological volumes created by framework modelling approaches. Hence characterization of heterogeneity within model volumes is discussed more as is the application of models within physical process-based software for fluid and heat flow modelling, and geophysical inversions.

Data Management

Overview

The relationship between GSOs and data support for geological 3D modelling is diverse and much less controlled by the GSO in many jurisdictions than would be imagined. Commonly, data support for modelling is divided between topographic, natural resources, environment, and hydrographic organizations. This can complicate acquisition, preparation, and updating of data for modelling. Data may be derived from public sector activity (e.g., geological mapping, topographic information) and private sector activities that have varying degrees of data permitting, reporting standards, management, and accessibility. Approaches vary enormously across jurisdictions and datasets. In a number of jurisdictions, the importance and value for managing subsurface data is being increasingly recognized, and efforts have been initiated to improve the collection and management of data across organizations and themes. However, in some GSOs data is managed on a project by project and data type basis, with no institutional database management structure. A number of strong emerging exemplars using contrasting approaches are discussed in Part 2 that can provide guidance and encouragement (e.g., Denmark, Netherlands, UK). Nevertheless, lessons learned may be hard to implement in many jurisdictions due to differences in governance structures and complications arising from legislative issues, organizational mandates, scale, and funding (e.g., Canada, USA).

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

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

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

- Netherlands: The Dutch geological survey TNO) has developed the DINO database that provides an underpinning for 3D geomodelling. Additionally, in 2015 legislation placed subsurface data and information in a system of key registries to be managed by TNO. This data framework manages subsurface data of 28 different data types, four jurisdictional models, and provides information on permitting and subsurface infrastructure.
- Germany: The Germany geological survey (BGR) initiated the Infra3D project which is facilitating data use and integrating it with cognitive interpretation to produce re-usable and sustainable 3D geological models. The Infra3D project objective is to upgrade the technical infrastructure to improve support for semi-automated model development and updates. Additionally the Geosciences in Space and Time (GST©; https://www.giga-infosystems.com/products) framework is a pillar of the Survey's 3D infrastructure.
- Bavaria: The Bavarian geological survey is building on the success of the previous GeoMol project to support two integrated projects for the Bavarian Molasse Basin, an internal project Infra3D and HotLime, one of 15 projects under the umbrella of GeoERA (**E**uropean **R**esearch **A**rea, http://geoera.eu/).
- European Community: European countries are benefiting from initiatives to standardize data for a variety of scales and applications. Illustrative European initiatives include the GeoERA Information Platform EGDI (http://www.europe-geology.eu/), and sub-elements such as the GeoERA project HIKE that is consolidating a fault database (http://geoera.eu/projects/hike/). Another example is the European Sub-Urban program (https://www.sub-urban.eu) which is part of the European Co-operation in Science and Technology (COST, https://www.cost.eu). Sub-Urban is a collaboration of geological surveys, cities and research partners to improve the management of the subsurface of cities.

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

Surface Topography Databases

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

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

Geological Map Databases

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

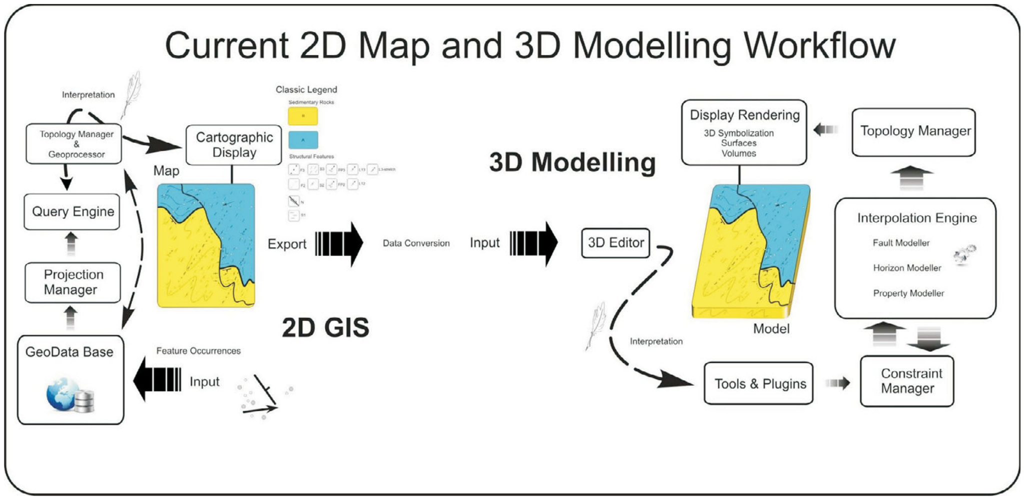

Figure 1. Illustrative workflow of 2D geological mapping that is transitioning to support for 3D modelling efforts. From de Kemp et al. (2017).

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

Subsurface Data

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

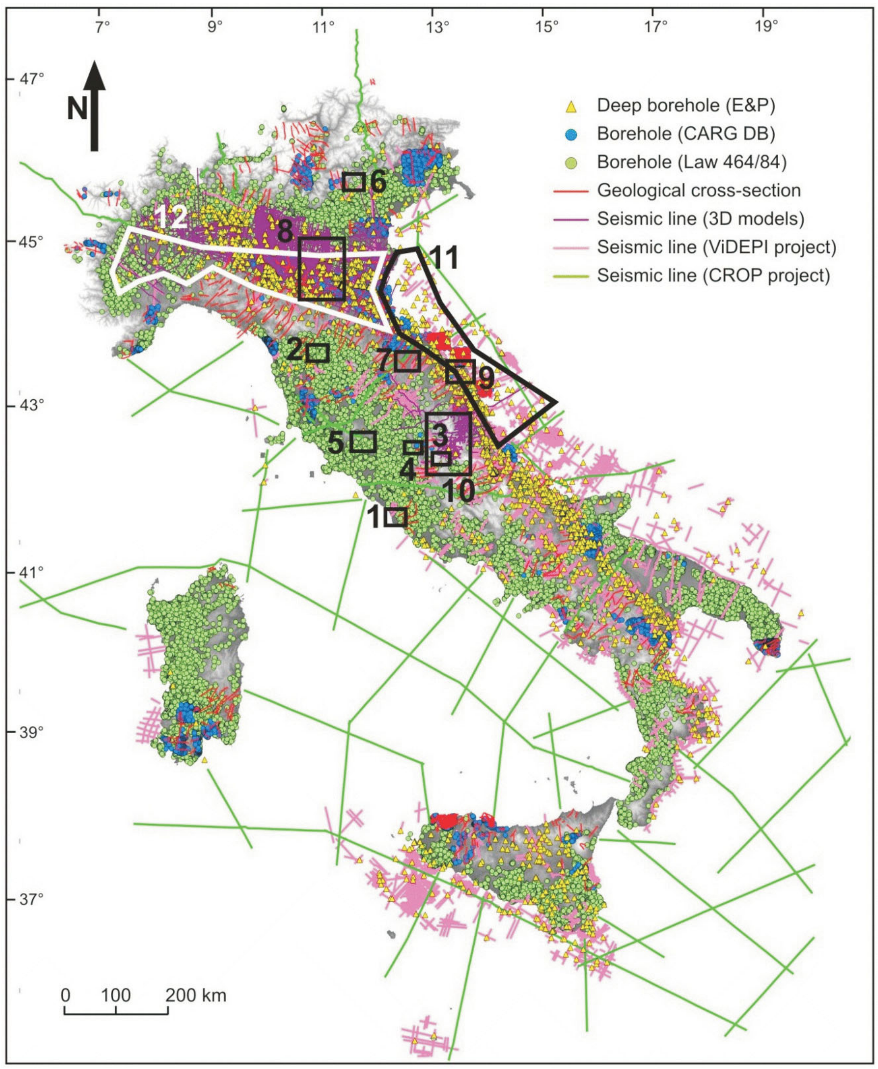

Figure 2. Distribution of principal publicly available geological data in Italy for national modelling. Note combination of borehole and seismic data, both onshore and offshore. Purple lines indicate seismic data available under a confidentiality agreement. Black polygons are areas of completed 3D models,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

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

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

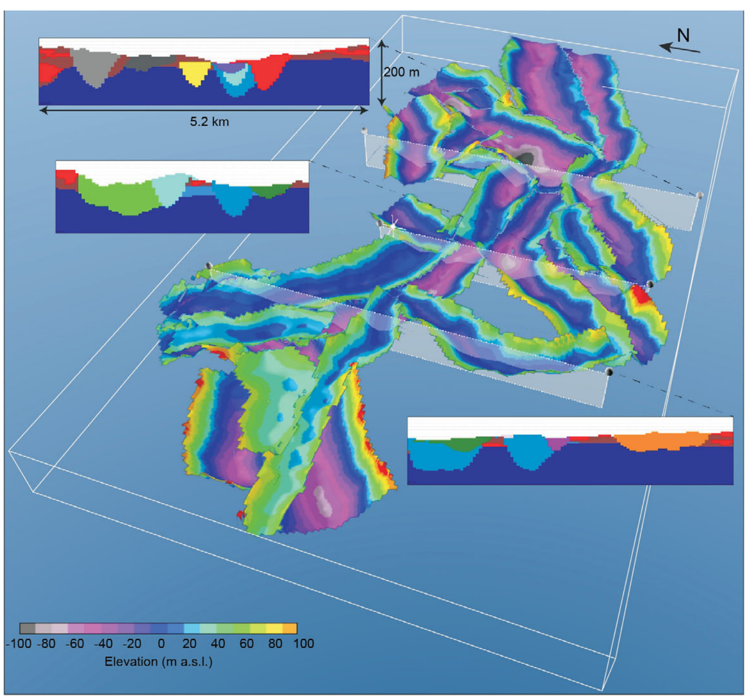

Figure 3. Integration of borehole and geophysical data to model buried valley in the Kasted area, Denmark. Valley generations highlighted by different colours. (From Sandersen et al., this vol., Chapter 11).

Model Databases

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

Data Standardization and Exchange

There is limited coverage of this subject in the volume, particularly with respect to international norms and more specifically those related to 3D data standards. An excellent point was raised by Diepolder et al. (this vol., Chapter 7) highlighting the contrasting challenges between technical interoperability and content-related interoperability. Eventual intermodel correlations can only be achieved by harmonization of the stratigraphic nomenclature prior to the modelling process. There is reference in a number of contributions regarding participation in European Union funded and sanctioned activities that saliently indicates that efforts are underway toward technical interoperability. However, these efforts may be predominantly focused on 2D data holdings. The EuroGeoSurveys (EGS) is an international non-profit organization representing the national GSOs from 36 European countries (http://www.eurogeosurveys.org). It is interested in the development of a Geological Service for Europe and the Geological Surveys Research Area (GeoERA) is a major initiative. GeoERA (2017-2021) is a collaboration of 45 national and regional GSOs from 33 countries in Europe. One of the four core components is the development of a European Geological Data Infrastructure EGDI (http://www.europe-geology.eu/) via which GeoERA projects will be distributing data. One of the 15 projects that will be delivering data via EGDI is 3D geomodelling for Europe (3DGEO-EU). Other data harmonization initiatives in the European Community include INSPIRE, COST, etc. A number of European contributions (e.g., Italy, Poland, Sweden) plan for, or are compliant with, the INSPIRE (https://inspire.ec.europa.eu) standard for much of their geological data. Individual contributions highlight various approaches that connect to broader international initiatives. Finland references the use of GeoSciML to support geological mapping. GeoSciML is an international data transfer standard for geological map data developed by the IUGS Commission for the Management and Application of Geoscience Information (CGI). The Swiss have a national database that is OGC compliant and interfaces with European initiatives such as GEOMOL. The Netherlands reviewed the development of internal standards for various data components to facilitate integration of disparate datasets. They bring home to the reader the long-term challenge of such work which took decades to develop, and which without, modelling would not have been possible. In Germany the Geosciences in Space and Time (GST©) framework is central to the German Survey's 3D infrastructure and is able to store and serve 3D models using open standards defined by the Open Geospatial Consortium. It is an outshoot of a European Union Initiative ProMine (2009-2013) that involved 11 EU member states and 30 collaborators from geological surveys and industry. The U.S. Geological Survey has maintained a standardized archive of geoscience information through its National Geological Map Database Program (https://www.usgs.gov/core-science-systems/national-cooperative-geologic-mapping-program) since the early 1990s, and is now implementing a new geological map schema (GeMS) for additional standardization. However, to date, there is no common standard for 3D data or model exchange. The current but changing tendency is for each GSO to embed data into the model through proprietary systems similar to the model followed in 2D for cartographic production.

Data Legislation

Many of the countries of contributing GSOs in Part 2 have enacted legislation to ensure the preservation, management, reporting, and accessibility of subsurface and other geoscience data. Depending upon the governmental structure, roles between state/provincial and federal GSOs, including the division of power and responsibility, GSOs can have varying degrees of problems with access to data. Data responsibility may be legislated to government agencies other than the GSO. Furthermore the management and accessibility of both private sector and contracted government data generally follow different models. Where private sector data is submitted to government agencies, it is often held under a confidential status for 2–5 years depending upon jurisdiction. For example, in New South Wales legislation requires that all drilling, geological, geophysical, and geochemical data acquired by companies on mining and exploration titles be submitted to the Geological Survey of New South Wales (GSNSW). In the Netherlands, legislation covering all subsurface borehole data requires submission to the National GSO. In contrast, in Germany the BGR lacks the proprietary rights to the relevant data which are often owned by industry and there is no legislative requirement for companies to share data. Enhancemnts in legislation toward more data sharing for public benefit would further support what is evolving into an Earth Science Commons. Such changes in legislation would definitely benefit jurisdictions ability to conduct better policy development, supported by increased model accuracy and ultimatrely have more sustainable socio-economic impacts.

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

Three-Dimensional Modelling

Overview

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

What is Explicit vs Implicit Approaches

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

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

The terminology used for data interpretation vs data interpolation can be a source for confusion in describing modelling approaches. For both implicit and explicit approaches, data interpretation and classification may be completed by a geologist or by machine-learning processes (Silversides et al., 2015). The question is the degree and nature of intermediate steps in the protocol and rules related to interpolation can vary widely. Explicit approaches, such as the cross-section approach, rely on the creation of an intermediate data interpretation by the geologist prior to interpolation. Subsequent interpolation is then highly constrained to secondary derivative datasets. In addition, confusion arises between the traditional use of 3D constraint data (e.g., borehole 'picks') to interpolate surfaces with kriging, IDW, Nearest Neighbour etc. and surface estimations using implicit mathematical functions. The former have been referred to as implicit stochastic or sometimes 'automated' or 'unbiased' estimators and can be the basis of simulation approaches such as Sequential Gaussian Simulation. The later 'implicit' estimator refers strictly to algorithms that perform an implicit calculation to create a directed distance-based 3D scalar potential field where the zero values represent the surface to be extracted from within the scalar field that is then rendered as a 3D mesh or point set (see Hillier et al., 2014 and references therein for background).

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

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

Explicit Modelling

Explicit modelling is the common entry point for geological modelling. It is commonly supported by abundant data with a high-degree of geological content and cognitive engagement of geologist(s). Evolving from pre-digital approaches, this method commonly involves cross-section development in either a digital or non-digital environment (Figure 4). It is an approach familiar to field mapping geologists and can easily facilitate user interaction to maximize the geological plausibility of the surfaces. Deterministic explicit models are singular realizations with limited options for model rebuilds in the future, or implementation of stochastic realizations.

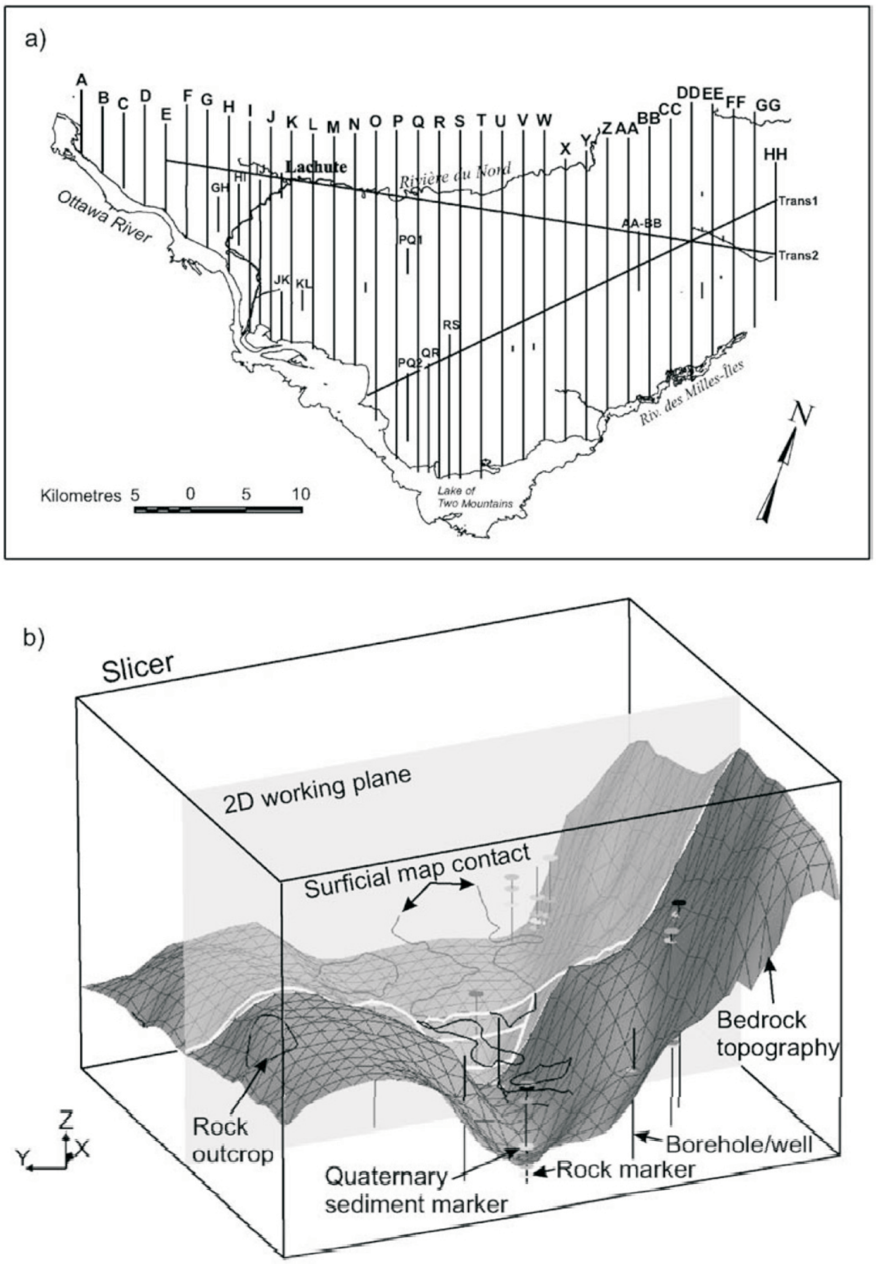

Figure 4. Cross-section approach for explicit deterministic modelling in GOCAD used to develop the input data for interpolation. Cross-sections were constructed interactively in GOCAD. (From Ross et al., 2005).

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

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

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

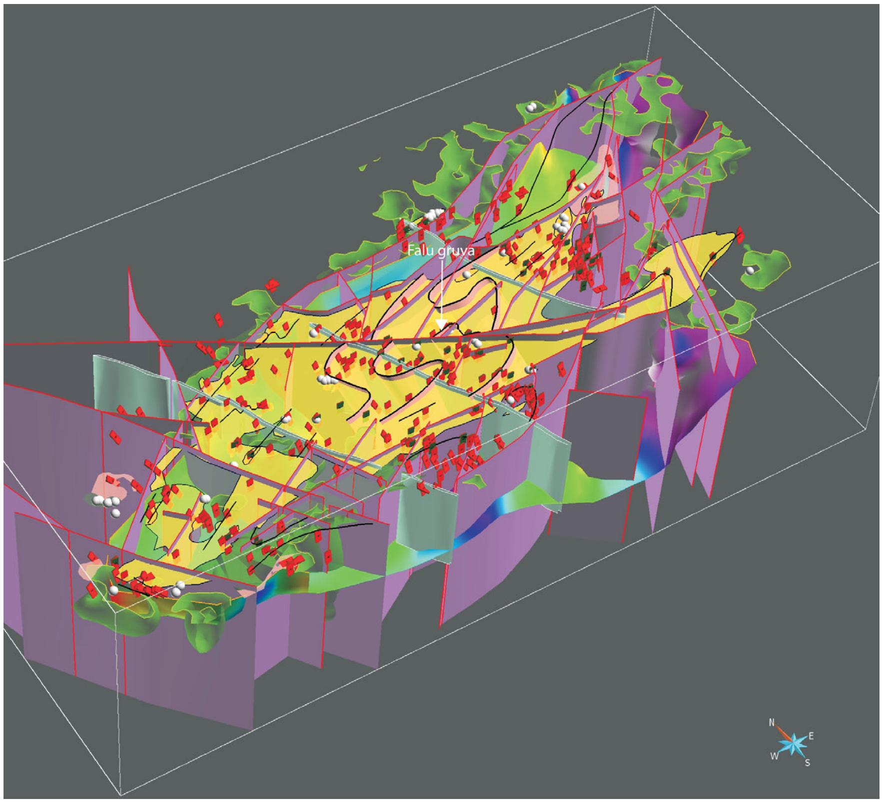

Figure 5. Three-dimensional model of a mineral deposit in a folded and faulted volcanic setting. Model constructed from multiple datasets derived from field surveys, with geological and geophysical modelling combined into a single model. The yellow area corresponds to the volcanic domain. The red tablets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

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

Implicit Modelling

Explicit modelling is gradually losing pre-eminence to implicit modelling and often hybrid approaches integrating both styles of modelling are now being used. A comparison with the 2011 volume (Berg et al., 2011) indicates a tenfold increase in contributions referring to implicit modelling. For an excellent review of state-of-the-art methods for implicit approaches see Wellmann and Caumon (2018). Implicit modelling is being used not only in data rich areas (e.g., Netherlands), but also in data sparse settings (e.g., Canada, New South Wales, New Zealand). In addition, implicit approaches are being used where primary data support involves geophysical data (e.g., Poland). There is current active methodological research addressing the challenge of improved integration of geophysical data and this will hopefully have an impact in developing the next generation of tools for 3D geological modelling for GSOs (See https://loop3d.org/). Recognizing the limitations of both methods and the desire for maximum geological reasonableness, hybrid approaches are on the increase (e.g., Alberta, Denmark). Highlighting one of the prime advantages of implicit modelling from Sweden is modelling national soil depth on an annual up-date cycle and integrating new information from boreholes, geophysical measurements, and surface mapping.

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

Expert System

Geological Survey Organizations, as experts in geoscience issues, recognize the need for expert geological input into the modelling exercise. This is in fact a consistent and persistent argument made by many for explicit modelling approaches. It is thus surprising to see the limited mention or identification of approaches that formalize this approach. This could be that to some extent the subject is cached in the terminology of implicit modelling. For example, expert knowledge is a crucial part of the "Loop" project within the Knowledge-Event Management component (Ailleres et al., 2018). Logan et al. (2006) describe a rules-based expert system used to model the surficial geology in Ontario, Canada. The approach used control datasets to produce training surfaces to then help constrain stratigraphic assignments to low-quality archival data through use of stratigraphic, spatial, and geometric (thickness) rules. This work was completed in traditional 2D GIS systems and then assembled within 3D visualization software.

Machine Learning

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

Stochastic Property Modelling

Submissions to the volume overwhelmingly document the development of deterministic models. In only a few instances are GSOs producing stochastic models. Reported modelling applications of stochastic approaches are related to lithofacies variability (e.g., Alberta, Canada, Denmark, Germany) for example in VMS systems (Schetselaar et al., 2018), fault networks (e.g., Finland), and hydraulic conductivity (e.g., Canada, UK). In some cases, the stochastic modelling was completed for purposes of integrating geophysical data with borehole data (e.g., Denmark). Stochastic modelling has also been applied to model shallow, heterogeneous surficial deposits (e.g., Canada, UK). Where stochastic modelling has been completed and reported on it is commonly completed to model volume attributes such as hydraulic conductivity (e.g., Canada, UK). The future may well see this change as there is increasing interest in understanding the potential of model variability and expressions of confidence in the model realization. Stochastic modelling can provide a powerful and comprehensive approach to supporting confidence measures. Stochastic realizations are often constrained in explicit modelling environments, but the growth of implicit modelling approaches will facilitate the adoption of stochastic methods. Furthermore, optimization in computer processing will reduce the computation obstacle inherent in stochastic realizations of large models through increased CPU speed and CPU/GPU parallel processing implementations.

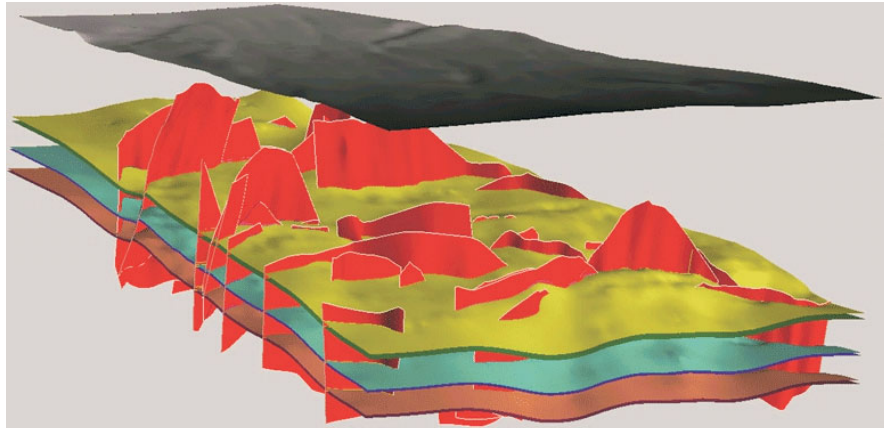

Figure 6. Discontinuous, nonlinear, and blind fault patterns in a 2000 km^2 area from the GeoMol project framework model in eastern Bavaria. Layers are pre-Tertiary surfaces of the sedimentary sequence, view from SW, total depth is >5 km. For clarity the Tertiary units are omitted and grey layer is topographic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

Modelling Considerations

Uncertainty Analysis

Three-dimensional geological modelling at many geological surveys is maturing and there is increasing interest by both the GSO and other disciplines to optimise the downstream use of such models. Many geological mapping applications are accustomed to high levels of uncertainty; however engineering, hydrogeological, and other disciplines increasingly require uncertainty to be identified both qualitatively and quantitatively. Mineral exploration studies are increasingly interested in modelling uncertainty far beyond the head frame targeting (mine site), especially when combining geophysical inversions and implicit modelling studies (Giraud et al., 2017). Uncertainty analysis is often focused on the end products and quantification of interpolative error or uncertainty related to data support, referred to as the aleatory uncertainty. Of equal importance is the uncertainty related to geological interpretations that underpin model development or epistemic uncertainty. From the contributions in this volume, it is clear that many GSOs are grappling with approaches (e.g., Germany) to quantify uncertainty, particularly the aleatory component. A range of approaches are detailed in the contributions and it is likely that this subject is under represented in the contributions. The documented approaches include basic statistical measures (e.g., Alberta), stochastic and probabilistic methods (Figure 7; e.g., Canada, Germany), data density maps (e.g., Illinois, Swiss), and user developed hybrid approaches (e.g., Ontario). An additional benefit of uncertainty analysis is also as a valuable metric in orientating future data collection to maximize the cost – benefit of scarce resources. As geological modelling and visualization increase in sophistication, particularly for example, with

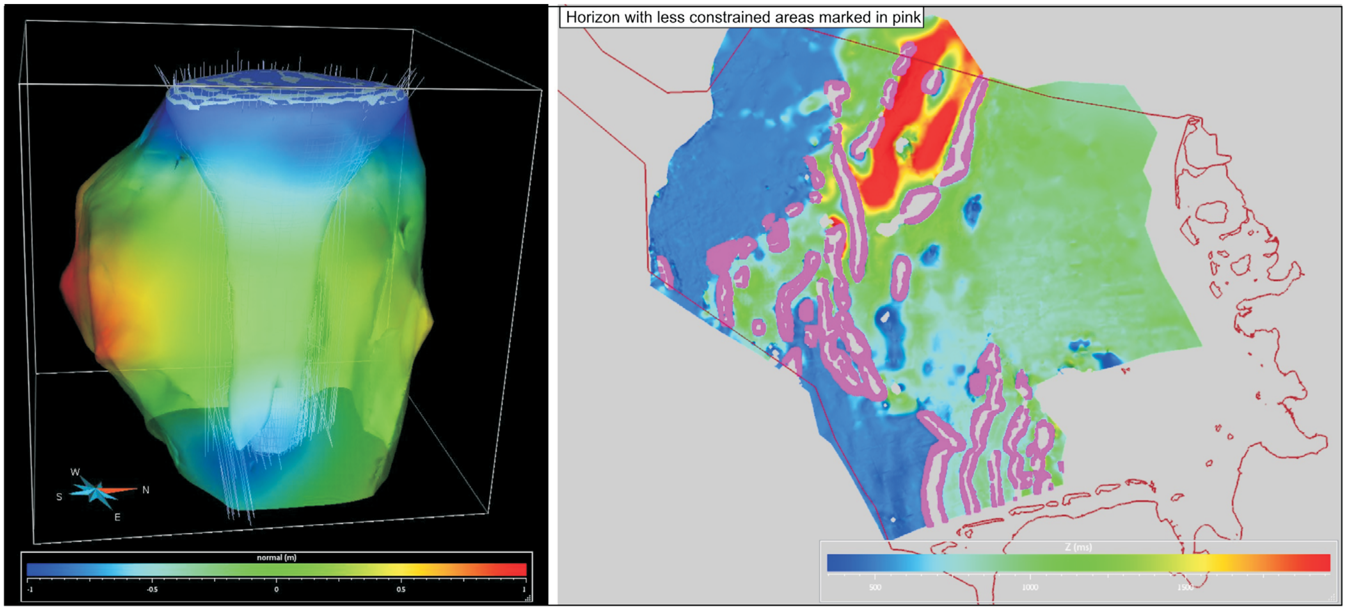

Figure 7. Uncertainty visualisation for interpreted salt structures in the Germany Basin, North Sea. Left: 3D model of a salt structure (blue) surrounded by a semi-transparent envelope indicating the seismically less constrained area. The color code on this envelope refers to the distance between the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

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

Collaboration and Software Development

An area that is completely reliant on collaboration is development and adoption of data standards. GSOs have been involved in standards development such as GeoSciML a long-term CGI initiative and Resource ML originally developed by the Australian Geoscience Committee and subsequently transferred to CGI (http://www.cgi-iugs.org). Beyond the GSO structure, examples from industry include RESQML from Energistics, an industry consortium (e.g., Hollingsworth and Schey, 2018). Additionally, there is research occurring in academia, for example on 3D standards such as Geo3DML which has been released by the Chinese Geological Survey as a standardized data-exchange format for 3D geomodels (Wang et al., 2014).

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

Examples from the Australian geological surveys demonstrate that it is entirely possible and advantageous to combine forces to provide shared data infrastructure and modelling expertise with federal, university, and industry organizations (i.e., CSIRO, UWA, Curtain, GSWA and 9 other companies) in the Capricorn project to deliver high quality and timely geoscience data and models (Hough, 2016). Coverage of the lessons learned from these examples is beyond the scope of this summary. However, future investigation is warranted in this era of reduced human resources and rare skills for 3D data management and modelling within GSOs.

Summary

A comparison of content in Berg (2011) and this volume (MacCormack et al., 2019) indicates GSOs are moving forward. There has been a significant increase in the number of GSOs embracing 3D mapping and modelling from 2011 to 2019. The 22 contributions on the subject provide an incomplete picture of the status of GSO activity in this area. Nevertheless, the methods, case studies and collaborative examples documented provide a solid representation of the status of work taking place. The contributions demonstrate advances in data management, data integration, and modelling approaches. The complexity of geology being modelled has increased with modelling examples from a range of geological settings. The use of implicit modelling approaches, often within a hybrid implicit – explicit approach, has experienced considerable growth. Methods are increasingly being developed to go more regional, beyond mine headframes or local aquifers to municipal, state and national scales. There is increasing interest in stochastic modelling, particularly for improved uncertainty characterization. GSOs are also addressing the societal needs for this type of work through increased collaboration to support transboundary harmonization and data exchange.

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