Chapter 2: Background and Purpose

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Introduction

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

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

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

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

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

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

Geological Survey Organizations (GSOs)

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

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

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

History of 3D Geological Mapping

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

Applications

The role of GSOs is to stimulate societal benefits related to resources, safety, public health, and natural heritage (Culshaw, 2005). Accumulation of data, new methods, intensified land use, and pressing societal issues are spurring GSOs worldwide to respond to urgent societal priorities and exciting research opportunities by accelerating progress on national, regularly-updated, well-coordinated, multi-resolution, seamless, 3D, material-properties-based geological mapping databases. Societal needs of escalating importance now benefiting from this 3D geological mapping include:

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

3D Workshops

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

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

The October 2009 GSA workshop in Portland, Oregon, featured an unprecedented representation from the world's leading GSOs in 3D geology. Workshop presentations indicated that although these GSOs shared the same vision for characterizing 3D geology, their methods, strategies, and business models were highly varied. It therefore was decided by workshop participants to produce a volume summarizing these various approaches, which appeared in 2011 as the first 'Synopsis of Current Three-dimensional Geological Mapping and Modeling in Geological Survey Organizations' (Berg et al., 2011).

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

State of the Activity

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

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

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

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

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

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

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

In summary, a commitment to a 3D program requires long-term, institutional, and jurisdiction-wide planning, such that needed data compilation and acquisition, followed by iterative mapping using methods suited to the geology, data, and context, can be achieved in a complete and consistent manner over years to decades. Therefore, it is crucial that GSO staff share their thinking so we all can make progress and enhance fulfilment of our mandates with efficiency and effectiveness.

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