OVERVIEW - 3D GEOLOGICAL MAPPING: DEVELOPING MORE WIDESPREAD ADOPTION BY GEOLOGICAL SURVEY ORGANIZATIONS

Russell1, H.A.J., Thorleifson2, L.H., and Berg3, R.C.

1 Geological Survey of Canada, Natural Resources Canada, Ottawa, hrussell@nrcan.gc.ca
2 Minnesota Geological Survey, St. Paul, Minnesota, USA.
3 Illinois State Geological Survey, Champaign, Illinois, USA.

1. INTRODUCTION

There is broad international attention to the need for sound subsurface geological models, and thus to the methods required to extend conventional geologic mapping methods to the construction of these models. Geological Survey Organizations (GSO’s) in a number of jurisdictions have made significant progress in the development and implementation of three dimensional (3D) mapping programs (Berg et al., 2011). Nevertheless, such examples are few in number and there is a need to develop a framework that will accelerate more comprehensive 3D geological mapping (Thorleifson et al., 2010). It is apparent that many small geological survey organizations feel they lack the critical human and financial resources to develop 3D geological mapping programs.

A number of western European and North American GSO’s stand out for their early adoption, visionary approach, and progress at the jurisdictional scale, and thus can serve as examples for others on how to proceed. Concurrently, numerous other national, regional and local scale models demonstrate equal integrity and innovation (Berg et al., 2011). Nations such as Britain, Holland, and Denmark are excellent examples of approaches to multiple-resolution 3D mapping of areas of a size comparable to many densely populated areas of the world. The British Geological Survey (BGS) has tackled national scale surface to lower crust depths within their LithoFrame subsurface schema at four scales that range from national 1:1,000,000 scale to local 1:10,000 scale (Mathers et al., 2011). The Dutch have focused on the shallow subsurface, the context of most concern for groundwater and geotechnical issues, and have developed two national scale (42,000 km2) layer models (Stafleu et al., 2011). They have further progressed to development of a solid model with physical property attribution. In Denmark, the need for high quality data was recognized and a program was embarked upon to conduct geophysical data acquisition, initially ground based and subsequently from aerial platforms with integrated data standards, and data management framework coordinated with academia and consultants (Thom森, 2003). Focus in North America has more commonly been on local to regional scale models, although Manitoba is noteworthy for its jurisdiction-wide approach based on long-term planning, early reconciliation of stratigraphic models, construction of comprehensive databases at jurisdiction rather than project scale, extensive geophysical surveys and drilling, and a comprehensive approach covering sediments and sedimentary rocks down to basement at several km depth (Keller et al., 2011). Illinois, concurrently, has been an early advocate and an influential example of the need to support 3D mapping, based on the tremendous importance of optimal information to support groundwater protection (Berg et al., 2011).

This paper reviews various approaches for 3D geological mapping common to many GSO’s and outlines the range of approaches to 3D model development depending upon data source, opportunities for data collection, and geomatics support. The intent is to demystify the requirements, and provide a concise context for GSO’s considering the need for 3D geological mapping.

2. 3D MAPPING

When undertaking a 3D program, a clear enunciation of the objectives, applications and limitations of the datasets and resultant models is required. Guidance to the user will ensure that a model completed at the achievable regional resolution will not later be used for applications that in fact require additional data and higher-resolution modeling. This consideration is well illustrated by Thomsen et al. (2004), who contrasted regional subsurface models based only on borehole data versus models integrating spatially dense geophysical data that were seen as being needed to establish site-specific groundwater protection zones.
The design of a 3D mapping program encompasses conceptual underpinnings, datasets, information management, model construction, property attribution, and uncertainty. Turner (2006) encapsulated these elements in a workflow that highlights two streams of data processing for geometric modelling and for the property attribution (Fig. 1). Stratigraphic data are used to create a 3D geometry model in the left hand column and in the right hand column property data are used to create a predictive model of properties; the double arrow shows the iterative process of model refinement.

**Conceptual Underpinnings**

The conceptual underpinning for 3D mapping of sediments and sedimentary basins is basin analysis, which developed as a method for understanding the paleogeographic history of sedimentary basins (e.g. Walker, 1992). This multidisciplinary approach to data collection and analysis provides a predictive knowledge framework for the basin (e.g. Sharpe et al., 2002). Central to basin analysis is stratigraphic correlation, which may follow well-established norms of lithostratigraphy and more recently allostratigraphy. Based on bounding surfaces, allostratigraphy (e.g. Walker, 1992) offers significant advantages over other stratigraphic approaches, particularly when integrating diverse datasets, as it correlates erosional surfaces and laterally equivalent conformable surfaces to delineate genetically related sedimentary units (e.g. Macfarlane et al., 1994; Weissmann and Fogg, 1999), while more directly addressing vertical connectivity and lateral facies changes that are important considerations when constructing a hydrostratigraphic framework (e.g. Fogg, 1986). Facies models based on an understanding of trends within stratigraphic units provide a basis for inferring likely deposit geometry and properties, while thus provide a crucial framework within which to apply geostatistical modeling of properties.

*Figure 1.* Conceptual workflow for model construction in 3D mapping. From Turner (2006).
Construction of inferred strata and their properties commonly is not straightforward, nor is a single solution necessarily apparent. Depending upon data input, scale of study area, geological complexity, staff expertise, and project objectives, there are two end-member approaches i) manual interpretation of cross-sections, ii) expert systems. Application of the best practices that have been developed over two centuries of plan-view mapping can best be facilitated using cross-section approaches, as exemplified by GSI3D (Mathers et al., 2011), thus allowing the cognitive power of the geologist to construct a framework that constrains subsequent interpolation and ensures conformity with the geological conceptual model. Using machine algorithms to interpolate geology requires adequate geological attribution, and integration of expert rules to replicate decision-making geologists implicitly infer as part of the process of geological mapping. The objective of both methods is to develop geologically plausible depictions of what is regarded to be the most likely deposit geometry and properties, while ensuring that rules of superposition are followed while all stratigraphic units are accounted for (e.g. Hughes, 1993). Alternatively, expert systems approaches have been used to ensure that rules are applied consistently, at the expense of geological realism (Logan et al., 2006).

Datasets

Data collection may span a broad array of scales, spatial continuity, and data types, such as airborne geophysics, downhole geophysics, geochemistry, hydrogeology, hydrology, paleontology, remote sensing, sedimentology, and surface geophysics. Datasets of points, lines, or polygons, and rasters may be archival, legacy and project collected. Archival data encompasses data collected for purposes other than geological investigations, such as water well records. Legacy data includes data from previous investigations compiled by a an agency such as a geological survey (e.g. Mathers et al., 2011), such as geological maps and structure contours (e.g. Keller et al., 2009). Project data collected to resolve specific geological hypotheses typically are most valuable while being least plentiful (Sharpe et al., 2002).

Information Management

The most successful data standards seem to be those implemented at the institutional scale (e.g. Ludascher et al., 2006; Møller et al., 2009; Mathers et al., 2011; Boisvert and Brodaric, 2011).

Model Construction: “Rome Was not Built in one Day”

Three-dimensional geological mapping customarily involves modelling contacts as regular grids or irregular triangulated networks representing unit bottoms or tops (e.g. Ross, 2005), and discretization of properties within the strata (Lemon and Jones, 2003; Turner, 2006). Successful programs directed toward jurisdiction-wide, multiple-resolution work typically have required long-term planning and dedicated staffing. Progress can, and likely is, however, being made by all geological survey agencies and their partners, given that a progression commonly is followed from two-layer models such as depth to bedrock, digitized and reconciled legacy stratigraphic models, cross-sections drawn from stratigraphic control points through lithologic data, interpolated stratigraphic data, to solid models built from comprehensive geological and geophysical data. The requirements of this progression ranges dramatically with respect to data, interpretation, support, and software. Most surveys or similar units possess software that will allow at least partial entry into this progression, such as GIS with extensions and custom scripts (e.g. Mei, 2008), or 3D GIS software (Kessler et al., 2011).

Two-layer model:

A two-layer model such as depth to bedrock commonly is a benchmark product that will motivate data compilation and clarify priorities for data collection such as geophysics and drilling (Jordan, 2008). A point file of bedrock surface elevations may undergo machine modelling by some method deemed appropriate after iterative approaches, or may be modeled by hand and digitized to introduce expert opinion on the rock surface geometry deemed most likely. Many regional jurisdictions and nation now have maps for depth to bedrock or depth to basement for large areas exceeding 100,000 km² (e.g. Gao et al., 2006). In Ontario, the regional bedrock surface model has provided a framework for more detailed studies of 500-1000 km² involving extensive drilling and geophysical programs.
Legacy stratigraphic models:
Regions that have produced oil and gas will in most cases have been the subject of stratigraphic compilations, such as sedimentary basin atlases depicting hand-drawn or machine-contoured structure contours (Keller et al., 2009; Mathers et al., 2011). Modeling will have been guided by well-established correlations based on micropaleontology, other stratigraphic markers, seismic surveys, and lithologic trends identified in borehole geophysics and other means. Bringing this stratigraphic mapping into a 3D GIS environment may require infilling of gaps left in hand-drawn contours, and may require reconciliation of intersecting surfaces in data-poor areas if the legacy work involved construction of one surface at a time. Keller et al. (2011) described examples of this approach, notably a 3D model for 450,000 km² area of Western Canada constructed from legacy stratigraphic maps of the Western Canadian Sedimentary Basin Atlas (Mossop and Shetson, 1994). The 1:100,000 scale Lithoframe model of the British Isles is similarly based on legacy mapping and deep boreholes, seismic profiles, and regional geophysical interpretations (Mathers et al., 2011); the model extends to the base of the crust at a depth of 30 km, and includes major faults and igneous plutons. Such models can provide immediate value, for example as a basis for modeling and as a framework to guide planning and to clarify the context for data collection and higher resolution modeling.

Cross-sections drawn through lithologic data:
Beyond basins previously mapped in relation to hydrocarbon potential or production, a common scenario is a region in which 3D mapping is needed to support groundwater management, and the available basis for modeling will at best be scattered drillholes and geophysical surveys, along with an abundance of water well data. In this circumstance, the optimal approach has in many cases been seen as data compilation, acquisition of stratigraphic control sites using coring and geophysics, and construction of cross-sections by the most knowledgeable and experienced geologist who will use an approach similar to mature approaches developed for plan-view mapping, followed by capture and correlation of the sections in 3D GIS. This approach results in depiction of a plausible and visually pleasing geology that conforms to the geological conceptual model, and from which heterogeneity has to some degree been filtered by the geologist (e.g., Aims et al., 1996). This approach forms the basis for the British Geological Survey’s development of GSI3D and is also commonly employed in an analogue to digital workflow (Keller et al., 2011). New stratigraphic data can not, however, be readily incorporated into a model constructed in this manner, unless the new data are well correlated and can thus be incorporated as the existing model is remodelled from selected synthetic drillholes derived from the preceding model. Kaufmann and Martin (2008) address this issue by development of a workflow that integrates both punctual and line data for interpolation in a modelling environment.

Interpolated stratigraphic data:
Well-distributed drillholes or other vertical profiles that have confidently been assigned a stratigraphic correlation by micropaleontology, recurring lithological sequences, or some other means may be available for modelling without intervening manual steps, although expert-generated synthetic profiles may be required in data-poor areas for an acceptable result to be obtained. Approaches may range from simple spatial interpolation of stratigraphic assignments in a database (e.g. Mossop and Shetsen, 1994) to expert system approaches to model construction (Hughes, 1993; Logan et al 2006). Stratigraphic assignments in this approach are also deterministic, although once assigned, they can readily be combined with new data and re-interpolated. A well-documented example of this approach with clear expert rules was used to model the 12000 km² Oak Ridges Moraine area of Southern Ontario (Logan et al., 2006). An alternative classification approach is the Support Vector Machine (SVM) that is commonly applied in image analysis (Smirnoff et al., 2008).

Solid Models:
A full progression from modeling of surfaces to full characterization of volumes ultimately will be essential to support applications in hydrogeology, resource and hazard assessment, and engineering (e.g. Turner, 2006; Lemon and Jones, 2003). This process may involve additional data collection, and transfer from one software platform to another depending upon the nature of the discretization and property attribution (Kessler et al., 2008). Ross et al. (Fig. 2; 2005) provides a description of the progression from contacts to the construction of regular 3D voxel model for a 1500 km² area. Alternatively, solid models may be constructed from geophysical data and converted from time domain to depth domain at the appropriate scale (Jørgensen et al, this volume).
Figure 2. Model constructions steps highlighting preliminary surface generation, cross section integration, final surface generation, conversion from boundary geometry model to voxel model. (From Ross et al., 2005)
Property Attribution

A challenge to be faced in solid modeling meant to support inferences such as generation of a 3D grid of hydraulic conductivity values is an accounting of likely heterogeneity. In densely populated regions, a high density of drillhole observations may be available for models of up to 5000km² or larger (e.g. Stafleu et al., 2011; Royse et al., 2008). In these cases, property attribution may use techniques such as continuous geostatistical models, Boolean, Indicator or Gaussian-Threshold models and Markov chain models (e.g. de Marsily et al., 2005). For regional studies, it may be necessary to work with a small set of physical property measurements, such as hydraulic conductivity, and use another dataset such as hydrofacies to propagate this information. Central to many of these approaches is an understanding of the paleogeographic framework (e.g. Ritzi, et al., 1995; Weissmann and Fogg, 1999). A number of examples now exist of exploiting water-well data, geological knowledge and local measurements to understand the spatial heterogeneity of buried valley fills in the mid-western USA (Ritzi, et al., 1995) and alluvial fans in California (Weissmann and Fogg, 1999).

Uncertainty

An issue in 3D geological mapping is the certainty that can be placed on the spatial position of a given modelled horizon (e.g. Culshaw, 2005; Royse et al., 2008). This uncertainty results from: i) geological complexity, ii) quality, accuracy and reliability of data, and iii) interpolation effects. It is difficult to represent all of these aspects of data quality in a single metric, although Tacher et al. (2006) provide a comprehensive attempt. As demonstrated by Weber and Guens (1990), the density of data support to represent the geology increases with the complexity of the geology, including feature scale and variability of orientation. Data quality, accuracy and reliability can be assessed qualitatively and commonly quantitatively given adequate variability in data inputs. For example, an error in location results in an error in the depth to the unit, and furthermore results in a translocation of the represented geology (Keefer, 2011). Questions of quality and reliability of data descriptions can be assessed by comparison of data when it is collocated or in close proximity, or is not represented by statistical datasets or geological knowledge developed from many studies (e.g. Russell et al., 1998). One attraction of stochastic modelling is the generation of a probability outcome for the sum of the model iterations where each iteration is considered equally plausible (Stafleu et al. 2011).

3. WHAT DOES AN INSTITUTION NEED: PEOPLE FIRST

The crucial factor in permitting an institution to accelerate its progress in 3D geological mapping commonly is the presence of an individual or group with the commitment and influence to advance a vision for the activity. The critical attributes of this person or people are the ability to think in three dimensions, to visualize the geology on a well-informed basis, to foresee the plausible options for data collection, to recognize achievable mechanisms to fund the activity, and to appreciate current and potential applications. Many existing 3D programs at GSO’s evolved from the vision and inspiration of individuals with no little or no background in geomatics or 3D modelling.

4. SUMMARY / CONCLUSION

Three-dimensional geological mapping in some manner is achievable for all GSO’s. The critical juncture to achieve progress is an individual with the commitment to forge the necessary interagency collaboration and to advance a mapping agenda suitable to the level of resources available. As demonstrated by a number of agencies, sound geological understanding with conventional geomatics support is adequate to construct a basic two-layer bedrock surface geological model. Once such a model is in place there is both a framework for future 3D mapping and an opportunity to test and revise the model – progress is assured. No 3D mapping is final and consequently it is a fallacy to believe 3D mapping needs to wait until you can integrate the latest geophysical data, the newest allostratigraphic framework, or have resources to acquire a new 3D GIS modelling package.

5. ACKNOWLEDGMENTS

Reviews by M. Hinton and M. Pyne of the Geological Survey of Canada are much appreciated. This is ESS contribution.
6. REFERENCES


