Rationale and Methods for Regional 3D Geological Mapping Programs

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Abstract

Regional three-dimensional (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, to support applications such as groundwater management, engineering, and sedimentary basin assessments. 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. 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 (Culshaw, 2005; Turner, 2006; Thorleifson et al., 2010; Smith and Howard, 2012).

Geological mapping is a mature field (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 thus is 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 material, process, 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, due to increased data availability, improved technology, intensified land use, and escalating societal expectations.

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), wellhead protection (EPA, 1998), hydrogeological conceptual modeling (Anderson and Woessner, 1992; Bredehoeft, 2005; Kresic, 2007; LeGrand and Rosen, 2000; Royse et al., 2010), hydrogeological property attribution, quantitative groundwater modeling, engineering (Fookes, 1997), sedimentary basin assessments, mineral resources assessment, hazards, and fundamental research.

Geological mapping is guided by well-established stratigraphic principles. Facies models and basin analysis (Miall, 2000; 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; Seaber, 1988; Weiss and Williamson, 1985).

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), and in applied hydrogeology (Kresic and Mikszewski, 2012).

One approach is required for layers no more deformed than subsidence and normal faulting, whose 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).

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, to digitize, to georeference, and to categorize by lithology (Thorleifson and Pyne, 2004).

Data acquisition – What field work is needed?

Some new field work will be required to benchmark the 3D mapping. Geophysical surveys (Everett, 2013; Pellerin et al., 2009; Styles, 2012) may include EM (Abraham et al., 2012; Jorgensen et al., 2013; Oldenborger et al., 2013), seismic (Pugin et al., 2009; Chandler and Lively, 2014), radar, borehole geophysical surveys, and marine geophysics (Todd et al., 1998). New drilling will be required in many programs to provide stratigraphic benchmarks that the models are anchored to.

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 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; Jones et al., 2009; Patel and McCechan, 2003; Kaufmann and Martin, 2008; 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 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 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), 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).

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).

Research on heterogeneity includes, for example, recognition of structure-imitating approaches, process-imitating models, and descriptive methods (Kolterman and Gorelick, 1996). 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). 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).

Examples – What have other people done?

Examples of successful yet steadily evolving 3D geological mapping programs are available in areas such as Australia (Gill et al., 2011), New Zealand (Raiber et al., 2012), Denmark (Thomsen et al., 2004; Møller et al., 2009; Jorgensen et al., 2012), Finland (Artimo et al., 2003), France (Castagnac et al., 2011), Germany (Lehné et al., 2013; Pamer and Diepolder, 2010), Italy (De Donatis et al., 2009), the Netherlands (Stafleu et al., 2011; Kombrink et al., 2012; Gunnink et al., 2013), Poland (Malolepszy, 2005), the UK (Aldiss et al., 2012; Tame et al., 2013; Mathers et al., 2011a; 2014), Canada (Russell et al., 2011; MacCormack and Banks, 2013; Keller et al., 2011; Bajc et al., 2012; Burt and Dodge, 2011; Sharpe et al., 2007; Ross et al., 2005; Tremblay et al., 2010), and the USA (Jacobsen et al., 2011; Faith et al., 2010; Pantea et al., 2011; Phelps et al., 2008; Keefer et al., 2011; Thorleifson et al., 2005).

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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