GROUNDWORK
Furthering the Influence of Earth Science

Geological mapping goes 3-D in response to societal needs

Harvey Thorleifson, *Minnesota Geological Survey, 2642 University Avenue West, St. Paul, Minnesota 55114, USA, thorleif@umn.edu;* ***Richard C. Berg,*** *Illinois State Geological Survey, 615 East Peabody Drive, Champaign, Illinois 61820, USA, berg@isgs.illinois.edu;* ***Hazen A.J. Russell,*** *Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A 0E8, Canada, hrussell@nrcan.gc.ca*

INTRODUCTION

In the early 1800s, state and federal geological survey agencies were conceived to address increasing demands for natural resource information to fuel the Industrial Revolution. More recent urbanization, however, has spurred surveys, along with their university and industry partners, to extend their applications from mining and energy to water supply, engineering, hazards, environment, and climate change, while more directly supporting the needs of decision makers.

Geological maps are at the heart of this decision support system. They are the method geologists use to synthesize and communicate an understanding of earth materials, processes, and history; however, for all geologic mapping, challenges remain in obtaining the information required to construct maps that are meaningful and helpful to users. This is particularly acute for subsurface mapping. Geologists must process data obtained through field work, geophysical surveys, and laboratory analyses and then compile that data to map the composition and distribution of materials in a format and resolution that serves map users. In turn, map users have an obligation to grasp the uncertainty of the map while providing the best possible service to their clients.

Previously, technological and data limitations dictated that a two-dimensional (2-D) paper map—accompanied by at most a few cross sections and a report—was the most appropriate publication format, so users were expected to infer subsurface conditions at their site. Over the past two decades, however, in response to demands for subsurface information in extensive areas of thick sediments and sedimentary rocks, 2-D geological mapping has been superseded by three-dimensional (3-D) mapping. Geological mapping thus has been redefined in these settings—from a single-layer 2-D map to a 3-D model showing thickness and properties of multiple stacked layers (Turner, 2003; Culshaw, 2006).

Having thus raised expectations among users for 3-D mapping, surveys and their partners are now seeking to rapidly improve their methods for construction, dissemination, and use of 3-D geological maps to support decision makers who must balance economic growth with environmental protection.

THE RISE OF 3-D GEOLOGICAL MAPPING

In the 1990s, surveys were under pressure in numerous jurisdictions, even threatened with closure or amalgamation, commonly due to their inability to communicate the value of geology to modern societies largely divorced from natural resource extraction. Surveys are now embracing both a resource and an environmental agenda, and a required element of this strategy is production of adequately detailed geological maps showing thickness and properties of strata, which are needed for applications such as groundwater modeling. For example, a 2000 U.S. National Research Council report (Committee on USGS Water Resources Research, 2000) called for better characterization of aquifers and their water resources. Concurrently, surveys are being called upon to produce similar assessments of carbon storage capacity, conventional energy, and geothermal energy, all of which require 3-D mapping.

The model for implementation of this sustainable development paradigm has varied. In the United States, the Great Lakes Geologic Mapping Coalition has produced 3-D mapping of the thickness of sand and gravel that is guiding a US$250-million-dollar water resource decision in northeastern Illinois. The coalition has also delineated a casting sand deposit in Michigan, leading to immense savings by the auto industry. The Canadian Framework for Collaboration on Groundwater is another example, and the British Geological Survey has developed a business model incorporating an institutional and national strategy on 3-D mapping (Howard et al., 2009). Other surveys have their own responses tailored to issues, political structures, and agency mandates.

The transition to 3-D mapping has been made possible by technological advances in digital cartography, GIS, data storage, analysis, and visualization (Whitmeyer et al., 2010). Concurrently, tools to assemble and manage large databases, such as drillhole data, have been adopted as part of a digital geological mapping business model. In the late 1990s, there was acceleration in our ability to work with innovative visualization methods, although these approaches presented challenges in cost, effort, and information exchange between varying, commonly proprietary software environments. Despite these challenges, technological advancements facilitated a gradual transition from 2-D maps to 2.5-D draped maps to 3-D geological mapping, supported by digital spatial and relational databases that can be interrogated horizontally or vertically and

GSA Today, v. 20, no. 8, doi: 10.1130/GSATG86GW.1

Figure 1. 3-D geological map of the 190-km-wide Fargo-Moorhead region of North Dakota and Minnesota, USA, constructed to clarify the context of regional groundwater systems (courtesy Minnesota Geological Survey).

viewed interactively. This evolution has taken us from depiction of a surface to specification of multiple layer thicknesses and properties.

Challenges associated with data collection, human resources, and information management are daunting due to their resource and training requirements. Nevertheless, reservations have been overcome by recognition of the urgency of emerging needs. In particular, the requirements of groundwater professionals have rendered 2-D maps insufficient; users now require the best available observations and predictions regarding thickness and properties of multiple strata so that they can model and manage water resources (e.g., Herzog et al., 2003) (Fig. 1).

The adoption of these methods has been charted over the past decade by six workshops[1] organized by the authors. Participants in the workshops have progressed from a realization that they are not alone in dealing with 3-D mapping issues to knowledge exchange that has evolved over the years from model construction methods to institutional workflows to online data delivery and to a comparison of national strategies.

The exchange of strategies at the workshops has highlighted the use of basin analysis to develop a process-based predictive knowledge framework that facilitates data integration (Sharpe et al., 2002). However, despite progress in technological advancements and a need for detailed geological information, there remains a woeful lack of necessary high-quality subsurface information, even in densely populated and industrialized nations. This continues to be a consistent theme for all mapping, and it highlights the importance of predictive geological models that can guide strategic data acquisition. Regardless of technological progress, a geologist's ability to conceptualize and visualize processes and events over broad spatial and temporal scales, and to predict material distributions into areas of sparse data, remains essential, as is well-planned coordination between geologists and modelers.

CONCLUSIONS

The progression from 2-D to 3-D geological mapping has demonstrated that surveys, working with their university and industry partners, are dynamic institutes that advance fundamental knowledge, that invent and utilize new technological opportunities, and that do what is required to optimize the quality of life enjoyed by the people in their jurisdictions. In this evolution of survey work, 3-D geological mapping has emerged as a natural progression—a direct result of both technological innovation and intensified land-use activity, especially in urban and suburban areas, transportation corridors, and environmentally sensitive regions. Three-dimensional geological information meets a public demand that fills in the blanks left by conventional 2-D mapping. Two-dimensional mapping will, however, remain the standard method for extensive areas of complex geology, particularly where deformed igneous and metamorphic rocks defy attempts at 3-D depiction. Nevertheless, for similarly large areas of undeformed sedimentary cover, where critical issues regarding sustainable land- and water-related decision making still exist, systematic subsurface information is required to guide economic development and environmental protection. Three-dimensional geological mapping directly addresses the need for improved subsurface depictions of materials and structures, as required for modeling by hydrogeologists, engineers, land-use planners, and industry.

Three-dimensional geological information is an essential technical requirement for addressing many current geoscience issues, while also being far more accessible to a wide audience. It allows land-use professionals, as well as the general public, to visualize their landmass as never before and enhances stakeholder understanding and subsequent engagement in planning and decision making. With this increased accessibility come mounting obligations for the producers of the information to convey uncertainty and to provide guidance to users. In addition, challenges remain in optimizing information delivery, particularly the Web accessibility now demanded by society. This rapid evolution in how surveys do business is essential to adequately respond to emerging issues. In seizing these opportunities and responding to these needs, geologists have changed our understanding of what a geological map can be, from a 2-D paper map to a 3-D multi-layered model, which is now being seen as simply one form of geological map and now commonly the format that is readily achievable and most needed.

ACKNOWLEDGMENTS

This paper is Earth Science Sector (ESS) contribution number 20090356 (H.A.J. Russell).

REFERENCES CITED

Committee on USGS Water Resources Research, 2000, Investigating groundwater systems on regional and national scales: National Research Council, Washington D.C., 143 p.

Culshaw, M.G., 2005, From concept towards reality: Developing the attributed 3D geological model of the shallow subsurface: Quarterly Journal of Engineering Geology and Hydrogeology, v. 38, p. 231–284.

Herzog, B.L., Larson, D.R., Abert, C.C., Wilson, S.D., and Roadcap, G.S., 2003, Hydrostratigraphic modeling of a complex, glacial-drift aquifer system for importation into MODFLOW: Ground Water, v. 41, no. 1, p. 57–65.

Howard, A.S., Hatton, B., Reitsma, F., and Lawrie, K.I.G., 2009, Developing a geoscience knowledge framework for a national geological survey organisation: Computers & Geosciences, v. 35, no. 4, p. 697–868.

[1] http://www.isgs.uiuc.edu/research/3DWorkshop/index.shtml

Sharpe, D.R., Hinton, M.J., Russell, H.A.J., and Desbarats, A.J., 2003, The need for basin analysis in regional hydrogeological studies: Oak Ridges Moraine, southern Ontario: Geoscience Canada, v. 29, no. 1, p. 3–20.

Turner, A.K., 2006, Challenges and trends for geological modelling and visualisation: Bulletin of Engineering Geology and the Environment, v. 65, p. 109–127.

Whitmeyer, S.J., Nicoletti, J., and De Paor, D.G., 2010, The digital revolution in geologic mapping: GSA Today, v. 20, no. 4/5, p. 4–10.

Manuscript received 3 Jan. 2010; accepted 17 May 2010.