Commentary -- Three-dimensional Geologic Modeling: Challenging our Terminology and our Understanding of Geologic Maps

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Introduction Significant advances in the process of making geologic maps have occurred since the mid 1980s with the advent of geographic information systems (GIS) and computer-assisted visualization tools. The computer has allowed us to analyze, store, and manipulate huge data sets and portray geologic information in ways that previously were not possible or took weeks or months to do by hand. Now, as can be seen in the many illustrations in this workshop volume, three-dimensional (3-D) illustrations such as block diagrams, fence diagrams, multiple cross sections, chair slicing, surface contour maps, isopachous maps, and pull-apart diagrams are becoming common ways to display geology.

As discussed in USGS Open-File Report 99-349 (Berg et al, 1999), the 3-D model shows the geometry of both surface and subsurface units. Because some of the erosional and depositional surfaces preserved in the stratigraphic record can be easily presented, snap shots of geologic time – the 4th dimension – become part of the model. Various perspective views can be reviewed, data can be checked for accuracy, and the geology can be interpreted to develop derivative maps. For example, a continuous and internally consistent 3-D geologic model is required to provide the most realistic portrayal of aquifer geometry and the variability of aquifer properties.

While traditional geologic maps remain quite useful, 3-D geologic models increasingly are being developed to portray subsurface relationships in an understandable fashion. This change is occurring for two reasons: 1) because software advances are making it practical to create these models using desktop computers, and 2) these models are excellent tools for defining, preserving, and communicating the geologist’s understanding of the subsurface, especially to the informed layman. This communication advantage not only helps geologists present their findings to fellow geologists, but also helps non-geologists better understand geologic complexities and use geologic information to help solve real-world water and land-resource problems.

Two basic questions arise from our ever-increasing use of and reliance on 3-D maps, particularly those that portray the shallow subsurface:

(1) What has the technology done to our terminology: What do we mean by the words “models”, “maps”, and “illustrations”?
(2) What is the cause, relevance, and impact of this recent surge in shallow 3-D geologic modeling?

These may seem like moot points, but, they have been and continue to be the subjects of discussion and controversy.

What has the technology done to our terminology? What do we mean by the words “models”, “maps”, and “illustrations”? Recent technological changes have led to some confusion about the meaning and use of these terms “models”, “maps”, and “illustrations”. The many desktop computer software packages that have contributed to the recent growth in 3-D mapping have had an impact on the meaning of the terms we use. Before the use of computers, our data were numbers and words and maps were maps. The maps were also typically 2-D representations of 3-D relationships. Illustrations of the geologic interpretations within 3-D volumes were very limited and tended to be thought of as fairly
independent from data and maps. Now, 2-D and 3-D models and their supporting data are clearly linked, as are illustrations of subsequent model interpretations.

Definitions of “model” from Merriam-Webster’s online dictionary include several listings that are important to our discussion, including: “a usually miniature representation of something; a description or analogy used to help visualize something that cannot be directly observed; a system of postulates, data, and inferences presented as a mathematical description of an entity or state of affairs.” From these definitions, it is clear that geologic maps, in any dimension, constitute models. In addition, the hand-drawn illustrations of 3-D geologic volumes also constitute models.

A 1998 article by J.H. Andrews lists 321 definitions of the word ‘map’ from 1649-1996 and sheds further light on the issue. Review of these definitions shows a common theme - that a map is a representation of any portion of the Earth. Below are a few selected definitions that seem particularly relevant to our discussion.

1649 - …an artificial representation of the earth and water under that form and figure of roundness which they are supposed to have…(Gregorri posthuma: or certain learned tracts written by John Gregorie, M.A. and chaplain of Christ-Church Oxford, London, p. 257).

1721 - A representation of the earth or some particular part thereof upon a plain superficies (Nathan Bailey, An universal etymological English dictionary).


1838 - A representation of the whole earth, or of a part of it, on a flat surface (James Thomson, An introduction to modern geography, Belfast, p. 4).

c. 1885 - A representation of the surface of the earth or of any part of it, or of the whole or any part of the celestial sphere, usually drawn on paper or other material: A distinct and precise representation of anything (John Ogilvie, The imperial dictionary of the English language, London).


c. 1950 - Any delineation of the surface of the earth, or of any part of it, drawn on paper or other material (Collins graphic English dictionary, London).

1989 - Holistic representations of spatial reality. The map is initially and primarily an intellectual abstraction of spatial reality but this must be subsequently communicated, i.e. modeled and coded, in a
form that exploits the human and/or digital spatial processing capabilities (M. Visvalingham, reported in British Cartographic Society Newsletter, i).

1993 - A symbolised image of geographic reality, representing selected features or characteristics, resulting from the creative efforts of cartographers, and designed for use when spatial relationships are of special relevance (quoted in Michael Wood, 'Whither maps and map design', Bulletin of the Society of Cartographers, xxvii, p. 8).

1994 - A representation of the surface of the earth or any part of it (Burlington dictionary [Bridlington]).

1995 - Two- or three-dimensional devices, allowing to give a spatial organization to phenomena, events, processes, things, etc in order to understand them (Christian Jacob).

Interestingly, the first mention of a “model” as part of a definition of a map is 1922 where a map – an ideal map - was defined as a model. Beginning with the 1989 example, definitions incorporate “new” types of maps that can be generated by computers. Definitions for maps as “holistic representations of spatial reality”, “symbolised image of geographic reality…designed for use when spatial relationships are of special relevance”, and “two- or three-dimensional devices” help to establish the relationship between models and maps. Furthermore, none of the 321 definitions of a map impose limiting factors for portrayal of the earth. A map as a “representation of the whole earth or part of it”, as stated in many of Andrews’ definitions, would logically include any portion of the earth’s subsurface.

Based on the above definitions and considering the changes that computer technology is making in geologic mapping, we suggest the following usages for the words, “illustration”, “model”, and “map”.

- First, the word “illustration” does not need any clarification in usage and should remain as defined by Meriam-Webster OnLine as, “a picture or diagram that helps make something clear or attractive”. Therefore, all visualizations from maps and models are illustrations, but obviously, not all illustrations are maps or models.
- We suggest that the word “model” be used to describe (1) the digital files that comprise an interpreted geologic column, surface, cross section, or volume, and (2) any conceptualization or illustration of the geology that these digital files represent. “Modeling” would, therefore, include any of the processes involved in creating a model.
- We propose the word, “map” be used to describe: (1) any illustration of the surface or subsurface of the earth or any part thereof, and (2) the digital files that comprise a geologic model. Angular perspectives, chair slices, fence diagrams, and illustrations of interpreted well logs are all representations of the earth, and as such, are all maps.

Together, these definitions provide a modern clarification of the more traditional understanding of a map as any representation of the earth, while providing a compatible definition of a model that considers computer applications. The process of mapping still describes all the procedures and products involved with the interpretation of geologic data. While map and model can be synonymous, these definitions also allow us to refer to a geologic interpretation as a model, and any associated illustrations as maps.

It is important to realize that neither the original definitions nor our proposed definitions include any requirements that ensure the quality or usability of any map. There are no constraints placed on required cartographic elements (e.g. north arrow, posted scale), on the use of a single,
consistent map scale, or on the accuracy of spatial relationships between map elements. We recognize that the use of these and other constraints help ensure that maps are useful. However, in agreement with the cited definitions, we feel strongly that these are not required characteristics of maps.

**What is the cause, relevance, and impact of this recent surge in shallow 3-D geologic modeling?** Three-dimensional geological models are not new to the field of geology. The oil industry has used them since the 1930s. However, 3-D geologic models of the near-surface – the upper hundred meters or so - particularly in glaciated areas, are relatively new. Accurately mapping and modeling the complexities of the materials left by glacial depositional and erosional processes, interspersed by long periods of soil formation, create daunting tasks for the geologists who are mapping, as well as attempting to explain the geology to colleagues and laymen. Policy makers can be particularly perplexed if they try to implement land- and water-use decisions based on traditional 2-D maps. Artimo et al. (2003) explain that 3-D geological models are truly integrated solid models that represent the geometry, stratigraphy, sedimentology, and hydrostratigraphy of aquifer and non-aquifer units. When supported by a sedimentologic model, based on depositional and erosional processes, 3-D models can provide sophisticated and detailed geological information, and therefore the greatest potential benefits to users. The model, constructed by interpreting the data, provides the most complete depiction of the subsurface – as true a representation of reality as possible from the available data - and an internally consistent and directly integratable conceptual model of the materials and their physical properties that can be used directly by hydrogeologists for groundwater flow modeling.

The techniques for 3-D mapping of deep bedrock units for oil and other resources are applicable for near-surface 3-D mapping of glacial and other unconsolidated deposits. However, understanding and describing the variability and discontinuity of these sediments, both horizontally and vertically, requires considerably more detail and accuracy to understand and describe than ordinary bedrock mapping. Therefore, we have been forced to develop new techniques to (1) deal with large data sets, (2) describe the complexities of the near-surface geology, (3) portray the 3-D geology, and (4) provide an improved understanding of the deposits. All of this is necessary to solve real-world environmental and earth-resource problems. It is to this end that improved interaction is needed between those mapping the geology and those using the geologic information for, among other things, groundwater modeling.

According to Kempton (1980), establishment of the concept of “environmental geology” in the mid 1960s (Frye, 1967) was the single-most important reason for needing 3-D mapping for shallow deposits. The need became apparent as greater attention was paid to environmental and land-use issues, mainly centering upon groundwater contamination and resource availability. A demand was created for more precise information on the character and distribution of surficial geologic materials. The demand stimulated the development of new techniques to obtain and analyze subsurface data, and procedures, such as stack-unit mapping, were developed to better understand and portray geological complexities.

Prior to this time, most efforts to depict geologic units three dimensionally were generally indirect and relied on separate maps showing thickness and structure. Compounding the problem, at least in Illinois, was that before 1958 glacial deposits were not assigned to rock-stratigraphic units. Older geologic maps mainly portrayed the age of units and did not focus on materials. Also, they did not provide the type of information, mainly in the subsurface, that would be most useful for groundwater and land-use interpretations.

Over the last 10 years, advances in GIS and other computer-assisted modeling and visualization tools have resulted in new ways to portray and understand the subsurface (e.g., block diagrams, pull-apart models, interactive animations, etc.). The most profound contrast between maps produced in the pre-computer era from those produced now is that the digital nature of recent maps and models makes it possible for them to become “living” documents. Additionally, delivery of the latest map/model edition need not wait until another edition is printed. Rather, maps and models can be viewed and downloaded directly from the internet, thereby providing users with ready access to the latest versions. New hardware and software tools also have provided superior geologic models for use by groundwater hydrologists and hydrogeologists in developing their groundwater flow models.

New computer-assisted mapping tools are not necessarily innovations in research, and generally do not offer improvements in mapping accuracy or precision. However, these new tools and techniques are having a profound effect on: (1) how we think about and visualize geologic systems, (2) how we map, both in the field and in the office, and (3) how geologic maps and data are being used by geologists and the public (Lasemi and Berg, 2001).

We suggest that the introduction of detailed 3-D geologic mapping in hydrogeologic studies has been slowed by four main road blocks:

1. obtaining 3-D geologic information is costly,
2. until recently, there have been few software packages that provide sufficient 3-D modeling capabilities at affordable prices,
3. many projects requiring groundwater flow investigations have not had sufficient time or money to obtain the detailed geologic interpretations they really needs, and
4. while many hydrogeologists have recognized that better geologic data could improve their modeling, they typically have not been sufficiently trained to interpret the complex geologic sequences, nor qualified to generate the necessary high-resolution geologic models.

We suggest that these roadblocks can be overcome by education and the proper allocation of time and resources. This workshop on "Three-dimensional Geologic Mapping for
Groundwater Applications" as well as the previous two workshops on the subject (Berg and Thorleifson, 2001 and Thorleifson and Berg, 2002) are intended specifically to address the need for education in the development and use of detailed, 3-D geologic maps. The goal of all three workshops has been for geologists to share information about methods for constructing 3-D geologic models specifically intended for use in groundwater flow models and to secure cooperation with groundwater professionals who understand the links between the latest geologic mapping techniques and their ability to work.

References


