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Defining a Three-Dimensional Geologic Map for the Appalachian Plateau

By Gayle H. McColloch, Jr. and Jane S. McColloch

West Virginia Geological and Economic Survey
1 Mont Chateau Road
Morgantown, WV 26508-8079
Telephone: (304) 594-2331
Fax: (304) 594-2575
email: *mccolloch@geosrv.wvnet.edu*, *janemc@geosrv.wvnet.edu*

Introduction

The West Virginia Geological and Economic Survey (WVGES) was introduced to geographic information systems (GIS) in the early 1980s when the venerable SYMAP package from the Harvard Laboratory for Computer Graphics and Spatial Design (Dougenik and Sheehan, 1975) was used to produce statewide coal quality maps on line printers. These were manually converted by a draftsman to mylar maps. In the late 1980s, in cooperation with the U.S. Geological Survey (USGS) Branch of Coal Geology, coal resource studies were completed using PACER for database management and GARNET for graphics and analysis. These were software programs designed to run on Prime minicomputers (Loud, 1988) and later ported to Sun workstations (Loud, Blake, and Fedorko, 1990). Although these were highly specialized software programs designed to classify coal resources, they clearly fit the definition of a geographic information system. The analytical functions of GARNET were later performed with the Geographic Resources Analysis Support System (GRASS) produced at that time by the Army Corps of Engineers (Loud, 1999).

By the early 1990s, several computer platforms were capable of running graphics-intensive two-dimensional GIS, and a number of commercial systems advertising diverse capabilities became available. The next obvious step seemed to be three dimensions, and discussions of exotic voxel and octree three-dimensional data models proliferated among geographers.

Three-Dimensional Problems

Several issues kept WVGES from immediately embracing the concept of producing three-dimensional geologic maps. The software and hardware supporting three-dimensional GIS was quite expensive. Although we had a large amount of data accumulated since the agency was formed in 1897, much digital data development had to take place before it was in a form to be used in even a two-dimensional GIS. Most geologists visualize three-dimensional relationships directly without the aid of computers or software, and expensive three-dimensional software and requisite hardware were a hard sell to management that has quite limited discretionary funds. Finally, most of the work of State geological surveys is regional in nature, and portraying three-dimensional representation requires extreme vertical exaggerations that can visually distort geologic relationships.

Processing Raw Data

In 1995, a controversy about the methods used by the West Virginia Division of Tax and Revenue to appraise mineral resources resulted in a legal settlement that involved revamping the appraisal system by developing GIS models of those resources. Although the actual process is more complicated, in essence those models were to be used to generate tax bills. This change resulted in a cooperative program between WVGES, the West Virginia Division of Tax and Revenue, and West Virginia University to collect raw data and to develop models, programming, and procedures for taxpayers to correct errors. Although some raw data are proprietary and must be held confidential, the models used for taxation must be public record and open to examination. After 14 years of consistent model development, we have a large, growing body of high-quality GIS information about West Virginia's mineral resources.

Geologic Mapping

Several years ago, we realized that this information can be processed to produce geologic maps. The procedures we use are detailed in our DMT'08 poster session entitled "Creating Geologic Maps for the Appalachian Plateau in a GIS Environment"; this is described elsewhere in these Proceedings. These procedures are effective, in part, because many rock unit contacts are stratigraphically at or near economically important coal beds. This means that the structure of major coal beds provides a three-dimensional framework. Because stratigraphic intervals vary consistently in the region and in this part of the geologic section, we are able to interpolate or extrapolate other horizons and to intersect all relevant horizons with digital elevation models in order to define outcrops. The end results are digital outcrops and contour maps of one or more structural horizons. After field checking and correcting errors and inconsistencies, these are used to construct a conventional geologic map. In the process, several additional intermediate data sets are produced, notably grids representing all important horizons. To date, these have been archived, but we have begun to realize that these data, if properly packaged, have other uses, and we are experimenting with how to best produce from these archived files a three-dimensional geologic map.

An Early Experiment

One experiment involved a request for assistance from a local golf course. The pond they use as a source of water for irrigation was leaking. The reason for the leak was that their pond was less than 50 feet above an old underground coal mine in the Pittsburgh coal. At this location the entire interval above the mine appears to be composed of the upper Pittsburgh sandstone of Hennen and Reger (1913). This sandstone unit is cross-bedded and has an unconformable basal contact. This unit is subject to failure along large joint sets, resulting in blocks of overlying rock subsiding into the old mine workings when coal pillars are crushed as a result of age and stress. The greenskeeper at the golf course determined by dye tracing that water was draining from one area of the lake bottom, and had already ordered a large quantity of bentonite to plug the hole. He was concerned about the fate of the water after it leaked from the pond; he had expected the water to emerge from mine entries at a nearby outcrop to the south of the pond and was puzzled when it did not appear. After examining the structure of the coal bed in this area, we explained to him that this outcrop was up-dip from the lake and that the groundwater was flowing to the north, in the down-dip direction. The presence of springs and seeps on the exposed hillside to the north of the golf course were verified in the field. However, the greenskeeper remained skeptical.

After this experience, we began looking at the data that we had accumulated and archived while completing the geologic map of the quadrangle where the golf course was located. We realized that this material could be used fairly efficiently to produce a visualization that would help to explain the situation. The result is Figure 1, which was produced with NVIZ, a part of the GRASS version 6.2 GIS package (GRASS Development Team, 2007). A high resolution digital orthophoto quarter-quad (DOQQ) is draped over a 1/9 arc-second digital elevation model (DEM) to form the portrayal of land surface. The lower surface is based on a grid of the structure of the base of the Pittsburgh coal, which was mined beneath this area. For clarity, this surface has been lowered significantly below the land surface. Elevation information is portrayed by color: red areas are the highest, yellows are intermediate, and blues are the lowest elevations. This illustration makes it easy to see that, in general, any water leaking downward through fractures in the lake bottom would flow into old mine workings, and from there would follow the north-trending dip of the coal and overlying sandstone unit, emerging at the outcrop in a valley on the north side of the golf course. This illustration is the most photogenic result from several experiments that applied open source or commonly available three-dimensional rendering software to the archived GIS data from our more recent geologic mapping projects.

Proposed Elements of a Three-Dimensional Geologic Map

In our preliminary testing, we have found the following set of items useful for three-dimensional GIS applications in the Appalachian Plateau region. They are in two categories: base layers and geologic elements.

Base layers:

- Orthorectified imagery
- Digital Elevation Model
- Hypsography
- Hydrography
- Infrastructure lines (roads, power lines, etc.)
- Cultural points (towns and other points of interest).

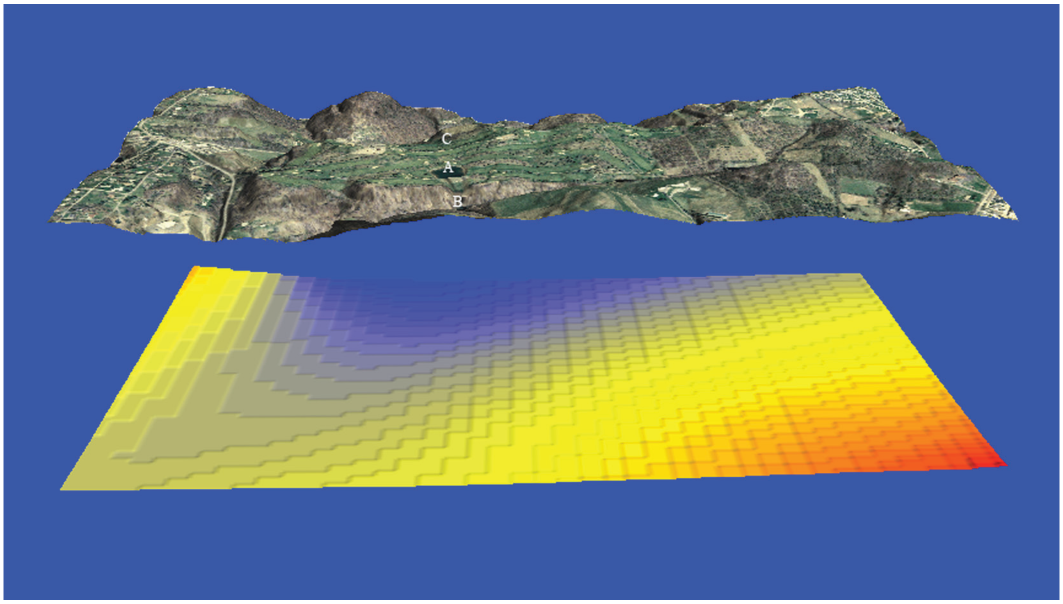

Figure 1. A visualization developed to explain direction of water flow from a leak in the bottom of the golf course lake (A) through old mine workings. North is to top of diagram. The golf course is at the center of the map area, the lake is marked "A," and the updip outcrop is marked "B." The lower surface is based on a grid of the structure of the base of the Pittsburgh coal. For clarity, this surface has been lowered significantly below the land surface. Elevation information is portrayed by color: red areas are the highest, yellows are intermediate, and blues are the lowest elevations. This illustration makes it easy to see that, in general, any water leaking downward through fractures in the lake bottom would flow into old mine workings and then flow northward and emerge from the downdip outcrop "C" in a valley on the north side of the golf course.

Geologic elements:

- Grids representing elevation of all important horizons occurring between land surface and sea level or the base of known geology
- Volume renderings of relevant rock units, if available
- Two-dimensional elements of geologic maps
- Stratigraphic information to fill gaps in the rock record
- Deep subsurface information, if available

The base layers commonly are available for the region. The most important geologic elements are grids of critical horizons. These critical horizons, in particular, are the bases of coal seams and certain other useful marker horizons such as fossiliferous limestone and shale units. Some of these serve as rock unit boundaries in the Appalachian Plateau and others are useful in understanding the stratigraphy. The two-dimensional elements of geologic maps include structure contours generated by contouring grids of selected geologic units and, possibly, fold axes where appropriate. Stratigraphic information includes measured sections, representative core logs, and generalized stratigraphic sections. Deep subsurface information includes various well logs, particularly those from oil or gas wells and other deep borings.

Other Significant Rock Units

In recent years, we have mapped several quadrangles in the Appalachian Plateau and have extensive experience in mapping and in responding to requests for information and assistance. Our goal in the current mapping work is to map traditional formations and groups as well as the most important marker beds, although we realize that there would be value in mapping other rock units where adequate data are available to do so. Notably, some of the laterally extensive sandstone and limestone units that have hydrogeologic, cultural, or environmental significance are important to map.

In the areas we have mapped in the northern part of the Appalachian Basin of West Virginia, the most significant of these units are the Waynesburg sandstone, the Grafton sandstone, and possibly the Sewickley and Benwood limestones (all of Hennen and Reger, 1913). The Waynesburg sandstone appears to be composed of sands deposited in one or more stream channels that meandered and "jumped" to create new channels, resulting in a sandstone of nearly continuous extent

(Donaldson and others, 1979). It is a subtle, but very recognizable unit in north-central West Virginia, where it forms gently rolling upland valleys that have traditionally been farmed (Figure 2). These valleys typically end at waterfalls formed in the Waynesburg sandstone (Figure 3). Detailed mapping of this unit would be time consuming, and it is beyond the scope of our 1-year STATEMAP quadrangle mapping projects.

Figure 2. Gently sloping upland farmland underlain by the Waynesburg sandstone of Hennen and Reger (1913) in north-central West Virginia.

Figure 3. A small waterfall has formed by an outcrop of the Waynesburg sandstone of Hennen and Reger (1913). The underlying Waynesburg coal has been mined locally for house coal at this location.

The Grafton sandstone of Hennen and Reger (1913) is present in both our north-central and northern panhandle mapping areas. In West Virginia's northern panhandle area, this unit appears to be composed of the sands deposited in one or more stream channels (Figure 4), whereas in north-central West Virginia it represents the prodelta of the Grafton fluvial system, which is in places cut by delta plain channels (Figure 5) (G.H. McColloch, unpub. data, 1975). The deposits of the northern panhandle are probably younger than those in north-central West Virginia because the Grafton represents a prograding shallow water delta system with downcutting of younger channels into older deposits. In both the Wheeling and Morgantown areas, it has formed rock terraces that had a significant role in controlling early human settlement patterns. Later, the Grafton rock terraces formed the flat areas where factories and residential neighborhoods were located.

Figure 4. Outcrop of the Grafton sandstone of Hennen and Reger (1913) in Brooke County in West Virginia's northern panhandle. The gap in this narrow ridge was created when one of two of the oldest tunnels on the western slope of the Appalachians was daylighted.

The Sewickley and Benwood limestones of Hennen and Reger (1913) are of interest because they form small caves (Garton and Garton, 1976) in a region that is otherwise devoid of karst features, and because they provide a local source of low quality aggregate. These karst features are not as significant as karst features in the thicker, purer carbonate units elsewhere in the Appalachians, but they have caused engineering problems. These units also provide a local source of impure limestone.

Figure 5. The Grafton sandstone of Hennen and Reger (1913) is present in the upper part of this road cut located in the Morgantown area. The dark zone (A) is the Harlem coal. The overlying Ames shale and limestone of Hennen and Reger (1913) (B) occurs between the Harlem coal and the Grafton sandstone (C). The Grafton at this location is sedimentologically complex, forming in several environments characteristic of a shallow water delta system and including rocks representing prodelta, lower delta channel deposits, and a coal formed in the abandoned channel (G.H. McColloch, unpub. data, 1975).

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