THREE-DIMENSIONAL VISUALIZATION AND MODELING AT THE U.S. GEOLOGICAL SURVEY: EXAMPLES AND ISSUES

M. Pantea*, P. Glynna*, G. Phelps*, G. Bawden*, and D. Soller*
*US Geological Survey,  pglynn@usgs.gov

1. INTRODUCTION

We need to use appropriate technologies and abilities to visualize, model, and work within the dynamic multi-dimensional earth. Natural processes are 3D/4D in character, yet scientists in the U.S. Geological Survey (USGS) often still research and share information of the natural world with 2D and 1D graphics and text. Current in-house 3D modeling and visualization efforts often consist of 2D map/GIS overlays stacked in 3D space. Static block diagrams and other 2D visuals do not allow efficient exploration of the rich multi-dimensional datasets and knowledge beyond the surfaces portrayed. Current capabilities and practice using 3D/4D tools vary widely across the USGS. Our research, science, and delivery efforts need to be brought up to date. This presentation considers several 3D/4D efforts within the USGS, and highlights important needs and challenges to be addressed.

2. SOME CURRENT PROJECTS

A geologic and hydrologic study with drill hole and field mapping data. A cooperative study between the USGS and the Camp Stanley Storage Activity (CSSA) military base, Bexar County, Texas, their cooperators, and the Environmental Protection Agency was conducted to define the framework geologic structure and the hydrostratigraphy of the area (Fig. 1). The basic regional geology and hydrology was not known sufficiently for the local management of resources. A detailed geologic study was conducted that defined previously unknown horst and graben structures. These structures were identified through both drill hole and surface mapping data and information. 3-D modeling was used to provide a visual framework for the information, improve understanding of the geologic framework, and to improve coordinated management of local resources, including groundwater. Understanding the geologic structure, such as local faults and fractures, provided an important first step to understanding the distribution of porosity and permeability, groundwater recharge, and migration pathways.

Figure 1: 3D visualization of the lowermost confining unit, structure, and cross section within the CSSA study area.
Volumetric regional geologic mapping for hazard and contaminant modeling. Surface geologic mapping to subsurface volumetric geologic mapping is well underway (Jacobsen and others, 2011), but fundamental challenges remain in mapping below-ground surfaces that cannot be directly observed. Volumetric geologic bodies are mapped indirectly both by extrapolating geologic structures observed at the surface and by estimating or inferring rock properties as proxies for direct geologic observation. Some proxies include: velocity for seismic data, density for gravity data, magnetism for magnetic data, and resistivity for electric data. Drill-hole information, when available, can be invaluable. However, study regions are often spatially undersampled, so that local structure observed in drill-hole data may be misinterpreted as regional structures. The objectives of geologic mapping dictates the methods used to address these challenges, as discussed below for two projects.

The Calico Hills Formation study is an effort to understand potentially contaminated groundwater flow through a heterogeneous sequence of overlapping and coalescing lava-flow aquifers and tuff confining units. The Calico Hills Formation within the study region is known only from drill-hole information. The information available is insufficient to resolve the number, extent, and connectivity of lava flows that occur between drill holes. The properties of these flows significantly affect the outcome of hydrologic flow models. A volumetric geologic map of the study region needs to match three types of data: geologic and lava flow configuration and estimated volumes, drill-hole data, and aquifer tests. Plausible volumetric lava and tuff configurations were created using a multi-point geostatistical approach. An idealized model of lava flows and tuffs, larger than the study region and free of drill-hole constraints, was generated using an automated object generator that was constrained using geologic knowledge and inferences from common lava flow dimensions and thicknesses. The proportion of lava to tuff, and the different shapes and distributions of lava flows relative to one another were quantified and stored in a pattern database. These patterns were correlated with drill-hole information resulting in a new plausible volumetric map of lava flows and tuffs for the study region. Hydrologic properties based on lithology were assigned to the volumes and used in a flow simulation, and the results compared with aquifer test data. A thousand volumetric maps were then made using the pattern database with drill-hole constraints; each map was equally likely given the available geologic and drill-hole information, and each map was compared with the aquifer test data. The subset of maps with flow simulation data that were consistent with aquifer test data was used to represent best guesses for the subsurface geologic configuration (Fig. 2). Volumetric maps in aggregate can be used to investigate general tendencies of the aquifer system. For example, one might learn that the presence of a large flow pathway along the eastern side of the study region is more likely than along the western side.

The San Andreas Fault project provides improved understanding of one of the world’s most dangerous fault systems by volumetrically mapping the San Andreas Fault and the surrounding geology, and by exploring the structural history of the fault. The study integrates mapping and modeling by field geologists and geophysicists who individually map structures and rock bodies to develop a volumetric map. At the scale of the study, structures such as local faulting or folding that would be important at the 24k scale are generalized in favor of structures important at approximately the 250K scale. Sparse drill-hole data are influenced by local structural features and are therefore not always honored exactly, but are honored regionally in a least-squares sense. Select portions of the volumetric map were examined both to better understand the fault history and to highlight problems with the mapping (Graymer and others, 2010). Portions of the map were discretized and used for predictive modeling of earthquake slip (Jachens and others, 2006). Final products are being published as volumetric spatial databases (e.g., Phelps and others, 2008).

Point clouds: novel multi-disciplinary uses. Dense point cloud datasets collected from airborne and ground-based LiDAR (Light Detection And Ranging) geodetic techniques and photogrammetric analysis provide a unique opportunity to address a broad range of scientific questions that were unanswerable 5 years ago. These 3D and often 4D datasets are used in a wide range of scientific analyses including: identifying previously unrecognized fault zones in forested regions, measuring biomass and biomorphic characterization of vegetation, measuring glacial velocities, resolving the surface roughness of river beds, imaging near-shore bathymetry, and directly measuring decimeter scale 4D snow-water-equivalent changes within a snowpack over time. New 3D/4D approaches and methodologies are being developed to extend the analysis from traditional 2D GIS algorithms to comprehensive 3D point-cloud derived surface models. The data are in 3D, but many of the software approaches remain in 2D.
A cooperative study with the University of California Berkeley, the Sacramento Area Flood Control Authority, and the USGS injected grout into ground squirrel burrows on an active levee in California to assess the spatial extent of the burrow complex. The levee was slowly excavated to expose the grouted burrow. An ultra-high resolution ground-based Tripod LiDAR (T-LiDAR) system was then used to measure the 3D relations of the mammal burrows with the original levee surface. At the two sites excavated, one burrow was found that went from the water to the landside of
the levee at a depth of 45 cm. 3-D visualization and modeling was then used to find relations between the burrows, the integrity of the levee, and the volume of material removed from the levee by the ground squirrels. Removal of too much material would have potentially disastrous consequences.

3. **RECENTLY INITIATED APPLICATIONS**

Permian-, Pennsylvanian-, and Mississippian-age aquifers of the Appalachian Plateaus cover portions of seven states and contain large amounts of coal, oil, and gas reserves with long histories of production. The USGS Appalachian Plateau Groundwater Availability Study seeks to expand the regional geologic knowledge of subsurface resources to better define groundwater availability and vulnerability. A regional geologic model of the Plateaus aquifers is not available, yet is needed to understand locally driven groundwater-flow systems in the context of hydrostratigraphy at the regional scale. In addition to the water study a 4D petroleum system model of the Appalachian Basin is being built to model oil and gas generation, migration, and accumulation through time for contained petroleum reservoir and source rocks. The research focuses on unconventional (continuous) oil and gas reservoirs.

A cooperative study between the USGS, the Arizona Department of Water Resources, the Nogales city water planners, and the Department of Homeland Security was initiated to expand knowledge of the geologic framework of the Nogales area, to more accurately define the hydrostratigraphy of shallow aquifers, and to better understand water flow and groundwater recharge. Specifically, a 3-D study is being conducted to define the depth and geometry of the alluvial aquifers and the lower confining unit. There are no deep drill hole data available, except for water wells which are less than 500 feet in depth. Use of 3D technologies is helping make full use of the sparse geologic information at depth.

4. **INSTITUTIONAL PROGRESS IN 3D VISUALIZATION AND MODELING**

The USGS conducted a groundwater workshop in 2012 that provided a snapshot of current state-of-the-art USGS experience with 3D/4D visualization tools useful for groundwater studies and numerical modeling; and for the integration and assembly of geologic, hydrologic, geophysical, geochemical and other information used in these studies. The workshop presentations and panel/open discussions (1) increased awareness of relevant tools available and in use by USGS scientists; (2) provided an opportunity to discuss future directions and needs for 3D/4D groundwater science and research; and (3) create a USGS interest group to help the USGS move forward using 3D tools for groundwater studies.

The training and the workshop sought to elicit answers to the following questions:
- Why do we need 3D visualization tools? (Hint: we are naturally wired to see in 3D rather than 2D)
- How can the tools be used? How have you used them?
- How can the tools be afforded? (One option is collaboration with teams or individuals that have the skills and software available to them or in-house training for the software).
- How can we “publish” 3D products and associated information, for access by and communication to others both within and outside the USGS, while minimizing information loss and introduced biases (i.e. in transitions to 2D media)?
- How can more value be added to publications to make them more useable? (i.e. interactive, add user data, animations…)
- Have you had some scientific breakthroughs that came about because you used 3D visualization?
- When is 2D representation clearly insufficient? (e.g. information biasing, information loss, smearing, discontinuities).

The workshop outlined the following reasons for use of 3D visualization tools:
- QA/QC’ing of data, consistency tests, and other types of information checking.
- Quick construction of geologic, geophysical, hydrogeologic, or combined models.
- Easier integration of diverse geoscience data and associated information.
- Exploration and interpretation of diverse information, i.e. easier building of better conceptual models.
- Easier presentation of modeling results and implications.
- Collaborative engagement/facilitation, either between scientists (possibly with different expertise), or between scientists and cooperators/resource managers/policy makers.
• Helping science get understood by larger and more diverse audiences.
• Education, easier to get information and understanding of the information to a larger audience.

Aside from discussing and formalizing the need for 3D/4D visualization and modeling tools, the workshop proved very useful in introducing members of the USGS groundwater community to a wide diversity of currently available commercial and open-source tools that could be used.

In addition to the 3D training mentioned above, the USGS has also made available a number of broadly used, relatively inexpensive software packages for constructing and interpreting (pseudo) 3D geologic models. Collaborative relations with other Geological Surveys such as the British Geological Survey have been highly beneficial in this endeavor.

5. ISSUES AND CHALLENGES FOR GREATER USE OF 3D VISUALIZATION AND MODELING
The USGS faces a number of important challenges that need to be overcome to facilitate greater access and use of 3D/4D visualization and modeling:
• Reward systems should encourage scientists to use currently available, and to research new 3D/4D technologies, tools, and media; for example by recognizing the value of innovative 3D/4D model publication outlets.
• Improved hardware and software capabilities, including immersive virtual reality rooms, need to be made more broadly available. This includes access to relatively inexpensive, open-source, multiplatform software that can be used to assemble and transform a wide diversity of data types. Access to immersive virtual reality workstations is needed to allow scientists to view and interact directly with their 3D/4D data. Hardware costs have dropped substantially over the past few years making these workstations affordable. Advancements in software that analyze and model 3D/4D geoscience data are not mainstream for our scientists and are a key missing step in the scientific discovery process. 3D data need to be analyzed and cross-validated in a 3D environment. Research and commercial software are available to view and manipulate 3D point clouds, and increasing functionality is being developed.
• To make best use of hardware and software resources, training must be provided to facilitate their introduction to scientists who have never used the available tools. Training can also be used to help scientists use 3D/4D tools for specific scientific projects and for improved communication with stakeholders and the public.
• Standards for data formats, procedures, and products need to be broadly adopted. These standards should provide robust descriptions and documentation on the source data used, the transformation and interpolation/extrapolation processes applied, and the final products developed. There is an especially strong need for standardization in data formats. These standards would greatly facilitate access by the geoscience community to source data and interpretations, both in current research and for unanticipated purposes for future research. The systematic nature of 2D studies, for example in geologic mapping over the past century, has produced a large body of information that is readily available for reuse in new studies. 3D/4D modeling and science in general, would greatly benefit from a large, ever-growing collection of subsurface information that could be used, and reused, to generate new studies. This implicitly requires that data repositories be available and managed.

6. REFERENCES