Benefits of Automation in Hydrostratigraphic Framework Modeling – 1
A New HFM for Pahute Mesa, Nevada

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ABSTRACT

A new hydrostratigraphic framework model (HFM) has been developed for the Pahute Mesa region of the Nevada National Security Site. The model encompasses an area of more than 2,700 km2 to a depth of more than 9 km. It includes 53 hydrostratigraphic units, 33 normal faults, 11 transverse faults, 2 detachment faults, 1 thrust fault, and 7 calderas. The model uses structural surface and isochore grids to achieve appropriate unit balance across all faults. An iterative development process was created to foster rapid model construction, and error checking and correction at all borehole and outcrop data points. The model matches 98% of 4,633 thickness values and 94% of 1,066 structural surface values where more than 50% of the errors are attributable to conflicting data and the model resolution. All development, output, and QA procedures were automated allowing the model to be readily revised for new data and modified or alternative interpretations. The new HFM will improve groundwater flow and contaminant transport modeling efforts both because it incorporates the most up-to-date data and interpretations, and because any aspect of the model framework can be revised as part of the calibration process in a reasonable timeframe and with transparent quality assurance.

INTRODUCTION

The Environmental Restoration Division of the U.S. Department of Energy (DOE) National Nuclear Security Administration, Nevada Field Office (NNSA/NFO) initiated the Underground Test Area (UGTA) Project to investigate the extent of contamination of the groundwater at the Nevada National Security Site (NNSS) and surrounding areas due to past underground nuclear testing. The UGTA investigation focuses on the geology and hydrology of the NNSS to determine how contaminants are transported by groundwater flow. A regional three-dimensional (3-D) computer groundwater model has already been developed to identify any immediate risk and to provide a basis for developing more detailed models of specific NNSS test areas, which have been designated as individual Corrective Action Units or CAUs (Figure 1). The regional model constituted Phase I of the UGTA project. The more detailed CAU-specific groundwater-flow and contaminant-transport models will be used to determine contaminant boundaries based on the maximum extent of contaminant migration at specified regulatory limits. The results of the individual CAU groundwater models will be used to refine a monitoring network to ensure public health and safety.

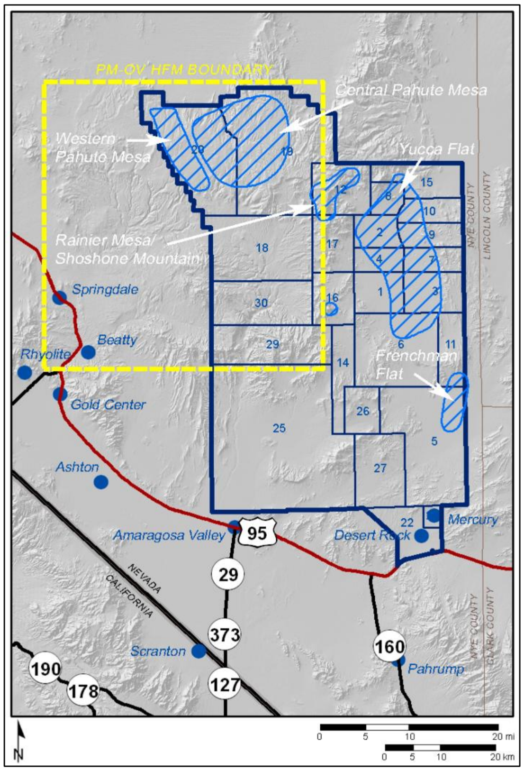

Figure 1. Boundaries of the PM-OV Phase-2 HFM relative to the Nevada National Security Site (NNSS) and Corrective Action Unit (CAU) boundaries, nearby roads and towns.

Hydrogeologic modelers who are developing CAU-specific groundwater-flow and contaminant transport models require a hydrostratigraphic framework that depicts the character and extent of geologic units and faults in three dimensions. The modelers will apply flow and transport algorithms to the hydrostratigraphic framework while varying parameters for the faults and the individual geologic “units” or groups of units in order to test a range of potential groundwater and contaminant scenarios. The grouping of adjacent geologic units has been done such that units with similar hydrologic properties are represented as a single hydrostratigraphic unit (HSU). The distribution and thickness of the HSUs relative to the faults throughout the 3-D volume encompassing the CAUs defines the hydrostratigraphic framework.

The fundamental purpose of the effort described in this report is to create a 3-D model of the hydrostratigraphic framework for the Central and Western Pahute Mesa CAUs (CAUs 101 and 102, respectively) that incorporates all available data and interpretations to reflect geologic reality as well as it is known, and is suitable for mathematical manipulation. Once complete, the hydrostratigraphic framework model (HFM) will be delivered to the hydrogeologic modelers and used as the basis for simulating groundwater flow and contaminant transport.

The HFM modeling is being performed by UGTA in conjunction with National Security Technologies, LLC (NSTec) where UGTA is responsible for the model construction and NSTec is responsible for the geologic interpretations used to develop the model and for verifying the veracity of the model simulations.

DATA SOURCES

The data points used to construct the Phase II HFM was derived from five sources: 1) borehole data; 2) geologic maps; 3) cross-sections exported from the Phase I HFM and verified by NSTec; 4) interpretations provided by NSTec in the form of cross-sections, thickness maps, and structural surface maps at model and area-specific scales; and 5) control points used to constrain gridding processes to conform to accepted interpretations.

MODEL CONSTRUCTION

Both the Phase-1 and Phase-2 PM-OV HFMs have been constructed with the EarthVision™ (EV) modeling software developed by Dynamic Graphics, Inc. (www.dgi.com). EV is a family of integrated software applications specifically designed to render digital 3-D framework models from a wide variety and any combination of spatially projected geologic data.

A 3-D framework model is typically constructed by creating 2-D grids describing the elevation or thickness of a series of geologic layers and the elevation of fault surfaces within the model domain. The grids are then stacked according to their stratigraphic and structural positions using a set of depositional rules to control how each unit is truncated by an overlying surface and how the unit surfaces behave across the faults.

Structural surface grids (X, Y, Elevation) are preferably constructed for units that are continuous across the model domain and for which there is sufficient data or knowledge to define fault offsets. The resulting model surfaces are termed “Reference Horizons.” Isochore grids (X, Y, Thickness) are preferably constructed for discontinuous units because the position of pinch-outs can be defined from thickness trends rather than specific interpretations, and fault offsets need not be defined if the unit thickness is believed to be preserved (balanced) across the faults. Once the isochore grids are constructed, the respective unit surfaces are established by adding or subtracting thicknesses to underlying or from overlying Reference Horizons. For this reason, the units defined by isochore grids are termed “Intermediate Horizons.”

Iterative Stacking Process

The Phase II HFM modeling approach relies heavily on the use of isochore (thickness) grids to provide a balanced and defensible geologic model. Structural surface elevations for all HSUs defined by isochore grids were established by adding (stacking) the isochore grids onto the relevant reference horizon. For example, the elevations of two units (A and B where B overlies A) defined by isochore grids above an underlying reference horizon would be derived according to equation set 1 shown below.

The primary benefit of this method is that it ensures that units will balance across faults wherever appropriate because the thickness is gridded without respect to the faults and then stacked onto reference horizons for which fault offsets have been defined. A drawback to this method is error in the simulated structural surface elevations for HSUs defined by isochore grids at partially penetrating boreholes.

Equation set 1

$$\text{Unit\_A}_{\text{Elev.}} = \text{Ref\_Horizon}_{\text{Elev.}} + \text{Unit\_A}_{\text{Thick}}$$
$$\text{Unit\_B}_{\text{Elev.}} = \text{Ref\_Horizon}_{\text{Elev}} + \text{Unit\_A}_{\text{Thick}} + \text{Unit\_B}_{\text{Thick}}$$

A partially penetrating borehole is one that does not fully penetrate the thickness between the uppermost and lowermost surfaces in the model. Within the Pahute Mesa model domain, all of the boreholes are partially penetrating. For each one, the lowest HSU penetrated is described by a contact elevation (the structural surface elevation) and a minimum thickness defined by the distance between the contact elevation and the elevation of the bottom of the borehole. Because there are fewer deep boreholes than shallow ones, the number of data points available to describe the elevation and thickness of a HSU is generally higher for units closer to the land surface.

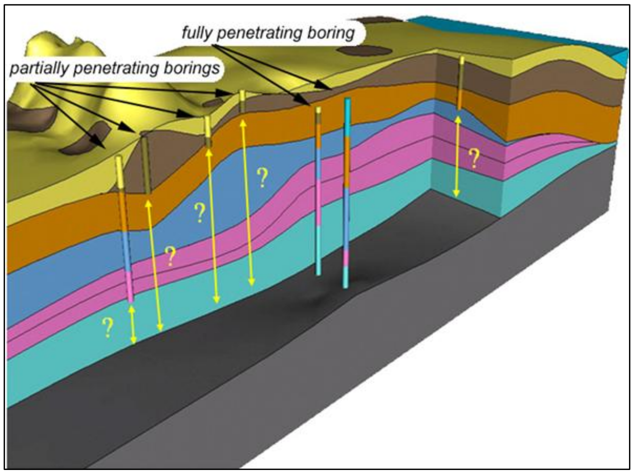

Figure 2. Hypothetical geologic model showing unconstrained unit thicknesses defined from partially penetrating boreholes that, when stacked, can result in unit elevation errors.

The error occurs at the lowest contact in partially penetrating boreholes when the stacking of underlying unconstrained surfaces and thicknesses results in a discrepancy between the simulated unit elevation and the borehole value (Figure 2). If left uncorrected, these elevation errors will be propagated up the stack as additional units are added onto the surfaces for which the errors occurred. The propagation will stop at the overlying reference horizon but the errors will be manifest in the reference horizon HSU as inaccurate thicknesses.

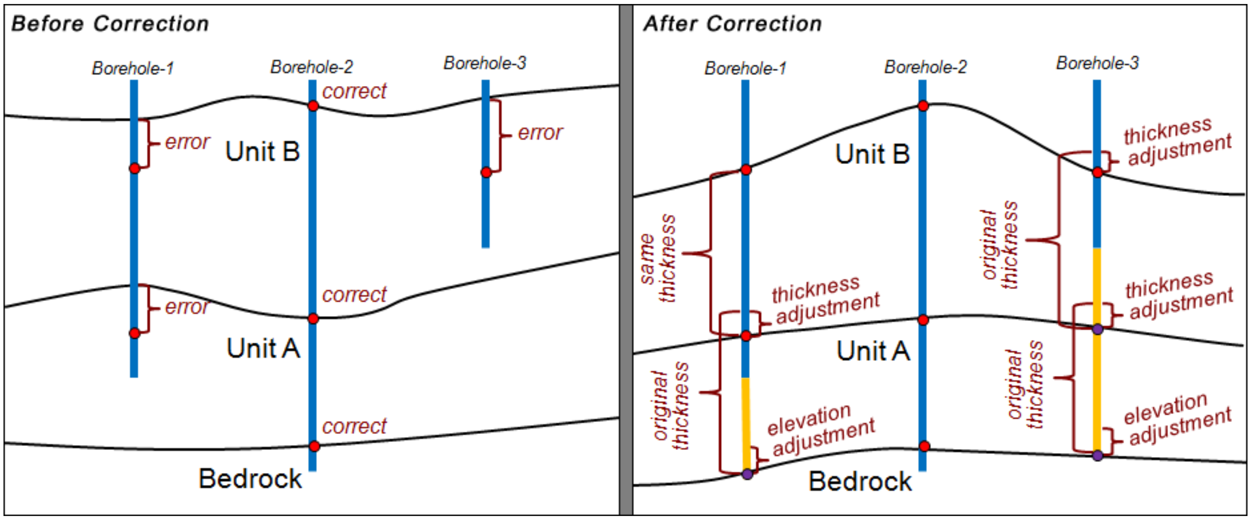

Figure 3.Illustration demonstrating the iterative stacking correction process wherein errors at partially penetrating boreholes (Before Correction) are distributed into the underlying HSU isochore and surface grids as control points according to the relative amount of real data describing the surface and thickness in each HSU (After Correction).

The typical approach to addressing these errors is to establish reference horizon dependencies such that all of the error is directed into as few units as possible and then to accept the resulting errors. The acceptance of arbitrary error in the delineation of unit thicknesses and elevations was however deemed unacceptable for the PM-OV modeling effort so a new method of correcting the errors was developed and implemented.

The process involved iteratively stacking isochore grids onto the relevant reference horizons and correcting the resulting errors at all partially penetrating borehole locations after each iteration. The stacking and correction process was repeated until the full stack of HSUs was constructed. The correction process entailed calculating the error at all partially penetrating boreholes in the respective HSU, adding control points to the isochore thickness and underlying reference horizon datasets to correct the errors, regridding, adding the next higher isochore grid, and repeating the process until the full stack of dependent isochore grids was added. The error at each point and in each progressively higher HSU was distributed into the units underlying the respective surface according to the relative percentage of fully penetrating boreholes intersecting the HSU stack. HSUs with more data points received less error (smaller corrections) than HSUs with fewer data points. Figure 3 demonstrates the beginning problem and the end result of this process.

This "iterative stacking" process was applied to correct all errors in the simulated surface elevations at partially penetrating boreholes such that the final model matches both the observed elevations and thicknesses at those locations. The same process was also applied to many of the outcrop data points where a structural surface elevation could be derived from the geologic maps. The outcrop corrections were particularly beneficial in areas that lack borehole control because the underlying units were thickened or thinned as necessary to meet the ground surface elevations while maintaining local and regional trends in thickness structural surface elevations. This level of agreement between model and data values marks a significant improvement over the Phase I model, which primarily matched only the elevations at partially penetrating boreholes.

Simulated Structural Features

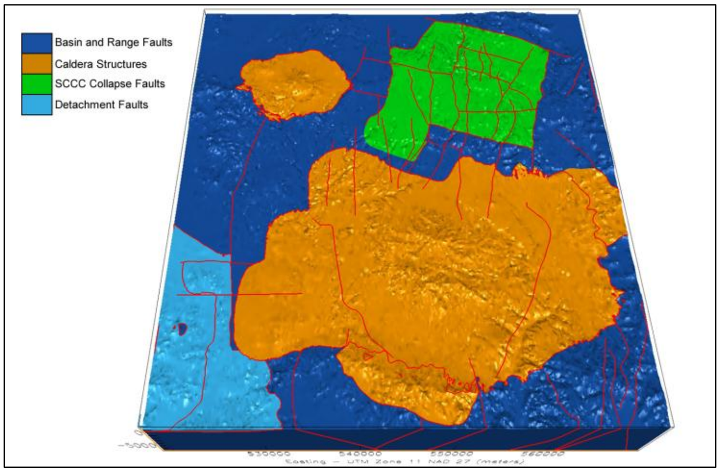

Figure 4. Location and trend of structural features simulated in the PM-OV HFM relative to the zones where four different mechanisms for structure formation are dominant.

Geologic structures are features produced in rock by earth movements. Structures define the geometric configuration of the PM-OV model area, including the distribution, thickness, and orientation of units, and thus are an important part of the hydrogeologic regime of the area. Synvolcanic structures, including caldera faults and some normal faults, had a strong influence on depositional patterns of many of the units. Some faults place units with different hydrologic properties in juxtaposition, which may have significant hydrogeologic consequences. Also, the structures may themselves act as either conduits of groundwater flow, if characterized by open fractures, or barriers to flow, if associated with fine-grained gouge or increased alteration of nearby rocks.

The beta HFM simulates five types of structural features: 1 thrust fault, 33 normal faults, 11 transverse faults/structural zones, 2 detachment faults, and 7 calderas. More generally, all of the structural features in the model can be classified by one of four mechanisms responsible for their formation: Basin and Range faulting, caldera formation, SCCC collapse, and the detachment faulting. Figure 4 shows the location and trend of the structural features in the model domain at the ground surface relative to the regions of the model in which each of the four formation mechanisms are dominant.

QUALITY CONTROL PROCEDURES

A fundamental objective of the Phase 2 HFM development process was to develop methods and tools capable of verifying the model-simulated hydrostratigraphic structure against the datasets and interpretations that it is intended to represent. This was done by directly comparing the model-simulated thickness and surface elevation values to the input data, and by generating isochore and structural surface maps for each HSU, cross-sections along the Phase 1 transects, and x, y, and z perspective slices cut at the respective node-spacing intervals, which were then assembled into interactive Adobe Flash animations. The development of all of this output was automated such that each set could be quickly regenerated and evaluated as the various model components were developed and revised.

SUMMARY

The OV-PM Phase I HFM provided a foundation for conceptualizing the structural and hydrostratigraphic framework of the model domain. Shortcomings identified in the initial effort were overcome in the Phase II HFM (Figure 5) through the application of new methods of model construction, largely based on the modeling team's application of automation to the model building, QC and output production procedures. Additionally, concepts including the use of intermediate surfaces and isochore grids were applied in order to produce stratigraphic balance across the complex structural setting and throughout the model domain. These methods and concepts are applicable to conceptual model development in many other complex geologic settings, and are easily adaptable once the problem is understood.

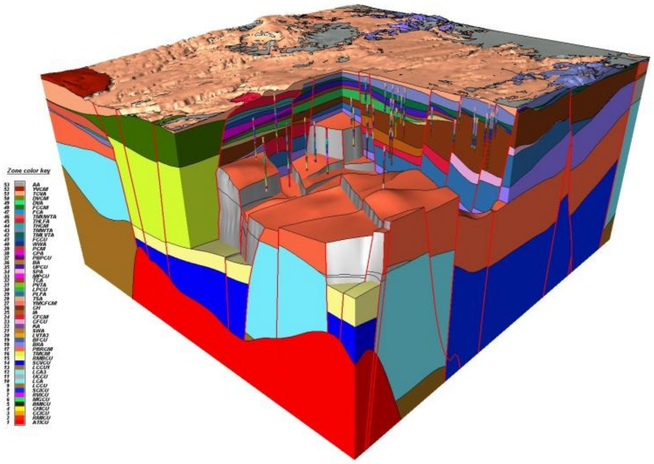

Figure 5. Pahute Mesa HFM cut to show hydrostratigraphy in the Silent Canyon Caldera Complex with supporting borehole data.

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