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THREE-DIMENSIONAL STRUCTURAL MODEL OF THE AMARGOSA DESERT, VERSION 1.0: REPORT TO ACCOMPANY MODEL TRANSFER TO THE NUCLEAR REGULATORY COMMISSION

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ABSTRACT

The three-dimensional (3D) structural model of the Amargosa Desert (Version 1.0) described in this report was developed by staff at the Center for Nuclear Waste Regulatory Analyses as the basis for analysis of groundwater flow in the vicinity of the proposed high-level radioactive waste repository at Yucca Mountain, Nevada. The model was constructed for the Nuclear Regulatory Commission using EarthVision software (Version 5.0.3) from Dynamic Graphics, Inc., of Alameda, California. The model, constructed from sparse data, provides the basic regional structural framework for abstraction into regional groundwater flow models. Version 1.0 contains fifteen faults, and six layers comprised of packaged lithostratigraphic layers. Construction of the model was based on published data, including borehole data, surface geologic maps, interpreted cross-sections, and seismic and geophysical data. The 3D model will be revised and modified as new data or interpretations are acquired, and as indicated by flow-modeling results. The 3D model identifies key uncertainties related to hydrostratigraphy and introduces new or revised interpretations of subsurface structures. This model was constructed to be used in independent reviews of the U.S. Department of Energy's (DOE) regional hydrologic flow models. Development of this model has allowed identification of uncertainties in this and in similar models used by the DOE.

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: The data used in this report are from published sources. Sources which are cited in the report should be consulted for determining the level of quality for those data.

ANALYSES AND CODES: EarthVision software (Version 5.0.3) from Dynamic Graphics, Inc. (Dynamic Graphics, Inc., 1998) was used to construct the three-dimensional structural model. This commercially available software is leased to the CNWRA and is not controlled under the Software Configuration Procedure.

1 INTRODUCTION

Yucca Mountain (YM), Nye County, Nevada, is currently being characterized by the U.S. Department of Energy (DOE) as a potential location for an underground high-level waste repository site. The Nuclear Regulatory Commission (NRC) is required to review and evaluate the DOE license application to construct and operate the proposed high-level waste repository. A key concern in evaluating the license application is whether the repository will provide effective long-term waste isolation from the accessible environment. If canister failure occurs, a likely scenario for release of radionuclides to the biosphere is that radionuclides will be transported downward by groundwater through the unsaturated zone to the saturated zone (SZ) where they will be transported laterally by the regional groundwater flow system beyond the repository footprint to potential receptors (Farrell et al., 1999; Nuclear Regulatory Commission, 1999a).

Saturated groundwater flow in the YM region occurs in four aquifer systems: an alluvial or valley fill system, a volcanic tuff system, and a lower carbonate system. However, for the purposes of repository performance assessment (PA) analyses, groundwater flow within the SZ is assumed to occur in two generalized hydrostratigraphic units, volcanic tuff and unconfined alluvium or valley fill (Mohanty and McCartin, 1998; U.S. Department of Energy, 1998). Flow within the volcanic tuff hydrostratigraphic unit occurs beneath and adjacent to YM. South of YM, groundwater flow transitions along a poorly defined boundary from the saturated volcanic tuff into unconfined alluvium. Flow in the tuff structure network predominates over flow in the tuff matrix. Within the alluvial system, matrix porosities generally are much greater than in the volcanic tuff hydrostratigraphic system, with the reverse being true for groundwater velocities. The lower velocities and increased porosities, coupled with the mineralogy of the alluvial system, generally lead to greater radionuclide sorption as compared to that in the volcanic tuff hydrostratigraphic system. As a result of the contrasting velocities and radionuclide sorption potential, the structure of the hydrostratigraphic system is of considerable importance to performance because it controls both radionuclide mass and travel times to compliance points located south of YM.

A primary control on the permeability anisotropy of stratified rocks is the difference in permeability of sequential rock layers. In nondeformed, vertically stacked rock sequences, layered inhomogeneities have little effect upon the lateral component of bulk permeability. Where layered inhomogenities are deformed or faulted, the lateral component of bulk permeability may be influenced strongly by fault zones and by the offset of layers. In faulted aquifers, such as those at YM, geologic structures exert additional controls on regional flow: (i) fault offsets alter the overall geometry of the aquifers and control aquifer communication between fault blocks (Allan, 1989); (ii) fault zones commonly form relatively impermeable barriers to cross-fault flow and permeable pathways for along-fault flow (Caine et al., 1996); (iii) relatively small fracture and fault zones may lead to permeability anisotropy within fault blocks; and (iv) fracture and fault zone conductivity and anisotropy may be influenced by the *in situ* stress field (Barton et al., 1995; Finkbeiner et al., 1997; Ferrill et al., 1995a,b; 1999a).

Owing to the region's complex geology, differing subsurface groundwater flow models have been proposed for the YM region (c.f. Farrell et al., 1999; Wittmeyer and Turner, 1995, and references therein). Many SZ flow modeling efforts have assumed homogeneous and isotropic permeability properties for aquifer strata in spite of evidence that indicates aquifer permeability is controlled strongly by fault zones and fractures (National Research Council, 1996; Ferrill et al., 1999a). For example, the DOE Total System Performance Assessment (TSPA) three-dimensional (3D) SZ flow and transport model assumed uniform permeability within hydrogeologic units. Faults were not explicitly included in the DOE TSPA 3D model, though two

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structures were represented by linear vertical features with low permeabilities (U.S. Department of Energy, 1998).

Tectonic and structural features such as fault zones exert a principal control on permeability and, therefore, groundwater flow. These effects occur over several scales of observation varying from tens of square meters to thousands of square kilometers (Nuclear Regulatory Commission, 1999b):

- At the regional scale (thousands of square kilometers), groundwater flow in the YM region flows from an area of recharge in higher altitude areas north of YM, to lower elevation areas of discharge in Amargosa Valley and ultimately the Death Valley pull-apart basin.
- At the subregional scale (tens to hundreds of square kilometers), large faults control the overall structural framework of YM and produce offset and tilting of aquifer strata and juxtapose different aquifers, allowing fluid communication between aquifers. In some cases, faults provide preferred pathways for groundwater flow.
- At the local scale (tens of square meters to several square kilometers), fault zones and fractures produce the primary aquifer permeability in many of the tuff and carbonate units. Fault and fracture permeability at the local scale can be addressed by dividing the subregion into domains represented by different permeability/conductivity tensors; some domains may represent specific fault zones or fault blocks.

Understanding of structural controls on groundwater flow can be enhanced by improving the definition of large-scale structural relationships between hydrostratigraphic units at YM and the surrounding region (Farrell et al., 1999). In an attempt to effectively abstract structure to the regional hydrostratigraphic system in PA, a 3D structural model of the Amargosa Desert was constructed.

The 3D model described in this report comprises the most current version of the structural model of the Amargosa Desert (Version 1.0) developed by staff at the Center for Nuclear Waste Regulatory Analyses as the basis for analysis of groundwater flow in the vicinity of the potential high-level radioactive waste repository at YM, Nevada. The model is a simplified 3D structural interpretation of large-scale hydrostratigraphic layers based upon available published maps and interpretive cross sections, borehole data, and seismic and geophysical data. Model stratigraphy is adapted from the SZ hydrogeologic units of Luckey et al. (1996).The model provides a structural framework of the regional hydrostratigraphy at YM. The model was constructed using EarthVision software (Version 5.0.3) from Dynamic Graphics, Inc. (Dynamic Graphics, Inc., 1998), and is being supplied with this report on 8-mm tape and compact disk. Transfer of the model in electronic format will make it possible for visualization of the model on hardware located in NRC offices at Two White Flint North, Rockville, Maryland. This report provides a concise description of the model.

2 DESCRIPTION

Boundaries of the 3D structural model of the Amargosa Desert, types of data used in development of the model, and characteristics of the model are discussed in this section.

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2.1 MODEL BOUNDARIES

Boundaries of the volume represented in the 3D structural model of the Amargosa Desert were selected to encompass a range of inferred groundwater flow directions (c.f. Czarnecki et al., 1997; Nuclear Regulatory Commission, 1999a). The 3D model includes the proposed repository block, portions of Crater Flat, and the Amargosa Desert (figure 2-1). The upper boundary is the topographic surface, and the model extends at depth to an elevation of −6,000 m [below mean sea level (msl)].

2.2 DATA AND MODEL CHARACTERISTICS

Version 1.0 of the 3D structural model of the Amargosa Desert that accompanies this report was constructed using data from the sources indicated in the following sections. Characteristics of the model were determined from the data incorporated into the model, and can be expected to change with the inclusion of additional data. An illustration of the model is shown in figure 2-2. Model coordinates are in Universal Transverse Mercator, Zone 11, NAD 83.

As the primary purpose of the 3D structural model of the Amargosa Desert is to evaluate the framework for regional groundwater flow models, and because the spatial extent is large (1,736 km^2), the resolution of the 3D model is optimized for export into flow models using approximately 300 by 300 m horizontally dimensional grid cells. This discretization is consistent with the proposed site-scale model.

2.2.1 Topography

The model upper (topographic) surface is constrained by U.S. Geological Survey 3 arc-second digital elevation data in Digital Elevation Model (DEM) format.

2.2.2 Stratigraphy

Lithostratigraphic units in the YM region are packaged in the model layers to correlate with hydrogeologic units selected from Luckey et al. (1996). SZ stratigraphy at YM as defined by Luckey et al. (1996) does not include Pah Canyon or younger tuffs. Younger tuffs are included in the 3D model packaged stratigraphy to include volcanic units exposed to the west. Hydrogeologic units represented in the 3D model are given brief descriptions and compared with lithostratigraphic units in DOE Geologic Framework Model Version 3.1 (GFM3.1) (U.S. Department of Energy, in preparation) in table 2-1.

2.2.3 Data

The 3D structural model of the Amargosa Desert encompasses the DOE GFM3.1 (figure 2-1). The NRC reviewed The DOE GFM3.1 and found it to be an adequate representation of the structural framework of YM (Nuclear Regulatory Commission, 1999b). To facilitate near-seamless integration of hydrogeologic models based upon the DOE GFM3.1, horizon data exported from the GFM3.1 were used, where practical, to model layers in the 3D structural model of the Amargosa Desert.

Borehole data used in construction of the model include borehole intercepts accompanying the DOE GFM3.1, Plume and La Camera (1996), Carr (1982), Carr and Parrish (1985), Carr et al. (1995), and the Nye County Early Warning Drilling Program (Nye County, 1999). Most borehole data are concentrated in the

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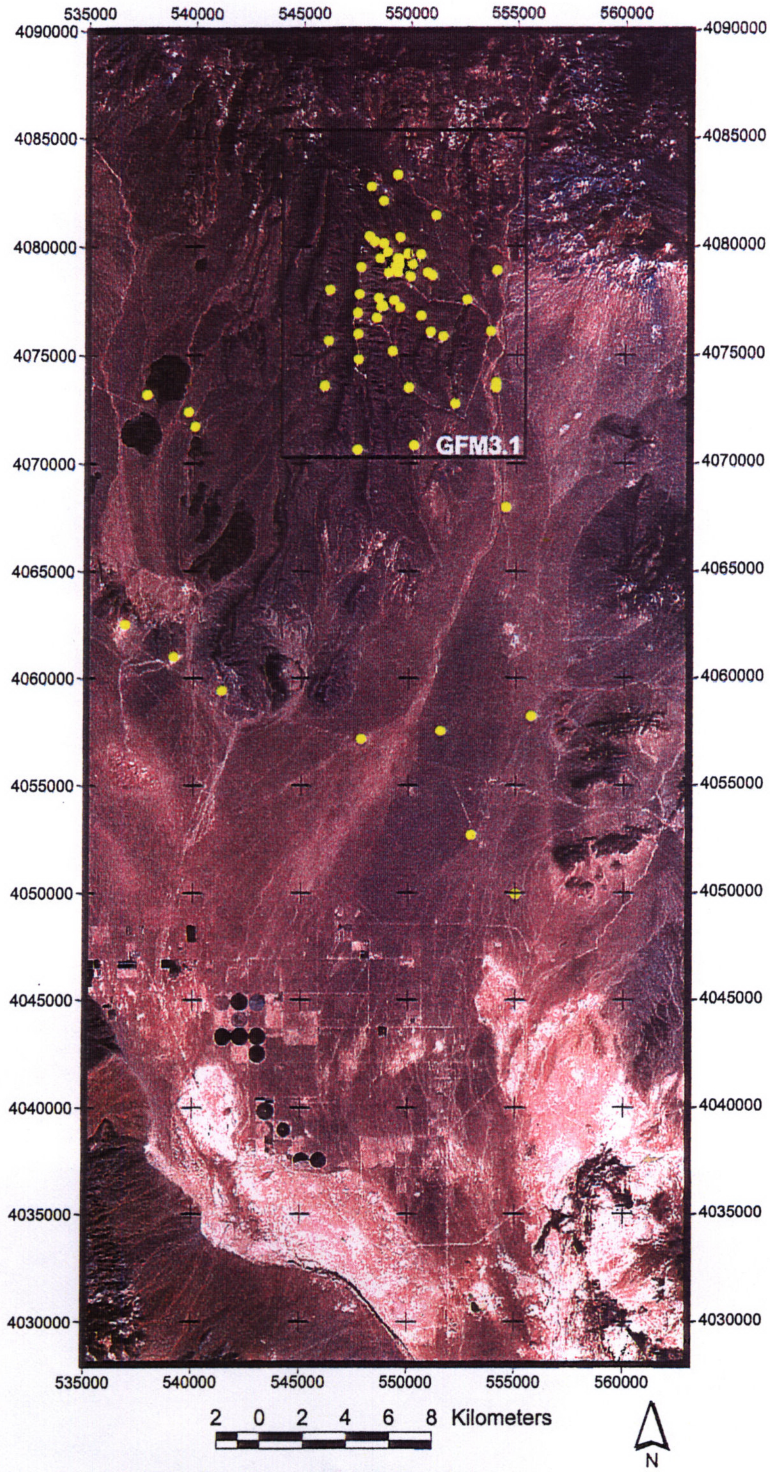

Figure 2-1. Thematic Mapper scene showing spatial extent of the three-dimensional structural model of the Amargosa Desert and locations of boreholes (yellow circles) used for subsurface control. Aerial extent of the U.S. Department of Energy's Geologic Framework Model 3.1 shown for reference (black outline in top half of view). Projection is Universal Transverse Mercator in meters, NAD83.

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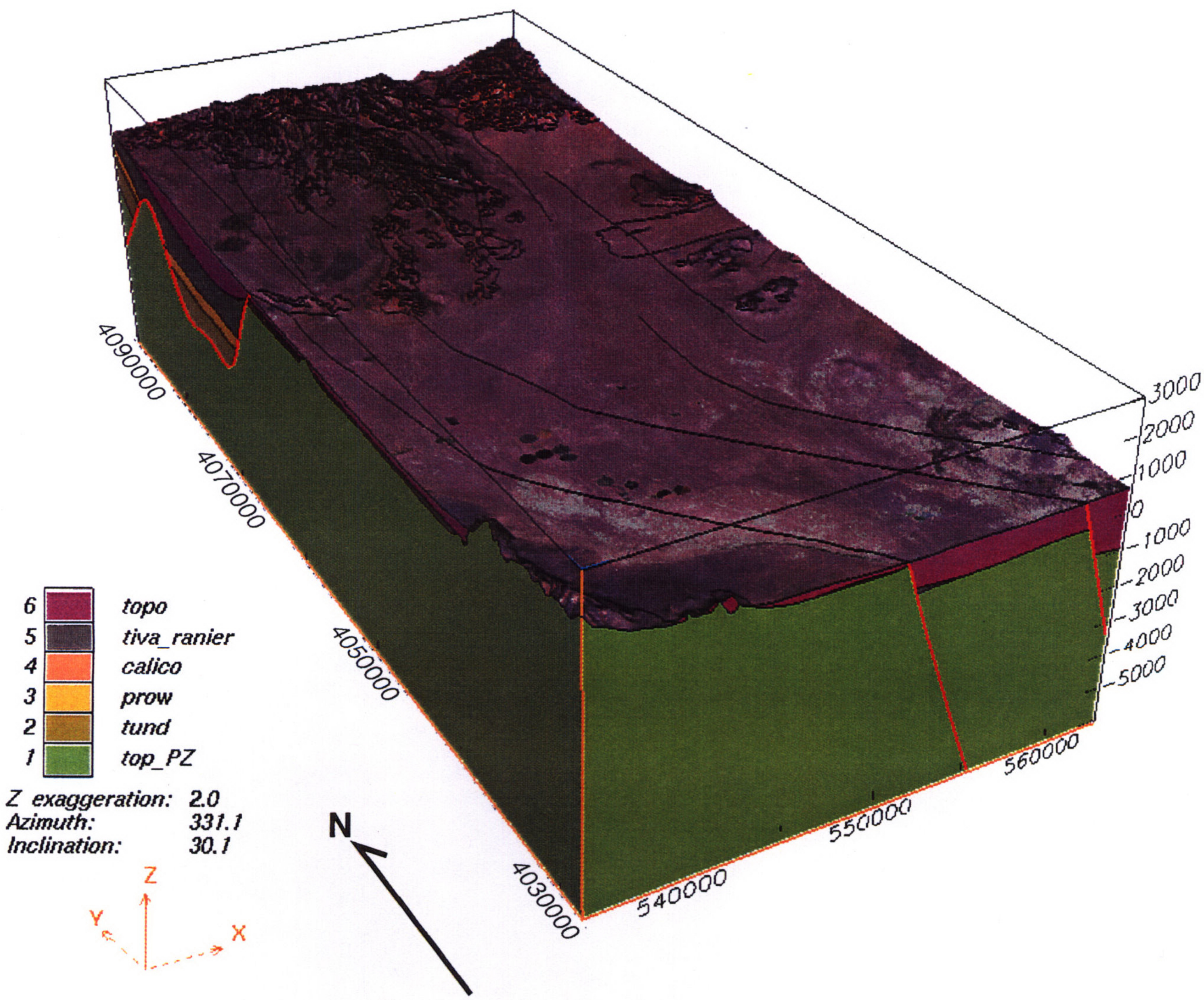

Figure 2-2. Oblique view of the three-dimensional structural model of the Amargosa Desert with Thematic Mapper scene draped over topography. View direction is to the northeast.

Table 2-1. Model stratigraphy

Model Layer	Description Relative to GFM3.1 Lithostratigraphy	Lithologic Units
topo	layer topo encompasses alluvium, colluvium, localized basalts, and lacustrine deposits, and extends at depth to the top of Tiva Canyon-Ranier Mesa volcanic units	alluvium
tiva	Top: top of Tiva-Ranier Base: top of Calico	Timber Mtn and Paintbrush Group
calico	Top: top of Calico Base: top of Prowuv	Calico Formation
prow	Top: top of Prowuv Base: top of Tund (tertiary units, undefined)	Crater Flat Group
tund	Top: top of Tund Base: top of Paleozoic (undifferentiated)	Lithic Ridge and older tuffs
top_PZ	Top: top of Paleozoic (undifferentiated) Base: −6000 m below mean sea level.	Paleozoic age rocks

northern half of the model (figure 2-1), and vertical control of subcrop decreases abruptly with distance from the YM site.

Published geologic maps, including interpretative cross sections, where available, were used to constrain outcrop and subcrop of model layers (Burchfiel, 1966; Sargent et al., 1970; Swadley, 1983; Maldonado, 1985; Swadley and Carr, 1987; Swadley and Parrish, 1988; Swadley and Huckins, 1989; Frizzell and Shulters, 1990; Monsen et al., 1992; Young et al., 1992a; Wright and Troxel, 1993; Faulds et al., 1994; Simonds et al., 1995; Day et al., 1998; U.S. Department of Energy, 1997).

Seismic data and interpretations, where available, were used to constrain subcrop, faulting, and subsurface geometries (Young et al., 1992b; Brocher et al., 1993, Brocher et al., 1998). Potential field geophysical data were used where available to constrain subcrop and buried faults in the model (Healey and Miller, 1971; Snyder and Carr, 1982; Snyder and Carr, 1984; Oliver and Fox, 1993; Ponce and Oliver, 1995; Langenheim and Ponce, 1995; Brocher et al., 1998).

2.2.4 Faults

Sixteen large-scale faults are represented in the 3D model (figure 2-3). Owing to the scale of the 3D structural model of the Amargosa Desert, only major faults were selected for construction of version 1.0. Faults with extensive outcrop or interpreted subcrop tracelengths and vertical offset were selected from published data (Piety, 1995; McKague et al., 1996a,b), or interpreted from geophysical or borehole data. Model structure is simplified by combining small faults into single throughgoing surfaces and by smoothing fault traces. For example, the trace at the southern end of the Solitario Canyon fault is extended and smoothed to capture displacements on small-scale faults. Although smaller scale faults are not included in

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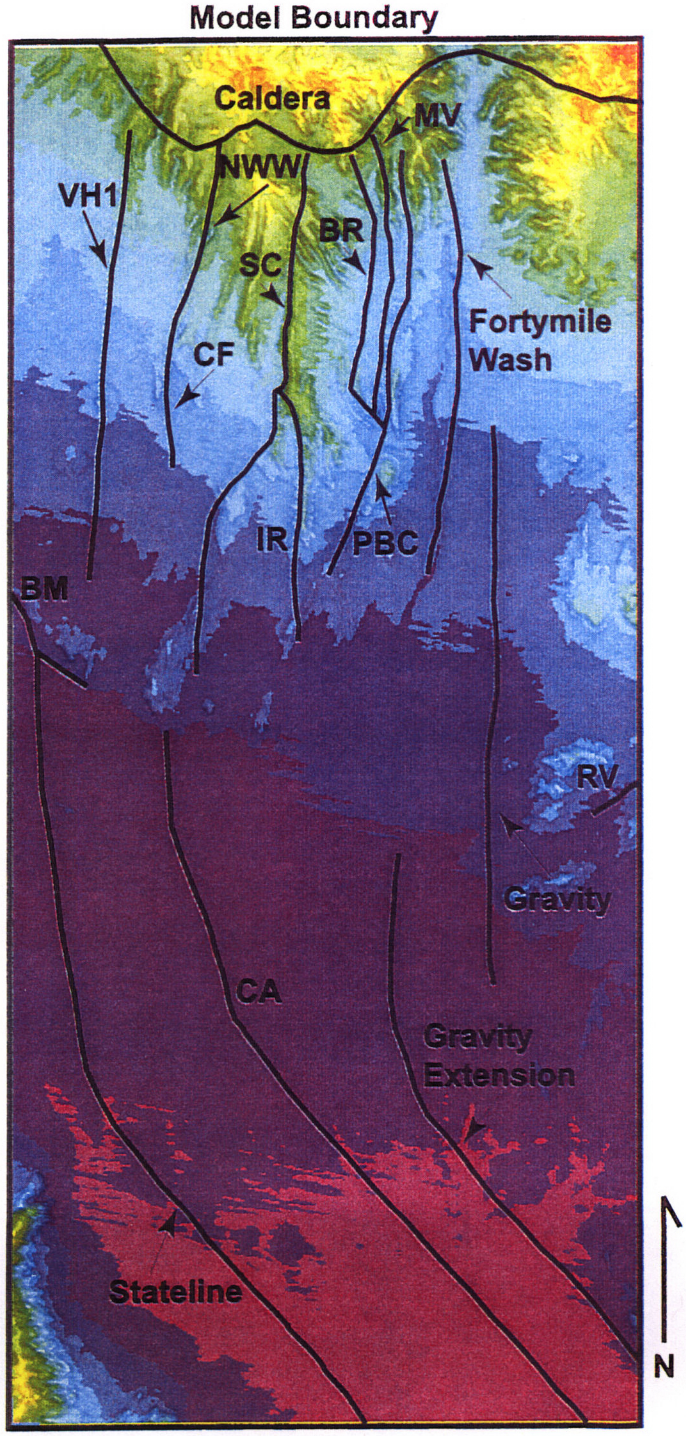

Figure 2-3. Schematic map of fault traces included in the three-dimensional structural model of the Amargosa Desert. SC—Solitario Canyon fault, PBC—Paintbrush Canyon fault, VH1—VH-1 fault, IR—Iron Ridge fault, MV—Midway Valley fault, CF-NWW—combined Crater Flat and Northern Windy Wash faults, RV—Rock Valley fault, BR—Bow Ridge fault, BM—Bare Mountain fault, and CA—Central Amargosa fault. Outline area, same as shown in figure 2-1, shows model boundaries. Color-contoured topography shows banding artifacts from Digital Elevation Model.

the model, layer morphology induced by subregional-scale faulting is modeled as irregularities in layer surfaces so that borehole-layer intercepts are honored.

3 DISCUSSION

The Amargosa Desert is located in the Central Basin and Range physiographic province. The northern portion of the 3D structural model of the Amargosa Desert includes the YM site, an extensional or trans-tensional half-graben bounded to the west by the east-dipping Bare Mountain fault and to the east by a series of west-dipping antithetic faults in volcanic rocks in the hanging wall of the Bare Mountain fault. The southern portion of the 3D model is interpreted as a similar graben or half-graben extensional system, with undifferentiated alluvial and lacustrine (playa) basin fill.

Construction of the 3D structural model of the Amargosa Desert resulted in the identification of newly interpreted structures, the reinterpretation of previously postulated structures, and most importantly, the identification of key uncertainties in the structural and related hydrogeologic framework of the Amargosa Desert.

3.1 FORTYMILE WASH FAULT

The 3D model includes an interpretation of the Fortymile Wash fault as first proposed by Young et al. (1992a), and later incorporated into the DOE GFM3.1 (figure 3-1). The fault extends north-south in the vicinity of Fortymile Wash, and is interpreted as a west-dipping normal fault (Ferrill et al., 1996).

3.2 BASIN-BOUNDING FAULTS

The Gravity fault (figure 2-3), a north-south trending fault along the western margin of the Striped Hills and Little Skull Mountain interpreted from steep gravity gradients (Winograd and Thordarson, 1975), is included in the 3D model. Examination of seismic line AV-1 (Young et al., 1992; Brocher et al., 1993), and borehole data from the Felderhoff Federal Wells (Carr et al., 1995) indicate that the southern tip of the Gravity fault is part of a relay structure that transfers displacement from the Gravity fault westward to the Gravity Extension fault (figures 2-3 and 3-1). The interpretation shown in the 3D model is that of a relay ramp between overlapping *en echelon* fault segments (see Ferrill et al., 1999b). The interpretation does not indicate that the ramp is breached. However, if the relay system as interpreted is correct, the two segments may be linked. This implies that a fault system of heretofore unrecognized magnitude exists within 100 km of YM.

The Gravity Extension fault is interpreted in the 3D model as the master fault in a graben system that defines the Amargosa Desert south of Fortymile Wash and Highway 95. Gravity profiles (Healey and Miller, 1971) indicate at least two large faults to the west of, and subparallel with, the southern extension of the Gravity fault (figure 2-3). These faults are interpreted as basin-bounding faults in the 3D model (figure 3-1). The westernmost fault, labeled stateline in the 3D model, interpreted as extending northward to Highway 95 at the mapped southern terminus of the Bare Mountain fault, indicates that the westernmost basin-bounding and Bare Mountain faults are possibly linked into a single system. Fault scaling relationships applied to the Bare Mountain fault indicates that the mapped trace of the Bare Mountain fault under-represents the trace length predicted by the Bare Mountain displacement profile (McKague et al., 1996b). If the westernmost

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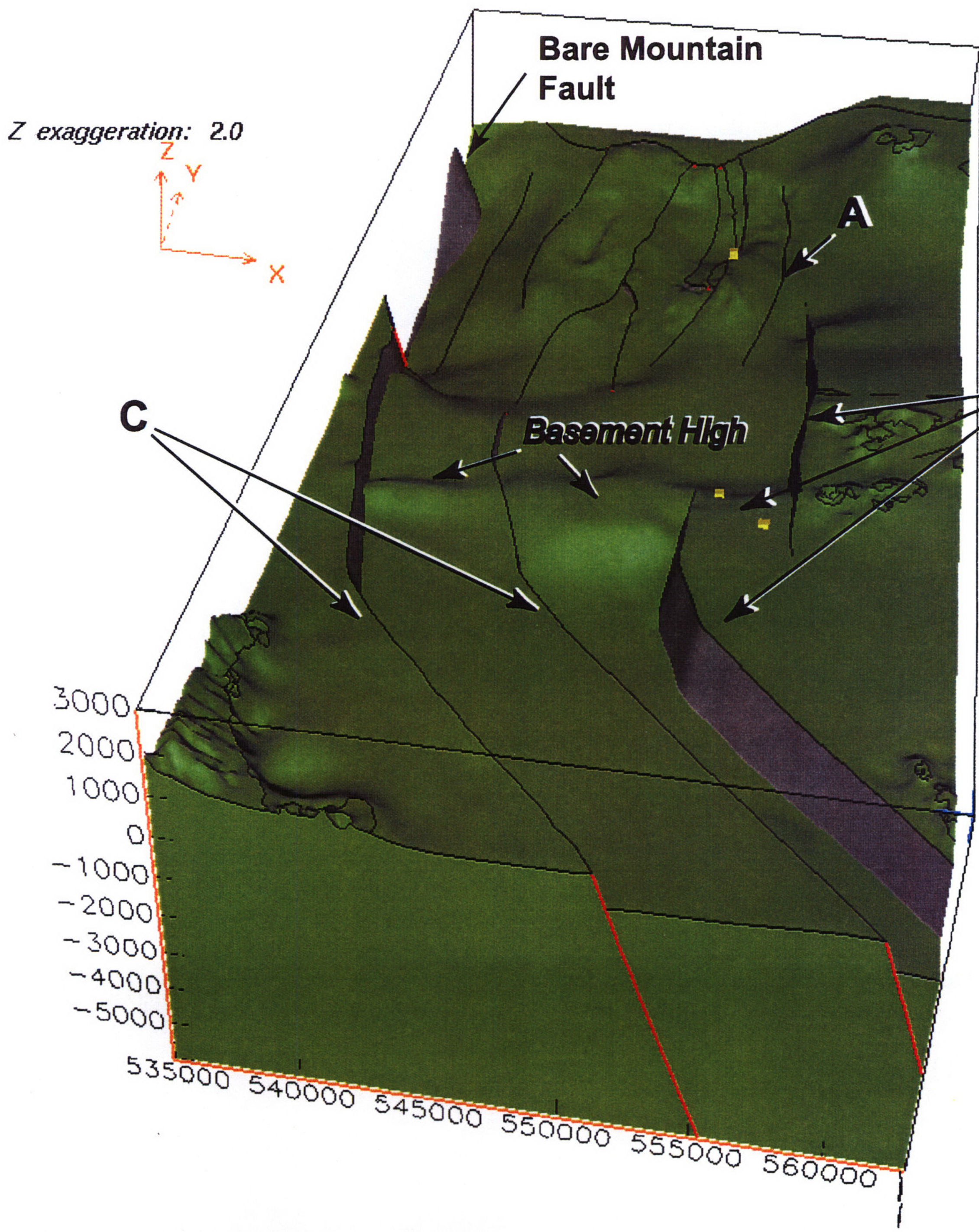

Figure 3-1. Oblique view of three-dimensional model surface showing top of basement (top_PZ). A—Fortymile Wash fault. B—Gravity fault and relay system linking the gravity fault to the southern segment. Felderhoff Federal Wells borehole intercepts (yellow cubes) shown on relay ramp structure between overlapping *en echelon* faults. C—Westward basin-bounding faults in southern Amargosa Desert. Basement high labelled in central portion of block. View direction is north-northwest.

interpreted basin-bounding fault is linked with the Bare Mountain fault, the uncertainty of the seismic hazard associated with the Bare Mountain fault may be greatly underestimated. Methods for reducing this uncertainty for seismic hazard assessment include the acquisition of new borehole data, the acquisition of additional geophysical data, and careful modeling of the additional and existing geophysical data.

In the interpretation shown in figure 3-1, faulting controls the thickness and extent of basin-fill hydrostratigraphy in the Amargosa desert. Methods for reducing the uncertainties associated with a lack of control on basin-fill thickness and extent are the same as the methods listed above for seismic hazard associated with the Bare Mountain fault.

3.3 HORIZON GEOMETRIES

All volcanic units packaged as hydrostratigraphic layers in the 3D model are interpreted as thinning southward (figure 3-2), with only the Tund and Tiva layers extending southward of the basement (Paleozoic) high shown extending westward from the Striped Hills (figure 3-2). The basement high is interpreted as a long-strike extension of the steeply dipping-to-overturned Paleozoic layers exposed in the Striped Hills (Maldonado, 1985) and downfaulted by the basin bounding faults (figure 3-1). There are little or no data to constrain the geometry, presence, litho-stratigraphic, and associated hydrostratigraphic character of volcanic units in the southern portion of the Amargosa Desert. As these units comprise important hydrostratigraphic layers, the absence of constraining data may increase the uncertainty of the interpretation and, therefore, the uncertainty associated with flow models of the Amargosa Desert. The uncertainties could be reduced with additional borehole data or with geophysical methods, including the gathering of additional data and the careful modeling of existing and new data.

Due to the current lack of data, the 3D model does not incorporate alluvial stratigraphy. As SZ flow in the southern Amargosa is through alluvium, significant uncertainties must be associated with flow modeling in this area. This uncertainty may be reduced as drilling of the Nye County boreholes and analysis of existing boreholes continues. Hydrostratigraphy developed from borehole or other data should be incorporated into future versions of the 3D model.

Paleozoic-aged rocks in the 3D structural model of the Amargosa Desert are not differentiated. As these rocks may comprise several hydrostratigraphic units, uncertainty is introduced into flow models where there is no control upon structure in the Paleozoic aged rocks. Uncertainties can be reduced by increasing the number of boreholes that penetrate the basement sequence.

3.4 THREE-DIMENSIONAL MODEL ARTIFACTS

Version 1.0 of the structural model of the Amargosa Desert does not include all mapped faults in the YM site locality. This artificial reduction in the number of known faults induces uncertainty into flow models extracted from the 3D model. However, version 1.0 was constructed to capture the detail of major structures while maintaining a manageable data set for initial modeling investigations. Increasing the number of faults incorporated into the model is recommended for future revisions. Results from flow modeling using the 3D model will be used to plan future additions to the fault population of the 3D model.

Only a few large-scale structures (faults) are interpreted in the southern portion of the 3D model (figure 2-3). These structures are interpreted from geophysical and scant seismic and borehole data. Considering the density of the fault population at YM, it is unlikely that the structure to the south is as simple

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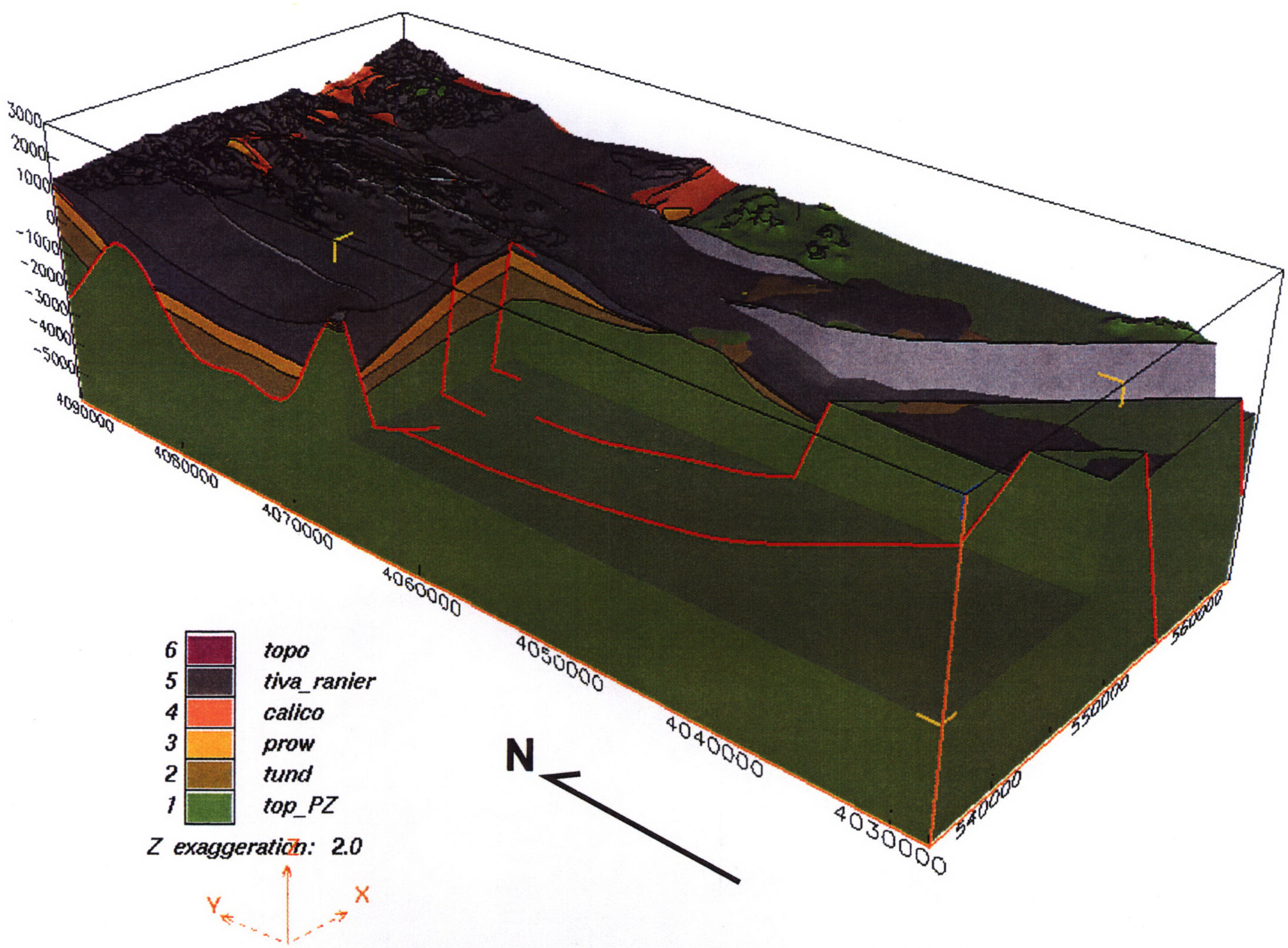

Figure 3-2. Cutaway oblique view of the three-dimensional model with alluvium (layer topo) removed and showing volcanic hydrostratigraphic model units thinning southward

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as depicted in the 3D model. The uncertainty associated with the simplified fault interpretation translates to uncertainty in flow models extracted from the 3D structural model. These uncertainties can be addressed by several methods: construction of additional boreholes, collection of additional geophysical data, careful modeling of the newly collected and existing data, or some combination of the preceding.

The northernmost reaches of the 3D model extend into caldera boundaries (Frizzell and Schulters, 1990). The caldera boundary in the 3D model is represented by the caldera fault zone (figure 2-3). This fault zone serves only to mark the caldera boundaries, and the subsurface 3D model structure within (north of) the caldera fault zone is associated with very large uncertainties.

4 RECOMMENDATIONS

The 3D structural model of the Amargosa Desert (version 1.0) will allow regional-scale flow models to be constructed with structural features that have the potential to affect groundwater flow. Fault zones in the structural model may, and should, be represented in the flow models, as well as the vertical offset of hydrostratigraphic layers. Modifications to future versions should be coordinated with the acquisition of new data or new interpretations, and in particular by feedback from regional flow models.

The fault population in the 3D model is a simplified representation of the mapped and interpreted structures in the Amargosa Desert. Future revisions should include additional faults and fault-block details. Increased fault density will decrease uncertainty in abstracted flow models by more accurately representing the structural and hydrostratigraphic geometry, and by increasing the number of fault-bounded blocks. In addition to fault-zone flow parameters, flow parameters (such as permeability tensors, c.f. Ferrill et al., 1999a) can be assigned to individual fault-bounded blocks, as required, to more closely represent the natural system.

As geologic structures control the relative transport distance in tuff versus alluvium, further effort should be concentrated upon determining the transition and distribution of groundwater flow between tuff and alluvium (Farrell et al., 1999) in Fortymile Wash. Effort should be made to increase control upon the geometry, thickness, and extent of the hydrostratigraphic units represented in the model, particularly in the areas where hydrostratigraphic structures are obscured by (and composed of) valley fill. Poor constraints on buried faults in the Fortymile Wash area and in the Amargosa Desert to the south increase uncertainties in permeability and anisotropy. Thickness and geometry of buried tuffs and of alluvial stratigraphy in these areas are very poorly constrained. Where indicated by flow modeling results, uncertainty in the 3D model can also be reduced by increasing the control upon undifferentiated hydrostratigraphic layers.

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