Influence of Faults on Groundwater Flow and Transport at Yucca Mountain, Nevada

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ABSTRACT

Numerical simulations of groundwater flow at Yucca Mountain, Nevada are used to investigate how faults influence groundwater flow pathways and regional-scale macrodispersion. The 3-D model has a unique grid block discretization that facilitates the accurate representation of the complex geologic structure present in faulted formations. Each hydrogeologic layer is discretized into a single layer of irregular and dipping grid blocks, and faults are discretized such that they are laterally continuous and varied in displacement varies along strike. In addition, the presence of altered fault zones is explicitly modeled, as appropriate. Simulations show that upward head gradients can be readily explained by the geometry of hydrogeologic layers, the variability of layer permeabilities, and the presence of permeable fault zones or faults with displacement only, not necessarily by upwelling from a deep aquifer. Large-scale macrodispersion results from the vertical and lateral diversion of flow near the contact of high- and low-permeability layers at faults, and from upward flow within high-permeability fault zones. Conversely, large-scale channeling can occur as a result of groundwater flow into areas with minimal fault displacement. Contaminants originating at the water table can flow in a direction significantly different from that of the water table gradient, and isolated zones of contaminants can occur at the water table downgradient. By conducting both 2-D and 3-D simulations, we show that the 2-D cross-sectional models traditionally used to examine flow in faulted formations may not be appropriate. In addition, the influence of a particular type of fault cannot be generalized; depending on the location where contaminants enter the saturated zone, faults may either enhance or inhibit vertical dispersion.

1. Introduction

Yucca Mountain, Nevada, is the proposed site for a nuclear-waste repository for the United States. It is underlain by a sequence of stratified volcanic rocks extensively faulted on a local and regional scale, and it is the effects of this faulted structure on the potential transport of radionuclides in the saturated zone that are deemed an important issue regarding the safety of the site [*TRW Environmental Safety Systems Incorporated*, 1998; *U.S. Nuclear Waste Technical Review Board*, 1998]. *Witherspoon* [1996] reviewed the geologic factors that 26 countries consider when choosing the location and design of high-level nuclear waste repositories. At all of the 14 sites situated in faulted terrain, faults pose a significant concern. Thus, the need to understand better the nature of groundwater flow patterns, and hence macrodispersion, that results from the presence of faults extends beyond that of Yucca Mountain.

In general, the effects of faults on groundwater flow have been studied in the context of the permeability characteristics of faults and the effects that these characteristics have on groundwater flow patterns. Most studies that used numerical methods to study the effects of faults employed 2-D cross-sectional models. For example, *Mailloux et al*. [1999] used a 2-D numerical model to assess the influence of tectonic movement and fault permeability on both paleohydrogeology and present-day hydrogeology of a faulted basin. *Wieck et al*. [1995] used a 2-D model to study the effects of fault displacement on hydrothermal fluid flow in horizontally bedded extensional tectonic basins. Other researchers have addressed the geothermal heating and convection within faults. *Forster and Smith* [1989] used a 2-D numerical model to study the influence of faults on groundwater flow and heat transfer, and on how faults control the temperatures of springs on a regional scale. *López and Smith* [1995; 1996] used a 3-D model of a dipping fault to examine the interaction of thermally driven groundwater in the fault and the surrounding country rock, which was considered homogeneous.

With regard to Yucca Mountain, *Barr et al.* [Chapter 11 of *Wilson et al*., 1994] present a 3-D saturated zone model that extends approximately 200 m below the water table. Fault offset is not explicitly modeled, as there are no lithologic changes across the offset. *Arnold and McKenna* [1998] developed a 3-D saturated zone model that extends 380 m below the water table and that is used for prediction of groundwater transport from the potential repository. Their model accounts for fault displacement between geologic units, but does not explicitly model faults. Thus, the effects of intra-unit permeability heterogeneity on transport were considered, but the fault permeability was not. *Faunt* [1997] integrated structural geologic data, crustal stress data, and fault-trace mapping to infer the effects of faults on regional groundwater flow in a 100,000 km^2 region extending from Death Valley, California, northward beyond Yucca Mountain. She showed, for example, that springs occur where large rock blocks are displaced against lower permeability rocks, suggesting that faults are flow barriers or that the fault zones have significant permeability. Other works related to the effects of faults include development of analytic solutions for steady-state and transient hydraulic head distributions in the presence of faults [*e.g.*, *Haneberg*, 1995; *Shan et al.*, 1995].

In this work, we examine the influence of faults on groundwater flow and transport using a three-dimensional groundwater flow model of Yucca Mountain, Nevada. Discretization of the model is based directly on a detailed three-dimensional geologic model of Yucca Mountain [*Clayton et al.*, 1997]. As a result, the flow model accurately represents hydrogeologic layers with variable permeabilities, thicknesses, and orientations, which are in turn displaced by permeable fault zones or faults with displacement only. Hence, the model acts as a prototype of faulted formations in general, and the features it considers have not been represented together in other studies. Three-dimensional simulations illustrate the groundwater pathways that result under different combinations of fault and layer permeabilities. These flow pathways elucidate the general spreading characteristics of potential contaminants via mechanical dispersion. Also, by performing both 2-D and 3-D simulations, we address whether 2-D cross-sectional models can adequately represent the complexity of 3-D flow in faulted groundwater basins.

2. Geology and Hydrology at Yucca Mountain

Yucca Mountain, Nevada, is located approximately 240 km (150 mi) northwest of Las Vegas (Figure 1). The region is characterized by northerly-trending and parallel normal faults that produce alternating ranges and valleys. Faults are pervasive in the area around Yucca Mountain, and they displace a sequence of volcanic strata within which distinct aquifers and aquitards are present. As a result of fault displacement, permeability contrasts at depth occur where high-permeability strata contact lower permeability strata. The water table is as much as 800 m beneath the surface because of the arid climate, and groundwater flow is generally east to southeast. Geologic and hydrologic characteristics of the basin and the different hydrogeologic units are described below.

2.1 Hydrostratigraphy

The stratigraphic section at and in the vicinity of Yucca Mountain consists of Paleozoic sedimentary and possibly igneous rocks overlain by more than 2 km of Tertiary tuffaceous rock that formed approximately 11 to 15 million years ago [*Carr et al.*, 1986; *Snyder and Carr,* 1982]. Table 1 shows the stratigraphic and hydrogeologic units at Yucca Mountain. The oldest rocks in the sequence are Cambrian undifferentiated clastic sedimentary rocks, which are in turn overlain by a sequence of Devonian to Cambrian undifferentiated carbonate rocks approximately 5 km thick. This second unit defines the Lower Carbonate Aquifer. The Eleana formation is a 2.5-kilometer-thick confining unit, and the Tippipah Limestone is approximately 1 km thick and defines the Upper Carbonate Aquifer [*Carr et al.*, 1986; *Fridrich et al.,* 1994]. This unit was penetrated by only one borehole at Yucca Mountain. The permeability was estimated to be greater than 10^{-13} m^2, based on the thickness of the tested interval and on transmissivity values reported by *Craig and Robinson* [1984].

The older tuffs of Tertiary age are present in only one borehole at the site and are at least 550 m thick [*Carr et al.*, 1986]. Most of these rocks are altered, low-permeability clays and zeolites. The older lava flows and breccias range between 0–200 m thick. Cores of the lava have little primary fracturing and are among the least permeable rocks at the site [*Fridrich et al.*, 1994]. The Lithic Ridge Tuff, 0–350 m thick, is a relatively homogeneous and nonwelded tuff with very fine-grained precipitates of clays and silica. The Lithic Ridge Tuff and the older tuffs, lavas, and breccias define the Lower Volcanic Confining Unit because of their shared low permeability. Permeabilities calculated from packer-injection tests range between 10^{-16} m^2 [*Thordarson et al.*, 1985] and 3×10^{-18} m^2 [*Rush et al.*, 1984].

The Crater Flat Group is approximately 550 m thick and consists of the Tram, Bullfrog, and Prow Pass Tuff. These units define the Lower Volcanic Aquifer and are perhaps the most significant hydrologically, since the water table is located in this aquifer over much of the area immediately downgradient from the proposed repository. Each unit is variably welded with depth and most often has a densely welded zone near the center, which is in turn surrounded by non- or partially-to-moderately welded intervals. Densely welded tuff has distinct columnar fractures and low porosity, whereas nonwelded tuff has less fracturing and larger porosity. Borehole flow surveys show that the central, fractured zones are the dominant pathways for groundwater. *Luckey et al.* [1996] report a permeability between 5×10^{-13} and 10^{-12} m^2 for the Lower Volcanic Aquifer, although these values represent a composite permeability for the aquifer. A suite of multi-well pumping tests performed at the C-Hole Complex [*Geldon*, 1993; 1996] found that the permeability of the Bullfrog Tuff is 1.4×10^{-11} m^2. A variety of pumping tests, injection tests, and borehole flow logging, either in combination or independently, yield permeability ranges for each unit in the Lower Volcanic Aquifer. The permeability of the Tram Tuff ranges between 10^{-15} m^2 and 10^{-13} m^2 [*Craig and Reed*, 1991; *Robison and Craig,* 1991; *Rush et al.*, 1984; *Thordarson et al.*, 1985], the permeability of the Bullfrog Tuff ranges between 10^{-13} m^2 and 10^{-11} m^2 [*Craig and Reed*, 1991; *Geldon*, 1996; *Luckey et al.*, 1996; *Robison and Craig*, 1991; *Rush et al.*, 1984], and the permeability of the Prow Pass Tuff ranges between 10^{-14} m^2 to 10^{-12} m^2 [*Geldon*, 1996; *Lobmeyer*, 1986; *Luckey et al.*, 1996; *Rush et al.*, 1984].

The Calico Hills Formation is approximately 30–400 m thick and is mainly nonwelded and zeolitized where it is present below the water table. It defines most of the Upper Volcanic Confining Unit. Permeabilities range between 4×10^{-14} m^2 and 2.5×10^{-15} m^2 [*Bodvarsson et al.*, 1997; *O'Brien*, 1998], although tests in an interval at the base of the unit yielded a permeability of 2×10^{-13} m^2 [*Geldon*, 1996].

The Paintbrush Group is approximately 430 m thick and consists of the Topopah Spring Tuff, Pah Canyon Tuff, Yucca Mountain Tuff, and Tiva Canyon Tuff. The Topopah Spring Tuff defines the Upper Volcanic Aquifer, which is mostly unsaturated at Yucca Mountain. It is the thickest and most laterally extensive unit within the Paintbrush Group and has the most primary and secondary fracturing. In addition, it is a relatively homogeneous unit. Results of air injection tests, model calibration, and a pumping test all yield a permeability between 1.2×10^{-12} and 8.5×10^{-13} m^2 [*Bodvarsson et al.*, 1997; *LeCain*, 1997; *Thordarson*, 1983]. The base of the Topopah Spring Tuff consists of a thin and low permeability vitric zone called the basal vitrophyre, which is part of the Upper Volcanic Confining unit.

The Pah Canyon Tuff and remaining geologic units are not present beneath the water table in the area around Yucca Mountain. They range in thickness from 15 to 180 m and have permeabilities ranging from 10^{-13} to 10^{-12} m^2 [*Bodvarsson et al.*, 1997]**.**

2.2 Structure and Faulting

Faulting began approximately 18 million years ago and ended 11.4 million years ago, after emplacement of most of the volcanic units and well after deposition of units that are now beneath the water table. Figure 2 is a fault map of the region around Yucca Mountain. *Day et al.* [1996] divide the faults into three main groups. The dominant set consists of north-trending normal faults that have steep down-to-the-west displacement over most of their length. These faults generally have vertical offsets ranging from tens to hundreds of meters and are laterally continuous for tens of kilometers. They define the boundaries of the relatively intact blocks of east-dipping volcanic strata and have therefore been termed block-bounding faults. They dip between 70° to 80°, except for the Paintbrush Canyon Fault, which dips approximately 60° [*Clayton et al.*, 1997]. The strata between the normal faults dip 5° to 10° to the east. The second fault set is composed of northwesterly striking strike-slip faults located north of the proposed repository. These faults have vertical offsets on the order of meters to tens of meters and are laterally continuous for tens of meters to a few kilometers. Intrablock faults define the third set. They are continuous on scales less than the defined fault blocks and are not connected with other faults. In addition, they probably do not persist to the water table [*Day et al.*, 1996].

Both brecciated and nonbrecciated faults are observed at the surface and in boreholes. *Dickerson and Spengler* [1994] mapped 8 km of the Paintbrush Canyon Fault scarp exposed north of Yucca Wash (north of WT #16, Figure 2). At several locations the fault is only a 1-meter-wide zone and is composed of polished planes and cemented breccia layers. Conversely, a 50-meter-wide brecciated zone is present at the Paintbrush Canyon Fault exposure west of Busted Butte (near WT #3, Figure 2) [R. Dickerson, U.S. Geological Survey, pers. comm., 1996]. A borehole flowmeter survey showed that water flowed from a fractured zone associated with this fault under ambient conditions [*Geldon*, 1993], thereby indicating that fault zones can be high-permeability features.

Clayton et al. [1997] constructed a 3-D geologic model of Yucca Mountain. Figure 3 is a horizontal slice through the model at elevation 706 m, which is approximately equal to the water table downgradient from the proposed repository. The figure is a good illustration of the complexity of the hydrogeologic structure at Yucca Mountain. An additional complexity is introduced by the permeability variation within units that results from variations in rock welding characteristics. Also, a heterogeneous permeability distribution at the water table is present because the layers dip and are faulted.

2.3 Hydraulic Gradients

Figure 4 shows the water table beneath Yucca Mountain as defined by *Bodvarsson et al*. [1996]. In general, the gradient decreases from the northwest to southeast and, in plan, the aquifer can be subdivided into zones of small, moderate, and large hydraulic gradients. The region of the moderate hydraulic gradient zone is more accurately depicted by the potentiometric-surface map of *Tucci and Burkhardt* [1995], although the general contour patterns are the same.

2.3.1 Large Hydraulic Gradient Zone

The large hydraulic gradient zone is to the north and northwest of the proposed repository, and the gradient is approximately 0.125. *Luckey et al*. [1996] reviewed the different models that have been proposed to explain the existence of this large gradient. Recent work in the unsaturated zone strongly supports the perched water model [*Ervin et al.*, 1994]. Perched water was observed in five unsaturated zone boreholes in the area of the large hydraulic gradient, and all of the perched water was encountered at the upper portion of the Upper Volcanic Confining Unit, the elevation of which coincides with the apparent water table in the large gradient zone. Also, apparent water levels in two saturated zone boreholes in that area (WT #6 and WT #16, Figure 4) are near the contact of these units. Other supporting data include pumping test results [*Craig et al.*, 1983] and neutron logging data, the latter of which shows that the units are not fully saturated immediately beneath the perched horizon [*Wu et al.*, 1996].

2.3.2 Moderate Hydraulic Gradient Zone

The moderate hydraulic gradient zone is west of the proposed repository along the Solitario Canyon Fault, across which the head drop is approximately 45 m and the gradient is 0.05. An exception is the 775-m elevation observed in borehole H-5. This elevation may result from a local hydraulic connection to the western side of the fault by a splay of the Solitario Canyon Fault, which was observed at the surface and interpolated to intersect the well [*Ervin et al.*, 1994]. The Solitario Canyon Fault may function as a barrier to flow because strata are offset by as much as 350 m, which would result in termination of the Lower Volcanic Aquifer against the Lower Volcanic Confining Unit. The fault may also function as a barrier because of low-permeability gouge. Fault gouge and siliceous infilling are present at the surface along the fault and have low matrix porosities. If the gouge persists beneath the water table, it could have lower permeability than the surrounding rock and create a moderate gradient [*Luckey et al.*, 1996]. Sub-site-scale saturated zone flow models of Yucca Mountain assume that a linear and vertically continuous low-permeability feature produces the moderate gradient [*Arnold et al.*, 1998; *Wilson et al.*, 1994; *Zyvoloski et al.*, 1997]. *Fridrich et al.* [1994] suggest that the moderate gradient could result from upwelling of water along the fault from the Upper Carbonate Aquifer.

2.3.3 Small Hydraulic Gradient Zone

A small hydraulic gradient zone extends eastward from the proposed repository. It is defined by water table elevations ranging from 731 to 728 m, and the gradient ranges from 0.0001 to 0.0003. This small gradient may be a result of flow in high-permeability rocks or to minimal flux resulting from restriction of flow from the west and northwest [*Luckey et al.*, 1996]. Potential radionuclides percolating from the potential repository will be transported in the small gradient zone.

2.3.4 Vertical Gradients

Upward flow in the Lower Volcanic Aquifer and possibly upwelling of water from the Upper Carbonate Aquifer are suggested by the presence of upward vertical hydraulic gradients. Borehole p#1 is located next to the Paintbrush Canyon Fault (Figure 2) and is the only borehole that penetrates the Upper Carbonate Aquifer, where the head is approximately 21 m greater than the water table elevation. It is unclear whether or not the Upper Carbonate Aquifer and Lower Volcanic Aquifer are hydraulically connected, however, since water levels in p#1 did not change during pumping at the nearby C-Hole Complex [*Luckey et al.*, 1996]. Large upward gradients are also present immediately east of the moderate and large gradient zones. In H-1, the head in the older unnamed tuffs is approximately 55 m greater than in the Bullfrog Tuff, and in H-3, the head difference between the upper and lower section of the borehole is approximately 24 m upward. In addition, vertical head gradients were observed in five other boreholes. The head difference between the upper and lower section of the borehole was less than 1 m, and downward gradients were observed in two boreholes. [*Luckey et al.*, 1996].

3. Numerical Model

Simulations are performed using TOUGH2 [*Pruess*, 1991a; *Pruess*, 1991b; *Pruess et al.*, 1996], a code for multidimensional coupled fluid and heat flow of multiphase, multicomponent fluid mixtures in porous and fractured media. It is based on the integral finite-difference method, which uses the mass and energy continuity equations in an integral form. Besides its capability to simulate numerous processes, it applies to regular or irregular spatial discretization in one, two, or three dimensions [*Pruess*, 1991a]. A model mesh can therefore be constructed of irregular polygons of varying geometries, which in turn provides the means to accurately represent complex geologic structures.

3.1 Mesh Discretization

A unique discretization scheme facilitates the explicit representation of stratified and faulted rocks. Figure 5 shows the 2-D horizontal mesh. The mesh covers an area of approximately 108 km^2, encompassing the location of the proposed repository and the large, moderate, and small hydraulic gradient zones. The top of the model is defined by the water table of *Bodvarsson et al.* [1997], who define the head distribution in the large gradient zone as a water table. The region of the moderate hydraulic gradient zone is more accurately depicted by the potentiometric-surface map of Tucci and Burkhardt [1995]. The top of the model in that region was therefore tailored to match their map. The lower boundary is defined by the base of the Lower Volcanic Confining Unit, and the model thickness ranges between 400 m and 1.1 km. Grid block dimensions are between 50 and 500 m, with several approaching 1 km near the model boundaries.

Only block-bounding faults are modeled explicitly because of their large displacement and lateral extent, which therefore make them the dominant fault set, as described above. The 3-D geologic model of *Clayton et al.* [1997] defines block-bounding faults as those with more than 30 m of vertical displacement and a 2-mile (3,200 m) or longer surface trace. These include the Solitario Canyon Fault, Iron Ridge Fault, Dune Wash Fault, Bow Ridge Fault, Midway Valley Fault, Paintbrush Canyon Fault, and Forty Mile Wash Fault. The model is discretized to account for these faults and four others located near the southern boundary of the model, for a total of 11 faults. Each fault is represented by a laterally continuous band of rectilinear and equal-width grid blocks. This approach properly represents the natural continuity of faults and enables modeling of a fault with no internal zone (displacement-only fault) or one that also has a fault zone (high-permeability or low-permeability fault). The location of faults in the model is based on their surface traces. The lateral dimensions of fault grid blocks do not represent the actual width of faults, but rather the width over which fault properties are averaged. Fault displacement varies along strike and is constant with depth, and faults are modeled as vertical features. The finely discretized region near the center of the model corresponds to the area around a cluster of wells used for multi-well pumping and tracer testing referred to as the C-Hole Complex [*Geldon et al.*, 1997]. Finally, the grid blocks in Figure 5 are Voronoi polyhedra [*Voronoi*, 1908], within which each interface is orthogonal to the linear bisector between adjacent grid block nodes. Aurenhammer [1991] discusses the history and application of Voronoi polyhedra.

Vertical discretization of model layers is based on the 3-D geologic model by *Clayton et al*. [1997]. That is, the elevation and isopach data that define geologic units, and the coordinates of and displacement of faults used to discretize the numerical model, are equal to those in the 3-D geologic model. The isopachs of the Lithic Ridge Tuff and lava flows and breccias are not defined in the 3-D geologic model and were therefore taken or created from other sources [*Cohen*, 1999]. Each of the 23 model layers in the flow model has the same horizontal grid block discretization as the 2-D horizontal mesh. However, each model layer has a variable thickness and orientation in accordance with the geometry of each hydrogeologic unit. A traditional finite-difference mesh oriented in the horizontal plane would require many more grid blocks to represent a dipping layer.

Model layers are subdivisions of geologic units in accordance with the observed permeability of the different layers in the volcanic tuffs. The central interval of the Prow Pass, Bullfrog, and Tram Tuff are more fractured than the surrounding intervals. Hence, these units are subdivided into 3 equal thickness layers, and permeabilities are assigned accordingly. Other geologic units are discretized into several sublayers based on similar data.

Vertical discretization of faults is achieved in a different manner. Each column along a fault consists of 46 grid blocks. The lateral interface area between two hydrogeologic layers on either side of the fault is represented accurately; the height of an individual fault grid block is equal to the vertical distance over which the adjacent layers are displaced, and the rock properties of the fault grid block correspond to the rock type on either side of the fault. Alternatively, a fault zone can be represented by setting the permeability of fault grid blocks to the measured or estimated values of fault permeability. Fault displacement varies along strike from zero to more than 300 m (Figure 6). Because of the scheme used to facilitate discretization of faults, there are 23 layers in every nonfault grid block column even though not all units are present beneath the water table everywhere. The grid blocks of hydrogeologic layers that are not beneath the water table have thicknesses ranging from 1 and 3 m, and these grid blocks are assigned the rock property of the unit present at the water table. In total, the model has 57,153 grid blocks and 199,854 connections. Figure 7a is a cross section through the flow model along A-A’, as shown in Figure 3, and Figure 7b is the same cross section through the 3-D geologic model. The layer thicknesses, fault displacements, and intersection of different units at the water table are represented explicitly. Although discrepancies between the actual geometry of the units and the numerical model do exist, in particular due to the assumption of vertical faults, the complexity of stratified and faulted formations is preserved.

In order to model the dipping layers and fault displacement, grid block connections across faults and within layers are not orthogonal to the grid block interface area. Deviations are generally less than 10 degrees.

3.2 Simulation Approach

Two-dimensional simulations are used to provide initial insight into the potential role of faults, and, by performing both 2-D and 3-D simulations, the shortcomings and validity of using 2-D simulations to model these systems can be examined. Figure 7a is the 2-D model, which is oriented approximately perpendicular to the water table contours near the center of the 3-D model. A continuous band of equal-width grid blocks along A-A' does not exist. Therefore, grid blocks closest to A-A' were chosen and the vertical and horizontal connection areas, connection distances, and grid block volumes of these grid blocks were recalculated such that they represent a 2-D model projection of A-A' onto the x-z plane.

Based on reported values, the western-most column of grid blocks is a constant head boundary of 776 m. The eastern-most column of grid blocks is a constant head boundary of 729 m, which is an interpolated value using measured heads near the eastern boundary. The top and bottom are no-flow boundaries. All simulations are steady-state and isothermal. Simulations of the effects of all fault types followed the same approach: permeabilities of hydrogeologic layers and/or faults were modified by a trial-and-error process until a “best-fit” calibration to the measured heads in boreholes H-4 and WT #14, and to the water table gradient in general, was achieved. The total flux through the model was also compared to estimated fluxes as a second calibration check.

The calibrated formation properties are nonunique. Therefore, in comparing two different fault types, a different layer permeability distribution could be used in each case. In order to examine the effects of faults only, the approach taken was to first calibrate the displacement-only faults model to define layer permeabilities and then to use these values as the initial distribution when calibrating the high- and low-permeability fault models. The permeabilities assigned to a particular hydrogeologic layer were constrained to the range of values determined from hydrologic tests (Table 1), and the permeabilities of faults were varied to consider a range of possible values. In addition, the central layer of the Prow Pass, Bullfrog, and Tram Tuff was assigned a permeability approximately ten times greater than in the surrounding layers in order to represent the more fractured central intervals observed in the field [*Luckey et al.*, 1996].

Pumping tests at the C-Holes suggest that the high permeability layers of the Crater Flat Tuff are continuous at least to a scale of several kilometers, since drawdown transients in five boreholes located as far as 3.5 km from the C-Holes yielded transmissivities with the same order of magnitude [*Geldon et al.*, 1997]. This finding suggests that assignment of a uniform permeability to these layers may be reasonable, at least on that scale. As an approximation, the remaining hydrogeologic layers were also assigned a uniform permeability, although the measured value used may not be representative of a similar spatial scale.

Simulation of a passive tracer using the EOS7 module for TOUGH2 [*Pruess*, 1991b] illustrates the flow pathways for different fault models. The tracer distribution results from advection and numerical dispersion only and is not used to simulate solute transport. Rather, it is used as a visualization tool and is therefore referred to as a "flow visualization tracer" in this work. It is used to infer flow pathways and the implied macrodispersion resulting from the flow heterogeneity. For a particular simulation, a constant tracer mass fraction (X_{tracer}) of 1.0 is specified at several gridblocks. The eastern column of grid blocks is both a constant head and zero tracer mass fraction boundary, so the lateral extent of the tracer is only an apparent travel distance. Furthermore, this boundary does not affect the tracer distribution because diffusion is not modeled. Some of the tracer spreading results from numerical dispersion. However, assuming the numerical dispersion is roughly the same for each simulation, the relative differences between different flow fields can be examined. Travel time is not evaluated, although a dimensionless time, t', is noted so that the relative difference in simulated time for different simulations is apparent.

4. 2-D Simulations

4.1 Displacement-Only Faults

Figure 8 shows the permeability distribution in the calibrated 2-D displacement-only faults model. The Prow Pass, Bullfrog, and Tram Tuff each have the characteristic higher-permeability central layer as observed in the field [*Luckey et al.*, 1996], and the permeability assigned to each layer is within the range of reported values. Figure 9 shows the steady-state head distribution and the tracer path of waters that percolate vertically downward from the potential repository into the Lower Volcanic Aquifer. Head contours are spaced at 0.5 m intervals in the small hydraulic gradient zone and at 5 m intervals across the Solitario Canyon Fault. In addition, the hydraulic head at borehole H-4 and WT #14 is shown. The residual head in borehole H-4 and WT #14 is +0.033 and +0.139 m, respectively, where residual head is the actual head minus the simulated head. The simulated gradient east of Solitario Canyon Fault is approximately 0.0002, which is within the observed range of 0.0001 to 0.0003 [*Luckey et al.*, 1996], and the simulated specific discharge is 0.55 m yr^{-1}, also of the same order as estimates provided by the Saturated Zone Expert Elicitation Project [*Geomatrix Consultants Incorporated*, 1997]. In addition, the simulated head drop across the Solitario Canyon Fault is approximately 45 meters, as observed in the field. Thus, a relatively large gradient across a fault can result from fault displacement only, not necessarily because of a low-permeability fault zone, as postulated by others. In this case, the fault displacement could be the cause of the small hydraulic gradient zone.

The actual hydraulic head in the Lithic Ridge Tuff in borehole H-4 is 15 cm greater than the water table elevation, and the resulting vertical gradient is one of several hypothesized to indicate vertical upwelling from the Upper Carbonate Aquifer [*Fridrich et al.*, 1994; *Luckey et al.*, 1996]. The simulated head in the Lithic Ridge Tuff in borehole H-4 is 40 cm greater than the water table elevation, which is of the same order as the observed difference. In addition, upward vertical head gradients are predicted over most of the model. Thus, upwelling from the Upper Carbonate Aquifer is not necessarily the cause of the observed upward gradients, at least not those with a magnitude similar to that in H-4. Rather, these gradients result from the relative position of higher and lower permeability units and the geometry of the formations. In this case, the higher-permeability Crater Flat Group overlies the Lower Volcanic Confining Unit. In general, measurements of upward vertical gradients in an aquifer suggest that infiltrating water would remain near the water table. Interestingly, the tracer movement shows that the abutment of higher-permeability units against lower-permeability units at faults causes water to flow upwards and then back into the higher permeability layers displaced on the eastern sides of the faults, as shown at the Midway Valley and Paintbrush Canyon Fault, for example. Hence, although the source water originates at the water table and upward gradients are present throughout, a contaminant would mostly remain within relatively thin high-permeability layers more than 200 m beneath the water table, and vertical dispersion would be inhibited. In contrast, downward head gradients are located near the Forty Mile Wash Fault. Here, water flows downward near the fault because the high-permeability layers on the east side are lower than the same units on the west side of the fault. Therefore, the vertical flow direction is a function of the direction of water table gradient, direction of fault dip, and the relative displacement of high- and low-permeability layers.

4.2 High-Permeability Faults

Given that at least some of the faults contain fractured zones that suggest high permeability, it is of interest to examine this alternative. To calibrate a model with high-permeability faults, we assumed the layer permeabilities used in the displacement-only faults model and the fault permeabilities were adjusted. However, the simulations showed that a simple high-permeability faults model is not feasible. In fact, a number of calibration adjustments were required. A high permeability (10^{-12} m^2) was assigned to the pre-Tram Tuff bedded tuff. This layer has a thickness between 10 and 50 meters over the cross section, and the high permeability assignment is one of several possible configurations, as borehole flow measurements in three boreholes showed that a significant fraction of pumped water originated from this layer [*Cohen*, 1999].

The moderate gradient across the Solitario Canyon Fault could not be replicated using a high-permeability fault zone. Rather, a permeability of 5×10^{-16} m^2 enabled calibration, as did a fault zone permeability of 10^{-12} m^2 for the Dune Wash, Bow Ridge, Midway Valley, and Paintbrush Canyon Fault. The latter permeability agrees well with available, albeit sparse data [*Bodvarsson et al.*, 1997; *LeCain*, 1998]. The Forty Mile Wash Fault needed to be represented as a displacement-only fault to attain a reasonable fit to the observed head distribution. Figure 10 shows the head distribution and flow visualization tracer in a high-permeability fault-zone model. The residual head in boreholes H-4 and WT #14 is 0.201 and -0.045 m, respectively, and the vertical gradient at H-4 is reproduced. The simulated specific discharge is 0.57 m yr^{-1}, which is of the same order as average estimates provided by the Saturated Zone Expert Elicitation Project [*Geomatrix Consultants Incorporated*, 1997]. Thirdly, the simulated small gradient is approximately 0.0002, which is consistent with field observations.

As in the displacement-only faults model, vertical gradients are present, although the potential for fluid upwelling is much greater. The tracer distribution in general is similar to the displacement-only faults case in that water flows through the dipping and higher permeability layers of the Lower Volcanic Aquifer and then upwards at faults. However, the tracer is more vertically dispersed in comparison to the displacement-only faults case (Figure 9). This results from the high permeability of the fault zones, through which water on the west side of a fault flows upwards within the fault and into the higher-permeability layers on the east side. A tracer flowing within one layer on the western side flows upwards and into multiple layers, for example, from the Prow Pass Tuff to the Prow Pass and Bullfrog Tuff. This implies that compared to displacement-only faults, the vertical dispersion would be greater in the presence of high-permeability fault zones. Note that a high-permeability faults model using the same layer permeabilities as in the displacement-only faults model yields a similar pattern of tracer model in the upper formations.

In the presence of a high-permeability layer at depth, deep waters can upwell hundreds of meters within fault zones, as illustrated in Figure 11. In this case, the tracer source is placed west of the Solitario Canyon Fault to illustrate the full flow field. Water from the west side of this fault is channeled within the high-permeability pre-Tram Tuff bedded tuff. Some of it then flows nearly 400 m upwards within the Dune Wash Fault into the Lower Volcanic Aquifer. This illustrates that significant upwelling can occur through faults in the absence of any hydraulic connection to the Upper Carbonate Aquifer. The upward flow in faults in Figure 11 could also contribute to dilution of a contaminant plume. In fact, the simulated lateral flux within the Bullfrog Tuff increases eastward as a result of upwelling in faults.

4.3 Low-Permeability Faults

In the past, low-permeability fault models had been used to explain the cause of the large and moderate gradient [*Arnold et al.*, 1998; *Wilson et al.*, 1994; *Zyvoloski et al.*, 1997], and faults with low permeability characteristics have been observed at Yucca Mountain [*Dickerson and Spengler*, 1994]. However, the groundwater flow model could not be calibrated when a constant, low permeability was assigned to each fault zone. Modification of layer permeabilities did not significantly improve calibration. Low fault-zone permeability was defined as ranging between 10^{-17} and 10^{-14} m^2. Figure 12 shows the steady-state head distribution and flow visualization tracer for the case where all fault zones have a permeability of 10^{-14} m^2. A large gradient (~0.004) across the Bow Ridge, Midway Valley, and Paintbrush Canyon Fault results from the close proximity of the low-permeability fault zones. This gradient is approximately 20 times the observed small-gradient, illustrating the flow barrier effect of low-permeability faults. Simulations using lower permeability faults produced similar gradients. The tracer distribution illustrates some of the possible effects of low-permeability faults in general, although the model may not be applicable to Yucca Mountain. The vertically continuous low-permeability fault zone creates a barrier to flow in all of the higher permeability layers. As a result, water flowing within these layers flows upwards and downwards at a fault, as shown at the Forty Mile Wash Fault, for example. However, in a full 3-D system, water would also flow along fault strike due to the impedance, so the flow pathway shown is very likely exaggerated. Also, only constant fault properties were considered in the simulations described here, and a model with spatially varying fault permeability could possibly provide a better match to the data.

4.4 Effect of Contaminant Source Location

The influence of faults on flow paths is also a function of the location of the contaminant source. Water percolating from the potential repository could be diverted to the east because of the presence of the easterly dipping low-permeability basal vitrophyre of the

Topopah Spring Tuff. Under these conditions, the water would flow into the saturated zone where this unit intersects the water table, which is located immediately west of the Bow Ridge Fault. Figure 13 shows the resulting tracer distributions in the displacement-only and high-permeability faults model. Initially, the low-permeability basal vitrophyre of the Topopah Spring Tuff and the upper part of the underlying Calico Hills Formation restrict flow; at $t' = 1$, the tracer extends only 1.5 km to the east of the source, as compared to more than 7 km for the upgradient source cases (Figure 9 and Figure 10), in which the high-permeability Bullfrog and Prow Pass Tuff are present at the water table. In addition, the tracer remains close to the water table (Figure 13a) rather than moving downward in the Crater Flat Tuff because of the restriction to downward flow and presence of the Topopah Spring Tuff at the water table immediately downgradient from the tracer source zone. The tracer is present in the Calico Hills Formation downgradient because the base of this unit has a higher-permeability layer (Figure 8) that is close to the water table at the Midway Valley Fault and that is displaced against the Topopah Spring Tuff at the Paintbrush Canyon Fault. In addition, a downward hydraulic gradient is present near the Forty Mile Wash Fault, as described earlier.

In the high-permeability faults model (Figure 13b), water flows upwards within the fault zone, transporting the tracer from dipping layers on the west side of the faults up to the water table. As a result, the tracer remains very close to the water table several kilometers downgradient. Vertical dispersion of an analogous contaminant plume would therefore be inhibited, unlike when the source is upgradient in the high-permeability units of the Lower Volcanic Aquifer.

5. 3-D Simulations

A major limitation of using a 2-D cross section to model regional groundwater flow is that water must flow in a single plane, whereas the path of least resistance might be parallel to fault strike, for example. Thus, the degree to which upwelling and vertical dispersion may occur in a natural 2-D section may be exaggerated or underestimated.

A section of the full 3-D model was used to simulate flow downgradient from the proposed repository to examine more fully the flow fields in the small gradient zone directly beneath and east of the proposed repository. The upgradient boundary of the submodel is the 730.85-m water table contour located at the eastern side of the potential repository (Figure 14). Therefore, the fate of waters that percolate from the proposed repository can be simulated. The distance between the east and west side of the submodel is approximately 7 km. The remaining three model boundaries are constant head boundaries, with the heads defined by the potentiometric-surface map of Tucci and Burkhardt [1995]. The same layer permeabilities as in the 2-D displacement-only faults model were used in the 3-D simulations.

5.1 Displacement-Only Faults

Figure 14 shows the simulated steady-state water table for the 3-D displacement-only faults model. Contour lines are jagged because they are defined using linear interpolation of the heads at grid block nodes. The residual heads in borehole H-4 and WT #14 are -0.337 and +0.264 m, respectively, as compared to +0.033 and +0.139 m in the 2-D displacement-only faults model.

A prominent feature in Figure 14 is the relatively large hydraulic gradient at the southern portion of the Paintbrush Canyon Fault. The gradient is 0.04, which is more than ten times the observed gradient over the modeled area. It results from the 200-m–287-m fault displacement in this area (Figure 6) and the resulting absence of high-permeability layers; only several meters of the Bullfrog Tuff are present beneath the water table on the eastern side of the Paintbrush Canyon Fault, while the Prow Pass Tuff is completely absent. As a result, the Bullfrog and Prow Pass Tuff on the western side of the fault only have contact with the Tram Tuff and part of the Lower Volcanic Confining Unit. The contrast in permeability is as much as 10^5, which effectively creates a barrier to flow. Again, this illustrates that relatively large gradients can result from fault displacement alone.

Figure 15 shows the head distribution within the central layer of the Bullfrog Tuff. As indicated by the contour lines, water between the Bow Ridge and Midway Valley Fault flows to the south, whereas the water table gradients indicate more eastwardly flow

(Figure 14). Thus, the flow directions are significantly different at different elevations within the saturated zone, thereby illustrating that the water table gradient may not be a good indication of flow directions at depth.

The permeability heterogeneity introduced by the variation of fault displacement also results in large-scale flow channeling. Figure 16 shows the tracer path in the central, high-permeability layer of the Bullfrog Tuff. The tracer source is several meters below the water table in the Bullfrog Tuff, which effectively represents a source at the Bullfrog-Tuff water table contact several hundred meters to the west. East of the Midway Valley Fault the tracer path is deflected to the south because of the more than 200 meters of fault displacement (Figure 6) and the subsequent contact between high- and low-permeability layers. Interestingly, Midway Valley Fault displacement decreases southward to less than 10 meters near the junction of the Midway Valley and Paintbrush Canyon Fault (Figure 6). As a result, flow is focused through this region because the high-permeability Bullfrog Tuff is almost continuous across the fault. Further downgradient, the flow field bifurcates due to the presence of a flow barrier imparted by the large displacement at Paintbrush Canyon Fault. In this case, the scale of the effective low-permeability zone is several kilometers. With regard to contaminant transport, this flow behavior indicates that the heterogeneity imparted by the faulted structure could produce large-scale channeling and macrodispersion.

Another interesting phenomenon is the abrupt change from southward to northward flow across the Midway Valley Fault at approximately northing 230,000 m. The head distribution in the Bullfrog Tuff indicates that a northward component of the gradient on the east side of the Midway Valley Fault exists at this location (Figure 15). Again, this reveals flow phenomena that cannot be anticipated from 2-D models and water table contours. In this case, water flows northward rather than eastward.

Figure 17 shows the tracer distribution at the water table. Interestingly, upwelling caused by displacement-only faults results in the presence of repository-source fluids at localized regions near the water table downgradient from the source. For example, the locally high mass fraction near the junction of the Midway Valley and Paintbrush Canyon Fault results from the upwelling due to the large displacement along these faults. This flow pattern and the implied contaminant distribution is fundamentally different than the distribution predicted by analytic models. The concentration distribution in a 2-D horizontal flow field with a continuous point source will have a continuously decreasing concentration with distance from the source [*Bear et al.*, 1993], and a similar distribution is predicted for 2-D flow in the vertical plane [*Shan and Javandel*, 1997].

5.2 High-Permeability Faults

Figure 18 shows the simulated steady-state water table when all fault zones have a permeability of 10^{-12} m^2. The residual head in borehole H-4 and WT #14 is -0.304 and

-0.019 m, respectively, as compared to +0.201 and -0.045 m in the 2-D high-permeability faults model. Figure 19 and Figure 20 show the resulting tracer distributions. In general, water table gradients at the faults are less than those in the displacement-only faults model because the faults effectively connect high permeability layers displaced at the fault. As a result, water flows in the direction of the simulated water table and is not laterally diverted at the abutment of layers, as illustrated in Figure 19. This implies that horizontal spreading of contaminants is less in a formation with high-permeability faults, as compared to one with displacement-only faults. It also suggests that in this case a 2-D model oriented parallel to the water table gradient may indeed be sufficient to examine the flow regime, since out-of-plane flow is not significant. Figure 20 also illustrates that upwelling of fluids at faults is greater than in displacement-only faults, which is predicted by the 2-D model as well.

5.3 Low-Permeability Faults

Figure 21 shows the simulated steady-state water table when all fault zones have a permeability of 10^{-14} m^2. Both the water table gradient and head distribution in the Bullfrog Tuff indicate that water west of Bow Ridge Fault flows subparallel to the low-permeability faults, rather than across these faults as in the 2-D models. The flow barrier produced by the faults results in a lateral diversion of groundwater parallel to fault strike, and the groundwater flow follows the high-permeability layers, in this case the Bullfrog Tuff. We anticipate that in general, contaminants would appear at a water table at the contact of high permeability layers and the water table downgradient. Since the 2-D low-permeability faults model could not be calibrated, the differences between the 2-D and 3-D cannot be used to infer the shortcomings of a 2-D cross-sectional model of low-permeability faults, and the simulation results are not applicable to Yucca Mountain. However, by using the model as a prototype of faulted formations, both simulations illustrate the potential effects of low-permeability faults.

6. Summary and Discussion

A three-dimensional numerical model of groundwater flow was developed as an investigative tool to understand the influence of faults on groundwater flow patterns and regional-scale macrodispersion. The model is based on the hydrogeologic structure at Yucca Mountain, Nevada, which is composed of dipping geologic units with variable thicknesses and orientations, as well as a layered permeability distribution. Also, the site is pervasively faulted, which results in large-scale heterogeneities caused by the displacement of geologic units. Thus, the model serves as a prototype for faulted formations in general. The model presented here is unique, both in the way it is discretized and in the level of hydrogeologic detail that is represented. It is designed for use with the TOUGH2 simulation code [*Pruess*, 1991a; *Pruess et al.*, 1996], which can simulate flow in a mesh composed of irregularly shaped grid blocks. These meshes facilitate realistic representation of geologic features, which are themselves irregular. Individual hydrogeologic layers and the displacement of these layers are modeled explicitly. That is, each dipping and variable thickness hydrogeologic layer is represented by a single layer of dipping grid blocks. This discretization properly represents the lateral continuity of individual layers. Hydrogeologic layers on the opposite sides of a fault are connected by a fault grid block that has a thickness equal to the distance over which adjacent layers abut each other. The use of fault grid blocks enables representation of a fault with no internal zone (displacement-only fault) or one with a discrete width fault zone as well. The model has 23 layers and 11 faults, and fault displacement varies along strike from zero to more than 350 m.

Simulations reveal previously unrecognized effects of faults. In general, upward vertical flow can occur in the absence of any hydraulic connection to a deeper aquifer with a higher head. Both a displacement-only and high-permeability faults model had vertical gradients throughout. Yet none of these models included flow from the Upper Carbonate Aquifer, where the head is 21 m higher than in the Lower Volcanic Aquifer. Instead, the models show that upwelling can occur in the presence of any one or a combination of the following features: spatial variability of permeability and geometry within hydrogeologic layers, fault displacement, and permeable fault zones.

Water can be diverted upward at displacement-only faults when higher permeability units abut lower permeability units or permeability is relatively low in deeper units. Thus, contaminants that percolate into high-permeability layers that dip in the direction of the water table gradient will flow beneath the water table within these high-permeability layers. As a result, these contaminants could end up hundreds of meters beneath the water table downgradient even though vertical head profiles suggest upward flow throughout most the section. In general, however, the vertical flow patterns would be a function of the direction of the water table gradient, direction of fault dip, and the relative locations of high- and low-permeability layers.

High-permeability fault zones act to hydraulically connect displaced and high-permeability layers. For a hydrogeologic structure like that at Yucca Mountain, a contaminant plume flowing into a high-permeability fault zone will be channeled vertically and will then flow into high-permeability layers on the adjacent side of the fault. For example, water originating at the base of the Tram Tuff could be channeled several hundred meters upwards in the Dune Wash Fault zone and then into the Bullfrog Tuff. In addition, for contaminants that originate in the Bullfrog Tuff, the vertical dispersion downgradient is greater than that in a displacement-only faults model. However, the effects of a particular fault type cannot be generalized; vertical dispersion may be relatively large or small depending on the location where the contaminant reaches the water table. Whereas high-permeability faults cause significant vertical dispersion when the contaminants percolate into the Lower Volcanic Aquifer, vertical dispersion is inhibited if the contaminants are diverted eastward above the Upper Volcanic Confining Unit. Under this condition, contaminants will enter the water table where the top of this unit intersects the water table. Because of upwelling in faults, they will then flow near the water table if there are high-permeability fault zones. A similar behavior is observed for displacement-only faults, although the vertical dispersion is slightly larger because no direct upwelling occurs within faults.

A large-scale permeability heterogeneity results from the superposition of dipping units and fault displacement. Large-scale channeling and dispersion is caused by this heterogeneity. For example, large-scale channeling can occur in the presence of displacement-only faults. Since displacement is less in some areas than in others, groundwater from a high-permeability layer will flow subparallel to a fault where there is large displacement and hence contact between higher to lower permeability layers. It will then cross the fault where the displacement is less and the higher permeability units are continuous. The 3-D simulation of a displacement-only faults model showed that groundwater flowed for several kilometers southward and then eastward through a zone with small displacement. Large-scale dispersion can occur further downgradient due to flow bifurcation around a low-permeability zone.

The head gradient in hydrogeologic layers at depth can be significantly different from the direction of the water table gradient, indicating that the direction of contaminant flow cannot necessarily be inferred from a water table gradient. For example, whereas groundwater is forced to migrate vertically at the contact of high- and low-permeability units in a 2-D displacement-only faults model, it can instead flow subparallel to fault strike because the unit is continuous somewhere near along the fault strike. In the former, vertical dispersion is enhanced; in the latter, lateral channeling results. These contrasting results illustrate the difficulty of using 2-D models to examine these formations. In contrast, groundwater in a high-permeability faults model flows directly downgradient because of the effective continuity of high-permeability layers. This suggests that a 2-D model is sufficient to simulate flow in a formation where the fault permeability is high relative to the formation permeability.

Analytic models cannot describe how contaminants spread on a scale equal to that of the groundwater flow model. A particularly interesting phenomenon that results from the complex structure is the presence of contaminants at isolated locations near the water table downgradient from the source, even when the source is at the water table. This behavior is due to flow along dip, upwelling of waters at faults, and lateral flow resulting from variation of fault displacement along strike, as described above. This distribution is fundamentally different from that predicted by analytic models.

The simulations presented here are not intended to predict radionuclide flow and transport at Yucca Mountain, but rather to show ranges of possible flow behavior in faulted formations in general. Since the results are in part dependent upon the permeabilities and boundary conditions imposed, the conclusions reached may not be applicable to all stratified and faulted systems. Future work, for example, could consider varying the boundary conditions such that regional flow is in different directions. Also, stochastic simulations in which layer and fault permeabilities are varied could provide insight into the full range of possible flow patterns. Nonetheless, the simulations described here have provided new insights into some of the fundamental characteristics of groundwater flow and regional-scale macrodispersion in the presence of faults using a unique three-dimensional model.

Tables

Table 1. Stratigraphic and Hydrogeologic Units at and around Yucca Mountain [*Luckey et al.*, 1996]. Permeabilities of Hydrogeologic Units are also shown.

Figures

Figure 1. Site map of Yucca Mountain, Nevada.

Figure 2. Faults at Yucca Mountain, as defined by the ISM2.0 3D Geologic Framework and Integrated Site Model of Yucca Mountain [*Clayton et al.*, 1997]. The Exploratory Studies Facility (ESF) is a tunnel in the unsaturated zone shown by the heavy line. Coordinates are Nevada State Plane coordinates. Figure courtesy of Jennifer Hinds, Lawrence Berkeley National Laboratory.

Figure 3. Horizontal slice through ISM2.0: A 3D Geologic Framework and Integrated Site Model of Yucca Mountain [*Clayton et al.*, 1997]. Top of model shown is at 706 meters above sea level. The Solitario Canyon Fault is located at A and trends north-south. Hydrogeologic units defined by *Luckey et al.* [1996].

Figure 4. Water table map at Yucca Mountain, Nevada [*Bodvarsson and Bandurraga*, 1996].

Figure 5. 2-D mesh of the groundwater flow model. Shaded region is area of the proposed repository. Dots mark boreholes in the saturated zone.

Figure 6. Fault displacement in the saturated zone model (in meters). Positive values represent down-to-the-west displacement. Negative values represent down-to-the-east displacement.

Figure 7. (a) Cross-section along A-A’ in the groundwater flow model; (b) geologic section along A-A’ through ISM2.0: A 3D Geologic Framework and Integrated Site Model of Yucca Mountain [*Clayton et al.*, 1997].

Figure 8. Permeability distribution in the 2-D displacement-only faults model. Vertical exaggeration = 4x.

Figure 9. Steady-state head distribution and flow visualization tracer at t′ = 1 in the 2-D displacement-only faults model. Vertical exaggeration = 4x.

Figure 10. Steady-state head distribution and flow visualization tracer at t′ = 1 in the high-permeability faults model. Vertical exaggeration = 4x.

Figure 11. Flow visualization tracer at t′ = 1 in the 2-D high-permeability faults model with tracer source west of Solitario Canyon Fault. Vertical exaggeration = 4x.

Figure 12. Steady-state head distribution and flow visualization tracer at t′ = 1 in the 2-D

low-permeability faults model. Vertical exaggeration = 4x.

Figure 13. (a) Flow visualization tracer at t′ = 13 in the 2-D displacement-only faults; (b) flow visualization tracer at t′ = 13 in the high-permeability faults model. Both simulations consider a tracer source at the Topopah Spring Tuff-water table contact. Vertical exaggeration = 4x.

Figure 14.   Steady-state water table in the 3-D displacement-only faults model.

Figure 15. Steady-state head distribution in the central layer of the Bullfrog Tuff in the 3-D displacement-only faults model.

Figure 16. Flow visualization tracer in the central layer of the Bullfrog Tuff in the 3-D displacement-only faults model.

Figure 17. Flow visualization tracer at the water table in the 3-D displacement-only faults model.

Figure 18. Steady-state water table in the 3-D high-permeability faults model.

Figure 19. Flow visualization tracer in the central layer of the Bullfrog Tuff in the 3-D high-permeability faults model.

Figure 20. Flow visualization tracer at the water table in the 3-D high-permeability faults model.

Figure 21. Steady-state water table in the 3-D low-permeability faults model.

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