Effects of Faulted Stratigraphy on Saturated Zone Flow Beneath Yucca Mountain, Nevada

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1 Introduction

The S[4]Z Model[1] ("sub-site-scale saturated zone") is a 3-D TOUGH2[2,3,4] model that was developed to study the saturated zone (SZ) at Yucca Mountain, Nevada, and to aid in the design and analysis of hydrologic tests. Yucca Mountain is the proposed site for a nuclear waste repository for the United States.

The model covers an area of approximately 100 km^2 around Yucca Mountain, as shown in Figure 1. The proposed repository is located in the unsaturated zone, immediately above the area of equidimensional gridblocks east of Solitario Canyon fault, which defines the crest of Yucca Mountain. The finely discretized region near the center of the domain corresponds to the area near a cluster of boreholes used for hydraulic and tracer testing[5]. This discretization facilitates simulation of tests conducted there. The hydrogeologic structure beneath the mountain is comprised of dipping geologic units of variable thickness which are offset by faults. One of the primary objectives of the S[4]Z modeling effort is to study the potential effects of the faulted structure on flow. Therefore, replication of the geologic structure in the model mesh is necessary. This paper summarizes (i) the mesh discretization used to capture the faulted geologic structure, and (ii) a model simulation that illustrates the significance of the geologic structure on SZ flow and the resulting macrodispersion.

2 Mesh Construction

A horizontal 2-D mesh of unit thickness was constructed first to define a gridblock distribution and geometry that is common to all model layers with depth. The locations of nodes are based on the location of boreholes, faults, and discretization considerations. Gridblock geometries and connection interfaces are then calculated using a numerical grid generator. Nodes in and around faults are defined such that the gridblock contact areas along strike remain constant. The lateral continuity of faults is preserved. The locations of fault gridblocks correspond to the location of their surface traces, as shown in Figure 1. Faults are represented as vertical features.

The thickness, orientation, dip, and lateral continuity of strata, and the offset along faults are defined in the ISM2.0 3-D geologic model of Yucca Mountain[6]. This model was used directly to define the vertical discretization in S[4]Z. Figure 2 shows the vertical layering in S[4]Z, and the corresponding cross-section through ISM2.0. Note the preservation of geologic unit displacement and variation in layer thickness, elevation, and intersection of different units at the water table. Every gridblock column consists of 23 model layers. The model has approximately 50,000 gridblocks for the single continuum version.

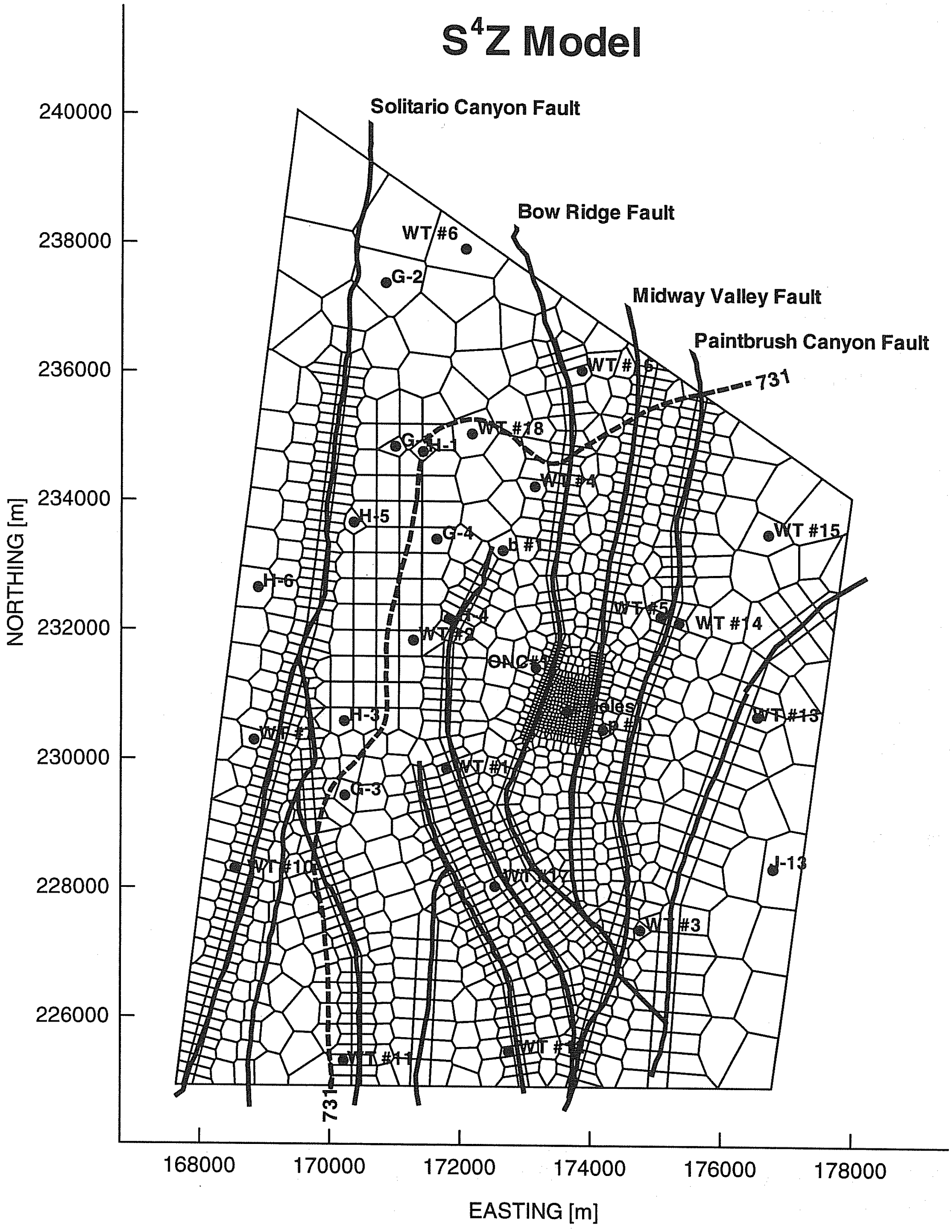
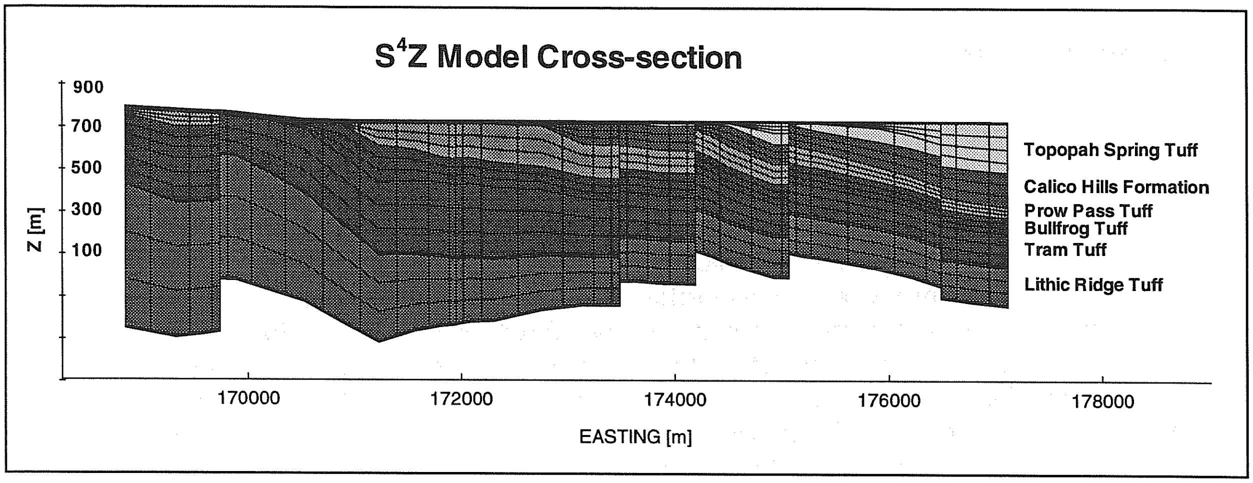


Figure 1. Numerical grid of the S^4Z Model. Dots mark location of saturated zone boreholes. Heavy lines represent fault traces. Dashed line is 731 meter water table elevation contour. Coordinates are Nevada state plane coordinates.



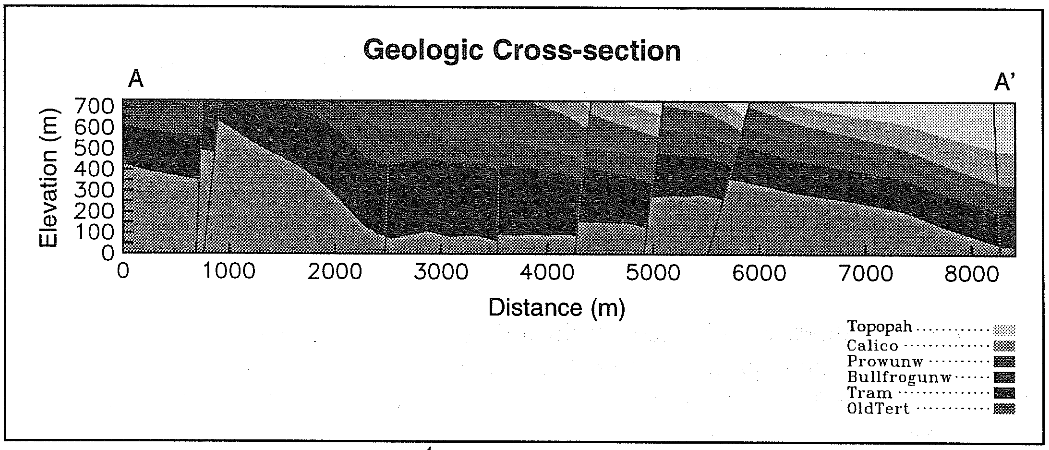


Figure 2. Cross-sections through S^4Z Model and ISM2.0 3-D Geologic Model, showing detailed geologic structure preserved by S^4Z discretization scheme.

The water table defines the top of the model, and the bottom represents the base of the Lithic Ridge Tuff, a thick confining unit[7]. Each S^4Z geologic unit is divided into three hydrogeologic layers to account for the layered permeability variation due to rock welding and associated fracture characteristics[7,8]. In order to account for the unit "pinch-outs" at the water table, the uppermost model layers in gridblock columns are assigned thicknesses between 1 and 3 m, and these gridblocks are assigned the rock property of the unit present at the water table. The distribution of units at the water table defined in the 3-D geologic model[6] is replicated.

A hydrogeologic unit or subunit is displaced at a fault and can abut against a different unit, or parts of multiple units on the adjacent fault side. This structure is accounted for by assigning lateral connections from a particular unit on one fault side to multiple units it abuts on the adjacent fault side. The proper gridblock interface areas and dips between adjacent fault layers is preserved. S^4Z fault displacement varies with strike, as observed in the field. In addition, a combined fault displacement and fault zone permeability structure can be considered by assigning a particular permeability to the fault zone blocks. High-permeability fault zones, low permeability fault zones, or faults with displacement only can be modeled, for example. The mesh generation method is similar to that used to construct an unsaturated zone model of Yucca Mountain[9], which is also based on TOUGH2. This reference describes the gridblock discretization technique in greater detail.

3 Simulation Results

The following simulation examines the effects of displacement-only faults on flow and resulting macrodispersion. These faults displace units and have no internal fault zone. The results illustrate potential fault effects in similar geologic environments, not only at Yucca Mountain. The simulation models the SZ pathway of waters that infiltrate into the Bullfrog Tuff, a high-permeability unit located at the water table directly down-gradient from the proposed repository. The infiltrating water may contain radionuclides from the repository. Only flow in the region east of the 731 m water table contour is considered, where the hydraulic gradient is approximately 0.0002[6]. A steady-state flow field is first established using constant head boundary conditions along the 731 contour, and along the eastern model side, where the head is 728.5 m. The northern and southern sides of the model east of the 731 contour are approximately perpendicular to the water table gradient. We use EOS7[10] to inject a passive tracer into the steady-state flow field. This tracer is used to observe the pathway of the infiltrating water.

Figure 3a shows the tracer distribution within the eastward-dipping Bullfrog Tuff five years after initiation of tracer injection. The black dots mark the locations of tracer injection. A high pore velocity results from the small fracture porosities used ($\sim 2\times10^{-4}$). Because steady-state fluid travel time is inversely proportional to porosity, the figure also represents the tracer plume at 50 yrs for a porosity of 2×10^{-3}, or 500 years for a porosity of 2×10^{-2}. This discussion focuses on the mechanical macrodispersion that results from the complex flow geometry, which is independent of porosity.

Figure 3a shows that both plumes are diverted southward along strike of the Bow Ridge and Midway Valley faults. These faults partially offset the Bullfrog Tuff against neighboring units that are assigned permeabilities 10^3 to 10^4 times less than the Bullfrog Tuff. This hydrogeologic structure effectively creates a lower permeability obstruction in these areas.

Figure 3b shows the plume distribution at the water table. Rather than a dispersed plume emanating from the constant source upstream, isolated areas of high concentration, up-gradient-source fluid are present. This behavior is not predicting by analytic dispersion models, and was not anticipated. The process that leads to this distribution is illustrated with simulation results of flow in a 2-D cross-section in the same area. Figure 3c shows how the plume descends within the high permeability and dipping Bullfrog Tuff. The complete abutment of the Bullfrog Tuff against lower permeability units at the Paintbrush Canyon fault causes flow bifurcation and hence vertical upwelling. Mixing and vertical hydraulic gradients result, even without a fluid source under the lower confining unit. Numerical dispersion contributes to the observed tracer distribution, but the general flow geometry is still observable. The large permeability contrast and the particular boundary conditions on the model sides contribute to the resulting macrodispersion. Sensitivity studies are being carried out to examine the range of effects under different fault and layer property distributions, and boundary conditions. Calibration to hydrologic, thermal, and geochemical data is used to constrain SZ properties and the resulting SZ flow behavior. Particle tracking is also being used to examine flow geometry in more detail.

4 Conclusions

A 3-D integral finite difference flow model called S^4Z was developed to study SZ flow beneath Yucca Mountain, Nevada. The model discretization captures the stratified and faulted structure present at Yucca Mountain, and fault offset is handled explicitly. Numerical simulations of the flow downstream from the region directly below the potential repository show that the high permeability Bullfrog Tuff may act as the primary conduit for repository source water, and because all geologic units are offset by faults, flow is diverted and bifurcated laterally and vertically downstream. This gives rise to unforeseen and complicated flow geometries that greatly contribute to mechanical macrodispersion.

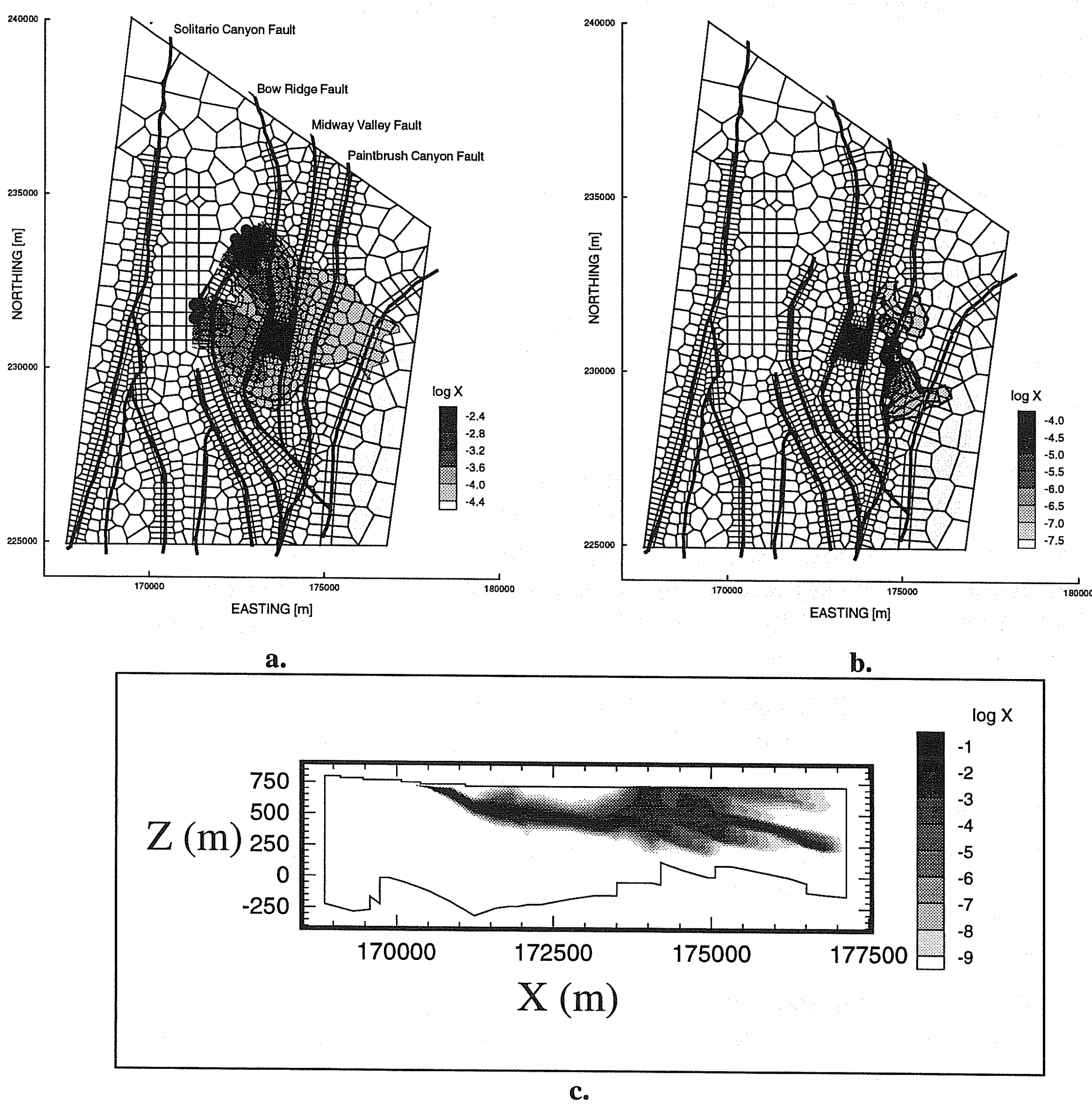


Figure 3. Log tracer mass fraction (log X) at 5 yrs ($\phi = 2x10^{-4}$), or 500 yrs ($\phi = 2x10^{-2}$): a) in the middle Bullfrog Tuff; b) at the water table; c) along west-east cross-section at latitude 232000 m. The sources of tracer are shown in Figure 3a by the black circles.

5 Acknowledgments

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