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MODELING FLOW AND TRANSPORT PATHWAYS TO THE POTENTIAL REPOSITORY HORIZON AT YUCCA MOUNTAIN

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I. INTRODUCTION

The isotopic ratios of $^{36}Cl/Cl$ are used in conjunction with geologic interpretation and numerical modeling to evaluate flow and transport pathways, processes, and model parameters in the unsaturated zone at Yucca Mountain. By synthesizing geochemical and geologic data, the numerical model results provide insight into the validity of alternative hydrologic parameter sets, flow and transport processes in and away from fault zones, and the applicability of $^{36}Cl/Cl$ ratios for evaluating alternative conceptual models.

II. HYDROGEOLOGIC SYSTEM AND THE CHEMICAL DATA BASE

Water flowing from ground surface to the potential repository block at Yucca Mountain will generally encounter alluvium, which varies in depth from 0 to 50 meters, the Tiva Canyon welded tuff (TCw), the Paintbrush nonwelded tuff (PTn), and the Topopah Spring welded tuff (TSw), respectively. Water is expected to flow readily in the pervasive fractures of the welded tuff. However, the role of the nonwelded PTn on controlling the flow rates and flux distribution at the potential repository has received increased attention. Of particular concern are 1) whether the PTn generally damps episodic infiltration pulses, thus providing a uniform flux at the potential repository horizon, and 2) what hydrogeologic features control isolated fast pathways through the PTn.

The Exploratory Studies Facility (ESF) is an 8-km long tunnel constructed at the site for the study of relevant properties of the potential repository horizon and is mostly below the PTn. Isotopic ratios for chloride leached from rock samples collected in the ESF provide constraints for flow models in which water enters the system at ground surface and percolates through the PTn to the sample location in the ESF. Fabryka-Martin et al.[1,2,3] have developed a database of $^{36}Cl/Cl$ ratios at about 250 sample locations, spanning almost the entire length of the ESF. These data support a conceptual model for fast paths linking faults to observations of bomb-pulse $^{36}Cl/Cl$ ratios in the ESF[1,2,3]. The conceptual model for fast paths also holds that the soil thickness above the fault must be less than 3 meters, and that the infiltration rate must be sufficiently high (on the order of at least 1 mm/yr) in order to sustain fracture flow in the faulted PTn. Away from fault zones, $^{36}Cl/Cl$ ratios greater than present day background, but less than the ratios found near faults, represent either water that entered the system more than ten thousand years ago when the ratios were higher[4] or the dilution of water containing bomb-pulse ^{36}Cl with older water.

III. MODEL RESULTS

Numerical transport modeling serves to evaluate the hydrologic parameters necessary to support the conceptual model, predict travel times and fluxes in regions of the potential repository block which have not been sampled, and interpret the meaning of the $^{36}Cl/Cl$ data. Flow and transport in the fractured, unsaturated zone at Yucca Mountain are simulated with the site-scale transport model[5] using the FEHM code[6]. Results of transport simulations in this study reconfirm previous findings that increased PTn fracture permeability in fault zones leads to simulated arrivals of bomb-pulse ^{36}Cl at the potential repository horizon[1].

Away from fault zones, the prediction of bomb-pulse ^{36}Cl at depth is sensitive to the PTn fracture-matrix interaction model, PTn fracture permeability, PTn thickness, and flow rate. Varying the PTn fracture-matrix interaction model or fracture permeability has little effect on simulated saturations, but may have a large effect on the depth to which bomb-pulse solutes can travel. Figure 1 contrasts simulated arrivals of bomb-pulse ^{36}Cl at the potential repository horizon for two different fracture-matrix interaction models.

With these parameter sets, the frequency of bomb-pulse ^{36}Cl arrivals at the potential repository horizon (away from fault zones) is predicted to increase as the PTn thins to the south. In the north, where the PTn is thicker, arrivals of bomb-pulse ^{36}Cl at the ESF are only simulated in fault zones. The results of the simulations in the south are inconsistent with the $^{36}Cl/Cl$ ratios measured in this portion of the ESF which are all very near present day background[3]. The discrepancy between model results and measured isotopic ratios in the southern portion of the ESF indicates that either the amount of fracture flow in the PTn is overestimated due to the PTn model properties[5,7] or high infiltration estimates[8], or the data are not representative of the true travel times of water from the surface to the ESF in these locations. These hypotheses can be tested with simple modifications to the model parameters. For example, using a new set of parameters recently developed for Yucca Mountain Performance Assessment[9], we find that no arrivals of bomb-pulse ^{36}Cl at the ESF away from fault zones are predicted.

For the simulations that yield arrivals of bomb-pulse ^{36}Cl at the ESF away from fault zones, some small portion of the flow in the PTn is sustained in fractures. However, these simulations do not indicate whether fluxes at the potential repository will be sensitive to temporal variations in the infiltration rate. Therefore, simulations were performed which considered episodic infiltration with large fluxes occurring over only a few days every 5 years. A range of PTn fracture permeabilities and fracture-matrix interaction models were considered in these simulations. In all cases, most of the flow still occurs in the PTn matrix and episodic fluxes are damped out everywhere except in fault zones. This damping is illustrated in Figure 2 with a 300 year simulation of fluxes at the potential repository for episodic infiltration both in and away from a fault zone.

IV. DISCUSSION

The elevated $^{36}Cl/Cl$ ratios associated with fault zones in the northern ESF are strongly suggestive of fast travel times of some solute from the surface to the sample location. Model hydrologic properties consistent with increased fracturing of the PTn in fault zones lead to predicted arrivals of some bomb-pulse ^{36}Cl at the ESF in such zones. Infiltration rates necessary to yield such predictions are consistent with independent infiltration estimates above the zones where bomb-pulse ^{36}Cl is found in the ESF[2,8].

Depending on the infiltration rate estimate, the fracture permeability, and the fracture-matrix interaction model, some arrivals of bomb-pulse ^{36}Cl can also be simulated at the ESF away from fault zones. Such results are currently obtained in the southern ESF because the PTn is thinner in the south than in the north. Thus, one hypothesis is that fast paths are not limited to fault zones. However, the ^{36}Cl data support such a solute transport model in the north but not in the south[1,2,3]. That is, higher than present day background ratios are found in the north but not in the south.

Another interpretation of the data is that fast paths only occur in fault zones in the north and elevated signals away from fault zones in the north are due to higher $^{36}Cl/Cl$ ratios from past climates[4]. Reasonable modification of the model infiltration rates and PTn fracture parameters leads to simulations consistent with the data. Namely, with reasonable modifications, fast paths are only simulated in fault zones in the north (due to sufficient infiltration) and away from fault zones, simulated travel times to the ESF in the north are greater than 10,000 years (and hence have a higher $^{36}Cl/Cl$ input[4]), while travel times to the ESF in the south are less than 10,000 years (and hence have the same input signal as the present day).

Sampling for other isotopes and ions in the ESF is currently underway and should reduce the uncertainty in the interpretation of the $^{36}Cl/Cl$ ratios measured away from fault zones. However, the simulated flux at the potential repository horizon remains insensitive to the subtle model variations needed to support the different interpretations of the data away from fault zones. Except in fault zones, most of the flow is predicted to occur in the PTn matrix, thus damping episodic infiltration events. Therefore, for repository design and evaluation, understanding the magnitude of the average annual infiltration rate away from fault zones is probably more important than how it is distributed in time. Studies coupling the infiltration estimates based on near surface measurements[8], the use of other chemical species[5,7,10], and interpretation of the $^{36}Cl/Cl$ ratios will serve to reduce uncertainty in percolation flux estimates at the potential repository.

V. ACKNOWLEDGEMENT

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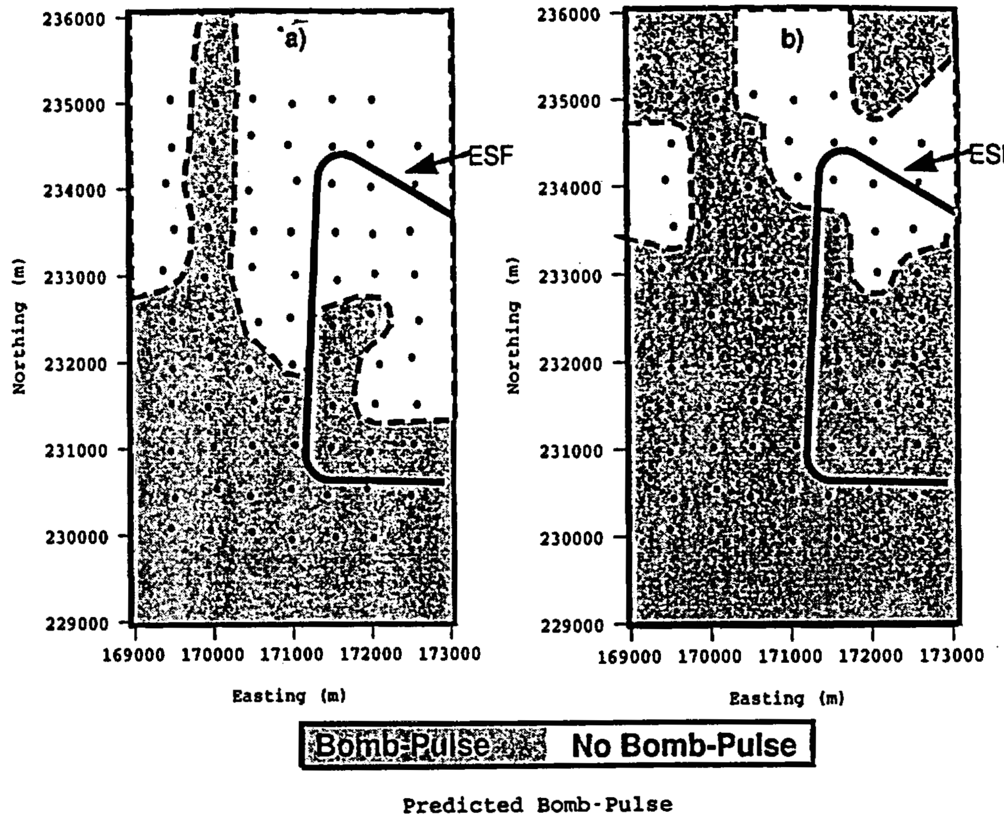

Figure 1. Predicted bomb-pulse 36Cl arrivals at potential repository horizon using two different fracture-matrix coupling models. PTn fracture-matrix coupling in case (b) reduced from that in base case (a) by approximately 2 orders of magnitude. This leads to more sustained PTn fracture flow in (b), hence more predictions of bomb-pulse 36Cl arrivals at potential repository horizon. In both cases, more bomb-pulse 36Cl arrivals at the potential repository horizon are simulated to the south where the PTn thins, as compared to the north.

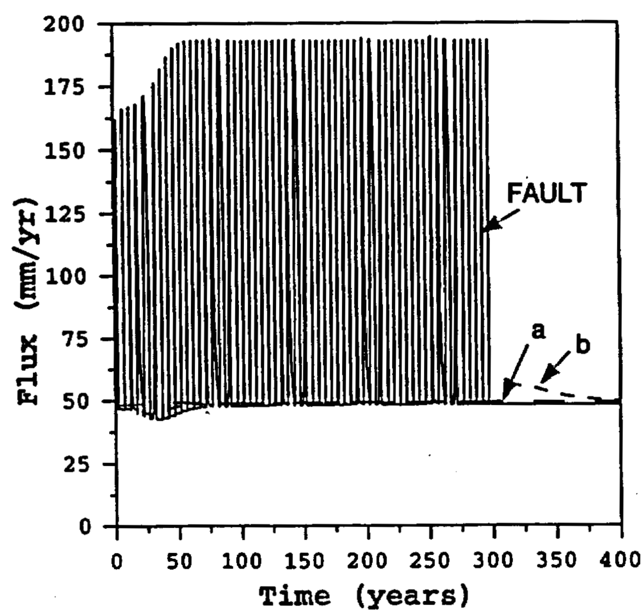

Figure 2. Simulated flux responses at potential repository using a 1-D model. Episodic infiltration model involves infiltration occurring for 10 days once every 5 years. The average rate is 50 mm/yr so the daily infiltration rate is 25 mm/day when infiltration occurs. Parameter sets (a) and (b) are the same as those used in the calculations for Figure 1. FAULT parameters represent increased PTn fracture permeability in fault zones. Significant flux variations at potential repository are simulated only when FAULT parameters are used.