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Title: USE OF CHLORINE-36 AND OTHER GEOCHEMICAL DATA TO TEST A GROUNDWATER FLOW MODEL FOR YUCCA MOUNTAIN, NEVADA

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Use of Chlorine-36 and other Geochemical Data to Test a Groundwater Flow Model for Yucca Mountain, Nevada

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Abstract

Defining the spatial distribution and timing of subsurface fluid percolation is one of the most important factors determining long term performance of the potential high-level radioactive waste repository at Yucca Mountain, Nevada. The potential repository would be constructed at a depth of about 250 m below the surface within rocks of the Miocene (12.8-12.7 Ma) Paintbrush Group. This sequence of volcanic rocks is greater than 460 m thick and consists of two regionally extensive, densely welded, fractured pyroclastic flows that are separated by an interval of generally nonwelded, bedded pyroclastic deposits. The nonwelded interval of the Paintbrush Group (PTn), which overlies most of the potential repository, has high matrix porosities and permeabilities and is mostly unfractured. The Exploratory Studies Facility (ESF) is an 8-km long, 7.6-m diameter, tunnel excavated beneath Yucca Mountain to the level of the potential repository horizon in order to provide access for characterization of these rocks. The thickness of the nonwelded PTn unit overlying the ESF varies from about 20 to over 70 meters.

Rapid fracture flow of water is expected to be pervasive in the welded units above and below the PTn; this expectation is supported by various geochemical, isotopic and other lines of evidence. Due to the higher porosity and low degree of fracturing of PTn rocks, matrix flow with very low vertical velocities would be expected to occur throughout most of this unit such that one would expect travel times on the order of several thousand years. However, several samples collected within the ESF have measured ^{36}Cl/Cl ratios that record anthropogenic ^{36}Cl (bomb-pulse ^{36}Cl), indicating that at least some fraction of the water has traversed the overlying PTn in 40 years or less and that flow is not confined to the matrix of that unit. The presence of a fast path transmitting bomb-pulse ^{36}Cl to depth appears to require the simultaneous presence of a structure (such as a fault) cutting the PTn and sufficiently high magnitude of surface infiltration to initiate and sustain at least a small component of fracture flow along the connected fracture path associated with the structure. The ^{36}Cl data have been simulated using the flow and transport model FEHM in order to establish bounds on infiltration rates at the site and to provide greater confidence in our understanding of unsaturated flow processes at the site by showing consistency between the observed and simulated data sets. An analogous effort simulating the distribution of porewater chloride concentrations is providing an independent means for confirming our conceptual model.

Introduction

Yucca Mountain, Nevada, is under investigation as a potential site at which to host the United States' first repository for commercial high-level radioactive waste. The site is in the northern Mojave Desert and lies 150 km northwest of Las Vegas in southern Nevada. About 500 to 750 meters of unsaturated rock are present at the site. For this and other sites, development and testing of conceptual flow and transport models for hydrologic systems is strengthened when the models specifically incorporate the use of natural environmental tracers. In this paper, we discuss the use of chlorine-36 data measured in samples from the unsaturated zone at Yucca Mountain, Nevada. Chlorine-36 (half-life, 301,000 years) is a radioactive isotope produced in the atmosphere and carried underground with percolating groundwater. High concentrations of this isotope were added to meteoric water during a period of global fallout from atmospheric testing of nuclear devices, primarily in the 1950s. This bomb-pulse signal can be used to test for the presence of fast transport paths and to provide the basis for a conceptual model for their distribution. Under wetter climatic conditions fast flow pathways will respond quickly to increases in infiltration and have the potential to become seeps. These data are also being used in numerical flow and transport models to establish lower bounds on infiltration rates, estimate ground water ages, and establish bounding values for hydrologic flow parameters governing fracture transport.

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. The relative thickness of these units and potential pathways for percolating water are shown in Figure 1. 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) what hydrogeologic features control isolated fast pathways through the PTn, and 2) whether the PTn generally damps episodic infiltration pulses, thus providing a uniform flux at the potential repository horizon.

Data Collection and Analysis

The Exploratory Studies Facility (ESF) is an 8-km long tunnel constructed for the study of relevant properties of the potential repository horizon. Hydrologic units exposed in the ESF include the TCw, the PTn, and the TSw, in order of increasing age and depth. The TCw and PTn are encountered in the first 1000 meters of the north ramp as well as the last 2000 meters of the south ramp (shown in Figure 3). The remainder of the ESF is in the TSw.

Over 250 ESF samples have been collected over the length of the tunnel[1,2]. Systematic samples collected at fixed intervals (either 100 or 200 m) along the tunnel comprise 20% of the sample inventory. The remaining samples were collected at targeted features such as damp zones, faults, fractures, or stratigraphic unit contacts in order to address key aspects of flow variability and permeability differences and to test conceptual models of subsurface percolation. About 2-5 kg of each sample was leached with deionized water to extract soluble Cl, and ^{36}Cl/Cl ratios were measured by accelerator mass spectrometry (AMS). Isotopic ratios for chloride leached from rock samples collected in the ESF provide constraints for both conceptual and numerical models of flow and transport at Yucca Mountain.

Results from Data Analysis

The ^{36}Cl/Cl data are plotted as a function of ESF location in Figure 2, and Figure 3 shows the relative locations of the ESF stations. The ^{36}Cl concentration is reported relative to the concentration of stable Cl in a given sample in order to adjust for the variable influence of evapotranspiration. The locations of faults projected from the surface to the ESF are also shown in Figure 2. The following observations are made:

- The majority of the samples (77%) have $^{36}Cl/Cl$ ratios ranging between 350×10^{-15} and 1000×10^{-15}, or 0.7 to 2 times the present-day background value of 500×10^{-15}. These results fall well within the range over which the atmospheric $^{36}Cl/Cl$ signal has varied during the past 30 ka or more, based on analyses of fossil packrat urine[3].
- A small number of samples extend significantly below the range of meteoric background values ($^{36}Cl/Cl$ ratios $< 350 \times 10^{-15}$). These low values may provide evidence for stagnant zones with travel times sufficiently long for radioactive decay of meteoric ^{36}Cl to have occurred (i.e., water ages on the order of 10^5 years). More likely, they indicate that the meteoric signal may have been diluted by a component of "dead" rock Cl in these samples.
- At a few locations, ratios extend well above the range of background values, to a maximum of 4100×10^{-15}. These high ratios are interpreted as indicating the presence of a component of bomb-pulse ^{36}Cl at these locations, a clear indication that some fraction of the water at the ESF level arrived there during the past 50 years. Based on statistical analyses, samples with ratios above 1250×10^{-15} are considered to contain a component of bomb-pulse ^{36}Cl. This interpretation is supported by measurements of bomb-pulse tritium and carbon-14 in Yucca Mountain borehole samples.
- 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[3] or the dilution of water containing bomb-pulse ^{36}Cl with older water.
- The ^{36}Cl signals in the northern part of the ESF are highly variable and elevated above present background levels. In contrast, signals in the south part of the ESF are nearly constant.

A Conceptual Model For Fast Paths

Detailed characterization of the structural settings of the ^{36}Cl sample locations and of their relationships to structural features and infiltration rates has provided the basis for a proposed conceptual model for fast pathways at Yucca Mountain[4]. The conceptual model states that three conditions must be present in order to transmit bomb-pulse ^{36}Cl to the sampled depth within 50 years:

- A continuous fracture path must extend from the surface to the sampled depth. This condition is necessary because travel times through the matrix of unfractured rock are expected to exceed 50 years. The condition of a continuous fracture path is easily satisfied in most of the welded portions of the Tiva Canyon and Topopah Spring units. The limiting hydrologic unit for controlling transport rates is the nonwelded PTn unit which is usually relatively unfractured. Hence, satisfying the condition of a continuous fracture pathway requires the presence of faults that cut the PTn unit and increase its bulk fracture conductivity.
- The magnitude of surface infiltration must be sufficiently high to initiate and sustain at least a small component of fracture flow along the connected fracture path. Transport simulations indicate that the threshold rate may be on the order of 1-2 mm/yr. However, the magnitude and recurrence frequency of episodic infiltration may be more important than the average annual infiltration rate.
- The residence time of water in the soil cover must be less than 50 years, i.e., the soil thickness must be less than 3 meters.

A case-by-case examination of the ESF data against the conceptual model's prediction of the presence or absence of bomb-pulse ^{36}Cl shows that the conceptual model is generally successful in predicting the presence of bomb-pulse ^{36}Cl. However, in some cases, the conceptual model does not adequately account for the observed ^{36}Cl data. In the southern part of the ESF, such as along the south ramp (beyond station 4500 in Figure 2), the PTn thins and faults are encountered but bomb-pulse ^{36}Cl has not been detected here to the extent that it is present in the northern ESF. One hypothesis for the difference is that the actual infiltration rate is probably less than what is currently predicted above the southern ESF. Thus, fracture flow can not be sustained, even in faults, in this region. However, the PTn is thin enough here that even with a lower infiltration rate, simulated travel times to the ESF are still less than 10,000 years (in and away from fault zones), hence the signals are not expected to show the predicted elevated ^{36}Cl/Cl ratios in the Pleistocene. This hypothesis is currently being tested against the alternative hypothesis which suggests that travel times to the ESF in the south are all less than 30 years, thus giving a post-bomb signal. Recent measurements of surface soils above the southern ESF have shown bomb-pulse ^{36}Cl/Cl ratios in all samples, thus reducing the later alternative hypothesis. Other activities underway to understand why bomb-pulse ^{36}Cl is not found in southern ESF fault zones and to evaluate these hypotheses include (1) measurement of other bomb-pulse nuclides to confirm the presence of or absence of bomb-pulse ^{36}Cl, (2) using porewater Cl concentrations to corroborate infiltration estimates[5], (3) detailed field investigation of sample locations relative to geologic structures, stratigraphy, and infiltration model estimates, and (4) evaluation of travel times to the ESF with predictive models.

Numerical Flow and Transport Modeling

The conceptual model is evaluated with a numerical flow and transport model which incorporates infiltration rate estimates and hydrologic parameters for the various geologic units in the unsaturated zone at Yucca Mountain. By synthesizing hydrologic, geologic, and geochemical data, the numerical model results provide insight into the implications of alternative hydrologic parameter sets, flow and transport processes, and the applicability of ^{36}Cl/Cl ratios for evaluating alternative conceptual models. The modeling exercise seeks to address the following interpretation of the data:

1. Increased PTn fracture permeability in fault zones is necessary to yield some travel times from the ground surface to the ESF of less than 50 years, thus providing a mechanism for bomb-pulse signals at the ESF.
2. Each sample represents a mixture of waters with different travel times from the surface to the sample location. Away from fault zones in the northern ESF, a significant component of the travel times making up each sample's distribution is greater than ten thousand years, thus providing a source of Pleistocene water with ^{36}Cl/Cl ratios greater than present day background (up to 2 times greater).
3. Away from fault zones in the southern ESF, travel times are less than 10 thousand years due to thinner PTn than in the North.
4. Infiltration rates in the south are too low to sustain PTn fracture flow in fault zones, thus leading to no bomb-pulse signals at the ESF.

Model Results

One- and three-dimensional simulations of ^{36}Cl migration in the unsaturated zone at Yucca Mountain are performed with the site-scale, dual permeability transport model[6] using the FEHM code[7]. Flow rates and hydrologic properties in and away from fault zones are considered with respect to their influence on ^{36}Cl transport. Using the Yucca Mountain Project's current infiltration model[8] and hydrologic property sets[9], the transport modeling seeks to investigate whether the four aspects of the interpretation stated above are consistent with expected flow and transport processes in the geologic media between the ground surface and the sample locations. Figure 3 shows the location of the one- and three-dimensional model domains relative to the ESF. The three different hydrologic properties considered are demonstrated in Table 1. BASE and FAULT properties are first used to examine the difference in simulated travel times in and away from fault zones. Then, PP parameters are used to investigate the sensitivity of simulated travel times away from fault zones to the model parameters. The BASE parameters are taken from a group of parameter sets[9] which were developed with differing assumptions about the fracture-matrix coupling model in the dual permeability formulation of unsaturated zone flow and transport. The BASE parameter set assumes a reduction in the fracture-matrix coupling which is scaled by the relative permeability in welded tuff and by the fracture saturation in nonwelded tuff. The PP parameters[10] are a recent revision of the BASE parameters, both of which were developed using numerical inversion to match measured matrix saturations in boreholes.

The first component of the modeling investigation examines whether increased PTn fracture permeability in fault zones leads to bomb-pulse arrivals at the ESF. A vertical one dimensional stratigraphic column is extracted from the three-dimensional site-scale model for this study because bomb-pulse ^{36}Cl/Cl ratios were found in the ESF at this location (see Figures 2 and 3). Unsaturated-zone flow and transport simulations are conducted for two different property sets, BASE and FAULT (see Table 1) over a range of percolation rates. The BASE property set is simply the base case for parameters away from fault zones. The FAULT property set increases the BASE PTn fracture permeability by one order of magnitude, consistent with field air permeability tests[2]. Figure 4 shows the simulated breakthrough curves at the ESF for a source released at ground surface. For both property sets, simulated mean travel times to the ESF decrease with increasing percolation rates. Once the percolation rate gets above 1 mm/yr, a small percent of the travel times to the ESF in fault zones are less than 50 years, while the simulated mean travel time is still on the order of one to ten thousand years in and away from the fault zone at this location. For infiltration rates of 1 mm/yr and less, simulated travel times are nearly identical for the BASE and FAULT parameter sets.

These results are encouraging because the estimated infiltration rate above this location is about 3.5 mm/yr[8]. Thus, these simulations are consistent with the data; using the estimated infiltration rate[8] and independently determined hydrologic parameters[9], the signal in fault zones would contain some bomb-pulse ^{36}Cl/Cl ratios and the signal away from fault zones would represent a mixture containing some Pleistocene water with a higher than present day background ^{36}Cl/Cl ratio.

The second component of the modeling investigation utilizes the three-dimensional flow and transport model and the spatially varying infiltration map[8] (I). As with the one-dimensional model, locations in the ESF are chosen at which breakthrough curves are simulated. The breakthrough curve at each location is dependent on the overlying PTn thickness, the infiltration rate in the region above the monitored location, and the hydrologic parameters. Figure 5 shows the breakthrough curves simulated with BASE parameters at six ESF locations. None of these locations are associated with fault zones in the three-dimensional geologic model (only the major faults, of which the fault at Station 3500 is not one, have been included in the three-dimensional geologic model to date). The simulated mean travel times to the ESF range between two and ten thousand years. However, the three southern ESF locations (4500, 6000 and 7700) show a small component of solute travel times to the ESF which are less than 50 years. Thus, even away from fault zones, the potential for bomb-pulse signals in the southern ESF are simulated. This discrepancy between model results and measurements, which do not indicate bomb-pulse in the southern ESF, indicates that either the amount of fracture flow in the PTn is overestimated in the simulations due to the PTn model properties[6,9] or high infiltration estimates[8], or the measurements are not sensitive to some fast travel times of water from the surface to the ESF at these locations. The first two hypotheses are tested with simple modifications to the site-scale model parameters.

By reducing the infiltration rate by a factor of three everywhere (the I/3 infiltration map), simulated mean travel times increase to the range of seven to fifteen thousand years (Figure 6), but a small component of bomb-pulse travel times is still simulated at the southern ESF stations. At the northern ESF stations, the simulations using the reduced infiltration map are consistent with the interpretation that signals greater than present day background, other than those which contain unambiguous bomb-pulse, are a result of higher ^{36}Cl/Cl ratios during the end of Pleistocene. Simulations at the southern ESF stations using the unaltered infiltration map are consistent with the interpretation that travel times to the ESF at the southern stations are less than ten thousand years due to a thinner PTn. The small component of very fast travel times to the southern ESF stations predicted using either infiltration map is not consistent with the data.

In order to examine the sensitivity of simulated travel times to model parameters, a comparison is done between two different model parameter sets. A new set of hydrologic parameters[10] for the three-dimensional model have been developed using inversion techniques similar to those that were used for the base case calculations[9] in this study. The new parameters (referred to here as the PP parameters), however, have lower PTn fracture and matrix permeabilities in some of the PTn subunits. Table 1 provides a comparison of the BASE and PP parameter sets. Simulations using the spatially varying infiltration map and either parameter set yield simulated saturations that are consistent with those measured in the PTn. Figure 7 shows a comparison of the simulated breakthrough curves at two of the southern ESF stations for the BASE and PP parameter sets. First, no bomb-pulse arrivals are simulated with the PP parameter set. Second, the mean travel time is several hundred years less at Station 4500 and several thousand years more at Station 6000. Although preliminary, these simulations show the sensitivity to the model parameters of bomb-pulse predictions and whether the simulated age distribution of a given sample includes some component of Pleistocene water. The corollary to this, of course, is that reasonable constraints on the model parameters can be made to insure that travel times consistent with the geochemical data are simulated. Thus, although the model parameter inversions are primarily based on matching measured saturations from borehole samples, such inversions are nonunique and invite the use of these additional chemical observations for narrowing the field of potential parameter sets. Other subsurface chemical data used to constrain model parameters and test infiltration estimates include porewater chloride and ^{14}C from the unsaturated zone and from perched water bodies.

The two primary reasons for trying to understand whether fast paths exist away from fault zones are 1) because transport processes above the potential repository may serve as an indicator of transport processes below the potential repository even though different rocks are encountered there, and 2) because fast paths to the potential repository may indicate that episodic infiltration due to transient weather patterns on the daily time scale are not damped in the PTn and thus must be accounted for in both the repository design and the characterization of the geologic barrier. The simulation studies described here have been extended to examine such behavior[3]. The conclusion from those studies is that away from fault zones, the subtle differences in PTn model parameters do not lead to predictions of transient fluxes at the potential repository. Rather, regardless of which parameter set is used, the PTn is predicted to dampen episodic infiltration events, yielding a relatively constant flux to the potential repository block in the TSw.

Conclusions

^{36}Cl/Cl ratios measured in the ESF provide valuable insight into flow and transport processes between ground surface and the sample locations. The measurements can be separated into two categories, those which indicate unambiguous bomb-pulse signatures and those which do not. The unambiguous bomb-pulse signals are well correlated with fault zones in the northern ESF. Away from fault zones, in the north, ^{36}Cl/Cl ratios are generally greater than present day background indicating either contributions from previous climates having higher signals or mixing of more recent water with bomb-pulse water. However, the data from the southern part of the study area contradict the second hypothesis. If bomb-pulse signals were penetrating the PTn, it makes more sense that it would be more prevalent in the south, not in the north, due to thinning of the PTn in the south.

In the south, the measured ^{36}Cl/Cl ratios are generally similar to present day background with some samples having ratios even less than present day background. There is no strong distinction between sample ratios measured near or away from fault zones. One interpretation of the southern ESF data is that travel times to the ESF are generally less than ten thousand years but greater than fifty years. The signals with ^{36}Cl/Cl ratios less than $350\text{x}10^{-15}$, however, may indicate stagnant zones with travel times sufficiently long for radioactive decay of meteoric ^{36}Cl (i.e. travel times on the order of 100,000 years). Alternatively, they may indicate dilution of the meteoric signal with ‘dead’ rock Cl released when the rock samples are crushed before leaching.

In the model simulations, prediction of bomb-pulse travel times at the ESF is entirely dependent on whether fracture flow is sustained through the entire PTn. 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 fault zones when the infiltration rate is sufficient. 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].

The simulated mean travel time to the ESF is dependent on the residence time in the PTn matrix which, in turn, depends on the infiltration rate and the hydrologic parameters. Using the same infiltration model and the BASE hydrologic parameters (which were altered only in fault zones to represent the increased PTn fracturing described above), simulated travel times to the northern ESF stations away from fault zones are between two and ten thousand years. These results are almost consistent with the interpretation that Pleistocene water provides the elevated ^{36}Cl/Cl ratios away from fault zones in the northern ESF. Reduction of infiltration rates or modification of PTn matrix parameters shift the travel times up, into the ten thousand year time frame needed for the Pleistocene signal to travel to the northern ESF.

Depending on the infiltration rate and model parameters, some bomb-pulse arrivals of ^{36}Cl can be simulated at the ESF away from fault zones. Such model results are currently obtained in the southern ESF due to thinner PTn in the south. In those locations, however, no bomb-pulse ^{36}Cl/Cl ratios have been measured. Constraining the model parameters to yield simulations more consistent with the data is done simply by reducing the amount of simulated fracture flow in the PTn. Parameter sets with such constraints (e.g. PP parameters) still yield predicted PTn matrix saturations consistent with field observations. These modifications, however, still do not explain why bomb-pulse signals are not found in fault zones in the southern ESF. Sampling for other isotopes and ions in the ESF is currently underway to identify whether any other bomb-pulse indicators are found in those fault zones. Alternatively, the necessary combination of increased PTn fracture permeability and adequate infiltration may not be present at those locations to transport bomb-pulse isotopes to the ESF.

Overall, numerical transport simulations using independently determined hydrologic parameters and infiltration rates come close to representing the travel times necessary to produce the ^{36}Cl/Cl signals measured in the ESF. Reasonable modification of the parameters or infiltration rate estimates leads to a much closer approximation of the travel times necessary to yield the observed ^{36}Cl/Cl ratios. Namely, increased travel times in the north can be achieved with modification of the infiltration rates or the PTn matrix parameters, and reduction of PTn fracture flow away from faults in the south (as well as the north) can be achieved with reduced fracture permeability or a modified fracture matrix coupling term. These results demonstrate that the base hydrologic model generally supports the primary interpretation of the ^{36}Cl/Cl data from the ESF. Then, modification of infiltration rates or model parameters within reasonable limits leads to elimination of most discrepancies between the predictions and the measurements.

MATRIX PROPERTIES

	Permeability m^2		Alpha 1/Pa		Lambda		Porosity	
Ptn1	1.60E-14	3.09E-14	4.05E-05	3.80E-05	0.233	0.321	0.369	0.369
Ptn2	3.76E-15	3.02E-15	1.09E-05	8.71E-06	0.518	0.488	0.234	0.234
Ptn3	1.43E-13	8.32E-14	4.49E-05	4.57E-05	0.274	0.287	0.353	0.353
Ptn4	1.12E-13	1.15E-13	4.59E-05	4.27E-05	0.346	0.349	0.469	0.469
Ptn5	2.10E-13	2.46E-13	1.92E-04	1.95E-04	0.277	0.279	0.469	0.469
	BASE	PP	BASE	PP	BASE	PP	BASE	PP

FRACTURE PROPERTIES

	Permeability m^2		Alpha 1/Pa		Lambda		Porosity	
Ptn1	3.09E-13	5.25E-13	1.10E-03	1.10E-03	0.496	.492	4.84E-04	4.84E-04
Ptn2	3.98E-13	1.95E-13	7.44E-05	1.82E-03	0.489	.492	4.83E-04	4.83E-04
Ptn3	2.56E-12	2.57E-13	3.45E-03	3.39E-03	0.481	.492	1.30E-03	1.30E-03
Ptn4	1.17E-13	6.17E-14	9.13E-04	9.33E-04	0.494	.492	6.94E-04	6.94E-04
Ptn5	2.19E-13	7.76E-14	1.11E-03	1.95E-04	0.492	.279	8.32E-04	8.32E-04
	BASE	PP	BASE	PP	BASE	PP	BASE	PP

Table 1. Model properties for the PTn unit. BASE and PP properties shown. Fault zone properties are BASE properties with 10x fracture permeability. For a complete description of the properties, see referenced models[5,7,10].

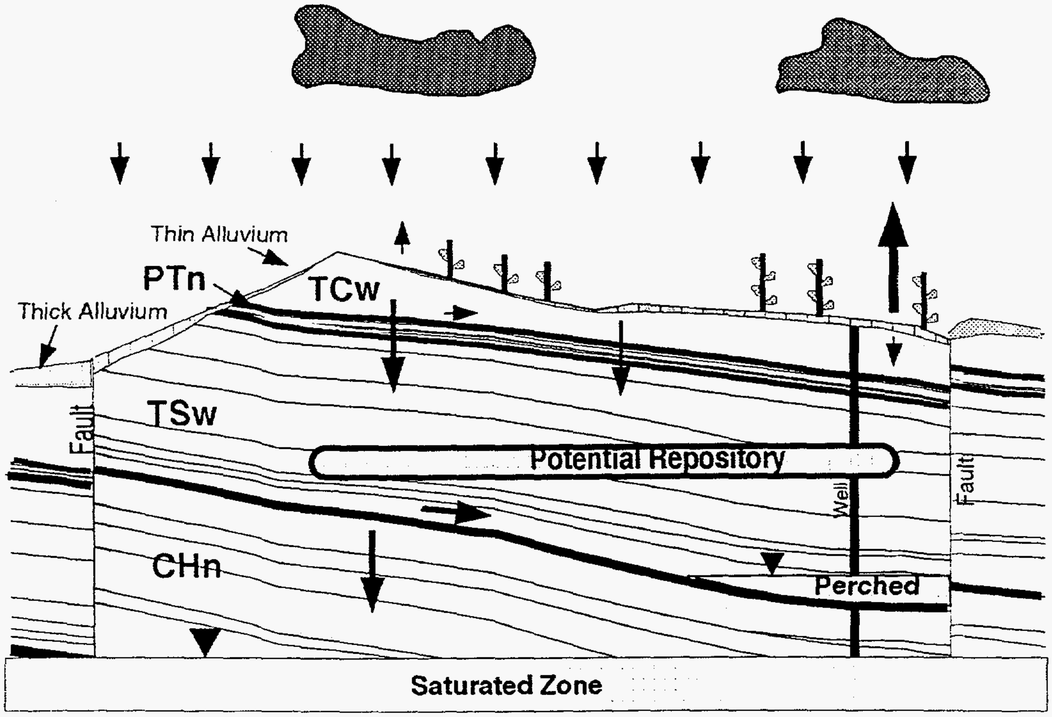

Figure 1. Stratigraphic cross section and conceptual model of flow pathways in the unsaturated zone at Yucca Mountain.

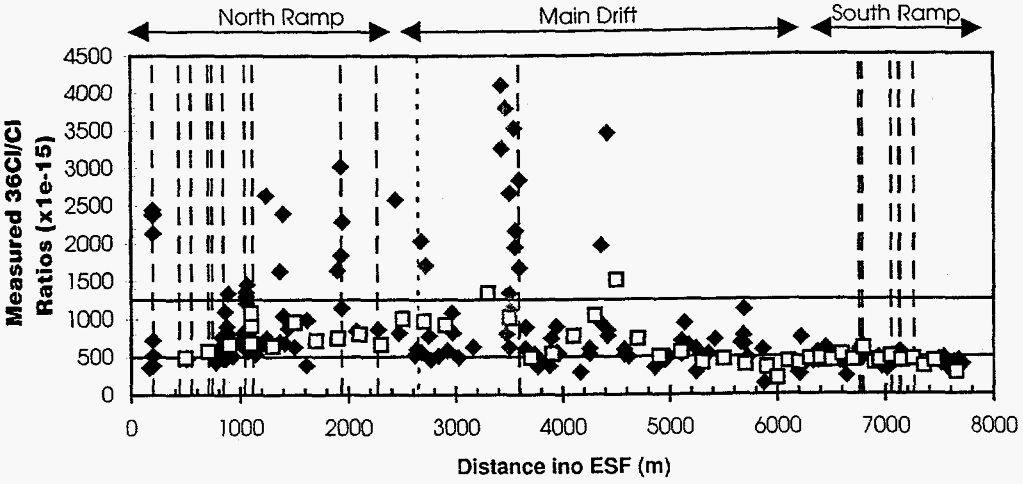

Figure 2. Distribution of ^{36}Cl/Cl ratios measured for rock samples in the ESF[2]. Open boxes are systematic samples and diamonds are feature based samples. Faults in the ESF that correlate with mapped faults at the surface are shown as vertical lines. Horizontal line at 1250 indicates maximum estimated ^{36}Cl/Cl ratio in infiltrating water prior to bomb-pulse.

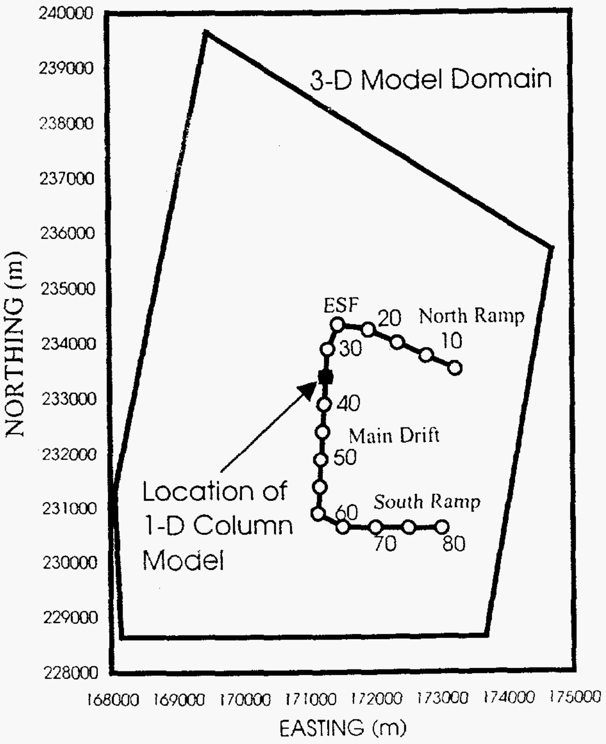

Figure 3. Plan view of model boundaries relative to the ESF. Scale is Nevada State Plane Coordinates. Numbers represent distance into the ESF (x100m).

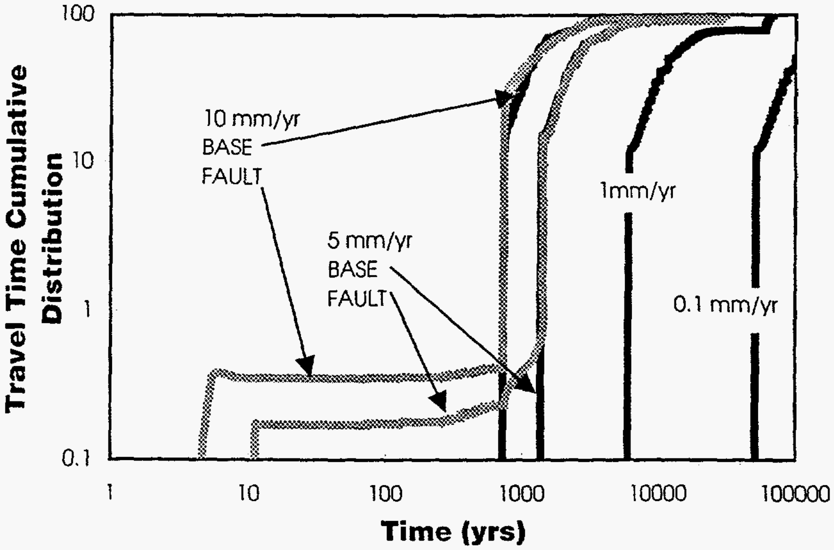

Figure 4. Simulated travel time distribution ESF stations using the one-dimensional transport model, different infiltration rates, and BASE and FAULT parameters sets. There are no distinguishable differences between runs using BASE and FAULT parameters for infiltration rates of 1 and .1 mm/yr.

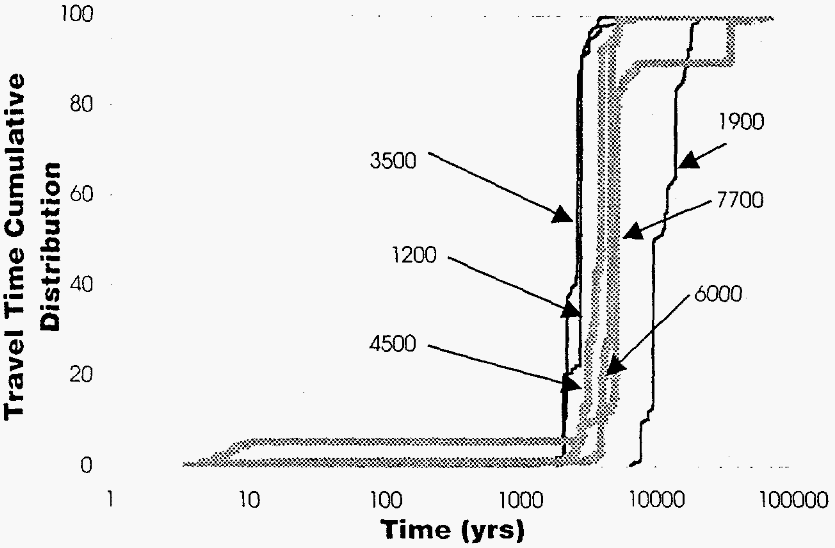

Figure 5. Simulated travel time distribution to six different ESF stations using the three-dimensional transport model, BASE parameters, and the base infiltration map (I). Numbers indicate distance (m) into ESF at which simulations were performed.

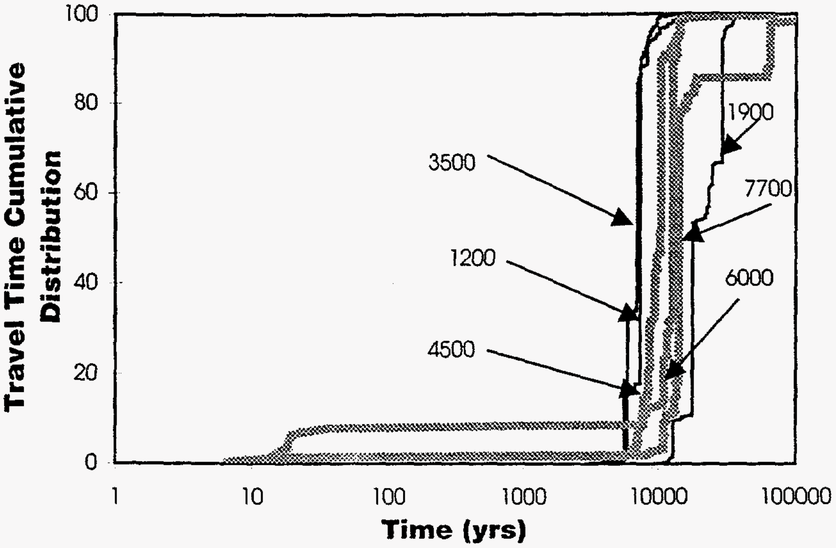

Figure 6. Simulated travel time distribution to six different ESF stations using the three-dimensional transport model, BASE parameters, and the modified infiltration map (I/3). Numbers indicate distance (m) into ESF at which simulations were performed.

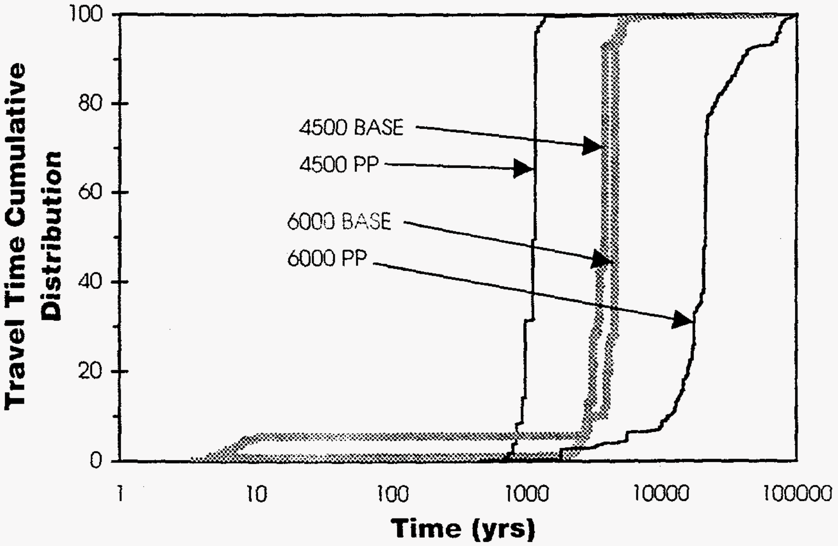

Figure 7. Simulated travel time distribution to two southern ESF stations using the three-dimensional transport model, the base infiltration map (I), and the BASE and PP parameters sets. Numbers indicate distance (m) into ESF at which simulations were performed.

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