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DISTRIBUTION OF FAST HYDROLOGIC PATHS IN THE UNSATURATED ZONE AT YUCCA MOUNTAIN

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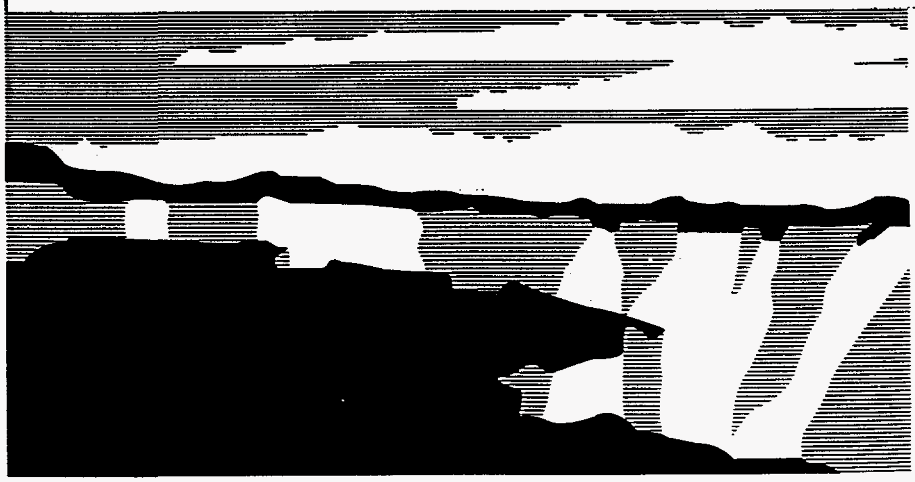

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DISTRIBUTION OF FAST HYDROLOGIC PATHS IN THE UNSATURATED ZONE AT YUCCA MOUNTAIN

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I. INTRODUCTION

Development and testing of conceptual flow and transport models for hydrologic systems are strengthened when natural environmental tracers are incorporated into the process. One such tracer is chlorine-36 (^{36}Cl, half-life, 301,000 years), a radioactive isotope produced in the atmosphere and carried underground with percolating groundwater. High concentrations of this isotope were also added to meteoric water during a period of global fall-out from atmospheric testing of nuclear devices, primarily in the 1950s. This bomb-pulse signal has been used to test for the presence of fast transport paths in the unsaturated zone at Yucca Mountain and to provide the basis for a conceptual model for their distribution.[1-3] Yucca Mountain is under investigation by the U.S. Department of Energy as a potential site at which to host an underground high-level radioactive waste repository. Under wetter climatic conditions, fast-flow pathways will respond quickly to increases in infiltration and have the potential to become seeps in the tunnel drifts. The ^{36}Cl 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.[1-5]

II. DATA COLLECTION AND ANALYSIS

Yucca Mountain 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. The Exploratory Studies Facility (ESF) is a 8-km long tunnel constructed at the site for the study of relevant properties of the potential repository horizon (Figure 1). Hydrologic units exposed in the ESF include the welded Tiva Canyon tuff (TCw), an underlying interval of variably welded pyroclastic deposits (PTn), and the welded Topopah Spring tuff (TSw), in order of increasing age and depth.

Over 250 ESF samples have been collected over the length of the tunnel.[1-2] Systematic samples collected at fixed intervals (initially every 200 m, decreased to 100 m) along the tunnel comprise 20 percent of the sample inventory. Remaining samples targeted specific 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 at the PRIME Laboratory (Purdue University).

III. RESULTS

The ^{36}Cl/Cl data are plotted as a function of ESF location 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.[7]

- A small number of samples in the southern portion of the ESF extend significantly below the range of meteoric background values (^{36}Cl/Cl $< 350 \times 10^{-15}$). 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). Alternatively, they may indicate dilution of the meteoric signal by a component of "dead" rock Cl released when the rock samples are crushed before leaching. Cl pore-water concentrations, which reflect surface infiltration rates, are being measured to address this question.[8]

- 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 to some extent by measurements of bomb-pulse tritium and carbon- 14 in borehole samples from other parts of Yucca Mountain.[9-10] However, an alternative hypothesis under investigation is whether the elevated ^{36}Cl signals could possibly be attributed to release of that produced by spallation of calcium in soil calcites.[13]

- 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.

IV. DISCUSSION AND CONCLUSIONS

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. 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.[1-2]

(a) 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 is 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 fracture conductivity.

(b) Surface infiltration rates 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.

(c) 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.

These conditions provide the basis for the predictive conceptual model shown in Figure 1. A case-by-case examination of the ESF data against the model's prediction of the presence or absence of bomb-pulse ^{36}Cl shows that the 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. For example, in the southern part of the ESF, faults are encountered at locations where the modeled infiltration rates exceed 2 mm/yr, but nonetheless bomb-pulse ^{36}Cl has not been detected to the extent it is present in the northern part. Activities underway to determine the reason for this difference include: (1) measurement of other bomb- pulse nuclides to confirm the presence or absence of bomb-pulse ^{36}Cl, (2) validation of results through resampling and reanalysis, (3) detailed field investigation of sample locations relative to geologic structures, stratigraphy and infiltration model estimates, (4) assessment of PTn hydrologic properties used in the numerical model, such as those relating to fracture-matrix interactions, (5) measurement of present-day ^{36}Cl/Cl ratios in surface soil to test whether the bomb-pulse signal may have been completely leached out, (6) refining aspects of the surface infiltration model[11], and (7) using porewater Cl concentrations to corroborate infiltration estimates.[8]

Finally, the apparent lack of bomb-pulse ^{36}Cl in most ESF samples suggests that the PTn, at least away from fault zones, significantly delays the timing and damps the magnitude of episodic fluxes.[2-3] If this concept holds true through further analysis, then it would suggest that repository design and performance assessment efforts can be based on fluxes that are uniform in time, except near fault zones. Although the ^{36}Cl data cannot be used to quantify fluxes directly, they do at least identify the type of fast path for which it may not be acceptable to assume damping of high fluxes.

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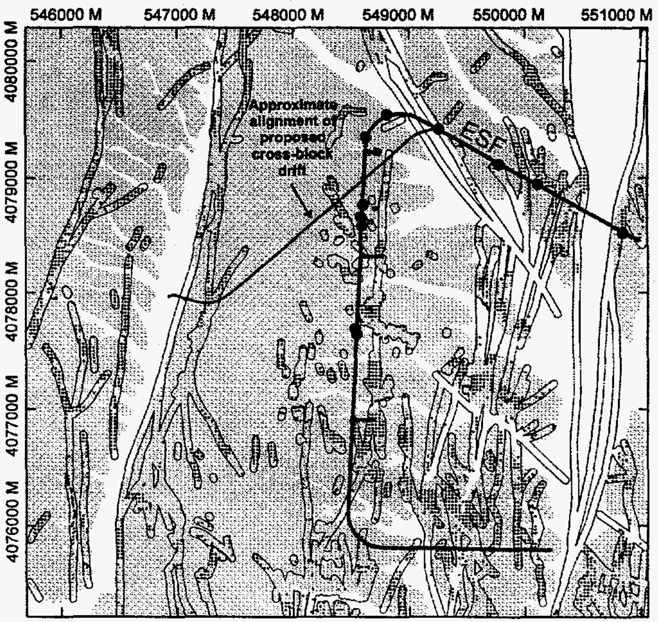

Figure 1. Predicted and measured distribution of bomb-pulse ^{36}Cl at Yucca Mountain. Small dots indicate areas for which the estimated infiltration rate exceeds 2 mm/yr and alluvial thickness is less than 3 m above a mapped fault at the surface, such that bomb-pulse ^{36}Cl is predicted to be present at the potential repository horizon (Ref. 2). Surface fault traces (from Ref. 12) are bounded on each side by a 30 m-wide envelope. Surface infiltration rate, using average annual precipitation, is from the numerical model of Ref. 11. Large solid black dots along the ESF trace indicate locations at which bomb-pulse ^{36}Cl has been measured in the tunnel. Map coordinates are Nevada State Plane coordinates, in UTM m.

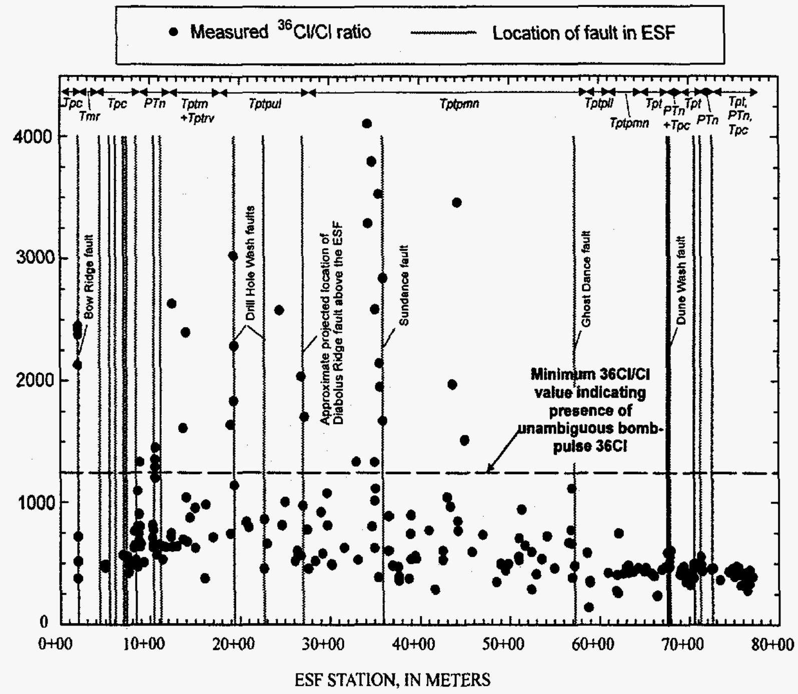

Figure 2. Faults and distribution of ^{36}Cl/Cl ratios measured for rock samples in the ESF at Yucca Mountain (Ref. 2). Faults in the ESF that correlate with mapped faults at surface (see Figure 1) are shown. General location of lithostratigraphic units (following the nomenclature of Ref. 6) exposed in the ESF is shown along upper axis.