Hydrologic Resources Management Program and Underground Test Area Project FY2005 Progress Report
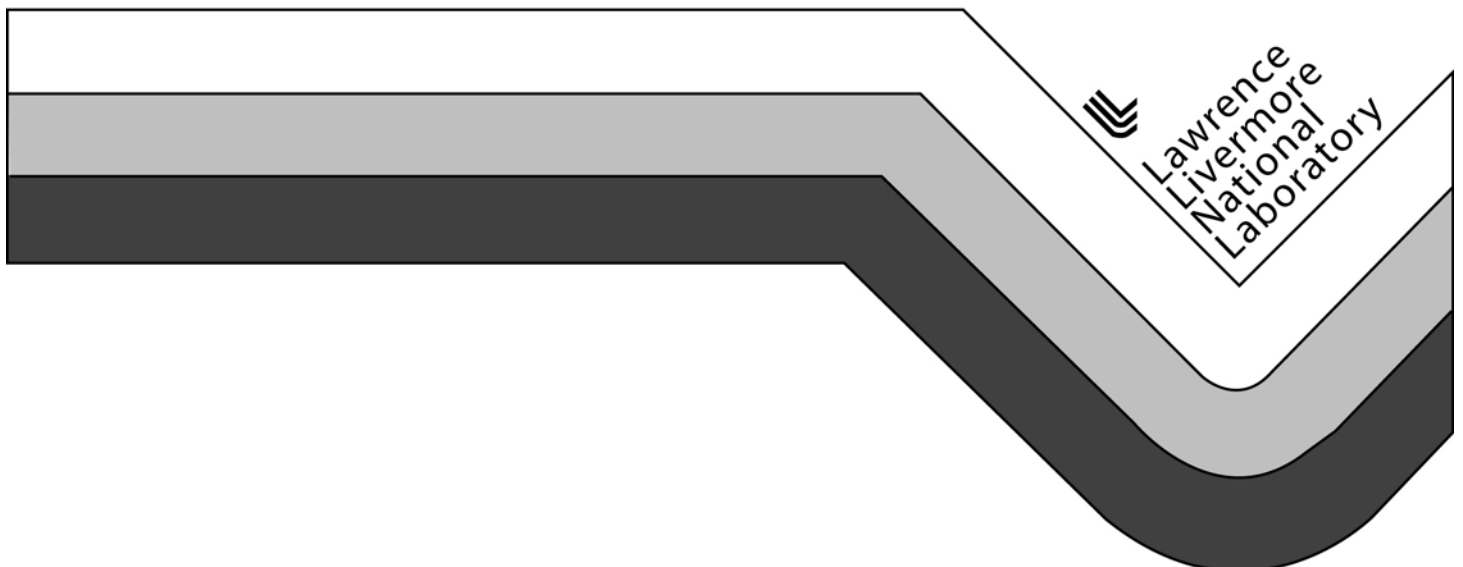
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March 2007

Lawrence Livermore National Laboratory

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Introduction

Hydrologic Resources Management Program and Underground Test Area Project FY 2005 Progress Report

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This report describes FY 2005 technical studies conducted by the Chemical Biology and Nuclear Science Division (CBND) at Lawrence Livermore National Laboratory (LLNL) in support of the Hydrologic Resources Management Program (HRMP) and the Underground Test Area Project (UGTA). These programs are administered by the U.S. Department of Energy, National Nuclear Security Administration, Nevada Site Office (NNSA/NSO) through the Defense Programs and Environmental Restoration Divisions, respectively. HRMP-sponsored work is directed toward the responsible management of the natural resources at the Nevada Test Site (NTS), enabling its continued use as a staging area for strategic operations in support of national security. UGTA-funded work emphasizes the development of an integrated set of groundwater flow and contaminant transport models to predict the extent of radionuclide migration from underground nuclear testing areas at the NTS.

The report is organized on a topical basis and contains five chapters that highlight technical work products produced by CBND. However, it is important to recognize that most of this work involves collaborative partnerships with the other HRMP and UGTA contract organizations. These groups include the Energy and Environment Directorate at LLNL (LLNL-E&E), Los Alamos National Laboratory (LANL), the Desert Research Institute (DRI), the U.S. Geological Survey (USGS), Stoller-Navarro Joint Venture (SNJV), and Bechtel Nevada (BN).

Chapter 1 is a summary of FY 2005 sampling efforts at NTS near-field "hot" wells, and presents new chemical and isotopic data for groundwater samples from four near-field wells. These include ER-20-5#1 and ER-20-5#3, U-3cn PS#2 (BILBY), and UE-2ce (NASH).

Chapter 2 is a summary of the results of chemical and isotopic measurements of groundwater samples from three UGTA environmental monitoring wells. These include an existing well ER-12-1 and two new wells ER-12-3 and ER-12-4 all located in Area 12 on Rainier Mesa.

Chapter 3 is a summary of the distribution of ^{99}Tc and ^{129}I in the vicinity of underground nuclear tests at the NTS, with particular focus on the recent drillback samples collected at CHANCELLOR in FY2005. This work was presented as part of the Methods and Applications of Radioanalytical Chemistry (MARC VII) conference held in Kailua-Kona, Hawai'i, USA, April 3 – 7, 2006. Proceedings are published in the Journal of Radioanalytical and Nuclear Chemistry.

Chapter 4 is a summary of the results of long term nuclear melt glass alteration experiments conducted at 120 and 200ºC. The secondary mineral phases and associated water from the nuclear melt glass dissolution experiments were characterized using Eh/pH, ion chromatography (IC), inductively coupled plasma mass spectrometry (ICP-MS), Liquid Scintillation Counting (LSC), Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS), X-ray Diffraction (XRD), and α-radiography. The nuclear melt glass sequesters the majority of the long-lived radionuclides and alteration of this glass contributes to the hydrologic source term.

Chapter 5 presents stable isotope data from precipitation, spring discharge, and soil water at four sites in central Nevada. Stable isotope measurements at the USGS High Altitude Precipitation (HAP) network in eastern Nevada are also discussed. The data from these sites can be used to improve our understanding of precipitation and recharge processes in Nevada, and can be applied to the development of conceptual models of hydrologic processes, for validating numerical groundwater flow models, and for monitoring potential changes in climate over time.

Chapter 1

FY 2005 Hot Well Data

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1.1   Introduction

This chapter summarizes the results of chemical and isotopic analyses of groundwater samples collected from near-field "hot" wells at the NTS during FY 2005. This work is the latest contribution to a long-standing effort aimed at understanding radionuclide transport processes at the NTS. These data are required in the development and verification of contaminant transport models for the Underground Test Area (UGTA) project. Collaborating agencies in the hot well sampling effort include Los Alamos National Laboratory (LANL), the U.S. Geological Survey (USGS), the Desert Research Institute (DRI), Bechtel Nevada (BN), and Stoller-Navarro Joint Venture (SNJV).

Groundwater samples were collected from four NTS near-field wells during FY 2005. These include ER-20-5#1 and ER-20-5#3 (both located ~280 meters southwest of TYBO and ~1.3 kilometeres south of BENHAM), U-3cn PS#2a (perforations located ~200 meters above the BILBY working point), and UE-2ce (located 180 meters south of NASH). Figure 1.1 shows the locations of these wells at the NTS. Laboratory analytical protocols are fully described in the LLNL Standard Operating Procedures written in support of the UGTA Project (LLNL, 2004). Tables 1.1 through 1.7 contain the analytical results for the FY 2005 samples together with comparative data for samples collected over the past several years. Significant features of the FY 2005 data are highlighted in the sections that follow.
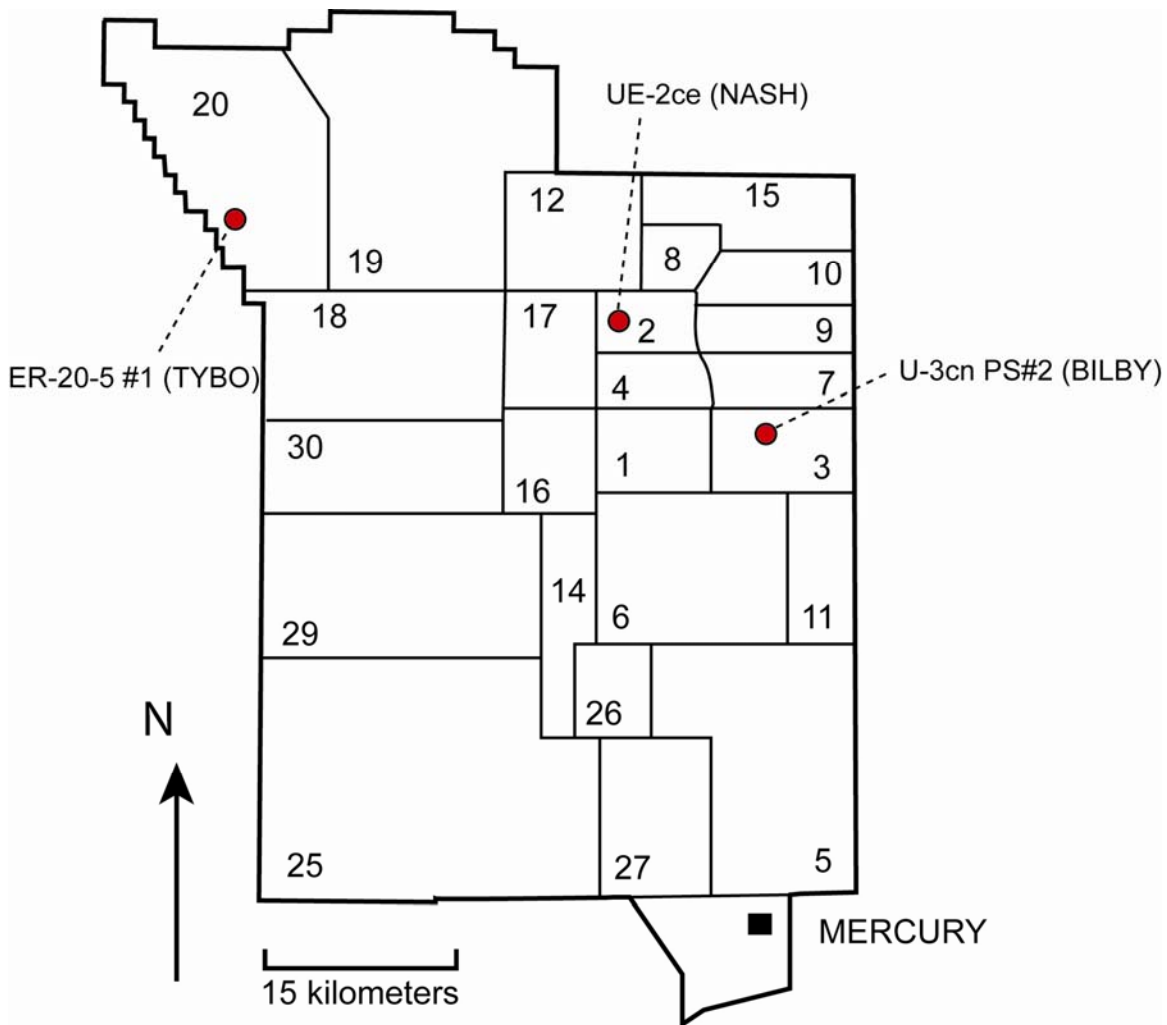
Figure 1.1 Map of the NTS showing Hotwell sampling locations for FY2005.

1.2   ER-20-5 #1

The ER-20-5 well cluster consists of two near-field monitoring wells (#1 and #3) located on Pahute Mesa, in Area 20 of the NTS. The wellhead for ER-20-5 #1 is situated less than 300 meters from surface ground zero of the TYBO underground nuclear test, which was detonated in the U-20y emplacement hole on May 14, 1975. The production interval for ER-20-5#1 is 701 to 784 meters below ground surface in Tertiary rhyolite of the Topopah Spring Tuff (Figure 1.2).

Groundwater characterization samples were collected from well ER-20-5 #1 on November 30, 2004. Approximately 29,340 gallons of water were pumped from the well prior to sample collection. Prior to 2004, ER-20-5#1 was last sampled on July 9, 1998 (LLNL, 1998). Since that time, there have been no significant changes in the chemical and isotopic characteristics of the groundwater.
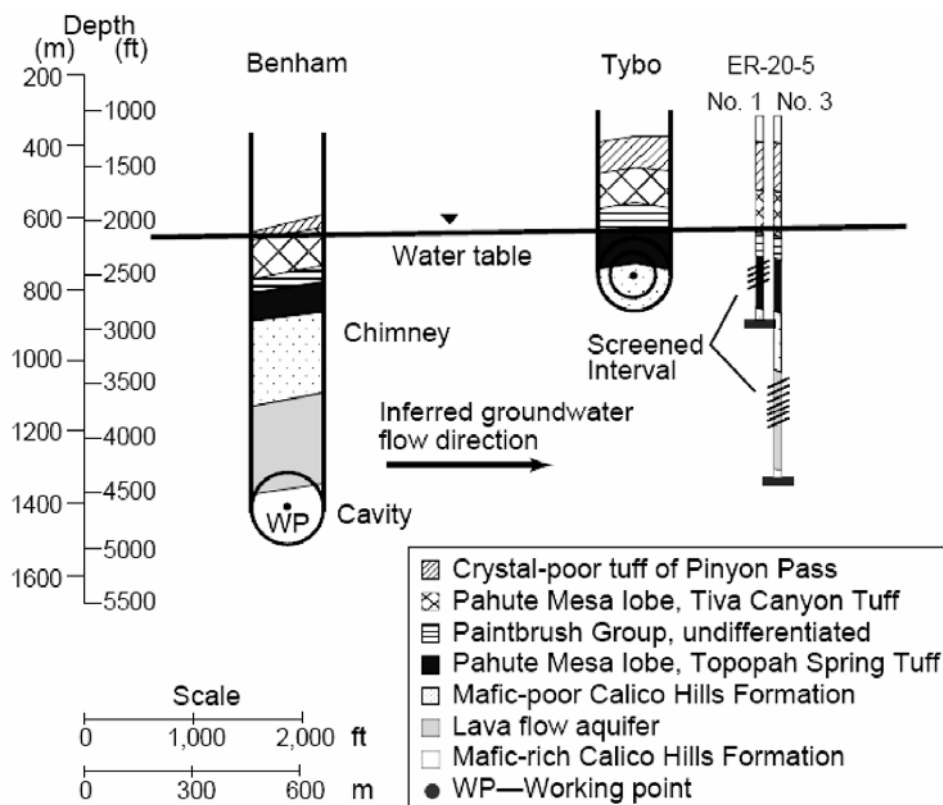
Figure 1.2 Location of the ER-20-5 well cluster relative to the TYBO and BENHAM tests. From Kersting et al. (1999). Cavity size is not to scale.

Well ER-20-5 #1 produces Na-HCO$_3$ groundwater with modest enrichments in chloride and sulfate anions. The well is located near the convergence of two separate groundwater flow systems that underlie Pahute Mesa (Rose et al., 2002). Groundwater to the east of this location is characterized by very low chloride and sulfate values (e.g. Water Well 20) whereas groundwater immediately to the west has much higher concentrations of these anions (e.g. well ER-EC-1). The groundwater from ER-20-5 #1 appears to contain a mixture of these two water types. The stable isotope composition of ER-20-5 #1 groundwater (δD = -115 ‰ and δ^{18}O = -14.9 ‰) is consistent with this interpretation.

The tritium activity in ER-20-5 #1 groundwater was 3.8×10^7 pCi/L at the time of sampling, as determined by liquid scintillation counting (LSC). The decay corrected value at time zero for the TYBO test is 2.0×10^8 pCi/L. This is in good agreement with the decay corrected tritium activity in the samples collected in 1998 (2.3×10^8 pCi/L). Kersting et al. (1999) showed that plutonium in ER-20-5 groundwater originates from the BENHAM underground test, which is located approximately 1.3 km north of the well cluster. It is uncertain whether *all* of the radionuclides that are observed at the ER-20-5 #1 well originated from BENHAM, or if some fraction of the more mobile species (such as tritium) may have originated from the TYBO test. It is notable that the tritium activity in ER-20-5 #1 is substantially higher than that of the deeper ER-20-5 #3 well. The

radioactivity encountered in the deeper well is more likely to have a direct source from BENHAM due to the presence of low permeability rocks between the two aquifers where the #1 and #3 wells are completed; this low permeability rock would inhibit downward leakage of contaminated groundwater from the TYBO test cavity.

Dissolved inorganic carbon (DIC) in ER-20-5 #1 groundwater has a ^{14}C value of 9.6×10^4 percent modern carbon (pmc), approximately three orders of magnitude higher than the modern atmospheric radiocarbon concentration. At the measured DIC concentration of 193 mg/L, this corresponds to a dissolved ^{14}C activity of 224 pCi/L. The relatively high δ^{13}C value of the water (-4.7‰) suggests it has largely equilibrated with fracture-lining calcite mineralization that is widely observed in the Pahute Mesa aquifers (Benedict et al., 2000).

^{36}Cl is a long-lived neutron activation product ($t_{1/2} = 3\times10^5$ years) that is produced during nuclear detonations, and is highly mobile as the soluble chloride anion. ER-20-5 #1 groundwater has a ^{36}Cl/Cl ratio (4.4×10^{-9}) that is four orders of magnitude above the modern atmospheric ratio for southern Nevada ($\sim5\times10^{-13}$, Fabryka-Martin et al., 1993). Due to its long half-life, the total ^{36}Cl activity in the ER-20-5 #1 groundwater is fairly low (3.6 pCi/L). This value is almost unchanged from the previous measurement in 1998 (3.3 pCi/L).

The fission products ^{99}Tc and ^{129}I were measured in ER-20-5 #1 groundwater for the first time in 2004. Technetium and iodine are both highly mobile as soluble anions under oxidizing conditions. For comparative purposes, the ^{99}Tc and ^{129}I concentrations in archival samples collected in 1998 were also analyzed. The measured ^{99}Tc activity was 0.35 pCi/L in the 2004 samples and 0.27 pCi/L in the 1998 samples. The ^{129}I activity is of a similar magnitude, with values of 0.19 pCi/L in 2004 and 0.27 pCi/L in 1998. The small differences between the 1998 and 2004 results are probably due to analytical uncertainties.

ER-20-5 #1 groundwater has a ^{87}Sr/^{86}Sr ratio of 0.71047, and a δ^{87}Sr value of 1.79‰. This is consistent with the range of previously reported values for groundwater from the volcanic aquifers in the NTS region (Peterman et al., 1993; Thomas et al., 2002). The concentration of dissolved uranium (14.1 µg/L) is elevated compared with most NTS groundwaters (Paces et al., 2002) but the ^{235}U/^{238}U ratio indicates the uranium is natural in origin. Elevated uranium concentrations are not unusual in some volcanic tuffs, and we infer that the high uranium content in the ER-20-5 #1 groundwater reflects the dissolution of uranium-bearing minerals present in the host rock. The ^{234}U/^{238}U activity ratio (2.90) reveals a modest enrichment in dissolved ^{234}U due to preferential leaching of this isotope from the aquifer matrix following α-decay of ^{238}U.

Plutonium is present at low concentrations (6.4 pg/L) in the 2004 groundwater samples, with a combined ^{239,240}Pu activity of 0.42 pCi/L. The observed plutonium activity is similar to previously reported values, and is strongly associated with the colloid fraction of the groundwater. As noted above, Kersting et al. (1999) demonstrated that the plutonium in ER-20-5 groundwater originated from the BENHAM test.

1.3   ER-20-5 #3

The ER-20-5 well cluster consists of two near-field monitoring wells (#1 and #3) located in the western part of Area 20, on the NTS. Well ER-20-5 #3 is situated less than 300 meters from surface ground zero of the TYBO underground nuclear test, which was detonated in the U-20y emplacement hole on May 14, 1975. The well was completed to a total depth of 1,309 meters below ground surface in rhyolitic lavas of the Calico Hills Formation, with a single slotted perforation interval between 1,046 and 1,183 meters (Figure 1.2).

Groundwater characterization samples were collected from ER-20-5 #3 on November 29, 2004. Prior to 2004, ER-20-5 #3 was last sampled on November 15, 2001 (Rose et al., 2003). No significant changes in the chemical and isotopic characteristics of the water were observed between these two sets of samples.

ER-20-5 #3 produces sodium bicarbonate groundwater with modest levels of Cl^- and SO_4^{2-} that is characteristic of the tuffaceous volcanic rocks beneath Pahute Mesa. The stable isotope composition of the groundwater (δD = -114 ‰ and $\delta^{18}O$ = -15.1 ‰) is similar to that produced from other wells in this area. The combined water quality and stable isotope data suggest that the ER-20-5 well cluster contains a mixture of groundwater from two distinct regional flow systems that underlie Pahute Mesa. These flow systems are characterized by modest differences in stable isotope values and significantly different concentrations of chloride and sulfate (Rose et al., 2002).

The tritium activity in ER-20-5 #3 groundwater was 1.13×10^5 pCi/L at the time of sampling, as determined by liquid scintillation counting (LSC). The decay-corrected value at time zero for the TYBO test (6.0×10^5 pCi/L) is very similar to the decay-corrected value measured in 2001 (6.3×10^5 pCi/L). This implies that radionuclide concentrations in the water have remained fairly constant over this time period. Despite the close proximity of the ER-20-5 well cluster to the TYBO test, plutonium isotope measurements indicate that the BENHAM test was the source of the Pu activity in both of the ER-20-5 wells (Kersting et al., 1999). Given that the BENHAM test is located >1 km up gradient from the ER-20-5 well cluster, these results have important implications for the long-range transport of radionuclides in fracture-dominated flow systems.

Dissolved inorganic carbon (DIC) in ER-20-5 #3 groundwater has a ^{14}C value of 1.68×10^3 pmc, and a corresponding ^{14}C activity of 2.7 pCi/L. This is similar to the activity measured on samples collected in 2001 (2.1 pCi/L). The $\delta^{13}C$ value measured in 2004 (-9.3‰) is more than 4‰ lighter than reported in November 2001. It is unlikely that this represents any change in the source of DIC in this aquifer and is more likely the result of analytical error.

ER-20-5 #3 groundwater has a $^{36}Cl/Cl$ ratio (2.27×10^{-11}) that is ~45 times the modern atmospheric ratio for southern Nevada. Although this ratio is well above environmental levels, the calculated ^{36}Cl activity in the groundwater is fairly low (0.013 pCi/L). Low activities were also observed for the fission products ^{99}Tc and ^{129}I, both of which are transported as soluble anions under oxidizing conditions. The measured ^{99}Tc activity is

0.017 pCi/L, while the ^{129}I activity is 0.0014 pCi/L. In general, these data indicate substantial dilution of the radionuclide source term compared with values typically observed in cavity fluid samples. Nevertheless, it is evident that a variety of radionuclides can be transported at low concentrations over fairly large distances.

The groundwater from ER-20-5 #3 has a ^{87}Sr/^{86}Sr ratio of 0.70841 and a δ^{87}Sr value of -1.11 ‰. These results are fairly typical of the values found in groundwater from the NTS volcanic aquifers (Peterman et al., 1993; Thomas et al., 2002). The concentration of dissolved uranium (5.6 μg/L) is within the normal range of values for groundwater from the NTS volcanic units (Paces et al., 2002), and the ^{235}U/^{238}U ratio indicates the uranium is natural in origin. The ^{234}U/^{238}U-activity ratio (2.53) indicates a moderate enrichment in ^{234}U due to preferential leaching of this isotope from the aquifer matrix following α-decay of ^{238}U.

The ER-20-5 #3 samples were analyzed for plutonium, but the measured concentration was very close to the method detection limit (0.6 pg/L) and it was not possible to obtain good quality isotope ratio data. Kersting et al. (1999) previously observed plutonium in ER-20-5 #3, but pre-concentration of large amounts of colloidal material was necessary to obtain reliable isotope ratio measurements.

1.4   U-3cn PS#2 (BILBY)

U-3cn PS#2 is located in the northwestern part of Area 3 of the NTS. The well head is located less than 300 m from surface ground zero of the BILBY underground nuclear test (249 kt announced yield), which was detonated under Yucca Flat in the U-3cn emplacement hole on September 13, 1963 (DOE, 2000). The BILBY test was the first underground nuclear test detonated below the water table at the NTS (Buddemeier and Isherwood, 1985).

U-3cn PS#2 was drilled into the chimney of the BILBY test, and originally perforated the test cavity (W.P. = 713 m). However, the pipe was crimped at 587 m shortly after completion, probably due to shifting blocks within the chimney (Garber, 1971), and the production interval is now between 512 and 527 m below ground surface, where saturated rocks consist of Tertiary-age rhyolitic tuffs of the Indian Trail Formation (Figure 1.3).
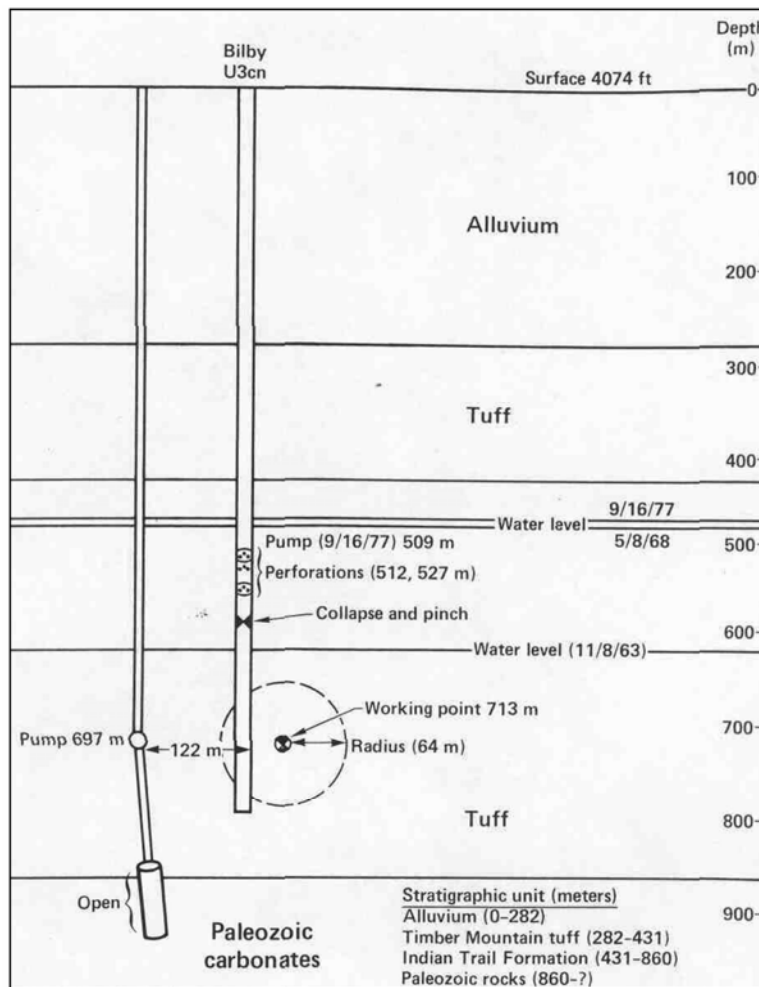
Figure 1.3 The BILBY near-field. From Buddemeier and Isherwood (1985).

Groundwater characterization samples were collected from well U-3cn PS#2 on December 9, 2004. Prior to sampling, a cumulative purge volume of ~1.5×10^4 gallons of water was pumped from the well. The well produces a sodium-potassium-bicarbonate groundwater that is low in Cl and SO_4, and is typical of the water found in tuffaceous volcanic rocks beneath Yucca Flat (Winograd and Thordarson, 1975). U-3cn PS#2 groundwater has stable isotope (δD and $\delta^{18}O$) values that are depleted in heavy isotopes relative to modern precipitation in Yucca Flat (Ingraham et al., 1991) and may reflect water that was recharged during cooler, wetter climatic conditions that were prevalent in this area during late Pleistocene time (e.g. Claassen, 1986).

The tritium activity of the U-3cn PS#2 groundwater, measured at LLNL by liquid scintillation counting (LSC) following sampling, was 7.9×10^6 pCi/L. The decay corrected value at time zero for the BILBY test is 8.0×10^7 pCi/L. This is in good agreement with the decay corrected tritium activity in the samples collected in 2001 (8.6×10^7 pCi/L) and 1997 (8.4×10^7 pCi/L).

Dissolved inorganic carbon (DIC) in U-3cn PS#2 groundwater has a ^{14}C value of 1.15×10^5 pmc, approximately three orders of magnitude higher than the modern atmospheric radiocarbon concentration. At the measured DIC concentration of 269 mg/L, this corresponds to a dissolved ^{14}C activity of 372 pCi/L. The $\delta^{13}C$ value of the water was -7.0 ‰, a little over 3 ‰ lighter than 2001.

^{36}Cl is a long-lived neutron activation product ($t_{1/2} = 3 \times 10^5$ years) that is produced during nuclear detonations, and is highly mobile as the soluble chloride anion. U-3cn PS#2 groundwater has a $^{36}Cl/Cl$ ratio (4.5×10^{-8}) that is five orders of magnitude above the modern atmospheric ratio for southern Nevada (~5×10^{-13}, Fabryka-Martin et al., 1993). The total ^{36}Cl activity in the U-3cn PS#2 groundwater is 25.5 pCi/L, less than the previous measurement in 2001 (43.2 pCi/L). The ^{36}Cl activity in U-3cn PS#2 groundwater is among the highest observed at the NTS.

The fission products ^{99}Tc and ^{129}I were measured in U-3cn PS#2 groundwater by ICP-MS and AMS, respectively. Technetium and iodine are both highly mobile as soluble anions under oxidizing conditions. For comparative purposes, the ^{99}Tc and ^{129}I concentrations in archival samples collected in 2001 were also analyzed. The measured ^{99}Tc activity was 62.6 pCi/L in the 2004 samples and 82.6 pCi/L in the 2001 samples. The ^{129}I activity in the samples was 0.25 pCi/L in 2004 and 0.16 pCi/L in 2001. There is no consistent increase or decrease in test-derived radionuclide tracer (^3H, ^{36}Cl, ^{99}Tc, and ^{129}I) concentrations between 2001 and 2004. Thus, changes in radionuclide tracer activities are not likely to be the result of physical transport processes.

U-3cn PS#2 groundwater has a $^{87}Sr/^{86}Sr$ ratio of 0.70984, and a $\delta^{87}Sr$ value of 0.9 ‰. This is consistent with the range of previously reported values for groundwater from the volcanic aquifers in the NTS region (Peterman et al., 1993; Thomas et al., 2002). The concentration of dissolved uranium (10.3 μg/L) is elevated compared with most NTS groundwaters (Paces et al., 2002) but the $^{235}U/^{238}U$ ratio indicates the uranium is natural in origin. Elevated uranium concentrations are not unusual in some volcanic tuffs, and we infer that the high uranium content in the U-3cn PS#2 groundwater reflects the

dissolution of uranium-bearing minerals present in the host rock. The ^{234}U/^{238}U activity ratio (2.80) reveals a modest enrichment in dissolved ^{234}U due to preferential leaching of this isotope from the aquifer matrix following α-decay of ^{238}U.

Plutonium was not detected in the groundwater from U-3cn PS#2 (^{239,240}Pu <0.01 pCi/L). Plutonium was measured on a bulk sample which includes both the colloidal and aqueous fractions of the groundwater.

1.5   UE-2ce (NASH)

UE-2ce is located in Area 2 of the NTS and lies at a relatively high elevation on the eastern rim of Yucca Flat. UE-2ce was completed on January 25, 1977 to a depth of 503 meters. It is located less than 183 m south from NASH surface ground zero. The NASH test was detonated in emplacement hole U-2ce at a depth of 368 meters on 19 January 1967 with an announced yield of 39 kt (DOE, 2000). Both the working point of the NASH test and the UE-2ce satellite well perforations are in the Paleozoic carbonate of the Lower Carbonate Aquifer (LCA). The cavity of the NASH test is entirely above the water table (cavity radius is 29.1 meters). However, ^{3}H has been consistently measured at the satellite well. The boundary between the LCA and the overlying volcanic tuff is at 340 m-bgs (Buddemeier & Isherwood, 1985). Near-field geometry and water level measurements at UE-2ce are plotted in Figure 1.4.
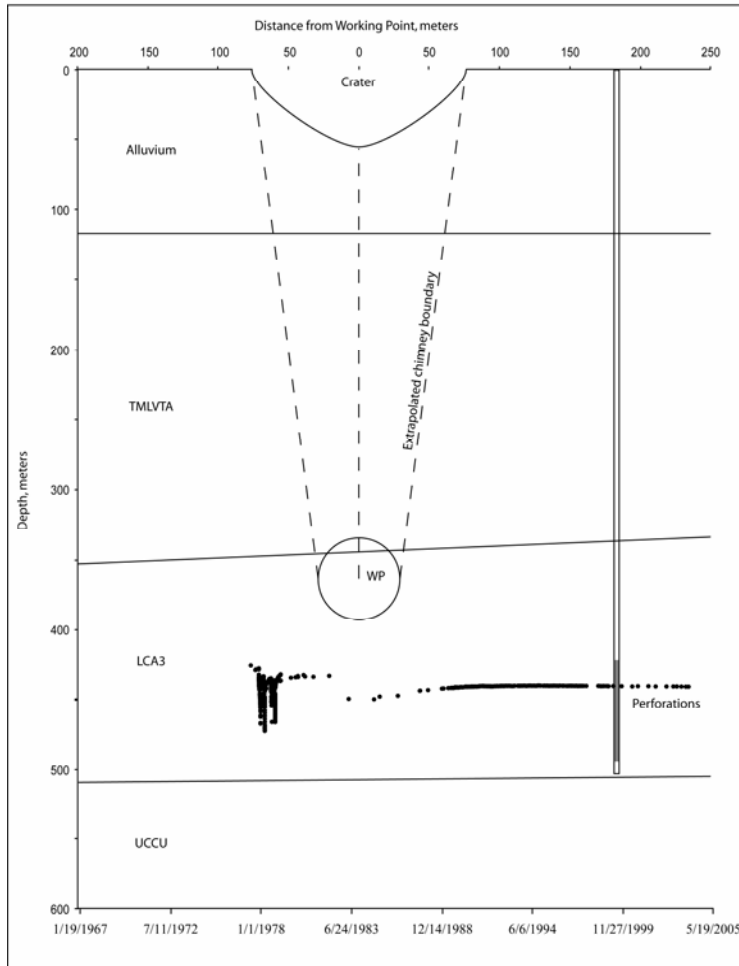
Figure 1.4 The NASH near-field geometry and water level measurements as a function of time.

Groundwater characterization samples were collected from well UE-2ce using evacuated steel pressure tubes, lowered into the hole with the USGS wire-line bailer, between July 11 and 13, 2005. Even though these samples were collected over a three day period, all were collected at the same depth (481 meters), and a common date of 12 July 2005 was assigned to all analytical samples collected during this period. The water depth at the time of sampling was approximately 441 meters, indicating that the water level has not drastically changed since the well was last sampled in August of 2001 (~ 448 meters). Importantly, it should be noted that the water level in UE-2ce has never returned to the levels measured soon after well completion and before significant pumping in the 1980s (Figure 1.4).

Well UE-2ce produces a Ca-Mg-Na-HCO$_3$ type groundwater that is low in Cl and SO$_4$, and is similar to other LCA waters (SNJV, 2006). UE-2ce has δ^{18}O and δD values that are enriched in heavy isotopes (δ^{18}O = -12.6 ‰; δD = -98 ‰) compared with most Yucca Flat waters, particularly those from the LCA. The data suggest that a significant fraction of the groundwater at UE-2ce may be derived from local recharge (SNJV, 2006).

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The tritium activity of the UE-2ce groundwater, measured at LLNL by liquid scintillation counting (LSC), was 9.3×10^4 pCi/L. The decay corrected value at time zero for the NASH test is 8.3×10^5 pCi/L. The decay corrected tritium activity for samples collected in 2001 was 9.9×10^5 pCi/L. It should be noted that the ^3H activities found in these bailed samples are much lower (~ 2 orders of magnitude) than in pumped samples collected in 1984 (Buddemeier and Isherwood, 1985).

Dissolved inorganic carbon (DIC) in UE-2ce groundwater has a measured DIC concentration of 337 mg/L and a ^{14}C value of 2.0×10^2 pmc that corresponds to a dissolved ^{14}C activity of 0.82 pCi/L. Though the ^{14}C activity is low, it appears to be test-derived and suggests that ^{14}C transport from NASH to the satellite well has taken place. The $\delta^{13}C$ value of the water was -6.6 ‰, about 1 ‰ lighter than 2001. Nevertheless, both values are indicative of dissolution of LCA rock to produce $\delta^{13}C$ values intermediate between soil zone $\delta^{13}C$ and LCA rock $\delta^{13}C$.

^{36}Cl is a long-lived neutron activation product ($t_{1/2} = 3 \times 10^5$ years) that is produced during nuclear detonations, and is highly mobile as the soluble chloride anion. UE-2ce groundwater has a $^{36}Cl/Cl$ ratio of 9.54×10^{-10} that is three orders of magnitude above the modern atmospheric ratio for southern Nevada (~5×10^{-13}, Fabryka-Martin et al., 1993). The total ^{36}Cl activity in the U-3cn PS#2 groundwater is 0.45 pCi/L, slightly less than the previous measurement in 2001 (0.83 pCi/L). However, both values are indicative of a test-derived source and suggest ^{36}Cl transport from NASH to the satellite well.

The fission products ^{99}Tc and ^{129}I were measured in UE-2ce groundwater by ICP-MS and AMS, respectively. Technetium and iodine are both highly mobile as soluble anions under oxidizing conditions. The measured ^{99}Tc activity was $<2.4 \times 10^{-3}$ pCi/L. The ^{129}I activity was 0.024 pCi/L. The ^{129}I value is similar to that measured in 2001 (0.032 pCi/L). There is no consistent increase or decrease in radionuclide activities between 2001 and 2005.

UE-2ce groundwater has a $^{87}Sr/^{86}Sr$ ratio of 0.71137, a $\delta^{87}Sr$ value of 3.1 ‰, and a Sr concentration of 194 μg/L.[1] This is consistent with the range of previously reported values for groundwater from the carbonate aquifer in Yucca Flat. However, both the Sr isotope ratio and Sr concentration are on the low end for LCA waters and suggest some interaction with volcanic aquifer rocks. The concentration of dissolved uranium (2.0 μg/L) is consistent with most NTS groundwaters (Paces et al., 2002) and the $^{235}U/^{238}U$ ratio indicates the uranium is natural in origin. The $^{234}U/^{238}U$ activity ratio (3.53) reveals a modest enrichment in dissolved ^{234}U due to preferential leaching of this isotope from the aquifer matrix following α-decay of ^{238}U.

Plutonium was not detected in the groundwater from UE-2ce ($^{239,240}Pu$ <0.07 pCi/L). The colloidal and aqueous fractions were measured by pre-concentrating 3 liters of sample. Pu was not detected in either fraction.

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[1] The value has been corrected since it was first reported in the UE-2ce well report dated July 14, 2006.

1.6   References

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Table 1.1 Hotwell Site Information

Well name	Test Name	Test Date	Latitude	Longitude	Surface Elevation	Well Depth	Open Interval	Water Depth	Sample Method	Volume Pumped	Sample Depth	Sample date
Units			*(d m s)*	*(d m s)*	*(ft)*	*(ft bgs)*	*(ft bgs)*	*(ft bgs)*		*(gal)*	*(ft bgs)*	
Hot Wells - Frenchman Flat												
UE5n	CAMBRIC	14-May-65	36 49 34	116 06 59	3112	1690	720-730	---	pump	---	---	12-Feb-04
UE5n	CAMBRIC	14-May-65	36 49 34	116 06 59	3112	1690	720-730	702	pump	---	702	19-Apr-01
UE5n	CAMBRIC	14-May-65	36 49 34	116 06 59	3112	1690	720-730	705	pump	---	730	09-Sep-99
RNM-1	CAMBRIC	14-May-65	36 49 28	115 58 01	3135	1302*	1063-1075*	789*	pump	1.68E+04	---	03-Jun-04
RNM-1	CAMBRIC	14-May-65	36 49 28	115 58 01	3135	1302*	1063-1075*	789*	pump	---	---	28-Jun-00
RNM-2S	CAMBRIC	14-May-65	36 49 21	115 58 01	3133	1120	1038-1119	723	pump	6.39E+07	---	10-Jul-03
RNM-2S	CAMBRIC	14-May-65	36 49 21	115 58 01	3133	1120	1038-1119	723	pump	1.00E+07	---	09-May-03
RNM-2S	CAMBRIC	14-May-65	36 49 21	115 58 01	3133	1120	1038-1119	723	pump	---	---	14-Jun-00
RNM-2S	CAMBRIC	14-May-65	36 49 21	115 58 01	3133	1120	1038-1119	723	pump	---	800	11-Oct-99
Hot Wells - Yucca Flat												
U4u PS2a	DALHART	13-Oct-88	37 05 13	116 02 51	4117	2280	1548-1644	1636	pump	7.06E+03	---	09-Oct-03
U4u PS2a	DALHART	13-Oct-88	37 05 13	116 02 51	4117	2280	1548-1644	1636	pump	---	1640	16-Aug-99
UE-7ns	BOURBON	20-Jan-67	37 05 56	116 00 09	4369	2205	1995-2199	1969	bailer	---	2025	21-Aug-01
UE-2ce	NASH	19-Jan-67	37 08 31	116 08 07	4764	1650	1385-1624	1448	bailer	---	1580	12-Jul-05
UE-2ce	NASH	19-Jan-67	37 08 31	116 08 07	4764	1650	1385-1624	1470	bailer	---	1550	22-Aug-01
U-3cn PS#2	BILBY	13-Sep-63	37 03 38	116 01 19	3994	2603	1680-1729	1550	pump	---	1652-1656	09-Dec-04
U-3cn PS#2	BILBY	13-Sep-63	37 03 38	116 01 19	3994	2603	1680-1729	1550	pump	---	1652-1656	18-Dec-01
Hot Wells - Pahute Mesa												
U20n PS1 DDh	CHESHIRE	14-Feb-76	37 14 25	116 25 24	6468	4253	4100-4110	2051	pump	---	4100	09-Jul-03
U20n PS1 DDh	CHESHIRE	14-Feb-76	37 14 25	116 25 24	6468	4253	4100-4110	2051	pump	---	4100	12-Oct-99
U19ad PS1A	CHANCELLOR	1-Sep-83	37 16 13	116 21 17	6656	2609*	2407-2579*	2240*	pump	2.04E+05	2370*	27-Sep-04
U19q PS1d	CAMEMBERT	26-Jun-75	37 16 49	116 21 54	6740	4991*	3665-3678*	2185*	pump	1.12E+04	3000*	16-Jul-03
U19q PS1d	CAMEMBERT	26-Jun-75	37 16 49	116 21 54	6740	4991*	3665-3678*	2185*	pump	1.47E+04	3000*	21-Oct-98
U19v PS1ds	ALMENDRO	06-Jun-73	37 14 53	116 20 57	6842	3837*	---		bailer	---		23-Jul-03
U19v PS1ds	ALMENDRO	06-Jun-73	37 14 53	116 20 57	6842	3837*	---	2187*	bailer	---	3089*	31-May-01
U19v PS1ds	ALMENDRO	06-Jun-73	37 14 53	116 20 57	6842	3837*	---	2170*	bailer	---	3089*	26-Sep-00
U19v PS1ds	ALMENDRO	06-Jun-73	37 14 53	116 20 57	6842	3837*	---	2170*	bailer	---	2999*	18-Aug-99
ER-20-5 #1	TYBO/BENHAM†	14-May-75	31 13 12	116 28 38	6242	2823	2301-2573	2055	pump	---	2300-2572	30-Nov-04
ER-20-5 #1	TYBO/BENHAM †	14-May-75	31 13 12	116 28 38	6242	2823	2301-2573	2055	pump	---	2300-2572	09-Jul-98
ER-20-5 #3	TYBO/BENHAM †	14-May-75	37 13 11	116 28 38	6242	4294	3430-3882	2060	pump	---	3383-3405	29-Nov-04
ER-20-5 #3	TYBO/BENHAM †	14-May-75	37 13 11	116 28 38	6242	4294	3430-3882	2060	pump		3383-340	15-Nov-01
ER-20-5 #3	TYBO/BENHAM †	14-May-75	37 13 11	116 28 38	6242	4294	3430-3882	2060	pump		3383-340	30-Apr-98

* Reported values are measured depths along a slanted borehole. Approximate slant angles: RNM-1 (21°); U19ad PS1A (22°); U19v PS1ds (20.6°); U19q PS1d (unknown).

† Both the TYBO and BENHAM tests are listed since the ER-20-5 well cluster was drilled in the near-field (~300 m from the surface ground zero) environment of the TYBO test. However, Pu isotopic signatures indicate the radionuclides in water samples from ER-20-5 wells are derived from the BENHAM test detonated ~1300 m up-gradient (Kersting et al., 1999). The date listed is the TYBO date, BENHAM took place on 12/19/1968.

Table 1.2 Field parameter and anion data

Well name	Test	Sample date	Volume Pumped	pH	T	Cond.	TDIC as HCO$_3^-$	F	Cl	Br	NO$_3$	SO$_4$
Units		date	(gal)		(°C)	(μS/cm)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Hot Wells - Frenchman Flat												
UE5n	CAMBRIC	12-Feb-04		8.2*	---	452*	178	0.7	11.7	0.1	6.0	31.9
UE5n	CAMBRIC	19-Apr-01		8.7	23.0	408	162	0.7	12.9	<0.1	6.7	32.0
UE5n	CAMBRIC	09-Sep-99		8.4	26.5	453	183	0.8	12.0	<0.03	8.1	31.8
RNM-1	CAMBRIC	03-Jun-04	1.68E+04	7.8*	---	432*	166	0.4	9.7	0.1	13.4	34.7
RNM-1	CAMBRIC	28-Jun-00		8.0	26.0	416	---	0.3	12.3	0.2	16.2	36.5
RNM-2S	CAMBRIC	10-Jul-03	6.39E+07	8.0	24.4	418	168	0.5	13.5	0.6	12.6	38.0
RNM-2S	CAMBRIC	09-May-03	1.00E+07	8.2	24.0	450	152	0.5	13.6	0.6	12.5	38.0
RNM-2S	CAMBRIC	14-Jun-00	---	7.8*	---	429*	130	0.4	14.8	0.2	14.3	36.8
RNM-2S	CAMBRIC	11-Oct-99	---	8.2	24.6	440	168	0.6	13.7	<0.03	13.9	37.0
Hot Wells - Yucca Flat												
U4u PS2a	DALHART	09-Oct-03	7.06E+03	6.7	---	385	174	1.6	5.1	<0.03	2.5	12.3
U4u PS2a	DALHART	16-Aug-99	---	8.2*	---	352*	160	0.7	5.8	<0.03	18.5	12.0
UE-7ns	BOURBON	21-Aug-01	wire-line bailer	8.0*	---	375*	166	0.8	22.9	<0.1	<0.09	1.6
UE-2ce	NASH	12-Jul-05	wire-line bailer	7.3	---	466	337	1.1	14.2	<0.02	1.6	16.6
UE-2ce	NASH	22-Aug-01	wire-line bailer	7.9*	---	435*	308	0.3	15.5	<0.1	<0.09	11.1
U-3cn PS#2	BILBY	09-Dec-04	1.51E+04	8.1*	---	528	269	1.38	17.3	1.0	7.2	19.2
U-3cn PS#2	BILBY	18-Dec-01	---	8.1*	---	490*	287	0.8	8.6	0.6	5.8	20.3
Hot Wells - Pahute Mesa												
U20n PS1 DDh	CHESHIRE	09-Jul-03	---	8.5	38.4	330	90	3.6	10.9	0.6	1.9	27.9
U20n PS1 DDh	CHESHIRE	12-Oct-99	---	8.2	38.2	324	108	3.6	11.1	<0.03	2.3	28.2
U19ad PS1A	CHANCELLOR	27-Sep-04	2.04E+05	9.4	47.0	941	110	36.0	43.5	<0.02	3.0	106.4
U19q PS1d	CAMEMBERT	16-Jul-03					496	15.5	7.2	<0.03	0.5	20.8
U19q PS1d	CAMEMBERT	21-Oct-98	1.47E+04	7.2	33.0	959	1016	31.5	10.4	<0.1	<0.07	29.7
U19v PS1ds	ALMENDRO	23-Jul-03	---	9.3	35.7	517	207	8.9	53.2	0.1	0.7	0.8
U19v PS1ds	ALMENDRO	31-May-01	---	---	---	---	250	9.7	66.5	<0.1	<0.09	2.5
U19v PS1ds	ALMENDRO	26-Sep-00	---	9.3*	---	742*	262	9.5	48.2	<0.1	<0.09	3.8
U19v PS1ds	ALMENDRO	18-Aug-99	---	8.2*	---	728*	120	9.9	40.5	<0.03	<0.02	3.9
ER-20-5 #1	TYBO/BENHAM†	30-Nov-04	---	8.1*	---	545*	193	10.8	24.7	0.1	1.8	43.2
ER-20-5 #1	TYBO/BENHAM †	09-Jul-98	---	8.1	32.3	510	182	9.6	24.5	<0.04	1.4	40.4
ER-20-5 #3	TYBO/BENHAM †	29-Nov-04	---	8.2*	---	376*	135	4.1	17.4	0.1	1.7	35.3
ER-20-5 #3	TYBO/BENHAM †	15-Nov-01	---	8.0*	---	345*	110	3.6	18.9	0.8	2.6	35.3
ER-20-5 #3	TYBO/BENHAM †	30-Apr-98	---	8.2	35.3	335	107	3.2	17.3	<0.02	1.2	33.3

* pH and conductivity values marked with an asterisk are laboratory measurements
† Both the TYBO and BENHAM tests are listed since the ER-20-5 well cluster was drilled in the near-field (~300 m from the surface ground zero) environment of the TYBO test. However, Pu isotopic signatures indicate the radionuclides in water samples from ER-20-5 wells are derived from the BENHAM test detonated ~1300 m up-gradient (Kersting et al., 1999).

Table 1.3 Cations and metals data

Well name	Test	Sample date	Na	K	Ca	Mg	Li	Al	Si	Fe	Mn	As	Se	Sr	Mo	Sb	I	Ba	Pb	U	Pu
Unit			(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(pg/L)
Hot Wells - Frenchman Flat																					
UE5n	CAMBRIC	12-Feb-04	86.7	7.7	8.3	2.2	<0.01	0.021	41.3	1.08	44	11.9	1.5	28	6.1	0.39	19.0	4.7	2.8	4.45	<0.2
UE5n	CAMBRIC	19-Apr-01	76.0	8.0	8.6	2.0	0.02	<0.05	27.4	<0.04	<6	22	---	22	4	---	20.3	21	---	0.41	---
UE5n	CAMBRIC	09-Sep-99	86.0	8.0	7.5	2.0	<0.05	<0.02	---	0.06	10	9	<2	50	5	---	30.0	<5	0.37	4.00	---
RNM-1	CAMBRIC	03-Jun-04	45.5	7.5	26.8	10.4	0.03	0.005	50.5	0.003	9.9	9.7	1.6	166	4.4	0.18	16.2	19.3	3.4	3.84	0.17
RNM-1	CAMBRIC	28-Jun-00	44.0	8.0	26.0	9.4	0.03	0.4	20	0.18	<6	9.8	1.5	300	5.1	0.15	17.9	18.5	0.01	4.00	---
RNM-2S	CAMBRIC	10-Jul-03	56.7	7.8	15.1	5.7	0.02	<0.05	37.2	<0.04	<6	<20	<24S	102	<3	---	12.2	6	<14	4.91	<0.2
RNM-2S	CAMBRIC	09-May-03	57.2	7.9	16.3	5.9	0.02	<0.05	35.5	<0.04	<6	27	<24	101	<3	---	12.1	5	<14	4.93	<0.2
RNM-2S	CAMBRIC	14-Jun-00	62.0	9.7	18.0	5.2	0.02	0.4	35	0.18	<6	10.5	1.6	140	4.4	0.14	12.0	17.3	<0.01	5.00	---
RNM-2S	CAMBRIC	11-Oct-99	63.0	9.2	17.0	5.6	<0.05	<0.02	32	0.01	<2	5	<2	110	3	---	11.0	<5	0.24	4.00	---
Hot Wells - Yucca Flat																					
U4u PS2a	DALHART	09-Oct-03	87.0	22.1	12.7	1.2	0.02	10.7	61.6	1.99	125	13.9	0.9	25	5.1	0.54	7.1	27.3	17.6	7.43	5.0
U4u PS2a	DALHART	16-Aug-99	72.0	14.0	13.1	2.7	0.14	12.0	37	1.30	90	4	<1	30	<1	---	3.1	30	8.6	4.20	8.7
UE-7ns	BOURBON	21-Aug-01	67.4	4.9	20.9	3.6	0.06	<0.05	10.0	0.21	55	21	<24	70	26	---	19.2	77	<14	0.04	<0.6
UE-2ce	NASH	12-Jul-05	38.1	17.6	46.0	24.9	0.08	0.0	13	12	199.6	5.5	< 0.6	194	8.9	1.09	4.0	22.5	551	2.00	<1
UE-2ce	NASH	22-Aug-01	45.6	21.8	49.1	25.4	0.10	<0.05	22.2	0.11	66	<20	<24	160	17	---	7.4	47	<14	0.39	<0.6
U-3cn PS#2	BILBY	09-Dec-04	89.4	15.3	11.9	3.3	0.02	1.23	46.9	4.23	173	5.6	1.5	21	7.2	0.88	9.5	18.7	104	10.31	---
U-3cn PS#2	BILBY	18-Dec-01	98.4	18.3	14.4	3.3	0.05	0.3	28.7	0.30	78	<20	<24	24	3.5	---	9.1	4	<14	10.67	<0.6
Hot Wells - Pahute Mesa																					
U20n PS1 DDh	CHESHIRE	09-Jul-03	60.7	1.9	3.8	0.1	0.06	0.7	30.9	0.81	170	<20	<24	12	9.1	---	2.0	3	<14	2.07	4.1
U20n PS1 DDh	CHESHIRE	12-Oct-99	65.0	2.2	4.7	0.1	<0.05	0.1	24	1.4	110	3	<2	10	10	---	13.0	<5	0.67	2.30	7.0
U19ad PS1A	CHANCELLOR	27-Sep-04	156.2	6.6	0.8	0.0	0.73	9.69	115.3	2.02	357	232	2.4	17	1024	30.6	19.4	72.9	21.8	2.60	369.9
U19q PS1d	CAMEMBERT	16-Jul-03	199.0	9.0	5.0	0.2	0.49	50	20.2	11.53	586	14.6	0.3	7.9	40.7	0.89	4.0	9.7	16.4	2.61	<0.2
U19q PS1d	CAMEMBERT	21-Oct-98	342.0	10.3	3.2	0.0	1.06	70	32	5.77	530	4	<3	<0.01	40	---	10.0	<10	0.60	<0.5	---
U19v PS1ds	ALMENDRO	23-Jul-03	140.0	8.8	1.0	0.1	0.17	0.04	22.8	10.6	160	341	0.08	18	2059	250	10.1	60	82	0.11	<0.2
U19v PS1ds	ALMENDRO	31-May-01	173.0	14.0	1.5	0.2	0.28	0.3	2.0	3.7	330	140	<24	44	1200	---	13.7	60	250	0.03	2.1
U19v PS1ds	ALMENDRO	26-Sep-00	131.0	11.6	0.7	0.1	0.24	0.3	6.6	0.19	---	50	<24	---	1100	---	11.4	20	22	0.02	---
U19v PS1ds	ALMENDRO	18-Aug-99	162.0	9.8	0.9	0.2	0.42	0.5	11	12.0	250	1716	8	40	1226	---	7.4	70	63	<0.5	58.2
ER-20-5 #1	TYBO/BENHAM†	30-Nov-04	117.5	4.6	6.2	0.1	<0.01	6.53	67.9	0.40	22	10.3	0.9	21	40.2	1.30	5.4	13.3	9.1	14.09	6.4
ER-20-5 #1	TYBO/BENHAM †	09-Jul-98	106.0	5.7	7.2	0.4	0.09	5.76	48.4	1.32	50	3.1	<3	20	0.03	---	7.0	<10	2.9	15.00	---
ER-20-5 #3	TYBO/BENHAM †	29-Nov-04	80.4	3.5	3.5	<0.04	<0.01	8.53	54.6	2.24	129	14.4	0.9	30	10.4	0.46	4.7	28.8	18.2	5.64	0.6
ER-20-5 #3	TYBO/BENHAM †	15-Nov-01	87.1	3.3	4.4	0.1	0.07	3.60	29	1.9	75	23	<24	31	5.8	---	5.8	17	<14	12.80	<0.6
ER-20-5 #3	TYBO/BENHAM †	30-Apr-98	68.0	2.1	1.8	0.1	0.07	1.03	24	0.46	20	4.8	<3	7	<0.01	---	8.0	<10	0.9	2.70	---

† Both the TYBO and BENHAM tests are listed since the ER-20-5 well cluster was drilled in the near-field (~300 m from the surface ground zero) environment of the TYBO test. However, Pu isotopic signatures indicate the radionuclides in water samples from ER-20-5 wells are derived from the BENHAM test detonated ~1300 m up-gradient (Kersting et al., 1999).

Table 1.4 Trace metal data

Well name	Test	Sample date	V	Cr	Co	Ni	Cu	Zn	Br *	Rb	Nb	Ru	Cd	Sn	Cs	Eu
Unit			(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)
Hot Wells - Frenchman Flat																
UE5n	CAMBRIC	12-Feb-04	15.5	1.29	0.17	0.65	BD	37.0	129	8.4	0.22	0.078	0.09	0.83	0.09	0.05
UE5n	CAMBRIC	19-Apr-01														
UE5n	CAMBRIC	09-Sep-99														
RNM-1	CAMBRIC	03-Jun-04	12.6	1.89	0.08	3.24	BD	21.5	119	8.1	0.08	0.019	0.04	1.05	0.05	0.02
RNM-1	CAMBRIC	28-Jun-00	12.8	2.15	0.05	1.95	BD	BD	123	8.3	0.15	0.007	0.01	0.06	0.02	BD
RNM-2S	CAMBRIC	10-Jul-03														
RNM-2S	CAMBRIC	09-May-03														
RNM-2S	CAMBRIC	14-Jun-00	15.8	3.58	0.08	0.75	BD	BD	139	10	0.10	0.003	0.01	0.02	0.03	BD
RNM-2S	CAMBRIC	11-Oct-99														
Hot Wells - Yucca Flat																
U4u PS2a	DALHART	09-Oct-03	7.0	3.02	0.18	0.99	BD	38.8	50	46	4.25	0.004	0.07	0.20	1.47	0.05
U4u PS2a	DALHART	16-Aug-99														
UE-7ns	BOURBON	21-Aug-01														
UE-2ce	NASH	12-Jul-05	< 0.9	3.4	1.43	9	38.8	488	n/a	39.7	< 0.09	< 0.42	< 0.6	n/a	< 0.6	< 0.012
UE-2ce	NASH	22-Aug-01														
U-3cn PS#2	BILBY	09-Dec-04	5.8	1.55	0.43	11.6	BD	126	68	51	0.15	BD	0.92	0.06	0.40	BD
U-3cn PS#2	BILBY	18-Dec-01														
Hot Wells - Pahute Mesa																
U20n PS1 DDh	CHESHIRE	09-Jul-03														
U20n PS1 DDh	CHESHIRE	12-Oct-99														
U19ad PS1A	CHANCELLOR	27-Sep-04	101	0.44	0.19	1.42	BD	42.3	158	80	9.10	0.003	0.58	0.69	11.7	0.44
U19q PS1d	CAMEMBERT	16-Jul-03	1.5	3.86	0.66	50.1	BD	336	56	57	3.95	0.002	0.12	1.61	3.69	0.01
U19q PS1d	CAMEMBERT	21-Oct-98														
U19v PS1ds	ALMENDRO	23-Jul-03	1.4	0.09	0.37	1.63	BD	65.6	127	66	0.25	0.005	0.78	0.02	1.24	BD
U19v PS1ds	ALMENDRO	31-May-01														
U19v PS1ds	ALMENDRO	26-Sep-00														
U19v PS1ds	ALMENDRO	18-Aug-99														
ER-20-5 #1	TYBO/BENHAM†	30-Nov-04	3.2	0.98	0.11	61.5	BD	42.0	134	27	1.24	0.002	0.05	0.16	2.86	0.004
ER-20-5 #1	TYBO/BENHAM †	09-Jul-98				<0.01										
ER-20-5 #3	TYBO/BENHAM †	29-Nov-04	6.1	1.94	0.38	68.9	BD	54.4	102	38	4.89	0.001	0.20	0.56	2.74	0.03
ER-20-5 #3	TYBO/BENHAM †	15-Nov-01														
ER-20-5 #3	TYBO/BENHAM †	30-Apr-98				<0.01										

† Both the TYBO and BENHAM tests are listed since the ER-20-5 well cluster was drilled in the near-field (~300 m from the surface ground zero) environment of the TYBO test. However, Pu isotopic signatures indicate the radionuclides in water samples from ER-20-5 wells are derived from the BENHAM test detonated ~1300 m up-gradient (Kersting et al., 1999).

Table 1.5 Stable Isotope data

Well name	Test	Sample date	δD_{SMOW}	$\delta^{18}O_{SMOW}$	$\delta^{13}C_{PDB}$	^3He	^4He	R/R_a	$^{20}Ne*$	$^{40}Ar*$	Kr	$^{130}Xe*$	$^{87}Sr/^{86}Sr$	$\delta^{87}Sr$
Unit			‰	‰	‰	atoms/g	atoms/g	$^3He/^4He$ sample/air	atoms/g	atoms/g	atoms/g	atoms/g	ratio	‰
Hot Wells - Frenchman Flat														
UE5n	CAMBRIC	12-Feb-04	-105	-13.5	-8.0	---	---	---	---	---	---	---	0.70871	-0.69
UE5n	CAMBRIC	19-Apr-01	-105	-13.4	-6.7	2.70E+09	2.34E+12	8.36E+02	4.66E+12	8.30E+15	---	1.14E+10*	0.71039	1.68
UE5n	CAMBRIC	09-Sep-99	-106	-13.4	-8.3	1.95E+09	3.16E+12	4.48E+02	7.25E+12	1.04E+16	---	1.19E+10*	---	---
RNM-1	CAMBRIC	03-Jun-04	-104	-12.8	-8.5	---	---	---	---	---	---	---	0.70772	-2.09
RNM-1	CAMBRIC	28-Jun-00	-104	-12.7	---	1.43E+09	2.05E+12	5.05E+02	4.15E+12	7.63E+15	---	---	---	---
RNM-2S	CAMBRIC	10-Jul-03	-105	-13.1	-9.5	4.29E+10	1.94E+13	1.60E+03	7.17E+13	---	---	3.63E+10	0.71049	1.82
RNM-2S	CAMBRIC	09-May-03	-105	-13.1	-8.2	2.53E+10	2.77E+12	6.62E+03	3.34E+12	---	---	1.35E+10	0.71051	1.85
RNM-2S	CAMBRIC	14-Jun-00	-105	-13.0	-5.3	2.50E+10	6.43E+12	2.84E+03	5.50E+12	9.11E+15	---	---	---	---
RNM-2S	CAMBRIC	11-Oct-99	-104	-12.9	-9.3	2.35E+10	6.40E+12	2.65E+03	4.35E+12	8.09E+15	---	---	---	---
Hot Wells - Yucca Flat														
U4u PS2a	DALHART	09-Oct-03	-104.5	-13.5	-9.4	5.56E+11	5.57E+12	7.23E+04	1.33E+13	---	---	1.08E+10	0.71275	5.01
U4u PS2a	DALHART	16-Aug-99	-100	-12.8	-8.7	---	---	---	---	---	---	---	---	---
UE-7ns	BOURBON	21-Aug-01	-106	-14.0	-2.0	1.93E+10	2.45E+12	5.71E+03	6.52E+12	9.30E+15	---	1.10E+10*	---	---
UE-2ce	NASH	12-Jul-05	-98	-12.6	-6.6	---	---	---	---	---	---	---	0.71137	3.06
UE-2ce	NASH	22-Aug-01	-100	-12.9	-5.3	4.78E+09	2.36E+12	1.47E+03	7.14E+12	9.31E+15	---	1.09E+10*	---	---
U-3cn PS#2	BILBY	09-Dec-04	-110	-13.9	-7.0	---	---	---	---	---	---	---	0.70984	0.9
U-3cn PS#2	BILBY	18-Dec-01	-108	-13.9	-3.8	5.98E+11	3.59E+12	1.21E+05	7.41E+12	9.30E+15	---	1.00E+10*	0.70974	0.76
Hot Wells - Pahute Mesa														
U20n PS1 DDh	CHESHIRE	09-Jul-03	-114	-15.0	-4.0	2.12E+12	1.02E+13	1.51E+05	5.63E+12	---	---	1.24E+10	0.71088	2.37
U20n PS1 DDh	CHESHIRE	12-Oct-99	-113	-15.0	-6.0	2.01E+12	1.01E+13	1.44E+05	5.70E+12	6.45E+15	---	---	0.71078	2.23
U19ad PS1a	CHANCELLOR	27-Sep-04	-112	-14.7	-8.6	---	---	---	---	---	---	---	0.71049	1.82
U19q PS1d	CAMEMBERT	16-Jul-03	-114	-15.0	+0.5	---	---	---	---	---	---	---	0.71190	3.81
U19q PS1d	CAMEMBERT	21-Oct-98	-113	-14.6	+1.5	2.02E+12	1.85E+14	7.90E+03	7.73E+12	---	---	---	0.71260	4.79
U19v PS1ds	ALMENDRO	23-Jul-03	-112	-13.4	+35.4	7.64E+10	9.52E+11	5.82E+04	5.74E+12	---	---	1.69E+10	0.71113	2.72
U19v PS1ds	ALMENDRO	31-May-01	-112	-13.3	+30.1	3.75E+11	1.50E+12	1.81E+05	4.42E+12	1.45E+16	---	3.86E+10*	---	---
U19v PS1ds	ALMENDRO	26-Sep-00	-111	-13.4	+30.2	---	---	---	---	---	---	---	---	---
U19v PS1ds	ALMENDRO	18-Aug-99	-111	-13.4	+45.0	---	---	---	---	---	---	---	---	---
ER-20-5 #1	TYBO/BENHAM†	30-Nov-04	-115	-14.9	-4.7	---	---	---	---	---	---	---	0.71047	7.79
ER-20-5 #1	TYBO/BENHAM †	09-Jul-98			-2.48	4.15E+12	2.64E+13	1.14E+05	7.55E+12	---	---	---	---	2.59
ER-20-5 #3	TYBO/BENHAM †	29-Nov-04	-114	-15.1	-9.3	---	---	---	---	---	---	---	0.70841	-1.11
ER-20-5 #3	TYBO/BENHAM †	15-Nov-01	-114	-15.0	-4.0	8.09E+09	7.48E+12	7.84E+02	7.49E+12	---	---	1.13E+10*	0.70864	-0.79
ER-20-5 #3	TYBO/BENHAM †	30-Apr-98			-5.6	1.21E+10	1.21E+13	7.23E+02	7.23E+12	---	---	---	---	-0.73

* Inconsistencies have been identified in the noble gas data. This issue will be addressed in the FY06 HRMP report.
† Both the TYBO and BENHAM tests are listed since the ER-20-5 well cluster was drilled in the near-field (~300 m from the surface ground zero) environment of the TYBO test.
   However, Pu isotopic signatures indicate the radionuclides in water samples from ER-20-5 wells are derived from the BENHAM test detonated ~1300 m up-gradient (Kersting et al., 1999).

Table 1.6 Radiochemical data

Well name	Test	Sample date	^{3}H (pCi/L)	^{3}H (pCi/L)	^{14}C (pmc)	^{14}C (pCi/L)	^{36}Cl/Cl ratio	^{36}Cl (pCi/L)	^{85}Kr (pCi/L)	^{99}Tc (pCi/L)	^{129}I/^{127}I ratio	^{129}I (pCi/L)
Unit		*date*	*(pCi/L)*	*(pCi/L)*	*(pmc)*	*(pCi/L)*	*ratio*	*(pCi/L)*	*(pCi/L)*	*(pCi/L)*	*ratio*	*(pCi/L)*
Half-life (a)		*collected*	*12.32*	*12.32*	*5730*	*5730*		*3.01E+05*	*10.73*	*2.13E+05*		*1.57E+07*
Ref. date		*in field*	*collect.*	*time zero*	*collect.*	*collect.*		*collect.*	*collect.*	*collect.*		*collect.*
Hot Wells - Frenchman Flat												
UE5n	CAMBRIC	12-Feb-04	1.5E+05	1.3E+06	1.66E+01	3.55E-02	6.49E-10	2.51E-01	---	5.6E-03	5.02E-07	1.70E-03
UE5n	CAMBRIC	19-Apr-01	1.4E+05	1.1E+06	2.84E+01	5.53E-02	5.38E-10	2.29E-01	---	---	---	---
UE5n	CAMBRIC	09-Sep-99	1.3E+05	8.9E+05	1.88E+01	4.14E-02	6.01E-10	2.38E-01	<40	2.3E-03	3.51E-09	---
RNM-1	CAMBRIC	03-Jun-04	3.4E+02	3.1E+03	1.22E+03	2.44E+00	1.38E-12	4.42E-04	---	<0.0034	2.06E-07	5.96E-04
RNM-1	CAMBRIC	28-Jun-00	2.8E+04	2.1E+05	---	---	1.06E-12	4.30E-04	---	---	---	---
RNM-2S	CAMBRIC	10-Jul-03	1.3E+05	1.1E+06	3.64E+02	7.35E-01	2.30E-10	1.03E-01	---	1.5E-03	6.16E-07	1.35E-03
RNM-2S	CAMBRIC	09-May-03	1.5E+05	1.3E+06	3.87E+02	7.07E-01	2.55E-10	1.15E-01	---	---	4.82E-07	9.07E-04
RNM-2S	CAMBRIC	14-Jun-00	1.9E+05	1.4E+06	---	---	1.62E-10	7.92E-02	---	---	---	---
RNM-2S	CAMBRIC	11-Oct-99	2.3E+05	1.6E+06	4.13E+02	8.34E-01	1.64E-10	7.40E-02	<40	1.3E-03	2.12E-07	4.18E-04
Hot Wells - Yucca Flat												
U4u PS2a	DALHART	9-Oct-03	2.7E+07	6.2E+07	1.56E+05	3.26E+02	1.74E-07	2.93E+01	---	3.51E+01	1.04E-04	1.32E-01
U4u PS2a	DALHART	16-Aug-99	1.6E+07	3.1E+07	1.19E+05	2.29E+02	4.45E-08	8.52E+00	---	1.31E+01	5.32E-05	2.85E-02
UE-7ns	BOURBON	21-Aug-01	4.6E+03	3.2E+04	6.97E+01	1.39E-01	1.85E-12	1.40E-03	---	---	1.75E-07	6.05E-04
UE-2ce	NASH	12-Jul-05	9.3E+04	8.3E+05	2.01E+02	8.15E-01	9.54E-10	4.47E-01	---	<2.4e-3	5.02E-06	0.024
UE-2ce	NASH	22-Aug-01	1.4E+05	9.9E+05	2.17E+02	8.01E-01	1.62E-09	8.27E-01	---	---	2.40E-05	0.032
U-3cn PS#2	BILBY	09-Dec-04	7.9E+06	8.0E+07	1.15E+05	3.72E+02	4.46E-08	2.55E+01	---	6.26E+01	1.48E-04	2.52E-01
U-3cn PS#2	BILBY	18-Dec-01	9.9E+06	8.6E+07	8.78E+04	3.03E+02	1.52E-07	4.32E+01	---	8.26E+01	7.38E-04	1.58E-01
Hot Wells - Pahute Mesa												
U20n PS1 DDh	CHESHIRE	09-Jul-03	4.4E+07	2.1E+08	1.69E+05	1.83E+02	2.22E-09	7.99E-01	---	1.23E+01	2.74E-04	1.47E-01
U20n PS1 DDh	CHESHIRE	12-Oct-99	5.1E+07	1.9E+08	1.54E+05	2.00E+02	1.15E-09	4.20E-01	2.77E+04	2.23E+01	4.91E-05	1.14E-01
U19ad PS1A	CHANCELLOR	27-Sep-04	2.2E+07	5.3E+07	3.06E+05	4.04E+02	6.39E-09	9.18E+00	---	4.60E+01	5.59E-04	1.94E+00
U19q PS1d	CAMEMBERT	16-Jul-03	1.1E+07	5.4E+07	4.92E+04	2.93E+02	7.73E-11	1.84E-02	---	---	2.85E-06	1.98E-03
U19q PS1d	CAMEMBERT	21-Oct-98	2.1E+07	7.8E+07	1.07E+05	1.31E+03	5.28E-11	1.81E-02	1.10E+05	8.4E-02	2.27E-06	4.07E-03
U19v PS1ds	ALMENDRO	23-Jul-03	1.4E+08	7.7E+08	2.99E+04	7.44E+01	3.20E-09	5.62E+00	---	---	1.89E-03	2.54E+00
U19v PS1ds	ALMENDRO	31-May-01	1.8E+08	9.0E+08	3.11E+04	9.33E+01	1.63E-09	3.58E+00	---	---	1.54E-03	2.33E+00
U19v PS1ds	ALMENDRO	26-Sep-00	1.5E+08	7.1E+08	3.19E+04	1.01E+02	2.30E-09	3.66E+00	---	---	2.09E-03	2.76E+00
U19v PS1ds	ALMENDRO	18-Aug-99	1.6E+08	6.8E+08	2.47E+04	3.56E+01	1.60E-09	2.14E+00	---	---	7.81E-03	1.39E+00
ER-20-5 #1	TYBO/BENHAM†	30-Nov-04	3.8E+07	2.0E+08	9.63E+04	2.24E+02	4.39E-09	3.57E+00	---	3.5E-01	1.99E-04	1.92E-01
ER-20-5 #1	TYBO/BENHAM †	09-Jul-98	6.2E+07	2.3E+08	8.17E+04	1.79E+02	4.11E-09	3.32E+00	502.00	2.7E-01	2.14E-04	2.68E-01
ER-20-5 #3	TYBO/BENHAM †	29-Nov-04	1.1E+05	6.0E+05	1.68E+03	2.73E+00	2.27E-11	1.31E-02	---	1.7E-02	1.66E-06	1.40E-03
ER-20-5 #3	TYBO/BENHAM †	15-Nov-01	1.4E+05	6.3E+05	1.57E+03	2.08E+00	3.49E-11	2.18E-02	---	---	1.34E-05	1.20E-03
ER-20-5 #3	TYBO/BENHAM †	30-Apr-98	1.6E+05	5.7E+05	1.35E+03	1.73E+00	1.93E-11	1.10E-02	<15	---	---	---

† Both the TYBO and BENHAM tests are listed since the ER-20-5 well cluster was drilled in the near-field (~300 m from the surface ground zero) environment of the TYBO test.
  However, Pu isotopic signatures indicate the radionuclides in water samples from ER-20-5 wells are derived from the BENHAM test detonated ~1300 m up-gradient (Kersting et al., 1999).

Table 1.7 Radiochemical data

Well name	Test	Sample date	$^{234}U/^{238}U$	$^{234}U/^{238}U$ activity ratio	$^{234}U/^{235}U$	$^{235}U/^{238}U$	^{234}U	^{235}U	^{238}U	$^{239,240}Pu$
Unit		date	ratio	ratio	ratio	ratio	(pCi/L)	(pCi/L)	(pCi/L)	(pCi/L)
Half-life (a)		collected					2.46E+05	7.04E+08	4.47E+09	
Ref. date		in field					collect.	collect.	collect.	collect.
Hot Wells - Frenchman Flat										
UE5n	CAMBRIC	12-Feb-04	8.95E+03	2.03	1.54E-02	7.25E-03	3.07E+00	6.92E-02	1.49E+00	<0.02
UE5n	CAMBRIC	19-Apr-01	1.13E-04	2.06	1.56E-02	7.25E-03	2.90E-01	6.00E-03	1.40E-01	---
UE5n	CAMBRIC	09-Sep-99	---	---	---	---	---	---	---	---
RNM-1	CAMBRIC	03-Jun-04	1.34E-04	2.44	1.85E-02	7.25E-03	3.18E+00	5.97E-02	1.28E+00	<0.02
RNM-1	CAMBRIC	28-Jun-00	1.36E-04	2.48	1.87E-02	7.29E-03	3.33E+00	6.00E-02	1.33E+00	---
RNM-2S	CAMBRIC	10-Jul-03	1.23E-04	2.25	1.70E-02	7.26E-03	3.72E+00	7.60E-02	1.64E+00	<0.02
RNM-2S	CAMBRIC	09-May-03	1.23E-04	2.25	1.70E-02	7.26E-02	3.75E+00	7.70E-02	1.65E+00	<0.02
RNM-2S	CAMBRIC	14-Jun-00	1.23E-04	2.24	1.69E-02	7.29E-03	3.77E+00	8.00E-02	1.66E+00	---
RNM-2S	CAMBRIC	11-Oct-99	---	---	---	---	---	---	---	---
Hot Wells - Yucca Flat										
U4u PS2a	DALHART	9-Oct-03	2.02E-04	3.69	2.78E-02	7.26E-03	9.25E+00	1.16E-01	2.48E+00	0.32
U4u PS2a	DALHART	16-Aug-99	---	---	---	---	---	---	---	1.2
UE-7ns	BOURBON	21-Aug-01	1.69E-04	3.08	2.31E-02	7.30E-03	4.60E-02	7.00E-04	1.50E-02	<0.04
UE-2ce	NASH	12-Jul-05	1.94E-04	3.53	2.67E-02	7.25E-03	2.39E+00	3.10E-02	6.69E-01	<0.07
UE-2ce	NASH	22-Aug-01	2.05E-04	3.74	2.82E-02	7.26E-03	5.00E-01	6.00E-03	1.30E-01	<0.04
U-3cn PS#2	BILBY	09-Dec-04	1.54E-04	2.80	2.12E-02	7.25E-03	9.77E+00	1.60E-01	3.44E+00	<0.01
U-3cn PS#2	BILBY	18-Dec-01	1.60E-04	2.92	2.21E-02	7.25E-03	1.05E+01	1.66E-01	3.56E+00	<0.04
Hot Wells - Pahute Mesa										
U20n PS1 DDh	CHESHIRE	09-Jul-03	1.93E-04	3.53	2.66E-02	7.26E-03	2.46E+00	3.20E-02	6.91E-01	0.31
U20n PS1 DDh	CHESHIRE	12-Oct-99	1.89E-04	3.44	2.63E-02	7.17E-03	3.00E+00	4.00E-02	8.60E-01	0.51
U19ad PS1A	CHANCELLOR	27-Sep-04	8.90E-05	1.62	1.18E-02	7.56E-03	1.43E+00	4.21E-02	8.68E-01	26.8
U19q PS1d	CAMEMBERT	16-Jul-03	1.05E-04	1.92	1.45E-02	7.25E-03	1.69E+00	4.10E-02	8.72E-01	<0.02
U19q PS1d	CAMEMBERT	21-Oct-98	1.65E-04	3.02	2.25E-02	7.35E-03	<0.509	<0.008	<0.167	---
U19v PS1ds	ALMENDRO	23-Jul-03	6.96E-05	1.27	9.59E-03	7.25E-03	4.80E-02	2.00E-03	3.80E-02	<0.02
U19v PS1ds	ALMENDRO	31-May-01	1.77E-04	3.24	2.44E-02	7.25E-03	3.40E-02	5.00E-04	1.00E-02	0.18
U19v PS1ds	ALMENDRO	26-Sep-00	1.72E-04	3.15	2.38E-02	7.23E-03	1.70E-02	3.00E-04	5.00E-03	---
U19v PS1ds	ALMENDRO	18-Aug-99	---	---	---	---	---	---	---	9.45
ER-20-5 #1	TYBO/BENHAM†	30-Nov-04	1.59E-04	2.90	2.20E-02	7.25E-03	1.38E+01	2.19E-01	4.71E+00	0.42
ER-20-5 #1	TYBO/BENHAM †	09-Jul-98	1.65E-04	3.01	2.27E-01	7.27E-03	1.52E+01	2.34E-01	5.01E+00	---
ER-20-5 #3	TYBO/BENHAM †	29-Nov-04	1.39E-04	2.53	1.92E-02	7.25E-03	4.83E+00	8.77E-02	1.88E+00	<0.04
ER-20-5 #3	TYBO/BENHAM †	15-Nov-01	6.35E-05	1.16	8.76E-03	7.25E-03	5.01E+00	2.00E-01	4.27E+00	<0.04
ER-20-5 #3	TYBO/BENHAM †	30-Apr-98	1.58E-04	2.89	2.18E-02	7.27E-03	2.64E+00	4.20E-02	9.02E-01	---

† Both the TYBO and BENHAM tests are listed since the ER-20-5 well cluster was drilled in the near-field (~300 m from the surface ground zero) environment of the TYBO test.
However, Pu isotopic signatures indicate the radionuclides in water samples from ER-20-5 wells are derived from the BENHAM test detonated ~1300 m up-gradient (Kersting et al., 1999).

Chapter 2

FY 2005 Environmental Well Data

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2.1   Introduction

This chapter summarizes the results of chemical and isotopic analyses of groundwater sampled collected from UGTA project environmental monitoring wells during FY 2005. Geochemical data gathered through this effort provide an independent means of evaluating groundwater flow model predictions for the NTS. The sampling program is a coordinated effort between the various UGTA contractors including Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), the Desert Research Institute (DRI), the U.S. Geological Survey (USGS), Stoller-Navarro Joint Venture (SNJV), and Bechtel Nevada (BN). During FY 2005, groundwater characterization samples were collected from three environmental wells on Rainier Mesa: ER-12-1, ER-12-3 and ER-12-4 (Figure 2.1). The analytical results from these sampling events are compiled in Tables 2.1-2.7, and data interpretations are discussed below. Laboratory analytical protocols are fully described in the LLNL Standard Operating Procedures written in support of the UGTA Project (LLNL, 2004).
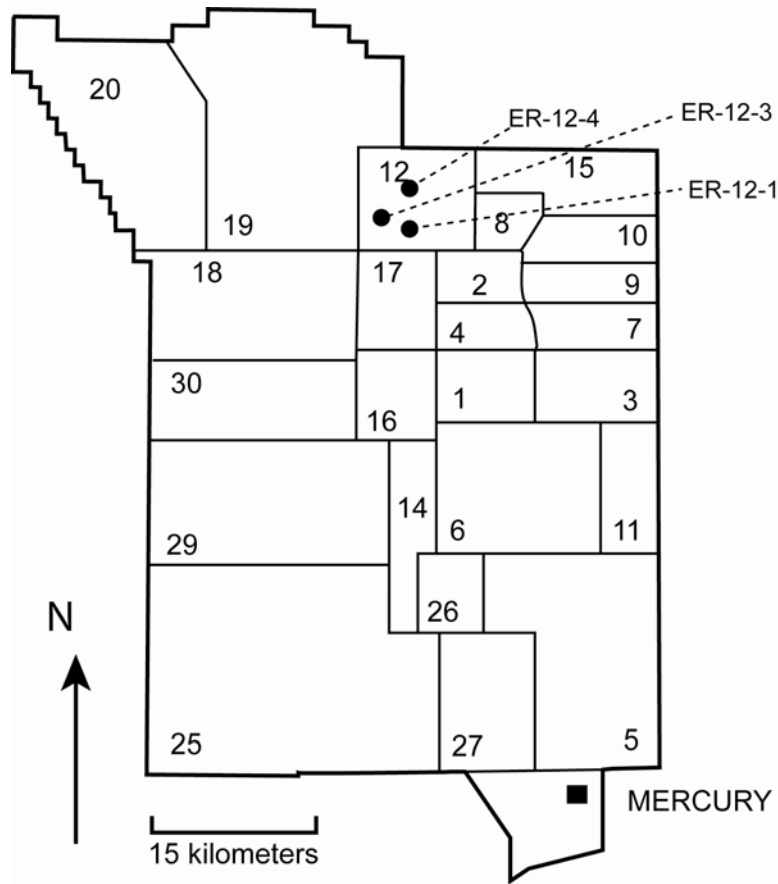
Figure 2.1 Map of the NTS showing environmental well sampling locations for FY2005.

2.2   ER-12-1

ER-12-1 is located on the eastern flank of Rainier Mesa along the U-12e tunnel access road, in Area 12 of the NTS. The well was drilled to a total depth of 1093.6 meters below ground surface in 1992, and was completed with five slotted intervals in Paleozoic carbonates and mudstones. Most the water is produced from the uppermost slotted interval (516 – 555 meters below ground surface) completed in the Sevy Dolomite (DOE/NV, 1996; Raytheon Services Nevada, 1992).

Approximately 19,600 gallons of water were purged from ER-12-1 prior to sampling on December 8, 2004, at an average pump rate of ~29 gallons per minute. LLNL participated in one previous groundwater sampling operation at ER-12-1 in January 1993 (LLNL, 1993).

ER-12-1 produces Ca-Mg-HCO$_3$ groundwater with a near-neutral pH that is typical of the carbonate aquifer waters at the NTS, but with unusually high levels of sulfate (355 mg/L). The presence of large amounts of iron in the water (5 mg/L) may indicate pyrite oxidation, which would account for the high sulfate concentration. The stable isotope composition of the water (δD = -94.5‰; δ^{18}O = -12.6‰) is very similar to reported

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values for perched water in the Rainier Mesa tunnels (Russell et al., 1987), and is substantially enriched in heavy isotopes compared to carbonate aquifer groundwaters found throughout most of Yucca Flat. These data suggest that ER-12-1 groundwater is derived from local recharge on Rainier Mesa.

The tritium activity in ER-12-1 groundwater (3.2 pCi/L) is more than a factor of 100 times lower than the measured activity in 1993 (361 pCi/L; LLNL, 1993). Since the half-life of ^{3}H is 12.3 years, we can assume the tritium that was observed in 1993 has either migrated away from the well bore or was removed by pumping. The original source of the tritium was speculated to be from the U12e tunnel effluent ponds, 500 meters to the west of the well site (DOE/NV, 1996). The ^{3}He/^{4}He ratio in the water (6.20×10^{-7}) is less than the ratio in ambient air (1.38×10^{-6}), indicating that the dissolved helium is dominated by a terrigenic ^{4}He source from the decay of uranium and thorium in surrounding host rocks. Assuming a radiogenic ^{4}He accumulation rate of 5×10^{-11} cm^3/g H$_2$O per year, the apparent ^{4}He accumulation age is 3,000 years. A mean groundwater recharge temperature of 6.4°C was calculated from the dissolved Ne, Ar, Kr, and Xe concentration data based on an assumed recharge altitude of 2,000 m.

Dissolved inorganic carbon in ER-12-1 groundwater has a ^{14}C value of 11.0 percent modern carbon, yielding an uncorrected ^{14}C age of 18,200 years. The δ^{13}C value of the water is unusually depleted in ^{13}C (-10.7‰) implying very little equilibration with carbonate minerals in the aquifer. While this may indicate that the water had a long residence time in a different lithologic unit (other than carbonate rock), the high Ca-Mg-HCO$_3$ concentrations in the water clearly indicate chemical equilibration with the carbonate host rock. The apparent lack of isotopic equilibration with the carbonate rock suggests that the uncorrected radiocarbon age may be close to the actual mean residence time of the groundwater.

ER-12-1 groundwater contains 17.7 mg/L chloride and has a high ^{36}Cl/Cl ratio (7.80×10^{-13}) compared to the modern atmospheric ratio for southern Nevada ($\sim 5 \times 10^{-13}$, Fabryka-Martin et al., 1993). The ^{36}Cl enrichment may reflect groundwater recharge during the last pluvial period (late Pleistocene), during which time the atmospheric production of ^{36}Cl was greater due to the reduced strength in the earth's magnetic field (Mazaud et al., 1991). This would imply a groundwater residence time in excess of 10,000 years, in accordance with the radiocarbon data. It should be noted, however, that the samples collected at ER-12-1 in 1993 contained much higher chloride (42 mg/L) and had a higher ^{36}Cl/Cl ratio (5.06×10^{-12}), implying an anthropogenic source of chloride was present in the water (possibly from drilling fluid or LiBr tracers). If some residual amount of this material is still present in the surrounding aquifer matrix, it may account for the elevated ^{36}Cl/Cl ratio in the 2004 sample.

The strontium concentration (0.21 mg/L) and ^{87}Sr/^{86}Sr ratio (0.71230) in ER-12-1 groundwater is consistent with water-rock reactions with the carbonate host rock. Although most marine carbonate rocks have unaltered ^{87}Sr/^{86}Sr ratios in the range of 0.7078 to 0.7093 (Faure, 1986), Peterman et al. (1992) showed that high groundwater ^{87}Sr/^{86}Sr ratios are common in the carbonate aquifers of the Ash Meadows flow system.

The elevated $^{87}Sr/^{86}Sr$ ratios in the carbonate rock may be related to an earlier episode of radiogenic ^{87}Sr enrichment from the underlying Precambrian clastic rocks.

The uranium concentration in ER-12-1 (1.63 µg/L) is within the range of expected values for LCA groundwater in southern Nevada (Paces et al., 2002), and the $^{235}U/^{238}U$ ratio indicates the uranium is natural in origin. The $^{234}U/^{238}U$-activity ratio (1.62) indicates a slight enrichment in ^{234}U, suggesting some natural disequilibria between the solubility of ^{234}U and ^{238}U in the crystal lattice structure of uranium-bearing minerals in the aquifer host rock.

2.3 ER-12-3

Well ER-12-3 was constructed on Rainier Mesa and drilled into the carbonate aquifer with the objective of acquiring data on the radiological and hydrogeologic environment beneath Rainier Mesa. Well completion, development, lithology and hydraulic testing data are summarized in BN (2006a) and SNJV (2006a). ER-12-3 was drilled to a total depth of 1,496 meters on April 28, 2005 with two intervals of slotted casing in the Lower Carbonate Aquifer (LCA). The upper interval is between 1,095 and 1,160 meters and the lower interval is between 1,278 and 1,474 meters. Saturated rocks consist of Paleozoic dolomite in the upper slotted interval and Paleozoic limestone in the lower slotted interval. Both intervals have little apparent porosity but are populated with numerous hairline fractures mostly cemented by later stage calcite deposits (BN, 2006a; SNJV, 2006a). Importantly, annular space surrounding the slotted casing was not filled with sand or gravel. Furthermore, the slotted zones were not isolated from the overlying formation water. However, they were isolated from a perched water zone that was encountered between 420 and 808 meters. Water production rates from the dolomite and limestone sections are similar.

Groundwater characterization samples were collected from well ER-12-3 on July 6, 2005. At the time of sampling, the depth to water was measured at 950 meters, the pump rate was 29.6 gpm, and the cumulative purge volume was ~6.2×10^5 gallons of water. Measured Br$^-$ (<0.02 mg/L) indicates that purge water effectively removed drilling fluids (doped with LiBr tracer) from the well.

Well ER-12-3 produces dilute mixed type Ca-Mg-Na-HCO$_3$ groundwater with a conductivity value of 306 µS/cm and a slightly alkaline pH value (8.2). Although the water chemistry is typical of the carbonate aquifer, the concentrations of dissolved constituents are more dilute than normally observed in LCA wells. The stable isotope composition of the water is -106 ‰ for δD and -14.5 ‰ for δ^{18}O. The stable isotope composition is unlike that of other northern Yucca Flat wells completed in the carbonate aquifer. Instead, it is isotopically lighter (i.e., more negative δ-values), which may result from mixing with a combination of local volcanic aquifer paleo-waters (e.g. HTH #1 type water) and Rainier Mesa tunnel waters. Interestingly, these results suggest that the groundwater is in poor communication with the northern Yucca Flat carbonate aquifer waters.

The tritium activity of groundwater from well ER-12-3 was determined by the helium accumulation method (Surano et al., 1992). The tritium activity is only 0.5 pCi/L and is significantly less than the activity in other nearby wells on and near Rainier Mesa. The ^{3}He/^{4}He ratio in ER-12-3 groundwater (R = 1.8×10^{-7}) is much lower than the atmospheric helium isotope ratio ($R_a = 1.38 \times 10^{-6}$), giving an R/$R_a$ value of 0.13. The low abundance of ^{3}He indicates the water never contained a large amount of tritium. Conversely, ^{4}He is moderately enriched relative to the equilibrium atmospheric helium solubility for this location, indicating the presence of excess helium from the α-decay of U and Th in the host rock. Assuming a ^{4}He in-growth rate of 1.35 x 10^9 atoms/year, and correcting for the presence of non-equilibrium 'excess air' in the sample, the ^{4}He data imply a mean aquifer residence time on the order of 13,000 years.

Dissolved inorganic carbon (DIC) in ER-12-3 groundwater has a δ^{13}C value is -5.4 ‰ and a ^{14}C value of 2.9 pmc, yielding an uncorrected ^{14}C age of ~28,300 years. The low ^{14}C and moderately heavy δ^{13}C are indicative of groundwater interaction with the carbonate host rock in which the well was completed. These water-rock reactions cause the measured ^{14}C age to appear older than the actual age of the water. Corrected radiocarbon ages can be calculated using chemical modeling programs (NETPATH or PHREEQC) to account for these reactions. It should be noted that the total dissolved inorganic carbon (TDIC) in ER-12-3 groundwater is only 125 mg/L, which is at the lower end of measured carbonate aquifer TDIC values. This may reflect dilution during mixing with low-TDIC groundwater from the overlying volcanic units.

ER-12-3 groundwater has a dilute chloride concentration (5.7 mg/L) and a ^{36}Cl/Cl ratio (5.39×10^{-13}) that is in the range for the modern atmospheric ratio for southern Nevada (~5×10^{-13}, Fabryka-Martin et al., 1993). It is significantly higher than most LCA ^{36}Cl/Cl ratios and may again be an indication of mixing with overlying perched volcanic aquifer waters.

The groundwater from ER-12-3 has a ^{87}Sr/^{86}Sr ratio of 0.71055 and a δ^{87}Sr value of +1.9 ‰. The relatively low Sr concentration (98 µg/L) and isotope ratios are also suggestive of significant mixing between LCA and overlying perched volcanic aquifers.[2] The concentration of dissolved uranium is 1.8 µg/L. This is in the normal range of values for groundwater from the NTS, and the ^{235}U/^{238}U ratio shows the uranium is natural in origin. The ^{234}U/^{238}U-activity ratio is 2.09.

2.4   ER-12-4

Well ER-12-4 was constructed in Area 12 on Rainier Mesa and drilled into the carbonate aquifer with the objective of acquiring data on the radiological and hydrogeologic environment beneath Rainier Mesa. Well completion, development, lithology and hydraulic testing data are summarized in BN (2006b) and SNJV (2006b). ER-12-4 was completed to a total depth of 1,132 meters on June 1, 2005 with 7 intervals of slotted casing, each about 13 meters in length. The top of the uppermost slotted casing is at 948 meters and the bottom of the lowermost slotted casing is at 1,118 meters. Saturated rocks

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[2] The value has been corrected since it was first reported in the ER-12-3 well report dated March 3, 2006.

consist of some Paleozoic dolomite but primarily Paleozoic limestone with little apparent porosity but populated with numerous hairline fractures mostly cemented by later stage calcite deposits (BN, 2006b; SNJV, 2006b). Interestingly, significant water production was only observed in the limestone. Also, production rates were significantly lower than those observed in ER-12-3.

Groundwater characterization samples were collected from well ER-12-4 on August 16, 2005. At the time of sampling, the depth to water was measured at 889 meters, the pump rate was 10 gpm, and the cumulative purge volume was ~4.9×10^4 gallons. Bromide tracer concentrations (<0.02 mg/L) suggest that the well was sufficiently purged prior to sampling. However, the total purge volume was ten times less than at ER-12-3.

Well ER-12-4 produces a dilute mixed type Ca-Mg-Na-HCO_3 groundwater with a low conductivity value (196 μS/cm) and a pH of 8.8. The stable isotope composition of the water is -103 ‰ for δD and -13.7 ‰ for $δ^{18}O$. The stable isotope composition is not unlike that of other northern Yucca Flat wells completed in the carbonate aquifer. However, it is also quite similar to that observed in T-tunnel waters in the past. The major element composition suggests that a significant proportion of the water is derived from volcanic aquifers. This suggests that the groundwater may be mixed with perched waters located in the overlying tuffs.

The tritium activity of groundwater from well ER-12-4 was determined by the helium accumulation method (Surano et al., 1992). The tritium activity is 89.7 pCi/L, and higher than the tritium activity from the deeper ER-12-3 well. It suggests a possible mixing with waters from overlying tuffs in which underground nuclear tests were located. Significant tritium may, however, be an artifact of drilling and the small purge volume (compared to the ER-12-3 sampling event), as described below.

Dissolved inorganic carbon (DIC) in ER-12-4 groundwater has a $δ^{13}C$ value is -7.6 ‰ and a ^{14}C value of 6.9 pmc, yielding an uncorrected ^{14}C age of 21,530 years. The low ^{14}C and relatively heavy $δ^{13}C$ are indicative of the interaction with LCA carbonate rock in which the well was completed. It should be noted that the total dissolved inorganic carbon (TDIC) was only 84 mg/L, which is at the lower end of measured LCA TDIC.

The ^4He value is quite low (1.1×10^{12} atoms/g). ^4He is not appreciably enriched relative to the equilibrium atmospheric helium solubility for this location. The ^4He result suggests that either the water is very young or that the water sampled was not representative of ambient waters in ER-12-4. ^3He value is also very low and inconsistent with the expected ingrowth from measured tritium concentrations in this sample. The ^3He value suggests that noble gases were partially lost during sampling, possibly as a result of the low production rates in this well.

ER-12-4 groundwater has a chloride concentration of 9.1 mg/L and a ^{36}Cl/Cl ratio (5.6×10^{-13}) which is in the normal range for the modern atmospheric ratio for southern Nevada ($\sim5\times10^{-13}$, Fabryka-Martin et al., 1993). It is significantly higher than most LCA ^{36}Cl/Cl ratios and may, again, be an indication of mixing with overlying perched volcanic aquifer waters.

The groundwater from ER-12-4 has a ^{87}Sr/^{86}Sr ratio of 0.71065 and a δ^{87}Sr value of +2.04 ‰. The relatively low Sr concentration (58 μg/L) and isotope ratios are also suggestive of significant mixing with overlying perched volcanic aquifers. The concentration of dissolved uranium (0.3 μg/L) is on the lower end of the normal range of values for groundwater from the NTS, and the ^{235}U/^{238}U ratio shows the uranium is natural in origin. The ^{234}U/^{238}U-activity ratio is 1.93.

2.5   References

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Table 2.1 Environmental well site information

Well name	Test Name	Test Date	Latitude	Longitude	Surface Elevation	Well Depth	Open Interval	Water Depth	Sample Method	Volume Pumped	Sample Depth	Sample date
Units			(d m s)	(d m s)	(ft)	(ft bgs)	(ft bgs)	(ft bgs)		(gal)	(ft bgs)	
Clean Wells - Frenchman Flat												
Water Well 5a	---	---	36 46 35	115 57 29	3092	910	642-877	695	pump	---	---	14-Aug-00
Water Well 5c	---	---	36 47 08	115 57 44	3081	1200	887-1187	689	pump	---	---	07-Aug-00
Water Well 5b	---	---	36 48 05	115 58 08	3093	900	700-900	683	pump	---	---	07-Aug-00
ER-5-4	---	---	36 49 28	115 57 48	3127	3732	1770-2113; 3136-3350	726	pump	3.74E+06	---	05-Jul-01
ER-5-4 #2	---	---	36 49 27	115 57 48	3127	7000	6486-6658	697	pump	4.00E+06	---	21-Nov-02
UE-5c WW	---	---	36 50 11	115 58 47	3216	2682	1100-2682	806	pump	---	---	08-Aug-00
UE-5 PW-3	---	---	36 52 01	115 58 16	3297	955	891-955	891	pump	---	---	09-Aug-00
ER-5-3	---	---	36 52 23	115 56 17	3334	2606	1480-1737; 2420-2549	927	pump	3.16E+06	---	28-Mar-01
ER-5-3 #2	---	---	36 52 23	115 56 18	3334	5683	4674-4868	952	pump	3.46E+06	---	17-May-01
Water Well 4a	---	---	36 54 12	116 01 39	3604	1517	944-1502	835	pump	---	---	08-Aug-00
Clean Wells - Yucca Flat												
ER-2-1	---	---	37 07 31	116 03 42	4222	2600	1642-2076	1723.0	pump	2.15E+04	---	03-Sep-03
ER-6-1 #2	---	---	36 59 01	115 59 35	3934	3200	1775-3200	1545	pump	3.80E+06	---	16-Jan-03
ER-6-2	---	---	36 57 39	116 04 34	4231	3430	1746-3430	1785	pump	3.37E+06	1904	04-Aug-04
ER-7-1	---	---	37 04 24	115 59 43	4247	2500	2182-2479	1854.0	pump	3.54E+07	---	17-Jul-03
Clean Wells - Rainier Mesa												
ER-12-1	---	---	37 11 06	116 11 03	5817	3588	1641-1846	1538	pump	1.96E+04	---	08-Dec-04
ER-12-2	---	---	37 10 19	116 07 21	4705	6883	2958-6883	191	pump	3.52E+05	---	01-Apr-03
ER-12-3	---	---	37 11 42	116 12 50	7385	4908	3591-3805; 4919-4834	3100	pump	6.32E+05	---	6-Jul-05
ER-12-4	---	---	37 13 11	116 10 59	6883	3715	3111-3669	2600	pump	4.91E+04	---	16-Aug-05

Table 2.1 Environmental well site information (continued)

Well name	Test Name	Test Date	Latitude	Longitude	Surface Elevation	Well Depth	Open Interval	Water Depth	Sample Method	Volume Pumped	Sample Depth	Sample date
Units			(d m s)	(d m s)	(ft)	(ft bgs)	(ft bgs)	(ft bgs)		(gal)	(ft bgs)	
Clean Wells – Pahute Mesa-Oasis Valley												
ER-EC-1	---	---	37 12 23	116 31 44	6026	5000	2298-2821; 3348-3760; 4449-4750	1859	pump	2.02E+05	---	3-Jun-03
ER-EC-1	---	---	37 12 23	116 31 44	6026	5000	2298-2821; 3348-3760; 4449-4750	1859	pump	2.80E+06	---	1-Feb-00
ER-EC-2A	---	---	37 08 52	116 34 05	4904	4974	1707-2179; 3077-3549; 4487-4916	748	pump	2.66E+04	---	8-Jul-03
ER-EC-2A	---	---	37 08 52	116 34 05	4904	4974	1707-2179; 3077-3549; 4487-4916	748	pump	2.34E+06	---	27-Jul-00
ER-EC-4	---	---	37 09 39	116 37 52	4760	3487	989-1224; 1910-2253; 3103-3404	749	pump	1.23E+05	---	24-Jun-03
ER-EC-4	---	---	37 09 39	116 37 52	4760	3487	989-1224; 1910-2253; 3103-3404	749	pump	2.84E+06	---	17-Aug-00
ER-EC-5	---	---	37 05 05	116 33 49	5077	2500	1197-1399; 1892-2094; 2246-2417	1017	pump	2.21E+05	---	15-Jul-03
ER-EC-5	---	---	37 05 05	116 33 49	5077	2500	1197-1399; 1892-2094; 2246-2417	1017	pump	3.50E+06	---	25-May-00
ER-EC-6	---	---	37 11 26	116 29 48	5605	5000	1628-1871; 2195-2507; 3438-3811; 4421-4904	1426	pump	2.15E+05	---	10-Jun-03
ER-EC-6	---	---	37 11 26	116 29 48	5605	5000	1628-1871; 2195-2507; 3438-3811; 4421-4904	1426	pump	2.2E+05	---	10-Feb-00
ER-EC-7	---	---	36 59 10	116 28 41	4800	1386	920-979; 1215-1304	719	pump	2.90E+05	---	21-Jul-03
ER-EC-7	---	---	36 59 10	116 28 41	4800	1386	920-979; 1215-1304	719	pump	3.60E+06	---	5-Jun-00
ER-EC-8	---	---	37 06 17	116 37 53	4245	2000	683-984; 1447-1507; 1677-1908	323	pump	2.34E+05	---	1-Jul-03
ER-EC-8	---	---	37 06 17	116 37 53	4245	2000	683-984; 1447-1507; 1677-1908	323	pump	3.82E+06	---	12-Jul-00
ER-18-2	---	---	37 06 21	116 22 22	5436	2500	1930-1960; 2000-2030; 2071-2101	1213	pump	9.76E+04	---	17-Jun-03
ER-18-2	---	---	37 06 21	116 22 22	5436	2500	1930-1960; 2000-2030; 2071-2101	1213	pump	2.22E+05	---	21-Mar-00

Table 2.2 Environmental well field parameter and anion data

Well name	Test	Sample date	pH	T	Cond.	TDIC as HCO$_3^-$	F	Cl	Br	NO$_3$	SO$_4$
Units		*date*		*(°C)*	*(μ S/cm)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*
Clean Wells - Frenchman Flat											
Water Well 5a	---	14-Aug-00	8.9	22.3	600	313	1.1	11.1	<0.2	3.7	28.5
Water Well 5c	---	07-Aug-00	8.7	28.2	601	306	1.0	11.3	<0.2	7.4	29.3
Water Well 5b	---	07-Aug-00	8.5	24.6	512	171	0.7	23.4	<0.2	12.8	55.0
ER-5-4	---	05-Jul-01	8.7	30.2	885	313	6.2	26.8	<0.3	4.0	120.0
ER-5-4 #2	---	21-Nov-02	8.7	38.1	1249	394	63.9	51.7	<0.5	<0.1	119.4
UE-5c WW	---	08-Aug-00	8.5	25.8	463	179	1.8	12.8	<0.2	7.5	43.7
UE-5 PW-3	---	09-Aug-00	8.3	21.5	371	153	0.9	9.4	<0.2	14.6	31.8
ER-5-3	---	28-Mar-01	8.3	30.0	445	169	2.5	15.5	<0.1	7.0	40.0
ER-5-3 #2	---	17-May-01	6.7	33.8	1158	797	1.3	38.0	<0.1	<0.09	64.0
Water Well 4a	---	08-Aug-00	7.9	26.5	409	157	1.2	13.2	<0.2	17.4	39.8
Clean Wells - Yucca Flat											
ER-2-1	---	03-Sep-03	9.3	21.3	368	189	1.8	4.4	<0.03	2.4	15.9
ER-6-1 #2	---	16-Jan-03	7.6	39.9	408	256	0.8	10.0	0.8	1.1	34.0
ER-6-2	---	04-Aug-04	7.5	34.9	617	433	1.4	23.9	0.1	1.4	52.4
ER-7-1	---	17-Jul-03	7.6	49.4	488	243.5	0.8	9.5	0.1	0.1	34.4
Clean Wells - Rainier Mesa											
ER-12-1	---	08-Dec-04	7.5	25.0	984	257	0.3	17.7	0.4	0.1	355.4
ER-12-2	---	01-Apr-03	8.1	35.2	528	303	2.2	7.0	0.7	<0.2	27.4
ER-12-3	---	06-Jul-05	8.2	30.6	306	125	1.5	5.7	<0.02	0.8	24.6
ER-12-4	---	16-Aug-05	8.8	23.9	196	84	0.3	9.1	<0.02	8.5	11.4
Clean Wells - Pahute Mesa-Oasis Valley											
ER-EC-1	---	3-Jun-03	8.1	34.8	782	148.9	2.3	97.0	1.4	2.1	119.0
ER-EC-1	---	1-Feb-00	7.9	37.0	818	148.5	2.4	97.0	1.1	2.5	145.0
ER-EC-2A	---	8-Jul-03	8.1	35.2	616	164.7	3.9	55.5	1.1	1.9	84.5
ER-EC-2A	---	27-Jul-00	7.8	40.4	706	170.5	5.9	63.0	0.6	1.2	99.0
ER-EC-4	---	24-Jun-03	7.8	35.9	750	150.4	3.0	80.6	1.2	2.4	109.0
ER-EC-4	---	17-Aug-00	7.9	38.5	793	158.1	3.6	95.7	1.3	3.2	130.0
ER-EC-5	---	15-Jul-03	7.9	29.7	412	180.4	4.3	15.9	0.7	1.7	36.3
ER-EC-5	---	25-May-00	7.9	29.9	424	175.7	4.6	16.1	n.d.	1.2	35.0
ER-EC-6	---	10-Jun-03	8.1	33.9	516	147.0	2.7	51.7	0.9	2.0	75.4
ER-EC-6	---	10-Feb-00	8.1	37.9	613	153.2	3.1	44.0	0.8	2.0	56.0
ER-EC-7	---	21-Jul-03	8.0	27.3	263	86.5	1.2	3.8	<0.03	5.6	13.6
ER-EC-7	---	5-Jun-00	7.9	30.0	315	118.8	1.3	5.2	n.d.	5.8	15.0
ER-EC-8	---	1-Jul-03	8.1	36.7	642	173.8	5.2	47.3	1.0	1.4	76.1
ER-EC-8	---	12-Jul-00	8.0	38.2	647	172.1	5.5	57.6	0.4	1.3	94.0
ER-18-2	---	17-Jun-03	7.9	43.0	1277	881.0	12.5	12.3	<0.2	<0.2	52.9
ER-18-2	---	21-Mar-00	7.6	55.2	1439	871.0	12.6	13.3	n.d.	<1.0	53.0

Table 2.3 Environmental well cations and metals data

Well name	Test	Sample date	Na	K	Ca	Mg	Li	Al	Si	Fe	Mn	As	Se	Sr	Mo	Sb	I	Ba	Pb	U	Pu
Unit			*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(μg/L)*	*(μg/L)*	*(μg/L)*	*(μg/L)*	*(μg/L)*	*(μg/L)*	*(μg/L)*	*(μg/L)*	*(μg/L)*	*(μg/L)*	*(pg/L)*
Clean Wells - Frenchman Flat																					
Water Well 5a	---	14-Aug-00	147.0	5.5	1.7	0.8	---	<0.05	18.8	<0.04	<6	37	<24	<13	8.3	---	---	1	<14	---	---
Water Well 5c	---	07-Aug-00	149.0	7.0	1.9	0.7	---	<0.05	25	<0.04	<6	32	<24	<13	7.3	---	---	1	<14	---	---
Water Well 5b	---	07-Aug-00	101.0	12.6	7.3	2.5	---	<0.05	26.3	<0.04	<6	<20	<24	<13	3.2	---	---	2	<14	---	---
ER-5-4	---	05-Jul-01	124.0	7.1	2.2	0.2	---	0.2	24.5	0	<6	47	<24	35	63	---	---	8	21	1.60	---
ER-5-4 #2	---	21-Nov-02	334.0	4.3	0.7	0.3	0.07	1.9	34.7	1	98	<20	<24	3.3	82	---	---	8	<14	36.40	---
UE-5c WW	---	08-Aug-00	100.0	6.7	6.9	1.8	---	0.6	33.3	0	<6	<20	<24	33	11	---	---	89	<14	---	---
UE-5 PW-3	---	09-Aug-00	61.8	5.0	16.4	6.7	---	<0.05	27.6	<0.04	<6	<20	<24	120	3.8	---	---	13	<14	---	---
ER-5-3	---	28-Mar-01	78.9	4.0	14.3	3.9	---	---	---	---	<6	30	<24	64	6.9	---	---	3	<14	0.97	---
ER-5-3 #2	---	17-May-01	145.0	15.8	86.1	32.6	---	---	---	---	92	35	<24	1018	4.3	---	---	230	<14	0.50	---
Water Well 4a	---	08-Aug-00	57.3	6.2	23.1	8.3	---	<0.05	28.0	<0.04	<6	<20	<24	130	5.8	---	---	3	<14	---	---
Clean Wells - Yucca Flat																					
ER-2-1	---	03-Sep-03	73.0	3.8	3.1	0.3	0.02	0.1	55.8	2.20	110	<20	40	6.7	<3	---	5.3	9 <1	<14	3.40	---
ER-6-1 #2	---	16-Jan-03	47.1	6.3	33.6	14.0	0.06	<0.05	16.4	<0.04	7	<20	<24	208	<3	---	---	160	<14	3.21	---
ER-6-2	---	04-Aug-04	72.1	10.2	67.4	22.3	0.18	0.01	40.1	0.03	38.3	38	0.905	231	5.4	3.15	---	154	0.35	2.17	---
ER-7-1	---	17-Jul-03	41.6	5.6	27.1	13.3	0.04	<0.05	18.3	<0.04	<6	<20	<24	156	10	---	8.1	230	<14	1.42	---
Clean Wells - Rainier mesa																					
ER-12-1	---	08-Dec-04	38.3	3.0	88.4	58.8	0.26	3E-04	29.34	4.99	141	106	0.457	210	10.6	0.48	---	35	BD	1.63	---
ER-12-2	---	01-Apr-03	117.2	2.1	6.5	2.1	0.19	<0.05	6.9	0.26	22	<20	<24	317	4.7	---	---	210	<14	0.02	---
ER-12-3	---	06-Jul-05	30.7	2.2	13.8	7.9	<0.03	0.003	6.8	0.3	26.6	7.5	< 1.5	102	5.9	0.36	3.59	24.88	0.3	1.83	---
ER-12-4	---	16-Aug-05	28.3	3.1	8.4	3.5	<0.005	0.02	3.53	1.0	45.3	< 4.2	< 1.5	63	2	< 0.3	---	12.6	0.24	0.30	---
Clean Wells - Pahute Mesa-Oasis Valley																					
ER-EC-1	---	3-Jun-03	143.7	4.9	18.7	0.4	0.11	0.2	28.7	<0.04	<6	<20	<24	16	<3	---	---		<14	9.51	---
ER-EC-1	---	1-Feb-00	154.0	6.0	19.0	0.4	0.15	<0.4	23	0.64	---	---	---	27	---	---	---	---	---	8.12	---
ER-EC-2A	---	8-Jul-03	127.8	2.2	8.7	0.2	0.15	0.1	26.5	<0.04	<6	<20	<24	28	6.8	---	---	15	<14	7.05	---
ER-EC-2A	---	27-Jul-00	123.0	2.5	13.1	2.5	0.14	<0.11	15	0.25	---	---	---	74	---	---	---	---	---	9.20	---
ER-EC-4	---	24-Jun-03	118.7	8.1	26.1	5.0	0.09	0.2	40.3	0.05	<6	<20	<24	136	4.7	---	---	2	<14	4.08	---
ER-EC-4	---	17-Aug-00	116.0	8.7	25.9	3.8	0.09	<0.11	21	0.18	---	---	---	160	---	---	---	---	---	4.10	---

Table 2.3 Environmental well cations and metals data (continued)

Well name	Test	Sample date	Na	K	Ca	Mg	Li	Al	Si	Fe	Mn	As	Se	Sr	Mo	Sb	I	Ba	Pb	U	Pu
Unit			*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(pg/L)*
Clean Wells - Pahute Mesa-Oasis Valley																					
ER-EC-5	---	15-Jul-03	70.8	1.1	19.8	0.8	0.09	<0.05	24.5	<0.04	<6	<20	<24	128	6.2	---	---	3	<14	3.34	---
ER-EC-5	---	25-May-00	75.0	1.8	21.0	0.6	0.01	0.2	15	0.13	---	---	---	170	---	---	---	---	---	3.30	---
ER-EC-6	---	10-Jun-03	119.6	1.8	4.6	0.2	0.10	0.2	27.4	<0.04	<6	<20	<24	4.1	<3	---	---	2	<14	5.43	---
ER-EC-6	---	10-Feb-00	128.0	2.0	4.0	0.0	0.15	<0.4	22	0.42	---	---	---	14	---	---	---	---	---	4.72	---
ER-EC-7	---	21-Jul-03	28.0	2.0	20.2	2.2	0.02	<0.05	20.7	<0.04	<6	<20	<24	81	2.4	---	---	4	<14	1.86	---
ER-EC-7	---	5-Jun-00	35.0	2.8	22.0	2.0	0.04	0.4	13	0.23	---	---	---	160	---	---	---	---	---	2.10	---
ER-EC-8	---	1-Jul-03	120.4	4.9	10.1	0.3	0.15	<0.05	28.4	<0.04	<6	<20	<24	2.2	10	---	---	2	<14	4.81	---
ER-EC-8	---	12-Jul-00	120.0	5.6	11.0	0.5	0.15	0.2	22	0.11	---	---	---	41	---	---	---	---	---	4.80	---
ER-18-2	---	17-Jun-03	344.0	2.1	5.9	0.5	0.22	0.3	26.1	<0.04	25	42	27	212	7.8	---	---	15	<14	8.53	---
ER-18-2	---	21-Mar-00	365.0	1.8	6.1	0.2	0.28	<0.4	22	0.06	---	---	---	230	---	---	---	---	---	7.26	---

Table 2.4 Environmental well trace metal data

Well name	Test	Sample date	V	Cr	Co	Ni	Cu	Zn	Br *	Rb	Nb	Ru	Cd	Sn	Cs	Eu
Unit			*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*	*(µg/L)*
Clean Wells - Frenchman Flat																
Water Well 5a	---	14-Aug-00	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Water Well 5c	---	07-Aug-00	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Water Well 5b	---	07-Aug-00	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-5-4	---	05-Jul-01	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-5-4 #2	---	21-Nov-02	---	---	---	---	---	---	---	---	---	---	---	---	---	---
UE-5c WW	---	08-Aug-00	---	---	---	---	---	---	---	---	---	---	---	---	---	---
UE-5 PW-3	---	09-Aug-00	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-5-3	---	28-Mar-01	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-5-3 #2	---	17-May-01	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Water Well 4a	---	08-Aug-00	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Clean Wells - Yucca Flat																
ER-2-1	---	03-Sep-03	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-6-1 #2	---	16-Jan-03	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-6-2	---	04-Aug-04	4.1	0.08	10.8	21.7	BD	32.3	---	41	0.04	0.001	0.01	0.01	7.75	0.01
ER-7-1	---	17-Jul-03	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Clean Wells - Rainier Mesa																
ER-12-1	---	08-Dec-04	0.6	0.10	0.41	15.2	BD	6.5	---	7.7	0.01	0.002	0.01	0.03	0.17	BD
ER-12-2	---	01-Apr-03	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-12-3	---	06-Jul-05	2.2	< 0.24	< 0.27	<2.9	< 0.9	259	---	7.3	< 0.042	< 0.3	< 0.6	---	< 0.99	< 0.012
ER-12-4	---	16-Aug-05	1.2	1.6	< 0.36	14.1	5.8	538	---	10.3	< 0.24	< 0.27	< 0.33	---	< 0.9	< 0.006
Clean Wells - Pahute Mesa-Oasis Valley																
ER-EC-1	---	3-Jun-03	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-EC-1	---	1-Feb-00	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-EC-2A	---	8-Jul-03	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-EC-2A	---	27-Jul-00	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-EC-4	---	24-Jun-03	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-EC-4	---	17-Aug-00	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-EC-5	---	15-Jul-03	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-EC-5	---	25-May-00	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-EC-6	---	10-Jun-03	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-EC-6	---	10-Feb-00	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-EC-7	---	21-Jul-03	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-EC-7	---	5-Jun-00	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-EC-8	---	1-Jul-03	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-EC-8	---	12-Jul-00	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-18-2	---	17-Jun-03	---	---	---	---	---	---	---	---	---	---	---	---	---	---
ER-18-2	---	21-Mar-00	---	---	---	---	---	---	---	---	---	---	---	---	---	---

* Bromide measured by ICP-MS

<p style="text-align:center">Table 2.5 Environmental well stable isotope data</p>

Well name	Test	Sample date	δD_{SMOW}	$\delta^{18}O_{SMOW}$	$\delta^{13}C_{PDB}$	^3He	^4He	R/R_a	$^{20}Ne*$	$^{40}Ar*$	Kr	$^{130}Xe*$	$^{87}Sr/^{86}Sr$	$\delta^{87}Sr$
Unit			‰	‰	‰	atoms/ g	atoms/ g	$^3He/^4He$ sample/ air	atoms/g	atoms/g	atoms/g	atoms/g	ratio	‰
Clean Wells - Frenchman Flat														
Water Well 5a	---	14-Aug-00	-110	-13.8	-4.8	4.62E+06	3.16E+12	1.06	9.43E+12	1.59E+16	---	---	---	---
Water Well 5c	---	07-Aug-00	-110.5	-14.0	-6.0	3.41E+06	8.67E+12	0.28	5.64E+12	9.90E+15	---	---	---	---
Water Well 5b	---	07-Aug-00	-108	-13.1	-9.5	3.85E+06	3.90E+12	0.71	5.52E+12	9.04E+15	---	---	---	---
ER-5-4	---	05-Jul-01	-109	-13.6	-4.6	4.10E+06	5.45E+13	0.054	1.00E+13	1.09E+16	---	2.90E+11	0.71056	1.92
ER-5-4 #2	---	21-Nov-02	-101	-13.3	+0.2	1.65E+06	1.35E+12	0.89	4.98E+12	8.25E+15	1.81E+12	2.43E+11	0.70902	-0.25
UE-5c WW	---	08-Aug-00	-106.5	-13.7	-7.2	5.18E+06	1.89E+13	0.20	4.91E+12	8.85E+15	---	---	---	---
UE-5 PW-3	---	09-Aug-00	-105.5	-13.5	-7.5	4.34E+06	2.15E+12	1.46	7.03E+12	1.15E+16	---	---	---	---
ER-5-3	---	28-Mar-01	-108.5	-14.1	-8.0	3.09E+06	5.20E+12	0.43	9.33E+12	9.87E+15	---	---	0.71017	1.37
ER-5-3 #2	---	17-May-01	-110	-14.1	-4.3	2.42E+07	1.28E+13	1.37	5.00E+12	4.75E+15	---	1.34E+11	0.71538	8.71
Water Well 4a	---	08-Aug-00	-101	-12.8	-8.4	2.42E+06	3.16E+12	0.55	4.65E+12	8.02E+15	---	---	---	---
Clean Wells - Yucca Flat														
ER-2-1	---	03-Sep-03	-109.5	-14.2	-12.1	7.36E+07	3.76E+12	14.2	7.65E+12	9.66E+15	2.02E+12	2.62E+11	0.71210	4.09
ER-6-1 #2	---	16-Jan-03	-105	-14.1	-5.9	---	---	---	---	---	---	---	0.71295	5.29
ER-6-2	---	04-Aug-04	-105	-14.1	-4.0	6.67E+06	7.05E+12	0.68	3.68E+12	5.13E+15	1.19E+12	6.97E+09	0.71281	5.09
ER-7-1	---	17-Jul-03	-106	-14.1	-5.8	3.28E+07	4.07E+13	0.58	4.79E+12	7.44E+15	1.81E+12	2.66E+11	0.71306	5.44
Clean Wells - Rainier Mesa														
ER-12-1	---	08-Dec-04	-94.5	-12.6	-10.7	4.24E+06	6.84E+12	0.45	1.12E+13	1.28E+16	2.67E+12	3.65E+11	0.71230	4.37
ER-12-2	---	01-Apr-03	-101	-13.5	-4.9	3.51E+06	9.24E+13	0.03	8.08E+12	1.03E+16	1.91E+12	1.16E+11	0.71662	10.46
ER-12-3	---	06-Jul-05	-106	-14.5	-5.4	3.24E+06	1.79E+13	0.13	7.30E+12	9.69E+15	2.14E+12	1.16E+10	0.71055	1.90
ER-12-4	---	16-Aug-05	-103	-13.7	-7.6	7.81E+05	1.08E+12	0.52	4.48E+12	7.63E+15	1.82E+12	1.19E+10	0.71065	2.04
Clean Wells - Pahute Mesa-Oasis Valley														
ER-EC-1	---	3-Jun-03	-116	-14.9	-3.1	9.44E+06	1.13E+13	0.60	7.22E+12	7.69E+15	1.58E+12	2.29E+11	0.71056	1.92
ER-EC-1	---	1-Feb-00	-116	-14.8	-4.0	9.03E+06	9.24E+12	0.71	9.93E+12	9.11E+15	---	2.34E+11	0.71023	1.45
ER-EC-2A	---	8-Jul-03	-116.5	-14.9	-2.0	8.36E+06	6.97E+12	0.87	4.28E+12	5.69E+15	1.21E+12	1.93E+11	0.70912	-0.11
ER-EC-2A	---	27-Jul-00	-116	-14.9	-1.5	1.03E+07	7.92E+12	0.94	1.07E+13	1.02E+16	---	---	0.70939	0.26

Table 2.5 Environmental well stable isotope data (continued)

Well name	Test	Sample date	δD_{SMOW}	$\delta^{18}O_{SMOW}$	$\delta^{13}C_{PDB}$	^3He	^4He	R/R_a	$^{20}Ne*$	$^{40}Ar*$	Kr	$^{130}Xe*$	$^{87}Sr/^{86}Sr$	$\delta^{87}Sr$
Unit			‰	‰	‰	atoms/ g	atoms/ g	$^3He/^4He$ sample/ air	atoms/g	atoms/g	atoms/g	atoms/g	ratio	‰
Clean Wells - Pahute Mesa-Oasis Valley														
ER-EC-4	---	24-Jun-03	-114	-14.6	-1.1	2.00E+07	1.41E+13	1.02	6.79E+12	7.16E+15	1.42E+12	1.97E+11	0.71010	1.27
ER-EC-4	---	17-Aug-00	-115	-14.6	-1.5	1.83E+07	1.30E+13	1.01	7.66E+12	8.55E+15	---	---	0.70998	1.11
ER-EC-5	---	15-Jul-03	-113	-14.9	-2.8	9.77E+06	6.07E+12	1.16	5.23E+12	6.54E+15	1.34E+12	1.96E+11	0.70916	-0.06
ER-EC-5	---	25-May-00	-113	-14.9	-2.5	1.06E+07	7.09E+12	1.08	8.88E+12	8.37E+15	---	1.84E+11	0.70912	-0.11
ER-EC-6	---	10-Jun-03	-117	-15.0	-2.7	1.72E+07	1.79E+13	0.69	4.76E+12	6.64E+15	1.49E+12	2.26E+11	0.71038	1.66
ER-EC-6	---	10-Feb-00	-116	-15.0	-3.4	1.76E+07	1.75E+13	0.73	6.90E+12	7.46E+15	---	2.29E+11	0.70982	0.88
ER-EC-7	---	21-Jul-03	-98	-13.2	-5.5	6.81E+06	5.87E+12	0.84	5.39E+12	7.42E+15	1.59E+12	2.22E+11	0.70948	0.39
ER-EC-7	---	5-Jun-00	-98	-13.2	-6.3	8.81E+06	7.46E+12	0.86	7.48E+12	8.20E+15	---	2.35E+11	0.70932	0.17
ER-EC-8	---	1-Jul-03	-115	-14.9	-0.9	5.18E+06	3.81E+12	0.98	4.68E+12	5.64E+15	1.13E+12	1.64E+11	0.70922	0.03
ER-EC-8	---	12-Jul-00	-116	-14.8	-1.0	6.43E+06	3.69E+12	1.26	5.16E+12	6.46E+15	---	---	0.70882	-0.54
ER-18-2	---	17-Jun-03	-111	-14.7	-0.5	5.11E+08	1.83E+14	2.01	2.95E+12	3.52E+15	6.94E+11	1.08E+11	0.70877	-0.61
ER-18-2	---	21-Mar-00	-112	-14.7	-0.7	6.81E+08	1.70E+14	2.89	3.83E+12	4.22E+14	---	---	0.70861	-0.84

* Inconsistencies have been identified in the noble gas data. This issue will be addressed in the FY06 HRMP report.

Table 2.6 Environmental well radiochemical data

Well name	Test	Sample date	^{3}H	^{3}H	^{14}C	^{14}C	^{36}Cl/Cl	^{36}Cl	^{85}Kr	^{99}Tc	^{129}I/^{127}I	^{129}I
Unit		*date*	*(pCi/L)*	*(pCi/L)*	*(pmc)*	*(pCi/L)*	*ratio*	*(pCi/L)*	*(pCi/L)*	*(pCi/L)*	*ratio*	*(pCi/L)*
Half-life (a)		*collected*	*12.32*	*12.32*	*5730*	*5730*		*3.01E+05*	*10.73*	*2.13E+05*		*1.57E+07*
Ref. date		*in field*	*collect.*	*time zero*	*collect.*	*collect.*		*collect.*	*collect.*	*collect.*		*collect.*
Clean Wells - Frenchman Flat												
Water Well 5a	---	14-Aug-00	1.5	---	2.60E+00	9.64E-03	8.43E-13	3.1E-04	---	---	---	---
Water Well 5c	---	07-Aug-00	< 1.5	---	3.40E+00	1.24E-02	---	---	---	---	---	---
Water Well 5b	---	07-Aug-00	< 1.5	---	1.31E+01	2.68E-02	7.83E-13	6.0E-04	---	---	---	---
ER-5-4	---	05-Jul-01	2.5	---	1.50E+00	5.72E-03	3.94E-13	3.5E-04	---	---	---	---
ER-5-4 #2	---	21-Nov-02	156.8	---	1.00E+00	4.69E-03	1.76E-13	3.0E-04	---	---	---	---
UE-5c WW	---	08-Aug-00	< 1.5	---	6.50E+00	1.39E-02	---	---	---	---	---	---
UE-5 PW-3	---	09-Aug-00	< 1.5	---	1.60E+01	2.94E-02	---	---	---	---	---	---
ER-5-3	---	28-Mar-01	<1.5	---	8.50E+00	1.73E-02	8.42E-13	4.3E-04	---	---	---	---
ER-5-3 #2	---	17-May-01	<1.5	---	1.60E+00	1.55E-02	2.29E-13	2.9E-04	---	---	---	---
Water Well 4a	---	08-Aug-00	< 1.5	---	1.83E+01	3.45E-02	6.47E-13	4.4E-04	---	---	---	---
Clean Wells - Yucca Flat												
ER-2-1	---	03-Sep-03	227.7	---	1.82E+01	4.14E-02	7.19E-13	1.04E-04	---	---	< 5E-10	---
ER-6-1 #2	---	16-Jan-03	≤ 30.8	---	2.40E+00	7.39E-03	4.33E-13	1.4E-04	---	---	---	---
ER-6-2	---	04-Aug-04	92.2	---	1.56E+00	8.12E-03	2.00E-13	1.6E-04	---	---	---	---
ER-7-1	---	17-Jul-03	117.2	---	5.30E+00	1.56E-02	3.77E-13	1.18E-04	---	---	< 1E-09	---
Clean Wells - Rainier Mesa												
ER-12-1	---	08-Dec-04	3.2	---	1.10E+01	3.40E-02	7.80E-13	4.56E-04	---	---	---	---
ER-12-2	---	01-Apr-03	4.3	---	1.50E+00	5.39E-03	6.90E-13	1.6E-04	---	---	---	---
ER-12-3	---	06-Jul-05	0.5	---	2.95E+00	4.43E-03	5.39E-13	1.0E-04	---	---	---	---
ER-12-4	---	16-Aug-05	89.7	---	6.86E+00	6.93E-03	5.56E-13	1.7E-04	---	---	---	---
Clean Wells - Pahute Mesa-Oasis Valley												
ER-EC-1	---	3-Jun-03	≤ 174	---	7.20E+00	1.28E-02	5.14E-13	1.64E-03	---	---	---	---
ER-EC-1	---	1-Feb-00	<1.5	---	5.90E+00	1.05E-02	5.46E-13	1.75E-03	---	---	---	---
ER-EC-2A	---	8-Jul-03	≤ 93	---	7.70E+00	1.52E-02	5.02E-13	9.15E-04	---	---	---	---
ER-EC-2A	---	27-Jul-00	<1.5	---	7.70E+00	1.58E-02	5.33E-13	1.11E-03	---	---	---	---
ER-EC-4	---	24-Jun-03	<1.5	---	5.90E+00	1.07E-02	4.80E-13	1.28E-03	---	---	---	---
ER-EC-4	---	17-Aug-00	<1.5	---	5.00E+00	9.54E-03	5.61E-13	1.77E-03	---	---	---	---
ER-EC-5	---	15-Jul-03	≤ 9.0	---	7.50E+00	1.62E-02	5.61E-13	2.95E-04	---	---	---	---
ER-EC-5	---	25-May-00	<1.5	---	6.30E+00	1.33E-02	6.53E-13	3.5E-04	---	---	---	---
ER-EC-6	---	10-Jun-03	≤ 64	---	6.60E+00	1.17E-02	5.07E-13	8.65E-04	---	---	---	---
ER-EC-6	---	10-Feb-00	<1.5	---	5.40E+00	9.86E-03	5.41E-13	7.9E-04	---	---	---	---
ER-EC-7	---	21-Jul-03	1.6	---	4.62E+01	4.80E-02	7.55E-13	9.47E-05	---	---	---	---
ER-EC-7	---	5-Jun-00	<1.5	---	3.65E+01	5.22E-02	1.18E-12	2.0E-04	---	---	---	---
ER-EC-8	---	1-Jul-03	5.4	---	8.00E+00	1.68E-02	4.90E-13	7.65E-04	---	---	---	---
ER-EC-8	---	12-Jul-00	<1.5	---	8.70E+00	1.80E-02	4.63E-13	8.8E-04	---	---	---	---
ER-18-2	---	17-Jun-03	<1.5	---	4.00E-01	4.13E-03	2.31E-13	9.38E-05	---	---	---	---
ER-18-2	---	21-Mar-00	<1.5	---	1.60E+00	1.70E-02	3.02E-13	1.3E-04	---	---	---	---

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Table 2.7 Environmental well radiochemical data

Well name	Test	Sample date	$^{234}U/^{238}U$	$^{234}U/^{238}U$ activity ratio	$^{234}U/^{235}U$	$^{235}U/^{238}U$	^{234}U	^{235}U	^{238}U	$^{239,240}Pu$
Unit *Half-life (a)* *Ref. date*		*date collected in field*	*ratio*	*ratio*	*ratio*	*ratio*	*(pCi/L)* *2.46E+05* *collect.*	*(pCi/L)* *7.04E+08* *collect.*	*(pCi/L)* *4.47E+09* *collect.*	*(pCi/L)* *collect.*
Clean Wells - Frenchman Flat										
Water Well 5a	---	14-Aug-00	---	---	---	---	---	---	---	---
Water Well 5c	---	07-Aug-00	---	---	---	---	---	---	---	---
Water Well 5b	---	07-Aug-00	---	---	---	---	---	---	---	---
ER-5-4	---	05-Jul-01	7.46E-05	1.36	1.03E-02	7.25E-03	7.30E-01	2.50E-02	5.30E-01	---
ER-5-4 #2	---	21-Nov-02	7.19E-05	1.31	9.92E-03	7.25E-03	1.61E+01	5.70E-01	1.22E+01	---
UE-5c WW	---	08-Aug-00	---	---	---	---	---	---	---	---
UE-5 PW-3	---	09-Aug-00	---	---	---	---	---	---	---	---
ER-5-3	---	28-Mar-01	1.86E-04	3.40	2.57E-02	7.26E-03	1.12E+00	1.50E-02	3.30E-01	---
ER-5-3 #2	---	17-May-01	1.80E-04	3.29	2.48E-02	7.26E-03	5.60E-01	8.00E-03	1.70E-01	---
Water Well 4a	---	08-Aug-00	---	---	---	---	---	---	---	---
Clean Wells - Yucca Flat										
ER-2-1	---	03-Sep-03	1.48E-04	2.71	2.04E-02	7.25E-03	3.11E+00	5.30E-02	1.14E+00	---
ER-6-1 #2	---	16-Jan-03	2.30E-04	4.19	3.17E-02	7.25E-03	4.55E+00	5.00E-02	1.07E+00	---
ER-6-2	---	04-Aug-04	2.39E-04	4.35	3.30E-02	7.25E-03	3.20E+00	3.40E-02	7.24E-01	---
ER-7-1	---	17-Jul-03	1.88E-04	3.43	2.59E-02	7.25E-03	1.33E+00	1.80E-02	3.83E-01	---
Clean Wells - Rainier Mesa										
ER-12-1	---	08-Dec-04	3.79E-04	1.62	5.22E-02	7.25E-03	1.43E+00	4.21E-02	8.68E-01	---
ER-12-2	---	01-Apr-03	1.79E-04	3.26	2.45E-02	7.30E-03	1.90E-02	2.70E-04	5.70E-03	---
ER-12-3	---	06-Jul-05	1.15E-04	2.09	1.58E-02	7.26E-03	1.30E+00	2.90E-02	6.12E-01	---
ER-12-4	---	16-Aug-05	1.06E-04	1.93	1.46E-02	7.24E-03	1.92E-01	5.00E-03	9.90E-02	---
Clean Wells - Pahute Mesa-Oasis Valley										
ER-EC-1	---	3-Jun-03	1.94E-04	3.54	2.66E-02	7.27E-03	1.13E+01	1.48E-01	3.17E+00	---
ER-EC-1	---	1-Feb-00	2.10E-04	3.82	2.89E-02	7.25E-03	1.05E+01	1.26E-01	2.71E+00	---
ER-EC-2A	---	8-Jul-03	2.74E-04	5.01	3.78E-02	7.25E-03	1.19E+01	1.10E-01	2.35E+00	---
ER-EC-2A	---	27-Jul-00	2.25E-04	4.11	3.09E-02	7.27E-03	1.28E+01	1.44E-01	3.08E+00	---
ER-EC-4	---	24-Jun-03	1.59E-04	2.90	2.19E-02	7.27E-03	3.99E+00	6.40E-02	1.36E+00	---
ER-EC-4	---	17-Aug-00	1.59E-04	2.90	2.18E-02	7.29E-03	3.97E+00	6.40E-02	1.39E+00	---
ER-EC-5	---	15-Jul-03	3.53E-04	6.45	4.85E-02	7.27E-03	7.27E+00	5.20E-02	1.12E+00	---
ER-EC-5	---	25-May-00	3.51E-04	6.41	4.82E-02	7.28E-03	7.20E+00	5.20E-02	1.11E+00	---
ER-EC-6	---	10-Jun-03	2.03E-04	3.71	2.80E-02	7.27E-03	6.79E+00	8.50E-02	1.81E+00	---
ER-EC-6	---	10-Feb-00	2.23E-04	4.07	3.07E-02	7.27E-03	6.52E+00	7.40E-02	1.58E+00	---
ER-EC-7	---	21-Jul-03	3.97E-04	7.26	5.48E-02	7.25E-03	4.57E+00	2.90E-02	6.22E-01	---
ER-EC-7	---	5-Jun-00	3.97E-04	7.26	5.46E-02	7.28E-03	5.19E+00	3.30E-02	7.10E-01	---
ER-EC-8	---	1-Jul-03	2.77E-04	5.06	3.82E-02	7.24E-03	8.22E+00	7.50E-02	1.61E+00	---
ER-EC-8	---	12-Jul-00	2.78E-04	5.08	3.82E-02	7.28E-03	8.18E+00	7.40E-02	1.59E+00	---
ER-18-2	---	17-Jun-03	6.98E-04	12.76	9.59E-02	7.29E-03	3.67E+01	1.33E-01	2.85E+00	---
ER-18-2	---	21-Mar-00	6.95E-04	12.70	9.56E-02	7.27E-03	3.54E+01	1.29E-01	2.76E+00	---

Chapter 3

Distribution of ^{99}Tc and ^{129}I in the Vicinity of Underground Nuclear Tests

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3.1   Introduction

^{99}Tc and ^{129}I are actinide fission products with long half-lives (2.15×10^5 years and 1.57×10^7 years, respectively), both of which occur as high-solubility anionic species in groundwater. Due to their weak sorption characteristics, both ^{99}Tc and ^{129}I have a high potential for migration in the subsurface environment.

At underground nuclear testing sites, the migration of ^{99}Tc and ^{129}I in groundwater is influenced by the initial distribution of these radionuclides in nuclear test debris. Unfortunately, very little information is available on this initial distribution. Our current understanding of ^{99}Tc and ^{129}I distribution within the test cavity-chimney is based primarily on IAEA experience from French underground tests in French Polynesia (IAEA, 1998). Based on both physical and chemical characteristics, the fraction of ^{99}Tc and ^{129}I incorporated into melt glass from an underground nuclear test was estimated to be 80% and 50%, respectively.

The main objectives of this investigation were to: (1) measure the ^{99}Tc and ^{129}I concentrations in melt glass and rubble samples from an underground test cavity, and use the results to empirically assess the IAEA partitioning estimates; (2) measure ^{99}Tc and ^{129}I in groundwater samples from a number of NTS near-field wells; and (3) compare groundwater and test debris data to determine water-rock partitioning (K_d).

3.2   Experimental

3.2.1   Technetium Analyses

For groundwater samples, we used TEVA resin columns to enrich and separate ^{99}Tc from interfering elements (Einchrom, 2002). Depending on the ^{99}Tc concentration, sample volumes of 10 mL to 2 liters were used. For melt glass and rock samples, a fusion method (Dixon et al., 1997; ASTM, 2005) was used wherein a powdered sample was reacted with sodium peroxide and low carbonate sodium hydroxide at 700 $^{\circ}$C for 30 minutes. This method is effective in fusing all rock-forming minerals while minimizing Tc

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volatilization (and potential loss) during the digestion process. The fusion cake was dissolved in nitric acid and a TEVA column was used to separate and purify the ^{99}Tc. A modified isotope dilution ICP-MS method was used for ^{99}Tc analyses. The NIST SRM-4288A solid and an aqueous solution of 32.61±0.37 kBq/g ^{99}Tc(VII) in 1×10^{-3} M KOH were used as ^{99}Tc reference standards. Stable rhenium was spiked in each sample (both groundwater and solid) as a tracer to monitor rhenium and, by analogy, ^{99}Tc recovery.

3.2.2   Iodine Analyses

NTS groundwater samples are normally in the neutral to slightly alkaline pH range and were directly analyzed for stable iodine after spiking with 5 μg/L of internal standard (rhodium, Rh) in 1% CFA-C. The CFA-C is a surfactant that coats the glassware and reduces the memory effect of iodine in the ICP-MS introduction system (Mas et al., 2004). Groundwater samples were prepared for ^{129}I analysis on the Accelerator Mass Spectrometer (AMS) using standard methods reported in the literature (Moran et al., 1995).

A microwave sample preparation system was used to digest and extract iodine from melt glass and rock samples. 4 mL of 5% tetra-methyl ammonium hydroxide (TMAH) solution was added to 0.5-1g of powdered sample in a Teflon vessel for the microwave digestion (Uchida et a., 1992; Zhou et al., 1996; Hamada et al., 1999). The power level and time for each digestion stage were programmed to reach a maximum value of 800 W over 15 minutes, and held there for an additional 10 minutes. To minimize potential iodine loss, the maximum temperature and pressure was not allowed to exceed 90 °C and 1241 kPa, respectively. After digestion, 6 mL of 1% CFA-C was added to the sample vessel. The total iodine in the supernatant was analyzed directly by ICP-MS. The ^{129}I targets were made using a stable ^{127}I carrier containing low ^{129}I to form AgI solid (Marchetti et al., 1997); the ^{129}I/^{127}I ratio was measured by AMS.

3.3   Results and Discussion

3.3.1   Results of Groundwater Samples

A total of 24 groundwater samples from 13 sampling sites were analyzed for ^{99}Tc and ^{129}I. Table 3.1 presents the measured ^{99}Tc concentrations in NTS groundwater samples using the ICP-MS method. For comparison, data from independent AMS (Bergquist et al., 2000) and liquid scintillation counting (LSC; this study) measurements of the same samples are also included. Measurement uncertainties reported in Table 3.1 are calculated from replicate analyses. The instrumental uncertainties for ^{99}Tc and ^{129}I analyses are <2% by ICP-MS measurements and 2-4% for ^{129}I/^{127}I ratio measurements by AMS. However, error propagation in overall procedures for groundwater samples results in uncertainties of 5 to 10%. Table 3.1 also includes an Irish Sea Water sample as a reference standard (Bergquist et al., 2000). Our measured ^{99}Tc value for the reference standard is in good agreement with the accepted value (0.22 ± 0.01 Bq/L).

Table 3.1 Technetium and Iodine in NTS Groundwater Samples

Test Name	Sampling Well / Location	Sampling Date	^{99}Tc (ICP-MS) (Bq/L)	^{99}Tc (other methods) (Bq/L)	Total Iodine (µg/L)	^{129}I / ^{127}I	^{129}I (mBq/L)
ALEMAN	UE-3e #4; 58 m from working point	09/23/1998	0.32 ± 0.01	0.48 ± 0.01 [a]	11.3	n.a.	
ALMENDRO	U-19v PS1ds; Cavity/chimney	08/18/1999	2.8E-03	n.a.	7.4	1.06E-03	53
		07/23/2003	4.1E-04	n.a.	10.1	1.41E-03	95
BILBY	U-3cn PS2; Chimney	12/18/2001	3.06 ± 0.03	2.96 [b]	9.1	9.74E-05	5.9
		12/09/2004	2.32 ± 0.23	2.50 ± 0.07 [b]	9.5	1.48E-04	9.4
BOURBON	UE-7nS; 137 m from working point	08/21/2001	<0.04	n.a.	23.1	1.47E-07	0.023
CAMBRIC	RNM-1; Cavity	06/03/2004	<1.3E-4	<0.037 [b]	16.2	2.06E-07	0.022
	RNM-2S; 91 m from working point	10/11/1999	<1.3E-5	(4.8 ± 2.6)x1E-5 [a]	11	2.12E-07	0.016
		07/10/2003	<1.3E-6	n.a.	12.2	6.16E-07	0.050
	UE-5n; 510 m from RNM-2S	09/09/1999	1.7E-04	(8.5 ± 7.0)x1E-5 [a]	30	3.51E-09	0.0007
		02/12/2004	2.7E-04	n.a.	19	5.02E-07	0.064
CAMEMBERT	U-19q PS1d; Chimney	10/21/1998	n.a.	(3.1± 0.7)x1E-3 [a]	4.1	5.54E-06	0.15
		07/16/2003	4.8E-04	n.a.	4	2.77E-06	0.074
CHESHIRE	U-20n PS1ddh; Cavity	07/25/1998	n.a.	1.15 ± 0.25 [a]	5.9	n.a.	n.a.
		09/21/1998	0.80 ± 0.04	0.74 ± 0.02 [a], 0.422 [b]	5.8	n.a.	n.a.
		10/12/1999	0.57 ± 0.04	0.83 ± 0.16 [a]	13	4.91E-05	4.3
CHANCELLOR	U-19ad PS1A; Cavity	09/27/2004	1.70 ± 0.01	n.a.	19.4	5.59E-04	73
DALHART	U-4u PS2a; Chimney	08/16/1999	0.49 ± 0.02	0.59 ± 0.02 [a], 0.55 [b]	5.8	2.80E-05	1.1
		10/09/2003	1.30 ± 0.13	1.29 ± 0.07 [b]	7.1	1.04E-04	4.9
NASH	UE-2ce; 183 m from working point	08/22/2001	<1.3E-4	n.a.	9.4	1.88E-05	1.2
TYBO /BENHAM [e]	ER-20-5 #1 (701-784 m)[d]; 280/1300 m from TYBO /BENHAM working points	07/09/1998	0.022	0.010 ± 0.002 [a]	7	2.14E-04	10.0
		11/30/2004	0.017	<0.04 [b]	5.4	1.99E-04	7.2
	ER-20-5 #3 (1046-1183 m)[d]; 280/1300 m from TYBO /BENHAM working points	04/30/1998	<0.04	<0.001 [a]	8.2	n.a.	n.a.
		11/29/2004	7.0E-04	n.a.	4.7	1.66E-06	0.052
Irish Sea Water	IAEA-381		0.2	0.22 ± 0.01 [c]			

n.a. = not analyzed.
[a] = ^{99}Tc analyses performed by LSC; [b] = ^{99}Tc analyses performed by AMS; [c] = Literature reported value; [d] = open interval where sampling occurred; [e] = Both the TYBO and BENHAM tests are listed since the ER-20-5 well cluster was drilled in the near-field (~300 m from the surface ground zero) environment of the TYBO test. However, Pu isotopic signatures indicate the radionuclides in water samples from ER-20-5 wells are derived from the BENHAM test detonated ~1300 m up-gradient (Kersting et al., 1999).

In general, cavity water samples contained higher concentrations of ^{99}Tc compared to near-field satellite wells. The highest values were observed in well U-3cn PS#2a (the BILBY test), with 3.1 Bq/L in 2001 and 2.3 Bq/L in 2004. Only three NTS near-field wells have produced water with ^{99}Tc activities above 1 Bq/L. Concentrations lower than 0.3 mBq/L ^{99}Tc were found in near-field satellite monitoring wells. Downstream migration of ^{99}Tc is apparent. However, local geochemical conditions, such as reducing conditions (sometimes encountered in test cavities) may be limiting ^{99}Tc migration from the test cavity.

Using Re to trace extraction efficiency, the ^{99}Tc concentration in U-19ad PS#1A groundwater (CHANCELLOR test) was measured to be 1.70 ± 0.01 Bq/L. This value was confirmed by an independent set of standard addition measurements. Using a TEVA column for pre-concentration and purification of 1-liter water samples, ICP-MS can provide a ^{99}Tc method detection limit (MDL) of 0.13 mBq/L. This is about one order of magnitude higher than that achieved by AMS, which has a reported MDL of 0.01 mBq or 1×10^8 atoms with 15-25% error for a 1-liter sample volume (Bergquist et al., 2000). The LSC detection limit is ~37 mBq/L.

The total stable ^{127}I concentrations, ^{129}I/^{127}I ratios, and corresponding ^{129}I activities in NTS groundwaters are also reported in Table 3.1. The ratio of ^{129}I/^{127}I in cavity and satellite well samples range from 10^{-3} to 10^{-6} and 10^{-4} to 10^{-9}, respectively. The ^{129}I/^{127}I ratio of uncontaminated environmental samples is $\leq 10^{-13}$. The results suggest that ^{129}I is migrating at a rate similar to ^{99}Tc.

3.3.2 Results of Solid Samples

Melt glass and rubble samples were recovered from the CHANCELLOR (U-19ad) underground test cavity during a drilling operation in 2004. Figure 3.1 shows the spatial distribution of samples collected from the test cavity. Samples were chosen over a wide depth interval (~130 meters). Table 3.2 lists the measured ^{99}Tc, total iodine, and ^{129}I/^{127}I ratios in the test debris samples. The uncertainties in measurements of ^{99}Tc and ^{129}I/^{127}I ratios for the solid samples are similar to if not smaller than those for the water samples. We obtained >95% chemical recovery of total iodine from three IAEA/SRM soil samples using the microwave digestion/TMAH extraction method. However, iodine recovery in melt glass samples may be lower due to the difference in sample matrix (soil vs. melt glass). We are currently assessing the quartz tube combustion method reported by Muramatsu and Wedepohl (1998) for total iodine measurement in rock samples.
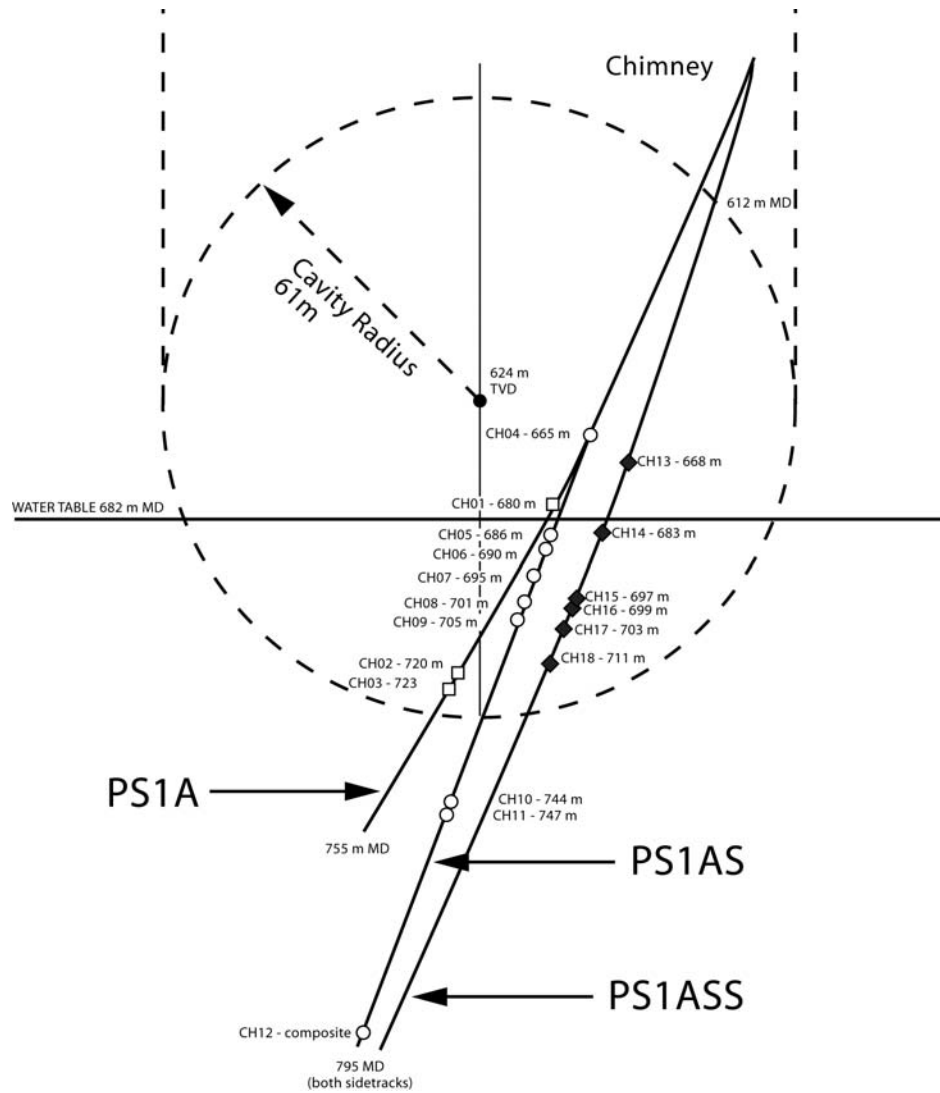
Figure 3.1 Cross section of the CHANCELLOR cavity, chimney, and post-shot boreholes showing the locations of sidewall core samples that were used in this investigation. Main hole (PS1A); first sidetrack (PS1AS) and second sidetrack (PS1ASS). MD: measured depth, TVD: total vertical depth.

Table 3.2 Technetium and Iodine Data of Solid Samples from the CHANCELLOR Test Cavity

Sample ID	sample description	^{99}Tc (ng/kg)	^{99}Tc (Bq/kg)	Total Iodine (µg/kg)	^{129}I/^{127}I	^{129}I (mBq/kg)
Blank		<1	<1		3.0E-13	
CH01a	gray volcanic rocks	9	5	23.6	3.1E-07	0.049
CH01b	gray volcanic rocks with some black melt glass on surface	1.9	12	26	3.7E-08	0.0064
CH03a	reddish-brown melt glass, non-vesicular	729 ± 31	458±20	14.3	8.8E-04	83
CH03b	pale-gray volcanic rock mix with small portion of melt glass	39 ± 4	24±3			
CH04a	vesicular brown melt glass	669	420	40.3	1.7E-04	45
CH04b	volcanic rock, some partially melted to form light-colored vesicular glass	61 ± 3	38±2	12.6	1.1E-04	9.1
CH06a	black melt glass	597	375	5	1.3E-03	44
CH06b	black melt glass mixed with volcanic rock	632	397	3.4	7.2E-04	16
CH09a	dark brown / black melt glass	742	466	0.9	3.9E-03	23
CH09b	dark brown / black melt glass	695	436			
CH12	black melt glass	645 ± 17	405±11	14.1		
CH14	volcanic rock, some partially melted to form light-colored non-vesicular glass	49 ± 3	31±2	16.7	4.4E-05	4.9
CH16	dark brown/black melt glass	747	469	3	2.4E-03	49

The ^{99}Tc concentrations correlate with sample type. ^{99}Tc in the dark melt glass exhibits a fairly uniform distribution, with a narrow range of 600−750 ng/kg. The non-melted volcanic rock contains <100 ng/kg ^{99}Tc. The ^{129}I activities in the solid samples range from 0.006 to 83 mBq/kg with highest concentrations found in the dark melt glass samples. The two samples (CH01a and b) that have very low ^{129}I activities also have the lowest ^{99}Tc concentrations of all samples.

3.3.3 Radionuclide Distribution in a Test Cavity

Based on the announced yield of the CHANCELLOR test (143 kt of TNT equivalent) (DOE/NV, 2000), the depth of burial, and the bulk density of the overlying rock, we estimate the test cavity radius (Pawloski, 1999) and generated mass of melt glass (Olsen, 1993) to be 61 m and ~1.43 × 10^8 kg, respectively. Assuming a density of 2.5 g/cm^3 and porosity of 30% for the melt glass and test debris, we can estimate the volume of melt glass and rubble in the cavity. The volume of groundwater in the cavity can be calculated assuming the saturated zone porosity is fully saturated and unsaturated zone is only 50% saturated.

Table 3.3 Distribution of Radionuclides in the CHANCELLOR Test Cavity

	Total Mass (g)	Total ^{99}Tc (MBq)	^{99}Tc%	^{99}Tc% IAEA	Total ^{129}I (MBq)	^{129}I%	^{129}I% IAEA
Melt Glass	1.43E11	6.14E4	65%	80	7.0	28%	50
Rubble	1.52E12	3.35E4	35%	20	5.3	24%	40
Groundwater	1.80E11	3.07E2	0.3%	0	13.0	48%	10

Using the measured ^{99}Tc and ^{129}I concentrations in the melt glass, rubble, and groundwater, the partitioning of ^{99}Tc and ^{129}I can be estimated (Table 3.3) and compared with IAEA estimates (IAEA, 1998). Approximately 65% of the ^{99}Tc is associated with the melt glass, and 35% is associated with the rubble. Our estimate agrees with IAEA values to within ±15%. Only a very small proportion of ^{99}Tc (0.3%) was dissolved in the cavity water, which is expected given its strong sorption under moderately reducing conditions (Lieser and Bauscher, 1987). Based on rubble and water concentrations, we estimate the ^{99}Tc K_d to be between 3 and 22 mL/g. Both Eh and iodine speciation measurements support the conclusion that the groundwater was reducing.

Using the same approach for ^{129}I, we estimate 28%, 24% and 48% of ^{129}I is in the melt glass, rubble and groundwater phases, respectively. Compared with IAEA estimates (IAEA, 1998), our results show that a larger fraction of the ^{129}I is present in groundwater, and a lower fraction is contained in the glass and rubble. Given the high volatility of iodine and its mass 129 fission product precursors, together with the solubility of iodine in groundwater, the high fraction of ^{129}I in the cavity fluid would appear to be reasonable. Based on rubble and water concentrations, we estimate the ^{129}I K_d to be between 0 and 0.12 mL/g. However, ^{129}I was measured in only a few rubble samples, and our procedure lacked an iodine tracer to monitor recovery. Incomplete recovery of ^{129}I from solid samples would lead to an overestimation of ^{129}I partitioning into the groundwater phase

and an underestimation of K_d. Quartz-tube combustion experiments for measuring low-level total iodine in rock samples are underway and will be used to compare with TMAH microwave digestion results described here.

While the partitioning estimates developed during this study are approximate, it is notable that the values differ from those reported by the IAEA for French underground tests. To some extent, these differences may reflect variations in the underground test conditions. For example, the type of geologic media and the water or CO_2 content of the rock can influence the amount of time that the cavity stands prior to collapse of the overlying rock. Cavity collapse results in the rapid cooling of the system, and disrupts communication between the vapor phase and melt. The timing of this 'quenching' event has a significant effect on the fission product distribution because the partitioning of these fission products is largely determined by the chemical behavior of fission chain precursor elements (Moody, 2003).

For example, most of the mass 99 and 129 fission chains are 'born' as short-lived precursors that decay to ^{99}Tc and ^{129}I on relatively short-time scales (half-lives of seconds to days). The chemical properties of these precursor elements will determine how the mass 99 and 129 species are distributed between the melt and vapor phases at the time of cavity collapse. Since each precursor species decays on a different time-scale, test cavities that are 'quenched' soon after the detonation will have a different fission product distribution than those that stand for a longer period of time. The future evaluation of radionuclide partitioning in underground test cavities that represent diverse cooling histories would provide additional constraints on the range in partitioning behavior.

3.4   Conclusions

^{99}Tc and ^{129}I are important contributors to risk assessment due to their long half-lives and high mobility as aqueous anionic species. ^{99}Tc and ^{129}I in groundwater samples from 13 wells and in test debris from the CHANCELLOR underground nuclear test cavity were analyzed using ICP-MS, LSC and AMS. In general, concentrations in the satellite wells are lower than in the test cavities for both ^{99}Tc and ^{129}I. The ^{129}I/^{127}I ratio ranges from 10^{-3} to 10^{-6} in cavity water and 10^{-4} to 10^{-9} in satellite wells. The ^{99}Tc concentration ranges from 3 to 10^{-4} Bq/L in cavity waters and from 0.3 to 10^{-4} Bq/L in satellite wells. Downstream migration is apparent for both radionuclides. However, it is affected by both retardation and initial distribution. For example, ^{99}Tc and ^{129}I K_ds calculated using rubble and water concentrations from CHANCELLOR are 3 to 22 mL/g and 0 to 0.12 mL/g, respectively, and are suggestive of mildly reducing conditions. Though both radionuclides appear to be relatively mobile, ^{99}Tc is likely to be retarded as a result of its reduction from the TcO_4^- anion to the more sorbing and insoluble TcO_2 species.

Using the analytical results of the water and test debris samples from CHANCELLOR, we have estimated the distribution of ^{99}Tc and ^{129}I between the melt glass, rubble and groundwater in the CHANCELLOR test cavity and compared them to reported values for underground tests in French Polynesia (IAEA, 1998). ^{129}I distribution in the melt glass, rubble and groundwater of the Chancellor test cavity is 28%, 24% and 48%, respectively;

for ^{99}Tc, it is 65%, 35% and 0.3%, respectively. Our partitioning estimates differ from those of the IAEA (1998), implying that fission product distribution may vary from test to test. Factors that may influence this distribution include geologic conditions (e.g. lithology, water and CO_2 content) and the cooling history of the test cavity.

3.5   References

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Chapter 4

Characterization of Experimentally Altered Nuclear Melt Glass

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4.1   Introduction

The nuclear melt glass that forms as a result of an underground nuclear test retains the majority of the actinide residual inventory (Borg, 1975). A major concern in risk assessment at these sites is the transport of actinides in groundwater. Secondary mineral precipitates that form as a result of melt glass dissolution can sequester insoluble radionuclides (e.g. plutonium) and minimize their migration. Secondary mineral precipitates may also form colloids and promote transport of radionuclides in groundwater. Understanding glass dissolution behavior and identifying the associated secondary mineral phases is essential to the accurate prediction of radionuclide transport.

The two major objectives of the experiments described in this chapter were: (1) understand the glass dissolution behavior of nuclear melt glass from the NTS and (2) characterize the secondary mineral phases that precipitate as a result of nuclear melt glass dissolution at elevated temperatures (120°C and 200°C). A previous study was conducted using a wider temperature range (40°C to 200°C) over a 3-month reaction period (Zavarin et al., 2004). This reaction time yielded little alteration at all temperatures except 200°C. The current experiments extended the reaction time at the two highest temperatures examined previously.

4.2   Methods

The experiments described herein examined the supernatant composition and the secondary mineral characteristics resulting from high temperature alteration of nuclear melt glass. Ion Chromatography (IC) and Inductively Coupled Plasma – Mass Spectroscopy (ICP-MS) were used to determine the chemical composition of the supernatant. The Eh and pH were also measured. Scanning Electron Microscopy (SEM) with the Energy Dispersive X-ray Spectroscopy (EDS) provided a means of qualitative chemical and morphological characterization of secondary mineral precipitates. X-ray Diffraction (XRD) was used to help identify the secondary mineral phases. Alpha-radiography, along with liquid scintillation counting, was used to determine the concentration of α-emitters in the solid and supernatant, respectively.

4.3 Procedure

4.3.1 Experimental protocol

In an effort to identify the minerals that form from the high-temperature alteration of nuclear melt glass in groundwater, three samples of melt glass were individually reacted with a simple synthetic groundwater (3×10^{-3} mol/L Na, 2×10^{-3} mol/L HCO_3/CO_3^{2-}) for 12 months at 120 and 200ºC. The synthetic groundwater is a simplified analog of groundwater present in the Pahute Mesa region of the NTS (Pawloski et al., 2001). Three samples were used in the dissolution experiments (Table 4.1). JMK#1 and JMK#3 nuclear melt glasses were selected from an undisclosed nuclear test location at the NTS. The chemical composition of the glasses was a high-silica rhyolite. Samples were crushed and sieved and the 25-53 microns particle size was used in all experiments. Glass samples were washed in dilute HF solution to remove any natural alteration products. Experiments were run in Parr® bombs placed in temperature controlled ovens. Details regarding the sample preparation and experimental procedure can be found in Zavarin et al. (2004).

Table 4.1 Glass dissolution experiment parameters

Sample	Amount gram	Temp ºC
JMK#3@200°C	1	200
JMK#3@120°C	1	120
JMK#1@120°C	1	120

4.3.2 Sample Characterization

After 12 months, the three samples were removed from the ovens and allowed to cool to room temperature. Samples were removed from their respective vessels and centrifuged in 30mL vials. The supernatant was decanted into second vial and analyzed by IC, ICP-MS, and LSC. The major elements measured included sodium, potassium, magnesium, and calcium. The elements measured by ICP-MS included aluminum, silicon, titanium, iron, [239]Pu, [238]U, [237]Np, and [241]Am. Eh and pH were also measured.

After 12 months, the solid residue in all three samples had visibly altered from the original glass (Figure 4.1). Milli-Q water was added to the vial to separate the primary glass from the secondary minerals. After shaking the vial, the larger glass particles were allowed to settle while the suspended solution (with secondary phases) was pipetted out. This was repeated until the majority of the high surface area (secondary mineral) particles were separated. The 200°C sample had 2 visually distinct secondary mineral precipitates. Sub-sample JMK#3@200°C**a** had a tan hue, while sample JMK#3@200°C**b** had a cream hue.

Figure 4.1 Centrifuge tubes containing primary and secondary minerals.

The secondary minerals were characterized by SEM, EDS, XRD, and α-radiography. The first SEM samples were prepared on small gold coated carbon dots. Later SEM samples were prepared on graphite discs, two of which were gold coated. SEM provides information on secondary mineral morphology. The EDS provides chemical information for images observed in SEM. However, the EDS data provide only gross sample characterization because the secondary mineral particle sizes (microns to 10s of nanometers) examined here were smaller than the EDS spatial resolution.

XRD was used to determine the secondary mineral phases present. In an earlier study (Zavarin et al., 2004), the secondary mineral phases identified by XRD did not differ significantly from the original phases present in the nuclear melt glass. Therefore, the secondary mineral products of glass dissolution could not be identified. In the present experiment, HF was used to remove secondary minerals from the starting material. Furthermore, at the end of the reaction period, secondary mineral precipitates were separated from the bulk melt glass. This allowed for much better secondary mineral identification. XRD of the two 120°C samples was accomplished by drying the wet samples on quartz plates. The quartz plates have the benefit of minimal XRD background. The 200°C samples were dried on 1" diameter carbon dots to make them less dispersive. A carbon dot standard was run and the background had no significant XRD features.

The technique of α-radiography was used to detect the presence and location of α-emitters in the solid samples. The α-radiography samples were prepared using small SEM plugs and carbon dots. A drop of the separated secondary mineral was spread across the carbon dot and dried. The α-radiography plastic film (TASTRAK CR-39), a polycarbonate plastic alpha-track detector, was placed on top of the dried samples and allowed to interact with the sample for 3.5 days or 15 hours. After exposing the film to the sample for the desired time, the film was etched by placing it into a bath of 6.25 N NaOH for 6 hours at 75°C. The α tracks were observed by optical microscope.

4.4 Results and Discussion

4.4.1 Supernatant Composition

All three experiments resulted in an alkaline supernatant (when cooled to 25°C). However, the 120°C samples had significantly higher pHs that the 200°C sample (Table 4.2). Interestingly, Pawloski et al. (2001) reported that precipitation of clay minerals is favored at lower temperatures and leads to fairly alkaline pHs while precipitation of zeolites and framework silicates is favored at higher temperatures and leads to more acid solution conditions. The supernatant solution pHs measured here are consistent with that analysis.

The measured Ehs of all the samples were relatively similar. However, the Eh was measured in an open centrifuge tube over an extended period of time (about 10-30 minutes) and was observed to change with time (Eh measurements listed in Table 4.2 represent the final reading). Thus, the Eh reported here may not represent Eh conditions in the reaction vessels during heating. Nevertheless, results suggest that glass dissolution will result in at least mildly reducing conditions (Figure 4.2). The results compare well with those of Zavarin et al. (2004).

Table 4.2 pH and Eh results for nuclear melt glass supernatant

Sample	pH	Eh (mV)
JMK#3@200°C	8.48	190.8
JMK#3@120°C	9.85	168.0
JMK#1@120°C	9.86	176.0
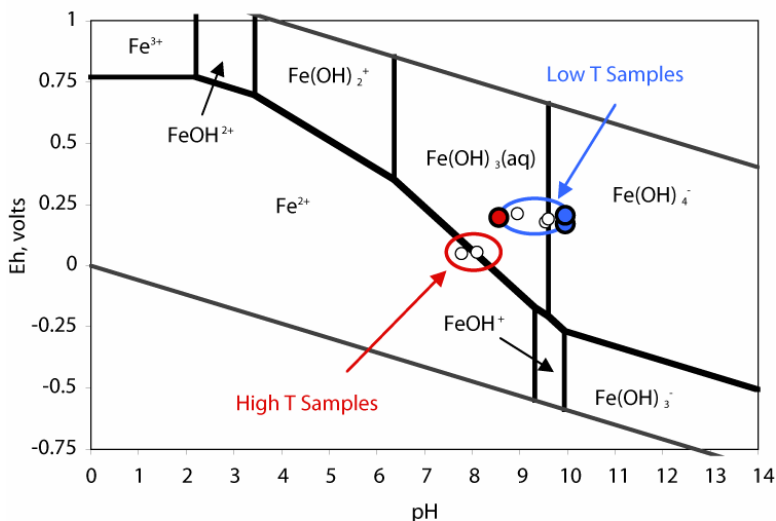
Figure 4.2 Eh-pH values for the 120°C (blue) and 200°C (red) samples superimposed on the Eh-pH diagram and data from Zavarin et al. (2004).

The supernatant composition (Table 4.3) reflects the glass dissolution and secondary mineral precipitation behavior at elevated temperatures over time. The original synthetic groundwater had a composition of $3x10^{-3}$ mol/L Na and $2x10^{-3}$ mol/L HCO_3^-/CO_3^{2-}. It should be noted that some changes in solution composition may have occurred during sample cooling. For example, the relatively low Si concentration in the 200°C sample (relative to 120°C) may have resulted from silica precipitation during sample cooling. Nevertheless, the following can be said:

- NO_3/NO_2 concentrations reflect mildly reducing conditions consistent with Eh measurements

- High measured Fe and Al concentrations and their known low solubilities suggest that colloidal material was present in the supernatant.

Table 4.3 Nuclear melt glass supernatant composition

Element	JMK#1 120°C	JMK#3 120°C	JMK#3 200°C
	---------------------- ppm ----------------------		
Na[a]	156	203	110
Mg[a]	0.04	2.82	1.15
Al[a]	9.4	26	9.8
K[a]	15.8	14.2	11.5
Ca[a]	1.03	4.24	0.68
Ti[a]	4.43	4.7	4.94
Fe[a]	1.93	12.8	16
Si[a]	207	219	188
$^{238}U^a$ (ppb)	5.18	5.71	22.4
F^{-b}	1.3	1.4	0.9
Cl^{-b}	3.9	20	7.5
NO_2^{-b}	0.23	0.68	0.66
NO_3^{-b}	12.5	2.3	7.2
SO_4^{2-b}	0.78	2.1	3.8
PO_4^{3-b}	0.53	5.9	0.52

[a] ICP
[b] IC

4.4.2 SEM and EDS

The SEM analysis provides insight into the morphology of the secondary minerals. Two samples at each temperature were prepared. The four samples are identified as JMK#1@120°C, JMK#3@120°C, JMK#3@200°Ca, and JMK#3@200°Cb. Using the SEM images, the secondary mineral phases were identified by visually comparing the

SEM images to ones found in the literature (Mumpton 1977). The phases were later verified using XRD.

The JMK#1@120°C sample had the least alteration material after the one-year reaction time. On the glass edges two distinct secondary mineral morphologies were observed (Figure 4.3). The first has sharp defined spikes about 1 to 3 microns in length, which are presumed to be mordenite. The second distinct morphology consists of thin wavy ridges, which could be classified as clay as it closely resembles smectite. Figure 4.2C depicts both morphologies on a particle of primary glass.
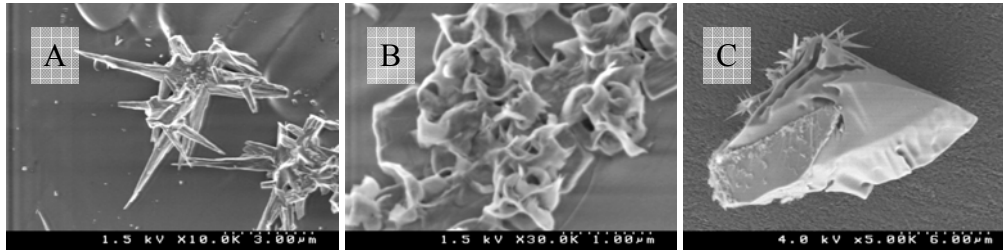
Figure 4.3 SEM Image of (A) mordenite morphology, (B) clay-like morphology, and (C) primary glass in JMK#1@120°C.

The JMK#3@120°C contains more secondary minerals than the JMK#1 sample (Figure 4.4). Many particles with clay-like morphology, identified by the layered features, were observed in this sample. Two other mineral morphologies were observed. The first consists of clusters of spikes or small fibers, which are presumed to be mordenite. While the second is the frayed edges of laminate mineral or glass sheets. It is not clear whether this morphology is representative of a specific mineral or simply the glass dissolution weathering pattern; Zavarin et al. (2004) presumed that it was a glass weathering pattern.
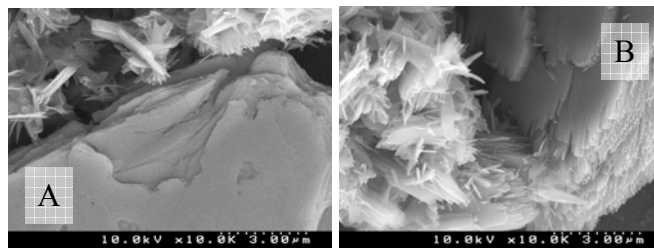
Figure 4.4 SEM image of (A) clay structure and (B) 2 other morphologies observed in JMK#3@120°C.

The JMK#3@200°C samples contain the most secondary minerals. Sample A, the tan colored sample, has three prominent morphologies (Figure 4.5). First are the 50-200nm radius fibers. The fibers, presumably mordenite, are observed throughout the sample, and the other morphologies are intertwined with the fibrous phase. The second morphology consists of blocky crystals in groups and within the fibrous regions. The well-defined blocky crystals are fairly uniform in size at about 1 by 2 microns and are presumed to be clinoptilolite. The third morphology consists of small clusters of nanospheres. These

grape-like clusters are located in cracks and crevices of the blocky crystals and the fibers. The mineral phase is undetermined.
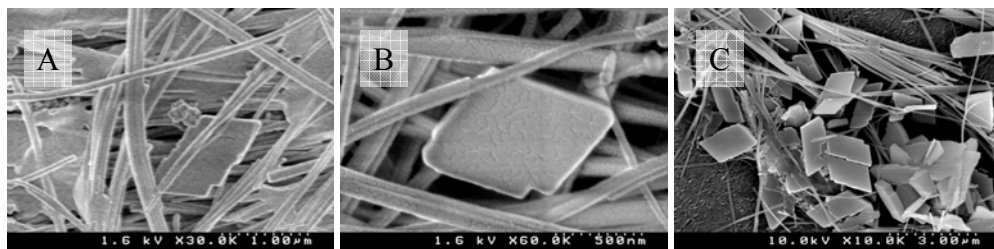
Figure 4.5 SEM image of (A) fibrous mordenite, (B) blocky clinoptilolite, and (C) grape-like clusters on clinoptilolite in sample JMK#3@200°Ca.

Sample B of the JMK#3@200°C had the same morphologies as Sample A, but the dominant feature was blocky crystals, indicative of clinoptilolite, as opposed to the fibrous particles, indicative of mordenite (Figure 4.6). A particle of primary glass was found in this sample and the concoidal surface had an interesting microstructure. Additional SEM figures are located in the Appendix.
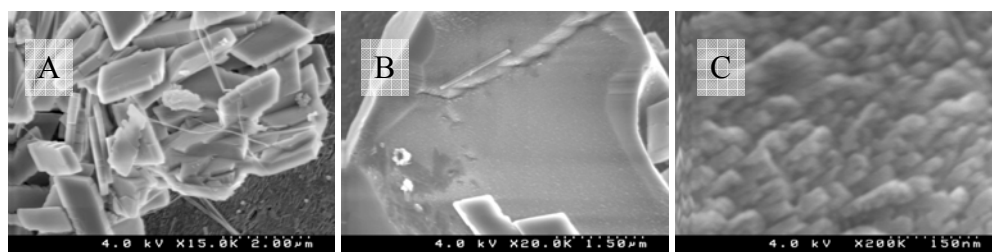
Figure 4.6 SEM image of (A) dominant blocky clinoptilolite, (B) concoidal primary glass and (C) weathering patterns from JMK#3@200°Cb.

The particle sizes shown in the previous section are generally smaller than the spatial resolution of the EDS elemental analysis capability. Thus, it is difficult, if not impossible, to resolve the chemical composition of the individual particles with specific growth morphologies. As a result, all 4 samples appear to have a relatively uniform chemical composition. We believe this to be an artifact of the EDS spatial resolution. Figure 4.7 is an example of a sample EDS spectra. The elements detected in all samples were O, Na, Al, Si, and K. The clay-like particles and an amorphous particles in JMK#3@120°C also contain some Fe, Mg, and Ti (Figure 4.8). To accurately characterize the mineral phases associated with the particular morphologies observed under SEM requires higher spatial resolution, such as that found with transmission electron microscopy (TEM).
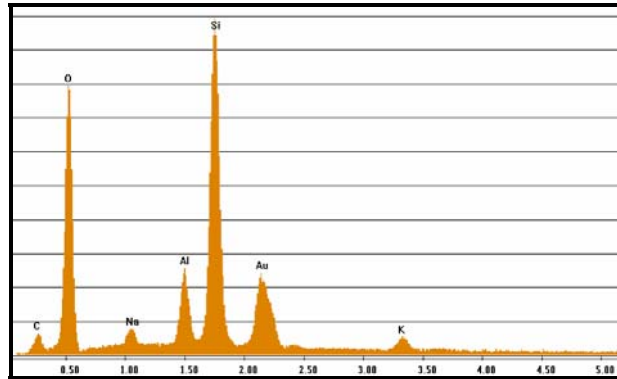
Figure 4.7 EDS Spectra of blocky crystal as seen in Figure 4.4, 10kV.
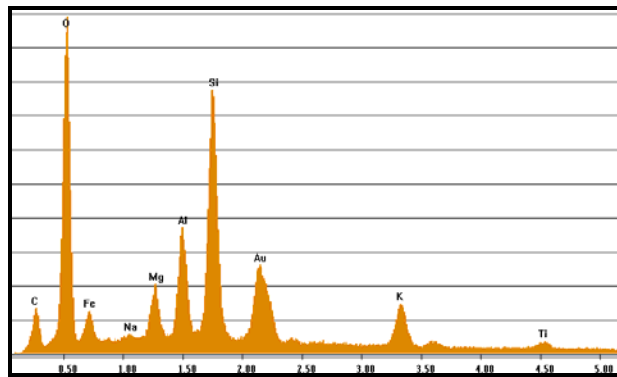
Figure 4.8 EDS spectra of a clay-like particle, 10kV.

4.4.3   XRD

The XRD spectra of the four samples isolated from the reaction vessels are plotted in Figure 4.9. The JMK#1@120°C spectrum contains no identifyable peaks with the exception of the single broad peak assigned to amorphous glass; it is estimated that alteration of the sample amounts to less than 10% of the sample. The other three spectra have peaks at nearly identical 2θ values, indicating similar alteration phases. The peak intensity is, to first order, correlated with the abundance of the phase associated with that peak. Thus, the more altered sample will tend to have higher peak intensities. However, changes in peak intensity will also be affected by the amount of material and its spatial distribution on the sample holder (e.g. a tightly packed sample will have higher peak intensities than a more loosely packed sample).

Using the JADE program, the secondary mineral phases were identified. The secondary mineral phases consisted of clinoptilolite, mordenite, albite, and illite-montmorillonite. The presence of additional zeolite and clay phases (i.e. heulandite, hydroxyapophyllite, and chlorite-vermiculite-montmorillonite) could not be ruled out.
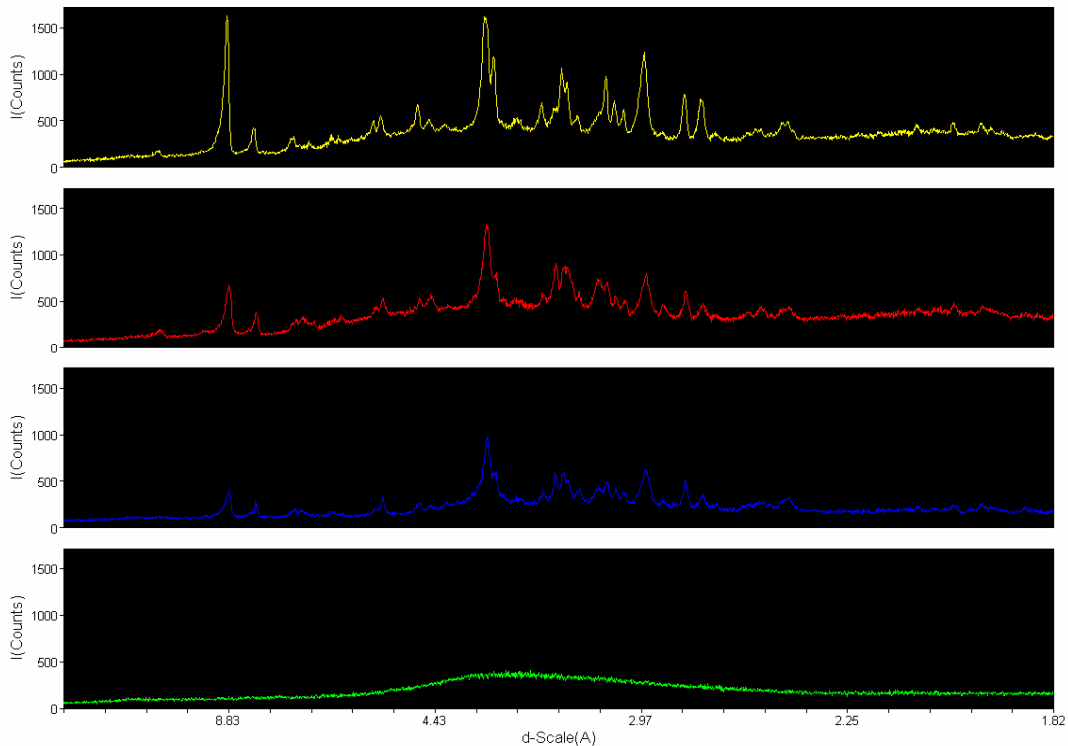
Figure 4.9 XRD spectra of reacted melt glass spectra; JMK#3@200°Cb, JMK#3@200°Ca, JMK#3@120°C, JMK#1@120°C (top to bottom).

4.4.4   Liquid Scintillation Counting

Liquid scintillation counting of the bulk supernatant provides information regarding the overall activity of the supernatant. The counts in the 0-18.6 keV range are primarily associated with tritium, while counts in the 50-500 keV range are primarily associated with α-emitters and high energy β-emitters. Identification of the isotope associated with the observed activity requires additional sample purification. However, the sharp peak seen in the 200°C sample spectrum (Figure 4.10) is believed to be an α-emitting radionuclide. The counts per minute (CPM) for each solution are listed in Table 4.4. The results were normalized to the amount of solution in contact with the nuclear melt glass solid during the experiment.

Importantly, the supernatant was separated from the solid by centrifugation. However, centrifugation only removed >250 nm particles. Thus, the supernatant includes both the aqueous and the majority of colloidal-bound activity. As expected, the 200°C sample had more α-emitting material in the supernatant than the samples reacted at the lower temperature. This alpha activity represents a mobile fraction comprised of both dissolved and colloidal material. These results indicate that glass dissolution provides a significant source of mobile alpha activity, particularly at high temperatures.
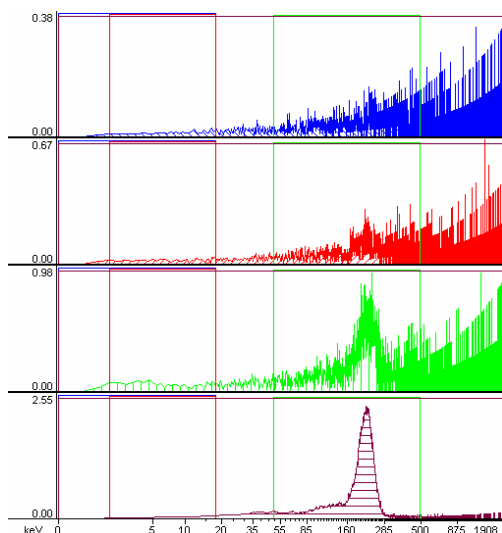
Figure 4.10 Liquid scintillation counting spectra for an activity-free standard, JMK#1@120°C supernatant, JMK#3@120°C supernatant, and JMK#3@200°C supernatant (top to bottom).

Table 4.4 Normalized liquid scintillation counting results

Sample	CPM (50-500 keV region)
JMK#1@120°C	5.5
JMK#3@120°C	12
JMK#3@200°C	316

4.4.5   Alpha-radiography

Two exposure times (3.5 days and 15 hours) yielded large numbers of α-tracks in all radiography films of all samples (Figure 4.11). The only spatial information gained from these data was the surprisingly homogeneous α-activity throughout the samples. However, the density of α-tracks in the 200°C sample is significantly greater than in the 120°C samples. The 200°C sample particle surfaces are primarily composed of alteration mineral coatings while 120°C sample surfaces are largely unaltered. The results suggest that α-emitting radionuclides, such as U and Pu, are concentrated in the secondary mineral alteration compared to the glass.

3.5 Day Exposure   15 Hour Exposure
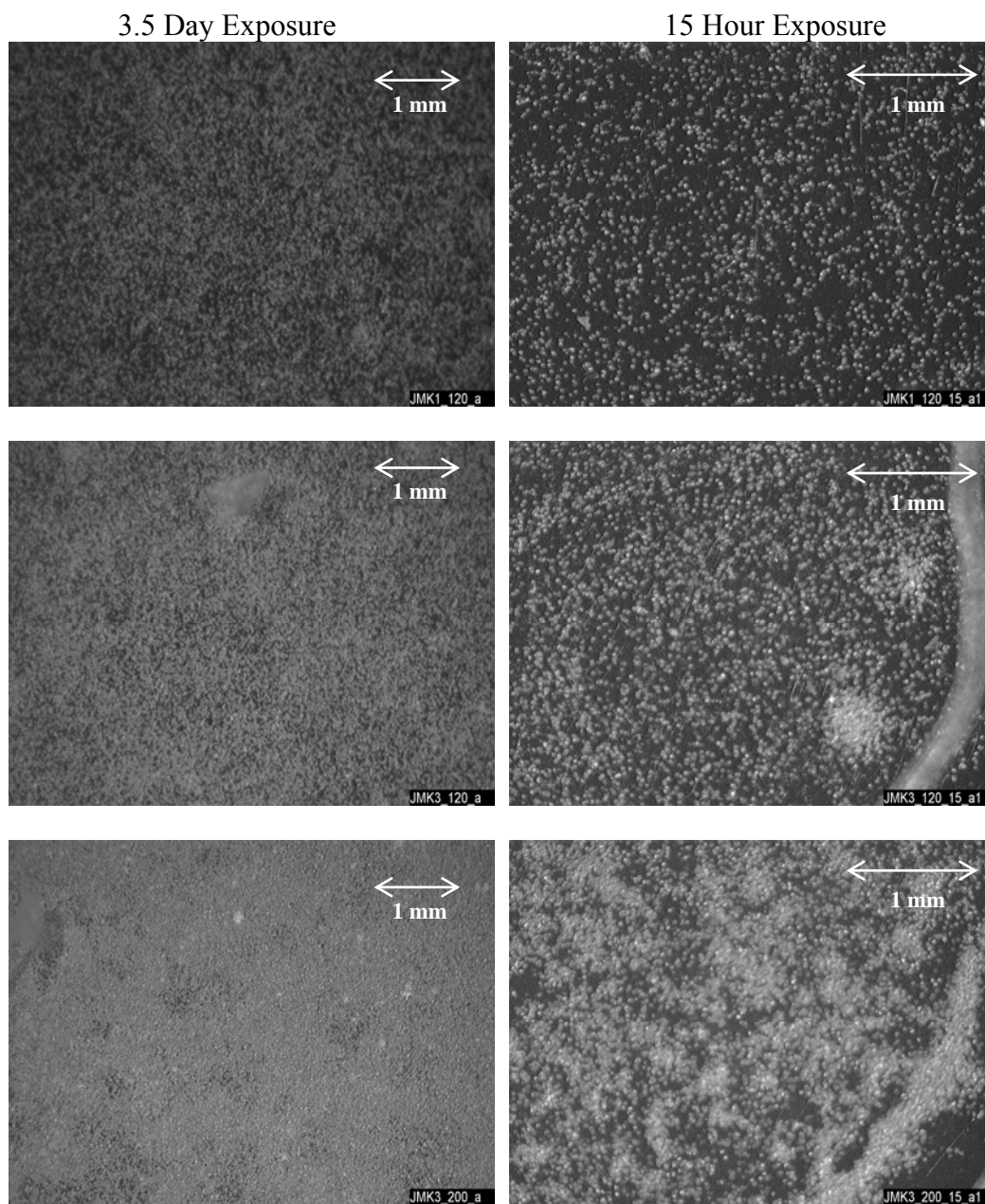
Figure 4.11 Alpha-radiography of altered nuclear melt glass samples.

4.5   Summary

The secondary mineral phases from a 1-year nuclear melt glass dissolution experiment were characterized using Eh/pH, IC, ICP-MS, and LSC of the supernatant and SEM, EDS, XRD, and α-radiography of the solids. Supernatant characterization indicates that glass dissolution produces mildly reducing conditions and that the aqueous+colloidal fractions include a substantial quantity of alpha activity. SEM and XRD data clearly indicate much greater glass alteration at 200°C compared to 120°C. The secondary mineral phases identified were: clinoptilolite, mordenite, illite/montmorillolite, and albite. The mineralogy of the glass alteration products is generally same at both 120°C and 200°C. However, the proportion of the mineral alteration products varies. Importantly, these phases are typical of fracture lining minerals identified in Pahute Mesa tuffs.

4.6   References

Borg I.Y. (1975).   Radioactivity trapped in melt produced by a nuclear explosion, *Nuclear Technology*. 26:88-100.

Mumpton F.A., (1977). Natural Zeolites. *Mineralogical Society of America Short Course Notes: Mineralogy and Geology of Natural Zeolites*. Vol. 4 p. 14

Pawloski G.A., Tompson A.F.B., and Carle S.F. (2001) Evaluation of the Hydrologic source Term from Underground Nuclear Tests on Pahute Mesa at the Nevada Test Site: The Cheshire Test, Lawrence Livermore National Laboratory, UCRL-ID-147023, Livermore California.

Zavarin M., Roberts S.K., Viani B.E., Pawloski G.A., Rose T.P., Nuclear Melt Glass Dissolution and Secondary Mineral Precipitation at 40 to 200°C (2004). Lawrence Livermore National Laboratory. UCRL-TR-204870.

4.7   Appendix

JMK#1@120°C
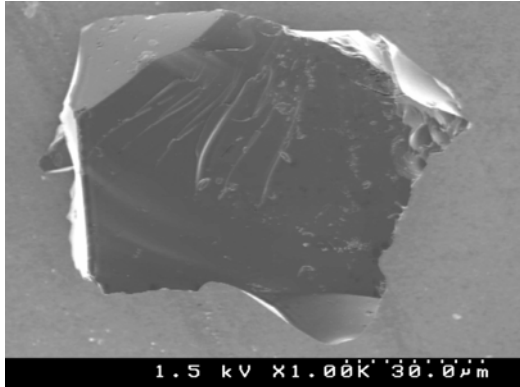
JMK#1@120°C
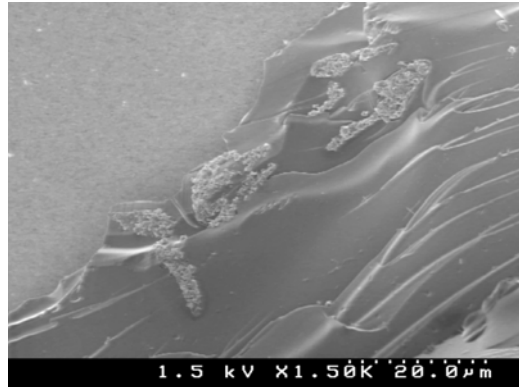
JMK#1@120°C
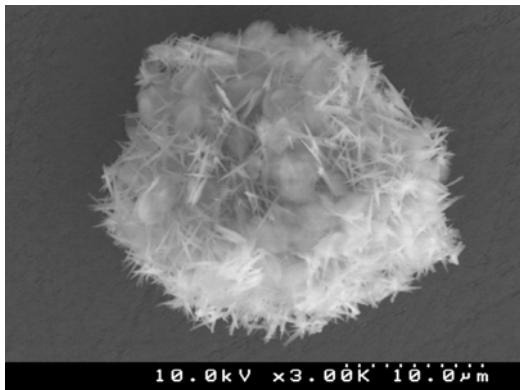
JMK#3@120°C
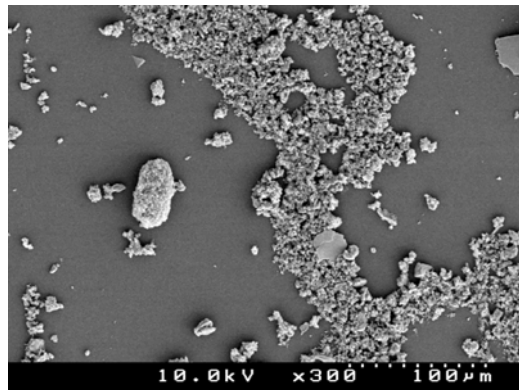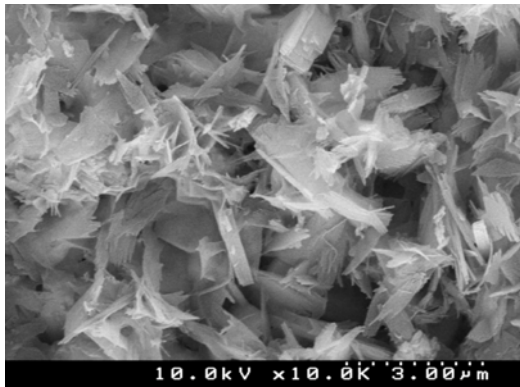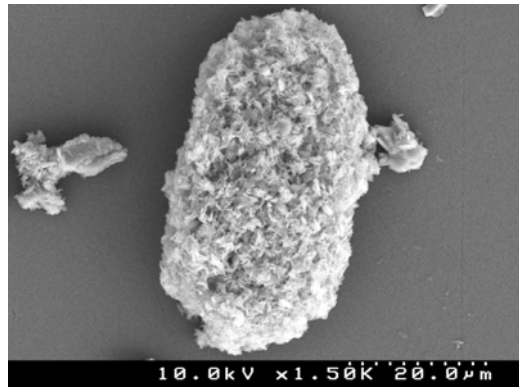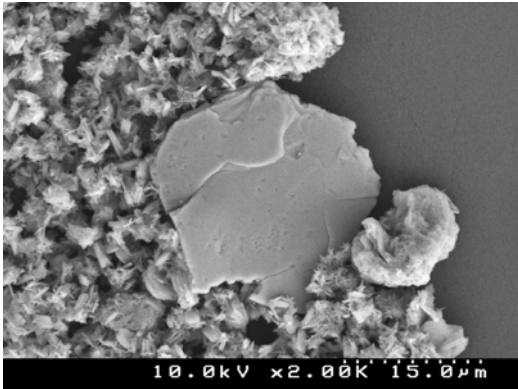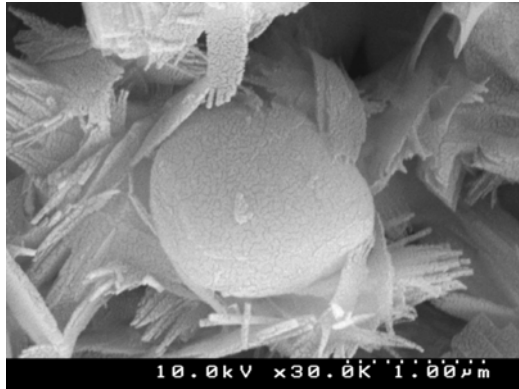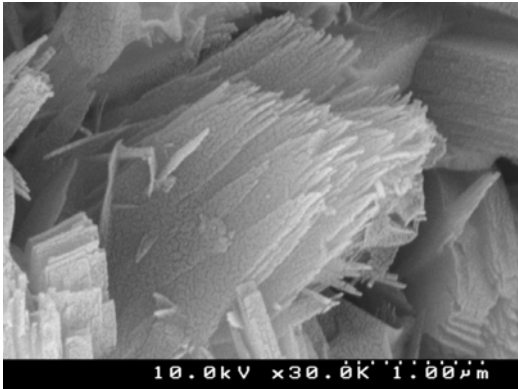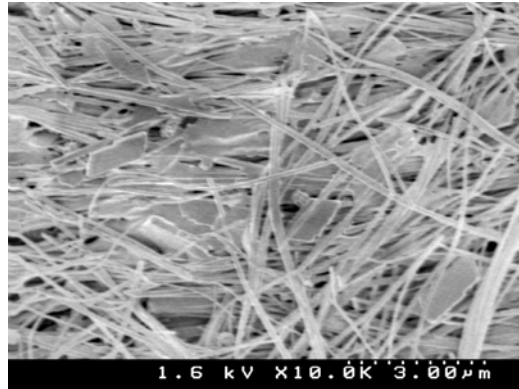
JMK#3@120°C

JMK#3@120°C
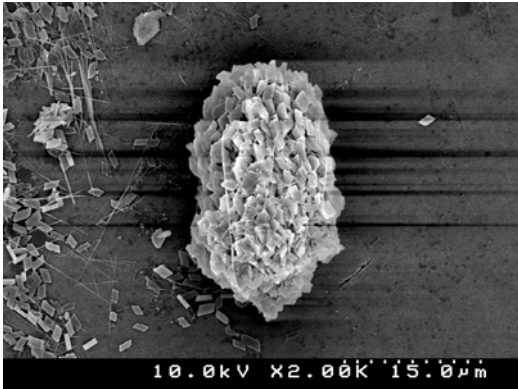
JMK#3@120°C

JMK#3@120°C

JMK#3@120°C

JMK#3@200°Ca

JMK#3@200°Ca

JMK#3@200°Ca

JMK#3@200°Ca

1.6 kV   X100K   300nm

JMK#3@200°Ca

1.6 kV   X20.0K   1.50μm

JMK#3@200°Ca

1.6 kV   X3.00K   10.0μm

JMK#3@200°Ca

10.0kV   X15.0K   2.00μm

JMK#3@200°Ca

10.0kV   X1.50K   20.0μm
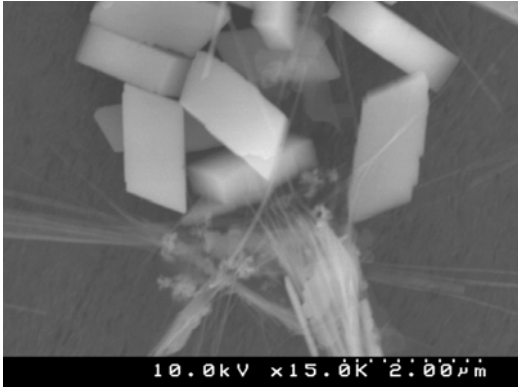
JMK#3@200°Ca
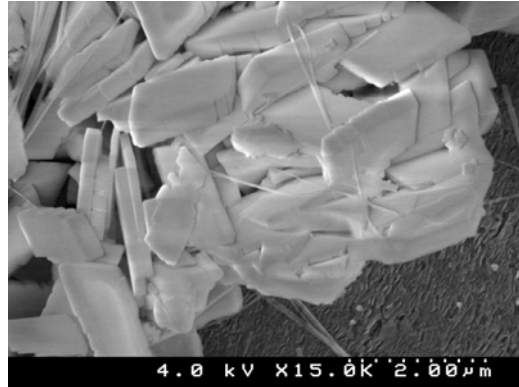

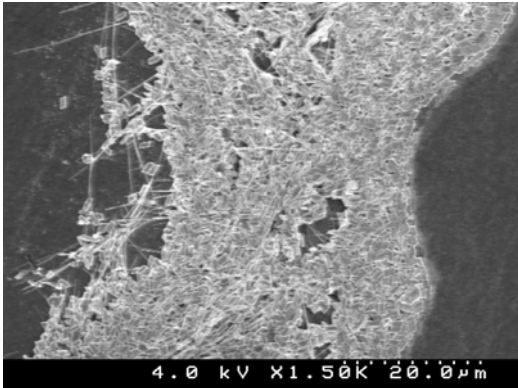10.0kV   X1.50K   20.0μm
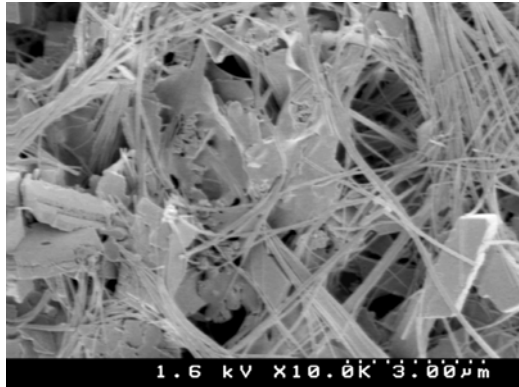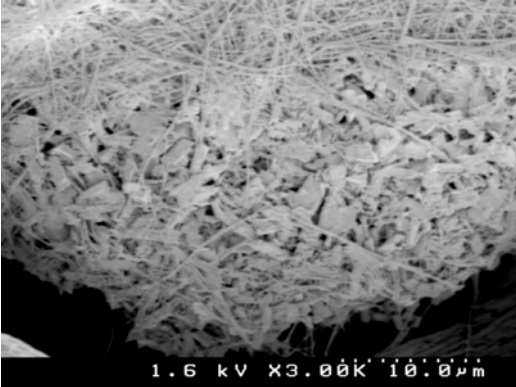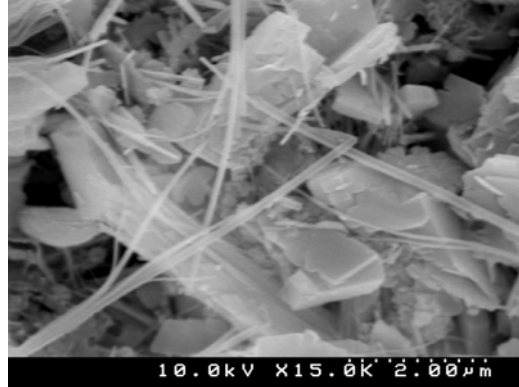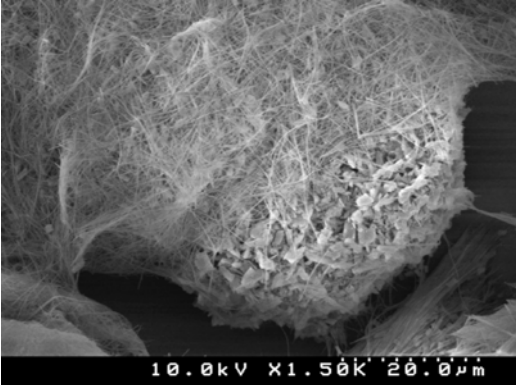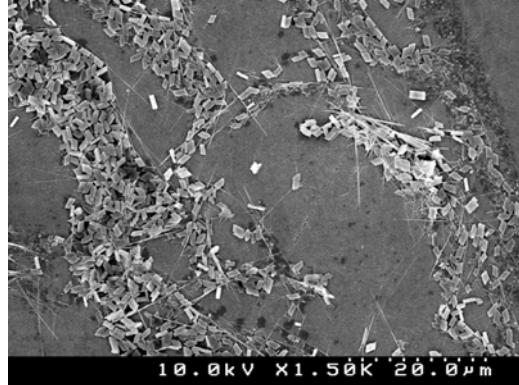
JMK#3@200°Ca

JMK#3@200°Ca

JMK#3@200°Cb

JMK#3@200°Cb

JMK#3@200°Cb

Chapter 5

Stable Isotope Investigation of Precipitation and Recharge Processes in Nevada

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5.1   Introduction

This chapter summarizes the results of an on-going stable isotope study of precipitation and recharge processes in Nevada. Funding for this study is provided by the National Nuclear Security Administration, Nevada Site Office (NNSA/NSO) Hydrologic Resources Management Program (HRMP), and earlier descriptions of this work are found in the FY2001-2002 and FY2003 HRMP-UGTA progress reports (Rose et al., 2003; 2004).

This study consists of two separate but interrelated activities:

(1) Precipitation, spring water, and soil water samples were collected from four sites in central Nevada starting in 1999. Data acquired from these sites is used to determine the average stable isotope (δD, $\delta^{18}O$) composition of precipitation, the relative contribution of cool and warm season precipitation to the recharge budget, and the timing and extent of evaporation during recharge. The sites were sampled bi-annually up through May 2004, and once each during 2005 and 2006. In the fall of 2006, the Desert Research Institute (DRI) took over sample collection responsibilities for these sites, and a return to a bi-annual sampling schedule is planned. LLNL will continue to perform stable isotope measurements on future samples from these sites.

(2) Precipitation samples were also collected on a biannual basis at five High Altitude Precipitation (HAP) stations maintained by the U.S. Geological Survey (USGS) throughout east-central and southern Nevada. Samples from these sites are sent to LLNL for stable isotope analyses. The HAP sites are more widely distributed geographically compared to the LLNL sites (Figure 5.1) and located at higher elevations (Table 5.1). These sites therefore provide insight into isotopic variations in precipitation as a function of both latitude and altitude that would not be possible with only the LLNL sites. Although most of the HAP sites were established in the mid-1980s, the present stable isotope investigation was initiated in 2002, and good quality isotope data were first generated in 2003.

**Table 5.1 Locations of Precipitation Gauges and Springs**

	Latitude (d m s)	Longitude (d m s)	Elevation (m)
LLNL Sites			
Austin Summit			
Precipitation gauge/lysimeter	39 28 53	117 02 22	2285
Spring	39 28 51	117 02 39	2240
Pinto Summit			
Precipitation gauge/lysimeter	39 27 03	115 56 06	2255
Spring	39 27 25	115 56 18	2240
Little Antelope Summit			
Precipitation gauge/lysimeter	39 23 46	115 28 01	2267
Spring	39 24 57	115 29 35	2200
Currant Summit			
Precipitation gauge/lysimeter	38 49 05	115 16 58	2140
Spring	38 49 22	115 18 04	2085
USGS HAP Sites			
Mt. Hamilton	39 14 36	115 32 39	3230
Mt. Washington	38 54 09	114 18 54	3180
Quinn Canyon Range	38 11 57	115 37 31	2775
Kawich Range	38 00 26	116 27 38	2775
Hayford Peak	36 39 29	115 11 58	2999

5.2 LLNL Monitoring Sites

Precipitation gauges were installed in January 1999 at three locations along the Hwy 50 corridor (Austin Summit, Pinto Summit, and Little Antelope Summit) and one location along Hwy 6 (Currant Summit). Site locations are shown in Figure 5.1. The precipitation gauges consist of 1 m segments of 15.7 cm diameter PVC pipe, capped at one end and mounted vertically in a stone foundation. Evaporation effects are minimized by adding mineral oil to the bottom of the gauges. Site elevations range from 2140 to 2280 m above sea level. Between 1999 and 2004, integrated samples of cool and warm season precipitation were collected on a biannual basis, usually in May and October. Following the May 2004 sampling event, samples were only collected once a year in 2005 and 2006. The measured precipitation amounts and stable isotope (δD and $\delta^{18}O$) values for each sampling event are presented in Table 5.2. Mean precipitation amounts and weighted mean isotopic values for each site are summarized in Table 5.3. Weighted mean isotopic values are calculated from the expression:

$$\delta \text{ mean} = \frac{\Sigma\, \delta_i\, x_i}{\Sigma\, x_i}$$

where δ_i is the measured isotopic value for a given sample, and x_i is the corresponding precipitation amount (in cm).
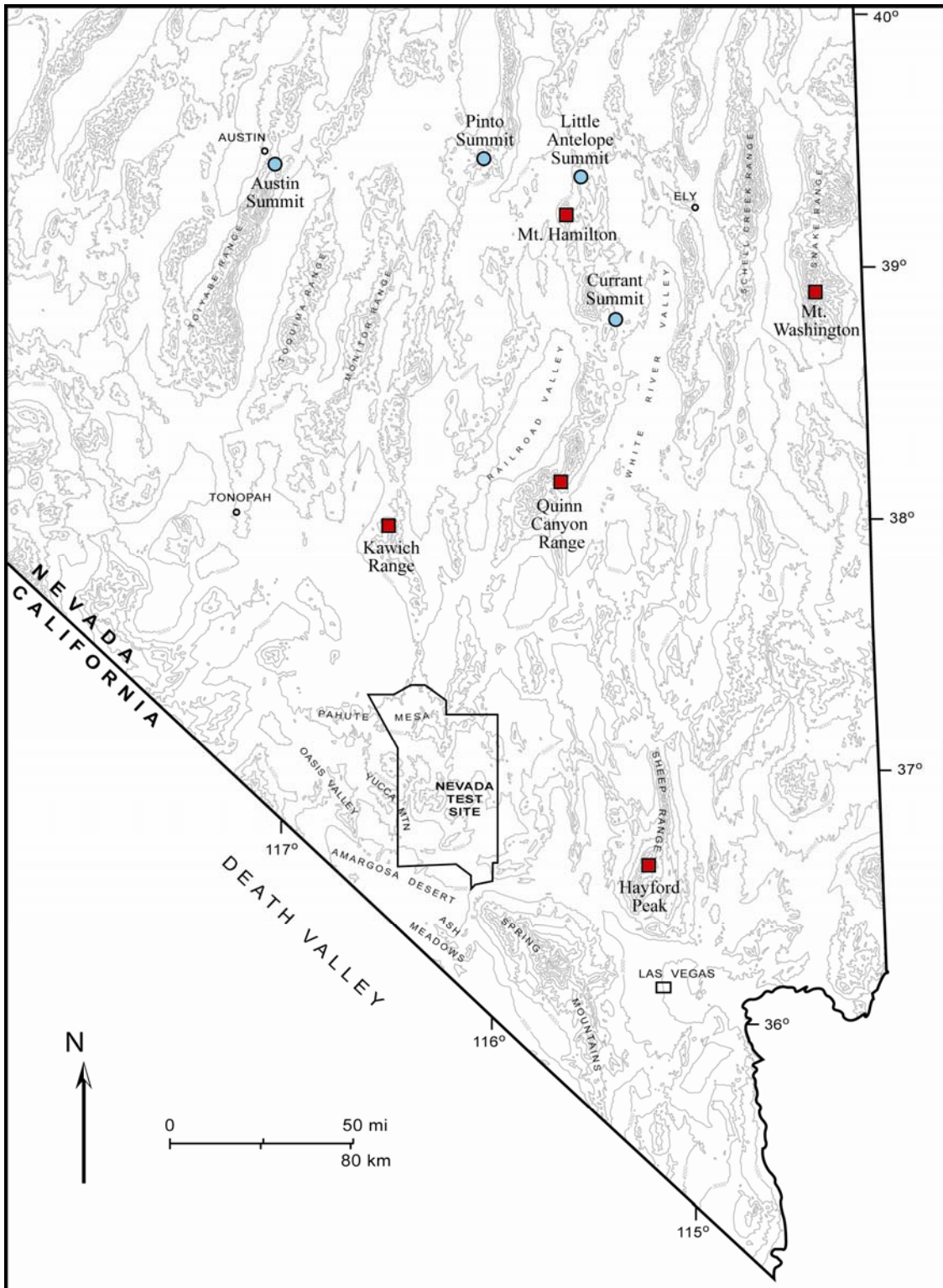
Figure 5.1 Map of southern and east-central Nevada showing the locations of sampling sites discussed in this report:
LLNL sites (circle); USGS HAP sites (square).

Table 5.2 Precipitation Data for LLNL Sites in Central Nevada

Location / Sample Date	Time Period	Precipitation Amount (cm)	$\delta^{18}O$ (‰)	δD (‰)
Austin Summit				
16-Jul-99	01/99 - 07/99	13.7	-14.7	-107
1-Nov-99	07/99 - 10/99	0.7	-5.9	-41
15-May-00	11/99 - 05/00	11.0	-17.1	-131
16-Oct-00	05/00 - 10/00	7.1	-12.0	-92
14-May-01	10/00 - 05/01	12.1	-15.8	-116
24-Oct-01	05/01 - 10/01	2.1	-6.2	-39
22-May-02	10/01 - 05/02	17.3	-14.6	-105
9-Oct-02	05/02 - 10/02	3.2	-8.9	-61
23-May-03	10/02 - 05/03	18.1	-15.1	-110
11-Oct-03	05/03 - 10/03	8.2	-5.7	-38
22-May-04	10/03 - 05/04	12.3	-15.6	-116
21-May-05	05/04 - 05/05	34.5	-15.5	-115
19-May-06	05/05 - 05/06	---	---	---
Pinto Summit				
16-Jul-99	01/99 - 07/99	20.7	-15.9	-119
2-Nov-99	07/99 - 10/99	2.6	-8.3	-50
15-May-00	11/99 - 05/00	19.5	-16.1	-117
16-Oct-00	05/00 - 10/00	12.6	-12.3	-89
14-May-01	10/00 - 05/01	25.9	-16.7	-121
24-Oct-01	05/01 - 10/01	3.9	-6.6	-43
23-May-02	10/01 - 05/02	23.4	-15.2	-111
9-Oct-02	05/02 - 10/02	6.4	-11.0	-79
23-May-03	10/02 - 05/03	27.8	-16.0	-118
12-Oct-03	05/03 - 10/03	3.7	-5.5	-36
22-May-04	10/03 - 05/04	17.1	-16.4	-123
21-May-05	05/04 - 05/05	52.7	-15.7	-115
19-May-06	05/05 - 05/06	35.4	-13.9	-99
Little Antelope Summit				
16-Jul-99	01/99 - 07/99	21.4	-15.7	-116
2-Nov-99	07/99 - 10/99	6.1	-6.7	-37
16-May-00	11/99 - 05/00	17.2	-17.4	-128
16-Oct-00	05/00 - 10/00	9.0	-10.6	-75
14-May-01	10/00 - 05/01	23.4	-17.6	-131
24-Oct-01	05/01 - 10/01	5.1	-5.6	-35
23-May-02	10/01 - 05/02	23.6	-15.2	-111
9-Oct-02	05/02 - 10/02	5.5	-15.1	-113
23-May-03	10/02 - 05/03	24.4	-15.7	-116
12-Oct-03	05/03 - 10/03	7.8	-7.8	-50
22-May-04	10/03 - 05/04	20.9	-16.6	-124
21-May-05	05/04 - 05/05	50.4	-15.3	-110
19-May-06	05/05 - 05/06	32.3	-14.6	-106
Currant Summit				
17-Jul-99	01/99 - 07/99	---	---	---
3-Nov-99	07/99 - 10/99	3.1	-6.6	-41
16-May-00	11/99 - 05/00	16.7	-16.1	-118
17-Oct-00	05/00 - 10/00	7.2	-9.4	-66
15-May-01	10/00 - 05/01	21.4	-16.6	-120
24-Oct-01	05/01 - 10/01	5.5	-5.8	-36
23-May-02	10/01 - 05/02	12.7	-16.5	-121
10-Oct-02	05/02 - 10/02	4.1	-11.9	-86
22-May-03	10/02 - 05/03	17.6	-15.6	-115
13-Oct-03	05/03 - 10/03	2.9	-6.8	-48
23-May-04	10/03 - 05/04	16.5	-14.5	-106
22-May-05	05/04 - 05/05	40.0	-15.2	-110
20-May-06	05/05 - 05/06	23.1	-13.5	-94

Dashed line indicates no sample was collected (due to vandalism).

Table 5.3 Mean Precipitation Amounts and Isotopic Values for LLNL Sites in Central Nevada

	Austin Summit		Pinto Summit		Little Antelope Summit		Currant Summit	
	Mean Precipitation Amounts							
	(cm)		(cm)		(cm)		(cm)	
Annual	21.1		33.0		32.2		24.4	
Warm Season	4.3		5.8		6.7		4.6	
Cool Season	14.2		22.7		21.9		17.0	
	Weighted Mean Isotopic Values							
	$\delta^{18}O$ (‰)	δD (‰)	$\delta^{18}O$ (‰)	δD (‰)	$\delta^{18}O$ (‰)	δD (‰)	$\delta^{18}O$ (‰)	δD (‰)
Full Record	-14.3	-105	-15.0	-109	-14.9	-109	-14.4	-104
Warm Season	-8.3	-60	-10.0	-70	-9.2	-62	-8.3	-57
Cool Season	-15.5	-114	-16.1	-118	-16.4	-122	-15.9	-116

Mean precipitation amounts range from 21.1 cm/yr at Austin Summit to 33.0 cm/yr at Pinto Summit, measured over a seven year period from July 1999 to May 2006. Seasonal data collected over a shorter period (1999-2004) reveal that only 20 to 23% of the annual precipitation occurs during the warm season (May to October), with the remaining 77 to 80% of the precipitation falling during the cool winter months. Note that the sum of the cool + warm season means is less than the annual means at all four sites (Table 5.3). This reflects the difference in sample collection periods (five years for seasonal data vs. seven years for annual data). The period from May 2004 to May 2005 was unusually wet, with annual precipitation rates between 156 and 164% of the mean values. These data were included in the annual means but not the seasonal means, which helps to explain why the former exceeds the sum of the latter.

The weighted mean δD and $\delta^{18}O$ values for seasonal precipitation samples show the expected enrichment in heavy isotopes (less negative values) during the warm season and depletion in heavy isotopes (more negative values) during the cool season, in accordance with the temperature dependence of isotopic fractionation between vapor and condensed phases (e.g. Criss, 1999). The annual mean δD and $\delta^{18}O$ values are strongly skewed toward the cool season average, which is consistent with the fact that ~80% of all

precipitation occurs during the cool season. Although the four sites are up to 150 km apart, the annual mean isotope values are remarkably similar at all locations, varying by only 0.7‰ in $\delta^{18}O$ and 5‰ in δD. This may reflect the tendency for winter low-pressure systems to be regional in extent.

To investigate local recharge processes, both soil water and spring water samples were collected from each monitoring site. Soil water samples were acquired over five winter seasons (2000-2004) using small lysimeters that were buried near the precipitation gauges. The lysimeter consisted of a 15.7 cm diameter funnel attached to a 2L-HDPE bottle with silicone sealant and wrapped with watertight tape along the seal. A 6 mm OD copper tube (approximately 0.5 m in length) is inserted through a separate hole at the top of the bottle to maintain a constant pressure between the interior of the bottle and the atmosphere. Mineral oil was added to the bottom of the lysimeter to prevent evaporation, and the mouth of the funnel was filled with smooth pebbles to facilitate drainage of water from the top of the funnel into the bottle. The lysimeter assembly was then buried with the top of the funnel at ~10 cm below the soil surface. The soil layer above the lysimeter was carefully replaced, loosely packed and then leveled to avoid forming a depression.

The lysimeter samples provide valuable information on the isotopic composition and amount of fluid that infiltrated the upper soil zone at a point location. The data are summarized in Table 5.4. Only one lysimeter was used at each site from 2000 to 2002, whereas two lysimeters were used in 2003 and 2004. The two collectors were installed at identical depths (10 cm) one to three meters apart. The data acquired in 2003 and 2004 shows that the volume and composition of the soil water can vary substantially at a single site. These variations may reflect localized differences in soil compaction, snow pack depth, and snowmelt infiltration rates. The δD and $\delta^{18}O$ values of the soil water samples also provide insight into how much evaporation occurred as the fluid moved through the uppermost soil zone. Evaporated waters always fall to the right of the global meteoric water line ($\delta D = 8\delta^{18}O + 10$; Craig, 1961) on a plot of δD versus $\delta^{18}O$ (see discussion below). In general, decreasing fluid infiltration volumes are correlated with increasing amounts of evaporation. Conversely, when the amount of soil water infiltration is 'large' (greater than about 1 cm rainfall equivalent) the composition of the fluid tends to plot along the meteoric water line. The lack of evaporation in the larger volume samples may indicate that infiltration occurred over a relatively brief period of time, such as during a rapid snow melt event.

Perched springs located near each gauging site are an additional source of comparative data. In contrast to the lysimeters, the perched springs represent the integrated δD and $\delta^{18}O$ composition of groundwater recharge over a much larger area. Discharge rate and water quality parameters (temperature, conductivity, alkalinity, and pH) were also measured at the spring sites. The data are summarized in Table 5.5. The spring waters at all four sites showed consistent isotopic compositions over time, though the discharge rates at three of the four sites sometimes varied by more than an order of magnitude. Water quality parameters also tended to vary over time. The slightly mineralized spring located near Little Antelope Summit showed the most consistent set of chemical, isotopic and discharge characteristics of the four springs.

Table 5.4 Lysimeter Data for LLNL Sites in Central Nevada

Location / Sample Date	Time Period	Infiltration Amount (cm)	Infiltration / Precipitation (ratio)	$\delta^{18}O$ (‰)	δD (‰)
Austin Summit					
15-May-00	11/99 - 05/00	0.2	0.02	-16.2	-132
14-May-01	10/00 - 05/01	0.7	0.06	-16.9	-124
22-May-02	10/01 - 05/02	10.3	0.59	-14.5	-105
23-May-03 (#1)	10/02 - 05/03	sample lost	---	---	---
23-May-03 (#2)	10/02 - 05/03	3.7	0.20	-16.4	-123
22-May-04 (#1)	10/03 - 05/04	8.1	0.66	-17.6	-133
22-May-04 (#2)	10/03 - 05/04	4.0	0.33	-17.1	-129
Pinto Summit					
15-May-00	11/99 - 05/00	<0.1	<0.01	-12.6	-101
14-May-01	10/00 - 05/01	10.4	0.40	-15.6	-115
23-May-02	10/01 - 05/02	<0.1	<0.01	---	---
23-May-03 (#1)	10/02 - 05/03	<0.1	<0.01	-15.1	-119
23-May-03 (#2)	10/02 - 05/03	0.1	<0.01	-18.6	-144
22-May-04 (#1)	10/03 - 05/04	7.2	0.42	-17.3	-129
22-May-04 (#2)	10/03 - 05/04	10.2	0.60	-17.8	-132
Little Antelope Summit					
16-May-00	11/99 - 05/00	<0.1	<0.01	---	---
14-May-01	10/00 - 05/01	0.1	<0.01	-18.3	-130
23-May-02	10/01 - 05/02	0.2	0.01	-15.2	-119
23-May-03 (#1)	10/02 - 05/03	6.8	0.37	-18.3	-137
23-May-03 (#2)	10/02 - 05/03	1.1	0.04	-17.7	-134
22-May-04 (#1)	10/03 - 05/04	1.4	0.07	-16.1	-118
22-May-04 (#2)	10/03 - 05/04	1.9	0.09	-15.9	-125
Currant Summit					
16-May-00	11/99 - 05/00	2.8	0.17	-16.2	-120
15-May-01	10/00 - 05/01	1.2	0.06	-15.3	-112
23-May-02	10/01 - 05/02	0.5	0.04	-13.4	-116
22-May-03 (#1)	10/02 - 05/03	0.9	0.07	-11.2	-101
22-May-03 (#2)	10/02 - 05/03	0.2	0.01	-10.9	-89
23-May-04 (#1)	10/03 - 05/04	0.9	0.05	-12.6	-97
23-May-04 (#2)	10/03 - 05/04	1.9	0.11	-10.9	-79

Table 5.5 Spring Water Data for LLNL Sites in Central Nevada

| Location / Sample Date	Est. Flow Rate (L/min)	Temp. (°C)	pH	Cond. (μS/cm)	Alkalinity (mg/L)	$\delta^{18}O$ (‰)	δD (‰)
Austin Summit Spring							
1-Nov-99	1.0	9	7.83	239	125	-16.0	-118
15-May-00	0.2	13	7.05	275	115	-16.1	-117
16-Oct-00	0.1	6	7.20	315	n.d.	-15.9	-116
14-May-01	< 0.1	18	7.05	277	140	-15.9	-118
24-Oct-01	< 0.1	7	7.80	377	150	-15.9	-120
22-May-02	0.3	7	7.15	311	130	-14.6	-107
9-Oct-02	1.5	10	7.35	333	n.d.	-15.9	-122
23-May-03	dry	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
11-Oct-03	0.1	11	8.10	301	115	-16.0	-120
22-May-04	0.5	10	7.84	283	120	-16.1	-122
21-May-05	4.5	9	6.96	348	120	-16.1	-122
19-May-06	6.0	10	6.93	320	120	-16.3	-123
Pinto Summit Spring							
2-Nov-99	5	4	8.10	299	175	-15.2	-120
15-May-00	15	7	7.50	395	150	-15.7	-120
16-Oct-00	2	5	7.69	372	n.d.	-15.4	-122
14-May-01	3	12	8.02	373	185	-15.4	-121
24-Oct-01	3	5	8.02	418	180	-15.2	-119
23-May-02	6	15	7.50	460	175	-15.1	-121
9-Oct-02	8	12	7.82	400	n.d.	-15.5	-121
23-May-03	10	18	8.36	368	200	-15.7	-122
12-Oct-03	2	16	7.37	355	175	-15.3	-121
22-May-04	6	14	7.28	382	200	-15.4	-121
21-May-05	30	13	7.35	394	190	-15.8	-122
19-May-06	8	14	7.55	439	225	-15.6	-118
Little Antelope Spring							
2-Nov-99	1.0	9	7.08	1421	350	-15.5	-122
16-May-00	1.0	8	6.98	1661	400	-15.7	-122
16-Oct-00	1.0	9	6.76	1665	n.d.	-15.6	-124
14-May-01	0.9	8	6.95	1684	350	-15.6	-125
24-Oct-01	1.0	9	7.05	1520	400	-15.6	-126
23-May-02	0.8	8	7.05	1521	400	-15.6	-125
9-Oct-02	0.8	9	6.79	1601	n.d.	-15.6	-125
23-May-03	0.75	9	7.10	1630	350	-15.6	-123
12-Oct-03	0.9	9	7.10	1672	400	-15.5	-124
22-May-04	0.2	8	7.53	1590	350	-15.7	-123
21-May-05	0.9	9	6.99	1738	400	-15.8	-125
19-May-06	1.2	10	7.46	1735	500	-15.8	-124
Currant Summit Spring							
3-Nov-99	0.5	12	7.51	381	170	-13.9	-108
16-May-00	0.1	2	7.20	477	160	-13.9	-110
17-Oct-00	0.3	8	7.21	446	n.d.	-14.0	-112
15-May-01	1.2	13	7.72	456	160	-14.0	-112
24-Oct-01	0.3	8	7.51	402	175	-13.9	-111
23-May-02	0.1	7	7.52	388	175	-13.9	-109
10-Oct-02	0.2	14	7.10	524	n.d.	-13.9	-110
22-May-03	0.03	25	8.41	513	175	-13.8	-109
13-Oct-03	0.6	14	7.08	468	200	-13.9	-111
23-May-04	0.03	19	7.90	420	160	-13.9	-109
22-May-05	0.07	16	7.73	437	175	-14.1	-109
20-May-06	0.2	14	7.43	438	180	-14.2	-111

n.d. = not determined

Figure 5.2 shows δD vs. $\delta^{18}O$ plots of weighted mean precipitation data (annual, cool, and warm season), weighted mean values for the lysimeter samples, and average spring water compositions for each monitoring site. The global meteoric water line is included for reference. All of the precipitation data plots very close to the meteoric water line, regardless of whether it was collected in the spring or fall. As noted above, the annual mean is much closer to the cool season average than the warm season average because most of the precipitation (~80%) occurs during the cool season.

Weighted mean isotopic values for soil waters (lysimeters) were calculated in the same manner as the weighted mean precipitation. If two soil water samples were collected at one site during the same year, the data were averaged before they were included in the weighted mean. The results provide some interesting insights into recharge processes. At three of the four locations, the soil water δD and $\delta^{18}O$ values plot fairly close to the meteoric water line, and are depleted in heavy isotopes relative to the average cool season precipitation (see data points labeled 'lysimeter' in Figure 5.2). This result was somewhat unexpected but can be interpreted in the context of snow melt processes.

As a snow pack melts, the bulk isotopic composition of the residual snow becomes more enriched in heavy isotopes (Arnason et al., 1973; Stichler et al., 1981). This is because the fractionation of stable isotopes between coexisting water and ice favors enrichment of the solid phase in heavy isotopes (O'Neil, 1968). The isotopic enrichment in the residual snow must be balanced by losses of light isotopes, either as melt water or water vapor. Hermann et al. (1981) showed that light isotopes predominate during the initial stages of snow melt runoff, and that the heavy isotope content of the runoff steadily increases with time. Applying this information to the present study, we can infer that a majority of the melt water infiltrating the upper soil zone must be derived from the early stages of melting. It may be that less infiltration occurs during late stage melting because the soil becomes fully saturated, requiring greater amounts of surface runoff.

The Currant Summit data shows a pattern that differs from the other three sites. The average soil water has δD and $\delta^{18}O$ values that are greater than the average cool season precipitation (Figure 5.2). In addition, the soil water ('lysimeter') data point is clearly shifted to the right of the meteoric water line, implying an evaporative isotopic enrichment process. On δD vs. $\delta^{18}O$ plots, evaporated waters fall along linear trends with slopes between about 2 and 5 (Fontes, 1980). We can infer an initial (pre-evaporation) soil water composition by projecting an imaginary line from the lysimeter data point back to the meteoric water line. At Currant Summit, a relatively high slope (m = 5) evaporation trajectory would yield a pre-evaporation composition similar to the cool season precipitation average – but no less than this composition. This may imply that a larger fraction of 'late stage' snow melt (which is more enriched in heavy isotopes) infiltrates the soil zone at this site.
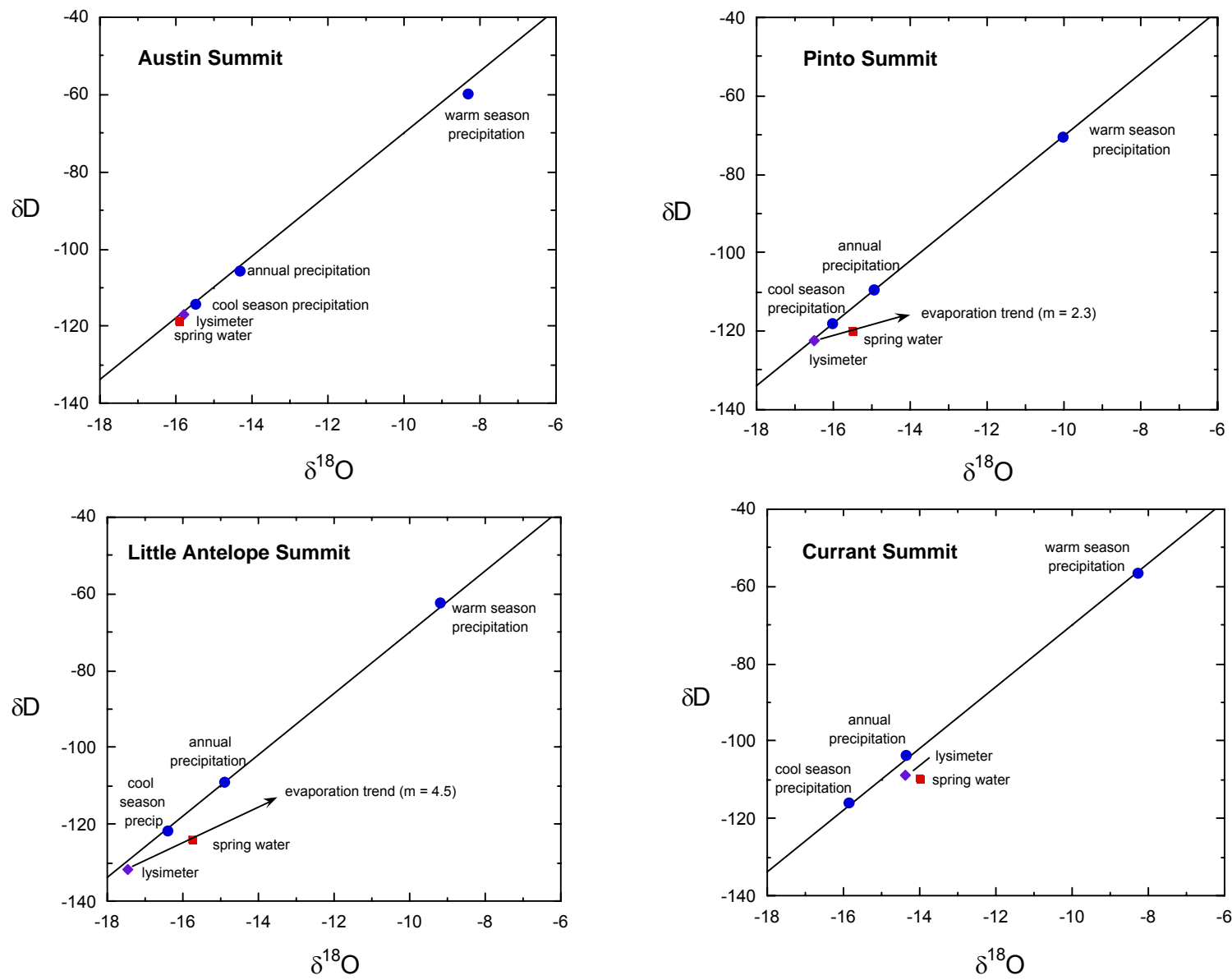
Figure 5.2 Plots of mean δD vs. δ¹⁸O values for water samples collected from LLNL monitoring sites in central Nevada. See text for discussion.

There is no obvious explanation for why the soil water is more evaporated at Current Summit compared to the other study locations (Figure 5.2). A previous snow hydrology study reported kinetic isotope enrichments (similar to evaporation effects) in the Current Summit snow pack *prior* to melting (Rose et al., 1999). These enrichments were interpreted as evidence for water vapor loss during snow metamorphism. Although isotope enrichment prior to recharge is possible, it is unclear why such a process would occur at Current Summit and not at the other three sites. An alternative explanation is that the existing dataset does not accurately represent the time-integrated soil water isotopic composition at Currant Summit. A longer term data record may be required to obtain a meaningful average value.

Further insight into recharge processes is gained by comparing soil water (lysimeter) and spring water isotopic data. The spring water composition is more evaporated than the average soil water composition at three of the four sites (Figure 5.2). Austin Summit is the only site where almost no evaporation is observed (i.e., all data plot very near the meteoric water line). The average soil and spring water compositions are nearly identical at this location (Figure 2). The lack of evaporation may be due to a difference in soil properties relative to the other sites. The Austin Summit site is located on granitic bedrock, and the soil cover consists of a thin veneer of coarsely weathered quartz and feldspar grains through which rainfall and snow melt can pass quickly to reach the underlying fractured rock. In contrast, the bedrock at the other three sites consists of volcanic rock that weathers to form a comparatively fine-grained soil matrix.

The Pinto Summit and Little Antelope Summit datasets show very similar patterns in their average precipitation, soil water, and spring water compositions (Figure 2). In particular, the spring water at both sites can be reasonably derived by modest evaporation of the soil water (lysimeter) composition. Although the slope of the evaporation trend is different at the two sites (2.3 at Pinto vs. 4.5 at Little Antelope) both slopes are within the expected range of values (between 2 and 5). At Currant Summit, the soil and spring waters show similar degrees of evaporation and have similar δD and $\delta^{18}O$ values, suggesting that both waters experienced a similar isotope enrichment pathway.

It is well known that spring waters are susceptible to evaporation after the water emerges from the spring orifice. During this study, post-discharge evaporation effects were minimized by collecting spring water samples directly from the point of discharge. For this reason, the evaporated isotopic signatures we observe at the perched springs are inferred to have been inherited during recharge. The conceptual model for this process is based on earlier studies of isotope profiles in soil moisture (e.g. Allison et al., 1983, Singleton et al., 2004). As the soil zone dries following a recharge event, the residual soil moisture gradually develops an evaporative stable isotope profile as a function of depth. With repeated episodes of wetting and drying, even the deeper soil moisture will evolve to a bulk isotopic composition that is evaporated relative to the initial soil moisture composition. Recharge events will push the evaporated soil moisture to the water table by piston flow. As a result, the bulk isotopic composition of the local water table (represented by perched springs) will be modestly evaporated relative to the initial

isotopic composition of the water when it first enters the soil zone (represented by the lysimeter samples).

Large volume soil water samples collected in the lysimeters showed little or no evidence of evaporation because mineral oil was used to prevent the water from evaporating after it had entered the collector. In a natural system, this would not be the case. Conversely, whenever small volumes of fluid (<1 cm rainfall equivalent) were collected in the lysimeters, the stable isotope signatures were always evaporated to some extent. These smaller volume samples probably reflect slower rates of soil moisture infiltration. In general, soil moisture evaporation is considered to be the most plausible mechanism to explain the evaporated isotope signatures of the perched springs.

5.3   USGS High Altitude Precipitation (HAP) Sites

The U.S. Geological Survey maintains a High Altitude Precipitation (HAP) monitoring network in eastern Nevada, within the Great Basin carbonate-rock province. Precipitation amounts are monitored on a bi-annual basis (spring and fall) and the data are published annually in USGS Water Resources Data reports (e.g. U.S. Geological Survey, 2006). The HAP network was originally established in the 1980s to support regional carbonate aquifer water-supply studies (e.g. Prudic et al., 1995; Thomas et al., 1996). Various aspects of these water resource investigations have continued to the present day (U.S. Geological Survey, 2005).

In 2002, LLNL staff began collaborating with the USGS office in Henderson, Nevada on the stable isotope analysis of samples from the HAP sites. During the first year of the project, the existing HAP gauges were used to collect samples. Unfortunately, various problems were encountered (see Rose et al., 2003) and it was necessary to abandon this approach. In June 2003, a new set of gauges referred to as 'bucket collectors' were installed at five HAP sites (see Table 5.1) including two new sites in the Kawich and Quinn Canyon Ranges. The first set of precipitation samples was retrieved from the bucket collectors in October 2003. These collectors yielded good quality stable isotope samples, and the sampling / analysis program has continued on a bi-annual basis since that time.

Analytical results for the USGS HAP samples are reported in Table 5.6. Precipitation amount data were provided by Tim Olson (USGS, Henderson). Although the data record is fairly short, it is instructive to calculate weighted mean δD and $\delta^{18}O$ values for the annual, cool season, and warm season samples at each site (see Table 5.7). Note that the annual mean is very similar to the cool season mean, particularly at the northernmost sites (Mt. Washington and Mt. Hamilton). The heavy precipitation that occurred during the 2004-2005 winter season exerts a strong influence on the weighted mean values for all sites because of the short duration of the record. Note also that in the case of Mt. Washington, the warm season 'mean' is represented by only one sample.

Weighted mean isotopic values are plotted in Figure 5.3 for cool and warm season samples from both the USGS HAP sites and the LLNL central Nevada sites. The two different datasets show overlapping compositions for the warm season averages, though the HAP data tends to plot slightly above the meteoric water line. The cool season HAP data is tightly clustered (with δD values between -105 and -110‰) and does not overlap with the LLNL data (δD values between -114 and -122‰).

In general, the δD and δ^{18}O values of meteoric waters become more depleted in heavy isotopes at lower air temperatures (Criss, 1999). Given that air temperature decreases with increasing altitude, precipitation falling at higher elevations is expected to have lower δD and δ^{18}O values compared to precipitation that falls at lower elevations. The HAP sites are 500 to 1000 meters higher in elevation than the LLNL sites, and should therefore have lower δ-values. However, the cool season δD and δ^{18}O averages are actually higher at the HAP sites compared to the LLNL sites (Figure 5.3). This suggests a longer data record is needed to obtain reliable long-term averages for the HAP sites.
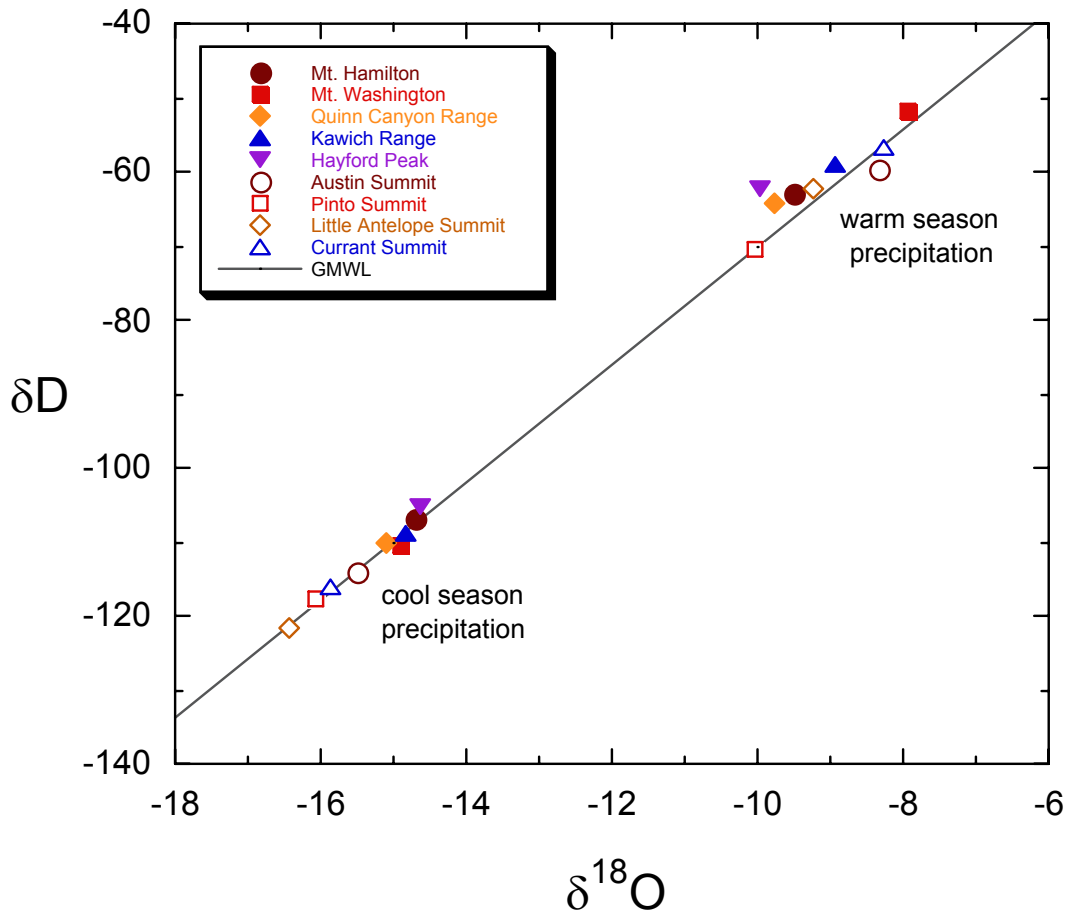
Figure 5.3 Plot of weighted mean δD vs. δ^{18}O values for cool- and warm-season precipitation samples collected from USGS HAP and LLNL central Nevada sites. GMWL = global meteoric water line (δD = 8δ^{18}O + 10).

Table 5.6 Precipitation Data for USGS HAP Sites

Location / Sample Date	Precipitation Amount (cm)	$\delta^{18}O$ (‰)	δD (‰)
Mt. Hamilton			
17-Oct-03	7.6	-7.8	-49
16-Jun-04	29.8	-15.4	-116
14-Oct-04	5.1	-12.0	-84
06-Jul-05	111.0	-14.5	-105
26-Oct-05	n.d.	-9.5	-66
05-Jul-06	35.6	-14.9	-105
Mt. Washington			
16-Oct-03	5.7	-7.9	-52
09-Jun-04	36.8	-17.2	-126
No sample collected in Oct. 2004 due to poor weather conditions			
12-Jul-05	116.8	-14.7	-110
No analysis in Oct. 2005 - sample damaged in shipment			
05-Jul-06	44.5	-13.6	-97
Quinn Canyon Range			
22-Oct-03	4.5	-8.0	-47
16-Jun-04	17.1	-15.6	-121
14-Oct-04	5.1	-9.5	-68
06-Jul-05	48.9	-15.9	-115
25-Oct-05	10.2	-10.7	-70
23-Jun-06	21.6	-13.0	-91
Kawich Range			
22-Oct-03	10.2	-7.4	-41
16-Jun-04	21.6	-15.7	-122
14-Oct-04	3.2	-9.9	-69
06-Jul-05	38.1	-14.5	-105
26-Oct-05	21.6	-9.5	-66
23-Jun-06	21.0	-14.7	-104
Hayford Peak			
22-Oct-03	10.2	-7.9	-47
16-Jun-04	25.4	-15.5	-115
14-Oct-04	12.7	-11.6	-74
06-Jul-05	70.5	-14.4	-102
20-Oct-05	26.7	-10.0	-63
No sample collected in June 2006 - collection bag burst			

n.d. = no data (leaky drain plug on gauge)

Table 5.7 Mean Precipitation Amounts and Isotopic Values for USGS HAP Sites

	Mount Hamilton	Mount Washington	Quinn Canyon Range	Kawich Range	Hayford Peak
Full Record					
δ^{18}O (wtd mean)	-14.4	-14.7	-14.1	-13.1	-13.1
δD (wtd mean)	-104	-109	-102	-94	-91
avg. amount (cm)	37.8	51.0	17.9	19.3	29.1
Warm Season					
δ^{18}O (wtd mean)	-9.5	-7.9	-9.7	-8.9	-10.0
δD (wtd mean)	-63	-52	-64	-59	-62
avg. amount (cm)	6.4	5.7	6.6	11.7	16.5
Cool Season					
δ^{18}O (wtd mean)	-14.7	-14.9	-15.1	-14.8	-14.6
δD (wtd mean)	-107	-110	-110	-109	-105
avg. amount (cm)	58.8	66.0	29.2	26.9	47.95

The precipitation gauges at Little Antelope Summit and Mt. Hamilton are located 19 km apart on the western side of the White Pine Range (Figure 5.1) at elevations of 2267 and 3230 m, respectively (Table 5.1). Assuming these two sites experience similar weather patterns, we can predict the mean isotopic value of precipitation at Mt. Hamilton using data from Little Antelope Summit together with the empirical altitude-isotope relationship reported in the literature: $\Delta(\delta^{18}$O$)/\Delta z$ = (-2.0 ± 1‰)/km (Criss, 1999). Precipitation at Little Antelope Summit had a mean annual δ^{18}O value of -14.9‰ for the period 1999-2006 (Table 5.3). Given the 963 m difference in elevation between Little Antelope Summit and Mt. Hamilton, we would predict a mean δ^{18}O value of -16.8 ± 0.95‰ for Mt. Hamilton. The equivalent δD value is -124‰. In comparison, the available three-year record for Mt. Hamilton yielded mean δ^{18}O and δD values of -14.4 and -104‰, respectively (Table 5.7). As the length of the record is extended over time, it will be interesting to see whether these data will 'evolve' to match the expected altitude-isotope effect.

Friedman et al. (2002) published a stable isotope study of precipitation in the Great Basin that includes data for Mt. Hamilton, Hayford Peak, and Austin (the latter is located only ~2.5 km from Austin Summit). The Friedman et al. (2002) study was conducted from 1991 to 1997, and unfortunately none of the measurements overlap with the present study. Nevertheless, it is interesting to compare the two data records, which are coincidentally similar in duration. Data from Friedman et al. (2002) are shown side-by-side with data from this study in Table 5.8. Comprehensive data were available only for δD in the Friedman et al. study.

Table 5.8 Comparison of Cumulative δD and Average Precipitation Data from Friedman et al. (2002) and This Study

	Mount Hamilton (Friedman)	Mount Hamilton (this study)	Hayford Peak (Friedman)	Hayford Peak (this study)	Austin (Friedman)	Austin Summit (this study)
annual						
δD (wtd. mean)	-105	-104	-95	-91	-120	-105
warm season						
δD (wtd. mean)	-90	-63	-89	-62	-109	-60
avg. amount (cm)	5.3	6.4	10.5	16.5	4.7	4.3
number of collections	5	2	3	3	5	5
cool season						
δD (wtd. mean)	-111	-107	-103	-105	-125	-114
avg. amount (cm)	36.2	58.8	30.8	48.0	13.1	14.2
number of collections	2	3	3	2	4	5

At Mt. Hamilton and Hayford Peak, the annual and cool season mean δD values do not show major differences between the two datasets, but the warm season δD values differ by 27‰ at both locations (Table 5.8). The difference in warm season data is quite striking and may be indicative of warmer summer air temperatures during storm events in 2003 to 2005 as compared to the early- to mid-1990s.

Comparison of the Austin and Austin Summit records reveals that mean δD values from Friedman et al. (2002) are lower than those from this study in all categories, with the greatest difference occurring in the warm season data (49‰ different). Moreover, the elevation of the Austin collection station used in Friedman's study was 1747 m whereas that of the Austin Summit gauge is 2285 m – a difference of 538 m. We would therefore expect the precipitation from the Austin site to have δD values that are higher (less negative) than the Austin Summit data. This is not consistent with the data comparison in Table 5.8. Further investigation into the source of these differences is warranted.

5.4   Summary and Conclusions

Stable isotope monitoring of precipitation, spring discharge, and soil water has been conducted at four sites in central Nevada since 1999. In addition, precipitation samples from five sites in eastern Nevada have been analyzed for stable isotopes since 2003. The latter sites are part of the USGS High Altitude Precipitation (HAP) monitoring network. The data from these sites can be used to improve our understanding of precipitation and recharge processes in Nevada, and can be applied to the development of conceptual models of hydrologic processes, for validating numerical groundwater flow models, and for monitoring potential changes in climate over time.

Analysis of the existing data led to the following conclusions, most of which are based on the dataset developed for the four LLNL sites in central Nevada.

- Warm season precipitation (May through October) accounts for only 20 to 23% of the annual precipitation total. The majority of the annual precipitation (77 to 80%) occurs during the cool season, primarily as winter snowfall.

- Precipitation samples have stable isotope compositions that plot very near the global meteoric water line. Cumulative annual mean δD and $\delta^{18}O$ values for precipitation are skewed toward the cool season average, reflecting the fact that most precipitation occurs during the winter season.

- Weighted mean δD and $\delta^{18}O$ values for soil waters (lysimeters) plot close to the meteoric water line at three out of four locations, and are depleted in heavy isotopes relative to the average cool season precipitation. This suggests that snowmelt-derived recharge occurs primarily during the early stages of melting, when the snowmelt exhibits the greatest depletion in heavy isotopes.

- The average δD and $\delta^{18}O$ values of perched springs can be derived from the weighted mean δD and $\delta^{18}O$ values of soil waters at all four central Nevada sites. At three of the four sites, the perched springs appear to be related to the soil water through evaporation processes. At one location, the spring and soil water have nearly identical compositions that lie on the meteoric water line.

- Soil moisture evaporation is considered to be the most plausible mechanism to explain the evaporated isotope signatures of the perched springs.

- Weighted mean isotopic values for precipitation samples from the USGS HAP sites have cool and warm season averages similar to that of the four central Nevada sites. However, the cool season HAP data has mean δD and $\delta^{18}O$ values that are greater than the central Nevada data despite the fact that the former is collected at higher altitudes. This suggests a longer data record is needed to obtain reliable long-term averages.

- Comparison of precipitation data from this study with data published by Friedman et al. (2002) for several of the same locations shows some discrepancies in the cumulative average δD values, particularly for the warm season samples. The source of these differences warrants further investigation.

5.5 References

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