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Office of Civilian Radioactive Waste Management,
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Meteoric Precipitation at Yucca Mountain, Nevada: Chemical and Stable Isotope Analyses, 2006–09



Scientific Investigations Report 2011–5140

Cover: Precipitation collectors for isotope and chemistry samples in Solitario Canyon. North-south trending ridge line of Yucca Mountain can be seen against the sky (Photograph by Richard J. Moscati, U.S. Geological Survey).

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KEN SALAZAR, Secretary

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Conversion Factors and Abbreviations

Multiply	By	To obtain
Length		
millimeter (mm)	0.03937	inch (in)
centimeter (cm)	0.3937	inch (in)
meter (m)	3.2808	feet (ft)
kilometer (km)	0.6214	mile (mi)
Volume		
microliter (μL)	3.382×10^{-5}	ounce, fluid (fl. oz)
milliliter (mL)	0.03382	ounce, fluid (fl. oz)

Stable isotope compositions are reported as delta (δ) values in units of parts per thousand (denoted as per mil or ‰) relative to a standard of known composition (Craig, 1961): Pee Dee Belemnite (PDB) for carbon (C), and Vienna Standard Mean Ocean Water (VSMOW) for oxygen (O).

Mil is a unit of length equal to one thousandth (10^{-3}) of an inch (0.0254 millimeter), used, for example, to specify the diameter of wire or the thickness of materials sold in sheets.

Chemical concentrations are given in metric units. Chemical concentration is given in milligrams per liter (mg/L). Milligrams per liter (equivalent to parts per million) is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. Specific conductance (or conductivity) is given in microsiemens per centimeter at 25°C ($\mu\text{S}/\text{cm}$).

Vertical coordinate information is referenced to the North American Datum of 1927.

Temperature in degrees Celsius ($^{\circ}\text{C}$) may be converted to degrees Fahrenheit ($^{\circ}\text{F}$) as follows:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$$

Meteoric Precipitation at Yucca Mountain, Nevada: Chemical and Stable Isotope Analyses, 2006–09

By Richard J. Moscati and Kevin M. Scofield

Abstract

Meteoric precipitation samples collected in 2006–09 at Yucca Mountain, Nevada, were analyzed for chemistry and stable isotope composition. Precipitation is the major source of infiltration to the unsaturated zone and of recharge to the saturated zone at Yucca Mountain.

On February 28, 2005, seepage of water was observed about 40 to 80 m below the ground surface within the Tiva Canyon Tuff in the South Ramp of the Exploratory Studies Facility (ESF) tunnel within Yucca Mountain. This seepage was preceded by a 5-month period of above-average precipitation. Chemical and isotopic analysis of this seepage could not be used to estimate travel time, extent of water-rock interaction, and (or) evaporative water loss during percolation through the unsaturated zone due to the lack of corresponding chemical and isotopic analyses of precipitation inputs to the infiltration events that produced the seepage.

In February 2006, collection of precipitation samples for chemical (major ions), delta oxygen-18 ($\delta^{18}\text{O}$), and delta deuterium (δD) analyses began at seven meteorological monitoring stations to provide baseline isotopic and chemical analyses. The sampling stations range in elevation from 1,131 to 1,562 meters. Each site has two collectors—one for chemical analysis and the other for isotopic analysis of precipitation. The collectors were sampled and emptied after each precipitation event.

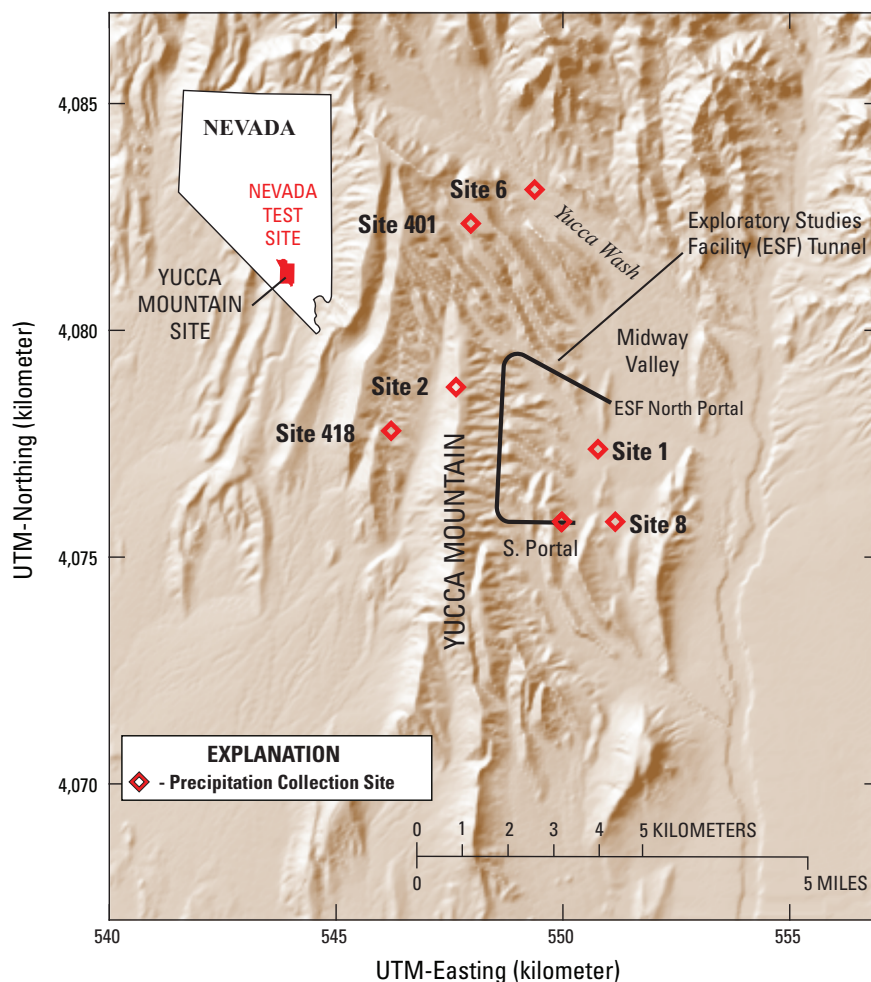
In 2006–09, 36 distinct precipitation events, with an average 3- to 4-day duration and an average 9.9 millimeters of accumulation, have been analyzed. The chemical composition of these samples of Yucca Mountain precipitation is relatively dilute but contains measurable and variable concentrations of Na^+ , Ca^{2+} , NH_4^+ , NO_3^- , and SO_4^{2-} . Dust transported by typical winter storms and generated from soil carbonates is the main contributor to this precipitation chemistry. Elevated nitrate and ammonium concentrations may be linked to agriculture in the nearby Amargosa River valley to the south and west of Yucca Mountain.

Cumulatively, $\delta^{18}\text{O}$ values range from 3.0 to -20.4 per mil (‰) and δD values range from 10 to -147 ‰. Winter-season precipitation commonly has isotopically lighter

compositions. The cumulative $\delta^{18}\text{O}$ plotted against δD shows that precipitation samples define a line with slope of 6.4, less than the 8 of the Global Meteoric Water Line. This difference in slope, typical of arid environments, is chiefly the result of evaporation of falling raindrops due to warmer air temperatures.

Introduction

Meteoric precipitation is the major source of infiltration to the unsaturated zone and of recharge of water to the saturated zone at Yucca Mountain, Nevada, a location studied for a formerly proposed nuclear waste repository (Levich and Stuckless, 2007). On February 28, 2005, seepage of water was observed in the form of wet spots on the crown, ribs, and invert of the Exploratory Studies Facility (ESF) tunnel, between stations 75+62 and 77+52 (Oliver and Whelan, 2006). (ESF locations are defined by stations at 100-meter (m) intervals; for example, station 75+62 is 7,562 m from the reference point near the north portal of the ESF). Stations 75+62 and 77+52 are 315 and 125 m, respectively, from the ESF South Portal (fig. 1). The seepage area was about 40 to 80 m below the ground surface within the approximately 12.7 million-year-old Miocene-age (Sawyer and others, 1994) Tiva Canyon Tuff middle nonlithophysal and lower nonlithophysal units (Buesch and others, 1996). The observed seepage was preceded by a 5-month period of 324 millimeters (mm) of precipitation (October 2004 through February 2005, at Site 1), well above the 1994–2006 5-month running average of 84 mm per month (Fransioli, 2007). Oliver and Whelan (2006) analyzed samples of this seepage for major ions, trace metals, and oxygen (O) and hydrogen (H) isotopic compositions in order to characterize the water and assess its interaction with the overlying soils and tuffs, or with anthropogenic materials used in the construction of the ESF. Corresponding baseline isotopic and chemical analyses of the precipitation inputs to the infiltration event(s) that produced the seepage were not available to Oliver and Whelan (2006) to estimate travel time, extent of water-rock interaction, or evaporative water loss during percolation through the unsaturated zone to aid further understanding of the hydrogeology at Yucca Mountain.



Universal Transverse Mercator (UTM) projection, Zone 11.
 Shaded-relief base from 1:24,000-scale Digital Elevation Model with 10-meter resolution using the North American Datum of 1927. Grid ticks are given at 5-kilometer intervals.
 Sun illumination from the northwest at 40 degrees above the horizon.

Figure 1. Shaded relief map of Yucca Mountain, Nevada, showing precipitation collection sites and the Exploratory Studies Facility.

One year later, in February 2006, a network of meteorological collection stations was installed (fig. 1) for chemical (major cations and anions, including short-chain organic acids and nutrients), delta oxygen-18 ($\delta^{18}\text{O}$), and delta deuterium (δD) precipitation collection for analyses to facilitate interpretation of data from future seepage events. This report summarizes the chemical and isotopic compositions of modern precipitation samples collected from those stations between February 2006 and January 2009. These data complement previous chemical and isotopic data compiled for precipitation in the region (Milne and others, 1987; Benson and Klieforth, 1989; Ingraham and others, 1990; Friedman and others, 1992; Moscati and others, 2008).

Equipment and Methods

Field Collection

The precipitation collection network consists of seven surface sampling stations adjacent to Yucca Mountain (fig. 1). The stations range in elevation from 1,131 m at Site 8 (near the south portal of the ESF) to 1,562 m at Site 401 (near the north end of the crest of Yucca Mountain) (table 1). Each site has two collectors for precipitation samples: one for isotope analyses and one for chemistry analyses. Samples for isotope

Table 1. Location of precipitation collection stations at Yucca Mountain, Nevada.

[Station coordinates are taken from the Universal Transverse Mercator (UTM) projection, Zone 11, using the North American Datum of 1927 for elevations; deg° min' sec", degrees, minutes, seconds]

Station name	Elevation meters	North Latitude deg° min' sec"	West Longitude deg° min' sec"	UTM-Northing meters	UTM-Easting meters
Site 1	1,143	36°50'34"	116°25'50"	550784	4077374
Site 2	1,478	36°51'19"	116°27'56"	547646	4078753
Site 6	1,315	36°53'40"	116°26'45"	549388	4083097
Site 8	1,131	36°49'42"	116°25'35"	551161	4075773
Site 401	1,562	36°53'16"	116°27'42"	547995	4082387
Site 418	1,301	36°50'48"	116°28'54"	546213	4077785
South Portal	1,198	36°49'42"	116°26'23"	549965	4075773

analyses are collected in a standard 4-in. [about 10-centimeter (cm)] diameter, plastic NovaLynx™ rain gauge (fig. 2A). The inner cylinder of the rain gauge, with a capacity of 1-in. (about 25 mm) of rainfall, contains approximately 5 millimeter (mL) of petroleum-based oil to retard evaporation of collected water. The top of the collector is fitted with a chemically inert mesh to prevent insects (which are attracted to the oil) from entering the collector, and with vertical plastic cable ties (see fig. 2A) to limit bird perching. During sampling, water is withdrawn from the collector using a syringe fitted with a small-diameter, flexible tube.

The collector for samples for chemistry analyses, modeled after a design described by Milne and others (1987) and Claassen and Halm (1994), is a 30.5-cm-diameter, heavy-walled polyvinylchloride (PVC) pipe (fig. 2B). The height of the cylinder is approximately 2 m, of which about 30 cm are buried to enhance stability. Secured with a hose clamp around the outside of the PVC pipe, a set of two nested, 6-mil, flat, polyethylene sample-collection bags (76 cm long) are hung inside the cylinder, with the innermost bag having a 1- to 2-cm-diameter restriction placed near the middle, so that the bag takes an hourglass shape. Double bagging ensures against samples being lost due to leakage, and the constriction of the bag minimizes exposure to atmospheric vapor and evaporation. The outer bag also prevents soil condensation from forming on the inner bag. The height of the cylinder limits contamination from surface dust stirred up by motor vehicles, wildlife, and wind. A precipitation sample was collected by removing the inner bag, snipping a lower corner with scissors, and draining the water into a sample bottle. The chemistry and isotope sample collectors both typically were sampled, emptied, and serviced within 24 to 48 hours after the cessation of a precipitation event. There was no filtering of the samples.

The initial network was installed in February 2006, with one collector at each station. After several months of sample chemistry analyses (cation and anion analyses by ion

chromatography), it became apparent that the presence of insects and residual oil in the collector were contaminating the samples (giving excessive organic and sulfate content) and limiting the usefulness of the chemistry data (Moscati and others, 2008). Therefore, a second set of oil-free collectors was installed at each site, and collection from the new collectors commenced in December 2007. The initial collector at each site continued to be used as the isotope sample collector because field experiments and results described by Friedman and others (1992) showed that the use of oil to prevent evaporation did not affect the isotope analyses. The chemistry data presented in this paper were obtained from this second set of collectors. Sampling Site 418 was eliminated from the network after the September 25, 2007 collection because of a permanent gate closure on the Nevada Test Site.

Major Cation and Anion Analysis

Major cations and anions were analyzed, respectively, by two ion chromatographs. In either case, an aliquot of 500 microliter (μL) of sample was introduced into the instrument. The sample was then separated and measured by use of a system consisting of a guard column, analytical column, suppressor device, and conductivity detector (O'Dell and others, 1984). The instrument software automatically calculated analyte concentrations from the sample and reported results in milligrams per liter (mg/L). Major-ion measurements of individual chemistry samples are ± 15 percent or better (2-sigma error), except for bicarbonate (HCO_3^-), which is ± 20 percent. That estimate of accuracy is based on the deviation of the measured values compared to accepted values for prepared standards for each analyte. Hydrogen activity (pH) was analyzed in the laboratory with a compact pH meter requiring approximately 0.5 mL of sample for analysis. The resolution of pH measurements is 0.01.



Figure 2. Precipitation collectors for isotope and chemistry samples at Yucca Mountain, Nevada.

Stable Isotopic Analysis

Deuterium (D) analyses were made after a 2- μL aliquot of sample was converted to hydrogen gas by reaction with zinc metal shavings at 500°C (Kendall and Coplen, 1985). Magnetic-sector mass spectrometry was used to measure the deuterium content of the hydrogen gas, to separate the HD^+ from H_2^+ , to determine the ratio of the two ions, and to compare the ratio to that in a known sample of hydrogen gas. The results are reported in delta (δ) notation as the per mil (‰) deviation relative to Vienna Standard Mean Ocean Water (VSMOW):

$$\delta\text{D} (\text{‰}) = [(R_{\text{sample}} - R_{\text{standard}}) / (R_{\text{standard}})] 1000, \quad (1)$$

where R_{sample} and R_{standard} refer to the ratio of deuterium to hydrogen in the sample and standard (VSMOW), respectively. Samples were run in replicate. The δD values are precise to $\pm 2\text{‰}$ (2-sigma error).

Oxygen-18 (^{18}O) analyses were made after a 200- μL aliquot of sample was equilibrated with carbon dioxide (CO_2) of known oxygen isotopic composition at 40°C for at least

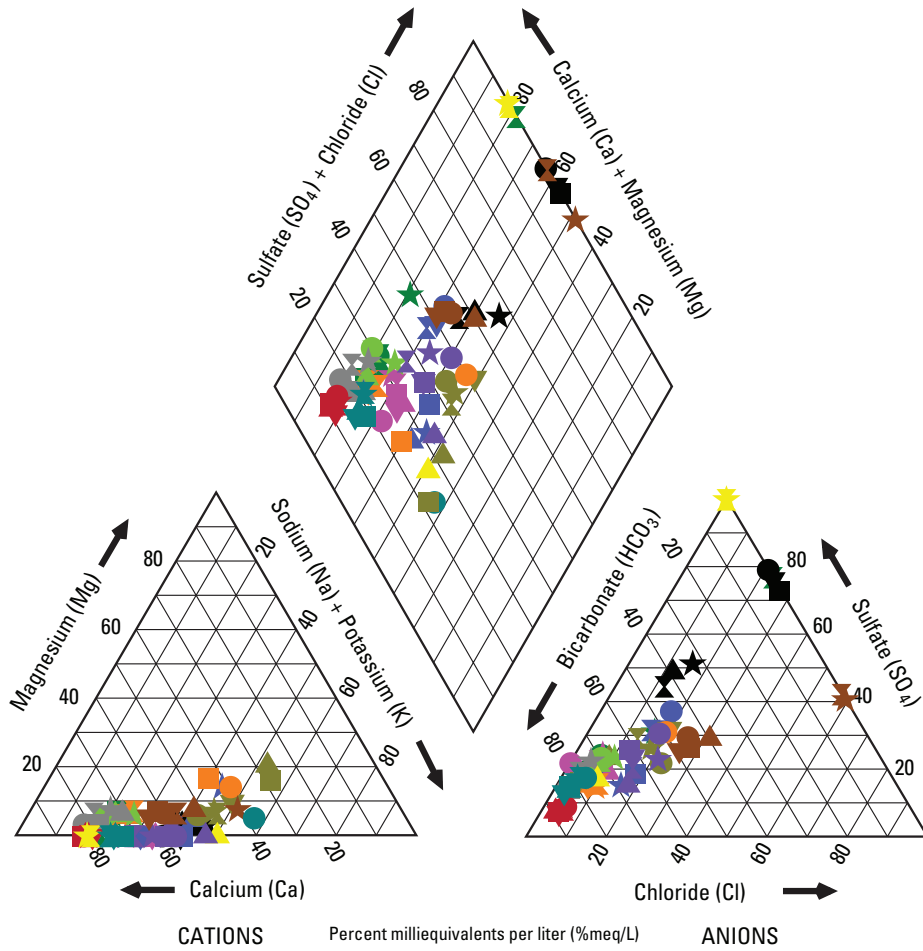
9 hours. The gas was then drawn through the Multiprep™ device where water was removed by passage through a cryogenic trap at dry-ice temperature (-78°C). The dried CO_2 was then analyzed for its $\delta^{18}\text{O}$ by magnetic-sector mass spectrometry. The results are reported in δ notation in ‰ units relative to VSMOW:

$$\delta^{18}\text{O} (\text{‰}) = [(R_{\text{sample}} - R_{\text{standard}}) / (R_{\text{standard}})] 1000, \quad (2)$$

where R_{sample} and R_{standard} refer to the ratio of oxygen-18 to oxygen-16 in the sample and standard, respectively. The $\delta^{18}\text{O}$ values are precise to $\pm 0.2\text{‰}$ (2-sigma error).

Major Cation and Anion Chemistry

Major cation and anion concentrations, calculated total dissolved solids (TDS), and calculated conductivity of 75 precipitation samples collected from December 2007 to January 2009 are reported in figure 3 and in table 2. The waters are relatively dilute, with resulting poor ionic charge balance.



EXPLANATION

- | | | | | |
|--------------------|--------------------|--------------------|--------------------|--------------------|
| ★ S. Portal 071210 | ★ S. Portal 080225 | ★ S. Portal 080528 | ■ Site 6 081006 | ★ S. Portal 090126 |
| ▲ Site 1 071210 | ▲ Site 1 080225 | ▲ Site 1 080527 | ⊗ Site 8 081006 | ▲ Site 1 090126 |
| ▼ Site 2 071210 | ▼ Site 2 080225 | ▼ Site 2 080527 | ● Site 401 081006 | ▼ Site 2 090126 |
| ■ Site 6 071210 | ■ Site 6 080225 | ■ Site 6 080527 | ★ S. Portal 081103 | ■ Site 6 090126 |
| ⊗ Site 8 071210 | ⊗ Site 8 080225 | ⊗ Site 8 080527 | ▲ Site 1 081103 | ⊗ Site 8 090126 |
| ● Site 401 071210 | ● Site 401 080225 | ● Site 401 080528 | ▼ Site 2 081103 | ● Site 401 090126 |
| ★ S. Portal 080108 | ★ S. Portal 081201 | ★ S. Portal 080714 | ■ Site 6 081103 | |
| ▲ Site 1 080108 | ▲ Site 1 081201 | ▲ Site 1 080714 | ⊗ Site 8 081103 | |
| ▼ Site 2 080108 | ▼ Site 2 081201 | ▼ Site 2 080714 | ● Site 401 081103 | |
| ■ Site 6 080108 | ■ Site 6 081201 | ■ Site 6 080714 | ★ S. Portal 081229 | |
| ⊗ Site 8 080108 | ⊗ Site 8 081201 | ⊗ Site 8 080714 | ▲ Site 1 081229 | |
| ● Site 401 080108 | ● Site 401 081201 | ● Site 401 080714 | ▼ Site 2 081229 | |
| ★ S. Portal 080128 | ★ S. Portal 081222 | ★ S. Portal 080909 | ■ Site 6 081229 | |
| ▲ Site 1 080128 | ▲ Site 1 081222 | ▲ Site 1 080909 | ⊗ Site 8 081229 | |
| ▼ Site 2 080128 | ▼ Site 2 081222 | ▼ Site 2 080909 | ● Site 401 081229 | |
| ■ Site 6 080128 | ■ Site 6 081222 | ■ Site 401 080909 | ★ S. Portal 081006 | |
| ⊗ Site 8 080128 | ⊗ Site 8 081222 | ★ S. Portal 081006 | ▲ Site 1 081006 | |
| ● Site 401 080128 | ● Site 401 081222 | ▲ Site 1 081006 | | |

Sample name contains collection date in "yyymmdd" (year/month/day) format.

Figure 3. Relative concentrations on piper diagram, in percent milliequivalents per liter, of the major ions in precipitation samples from monitoring stations at Yucca Mountain, Nevada, December 2007 to January 2009.

6 Meteoric Precipitation at Yucca Mountain, Nevada: Chemical and Stable Isotope Analyses, 2006–09

Table 2. Major cation and anion concentrations for precipitation samples at Yucca Mountain, Nevada, December 2007 to January 2009.

[Abbreviations: mg/L, milligrams per liter; TDS, total dissolved solids; $\mu\text{S}/\text{cm}$, microsiemens per centimeter; NA, not available. TDS and conductivity are based on calculations from ion concentrations, not field measurements. Sample name contains collection date format "yy/mm/dd" (year/month/day)]

Sample name	Na mg/L	NH ₄ mg/L	Mg mg/L	K mg/L	Ca mg/L	F mg/L	Acetate mg/L	Formate mg/L	Propionate mg/L
S. Portal 071210	0.27	0.53	0.05	0.06	0.93	<0.01	<0.01	<0.01	<0.14
Site 1 071210	0.31	0.54	0.05	0.14	0.95	<0.01	<0.01	<0.01	<0.14
Site 2 071210	0.46	0.87	0.08	0.09	1.57	<0.01	<0.01	<0.01	<0.14
Site 6 071210	0.30	0.61	0.06	0.06	0.96	<0.01	<0.01	<0.01	<0.14
Site 8 071210	0.21	0.49	<0.05	0.04	0.73	<0.01	<0.01	<0.01	<0.14
Site 401 071210	0.49	0.96	0.09	0.11	1.59	<0.01	<0.01	<0.01	<0.14
S. Portal 080108	1.40	0.49	0.06	0.27	1.47	<0.01	<0.01	<0.01	<0.14
Site 1 080108	1.02	0.38	0.05	0.06	1.31	<0.01	<0.01	<0.01	<0.14
Site 2 080108	0.74	0.28	<0.05	0.04	0.94	<0.01	<0.01	<0.01	<0.14
Site 6 080108	1.17	0.75	0.06	0.40	1.47	<0.01	<0.01	<0.01	<0.14
Site 8 080108	1.28	0.48	0.07	0.07	1.87	<0.01	<0.01	<0.01	<0.14
Site 401 080108	0.70	0.41	<0.05	<0.04	1.05	<0.01	<0.01	<0.01	<0.14
S. Portal 080128	0.17	0.28	<0.05	<0.04	0.39	<0.01	<0.01	<0.01	<0.15
Site 1 080128	0.20	0.27	<0.05	0.08	0.40	<0.01	<0.01	<0.01	<0.15
Site 2 080128	0.16	0.28	<0.05	0.06	0.33	<0.01	<0.01	<0.01	<0.15
Site 6 080128	0.16	0.24	<0.05	<0.04	0.30	<0.01	<0.01	<0.01	<0.15
Site 8 080128	0.16	0.25	<0.05	<0.04	0.32	<0.01	<0.01	<0.01	<0.15
Site 401 080128	0.15	0.24	<0.05	<0.04	0.28	<0.01	<0.01	<0.01	<0.15
S. Portal 080225	2.55	4.18	0.51	0.81	2.42	<0.01	<0.01	<0.01	<0.15
Site 1 080225	1.12	3.92	0.11	1.37	2.09	<0.01	<0.01	<0.01	<0.15
Site 2 080225	0.91	1.62	<0.05	0.22	1.99	<0.01	<0.01	<0.01	<0.15
Site 6 080225	1.15	1.72	<0.05	0.47	1.73	<0.01	<0.01	<0.01	<0.15
Site 8 080225	0.90	1.04	<0.05	0.12	2.01	<0.01	<0.01	<0.01	<0.15
Site 401 080225	0.72	1.31	<0.05	0.12	1.53	<0.01	<0.01	<0.01	<0.15
S. Portal 080528	6.16	4.70	0.59	1.61	6.27	0.02	<0.01	0.02	<0.15
Site 1 080527	8.45	30.4	4.46	22.4	9.71	0.02	0.04	0.06	0.16
Site 2 080527	6.53	0.49	1.11	6.25	7.36	0.03	8.90	<0.01	1.77
Site 6 080527	6.76	34.3	3.51	26.3	9.87	0.02	0.02	0.04	0.68
Site 8 080527	8.72	4.04	0.77	2.69	8.82	0.02	<0.01	0.02	<0.15
Site 401 080528	3.57	2.49	0.34	1.40	4.62	0.01	<0.01	0.01	<0.15
S. Portal 080714	0.84	1.09	0.14	0.44	3.33	<0.01	0.12	0.11	<0.15
Site 1 080714	0.68	1.46	0.14	0.73	2.70	<0.01	0.17	0.14	<0.15
Site 2 080714	0.98	2.59	0.24	0.95	3.85	<0.01	0.04	0.03	<0.15
Site 6 080714	2.48	13.9	2.09	11.8	8.84	0.01	0.04	0.10	0.30
Site 8 080714	1.41	1.79	0.31	1.10	4.61	<0.01	<0.01	0.03	<0.15
Site 401 080714	2.99	12.1	1.70	12.6	7.57	0.01	0.67	0.20	<0.15

Table 2. Major cation and anion concentrations for precipitation samples at Yucca Mountain, Nevada, December 2007 to January 2009.—Continued

[Abbreviations: mg/L, milligrams per liter; TDS, total dissolved solids; $\mu\text{S}/\text{cm}$, microsiemens per centimeter; NA, not available. TDS and conductivity are based on calculations from ion concentrations, not field measurements. Sample name contains collection date format "yy/mm/dd" (year/month/day)]

Sample name	Cl mg/L	NO ₂ mg/L	HCO ₃ mg/L	SO ₄ mg/L	Br mg/L	NO ₃ mg/L	PO ₄ mg/L	TDS mg/L	Conductivity $\mu\text{S}/\text{cm}$	Water-type
S. Portal 071210	0.22	<0.13	1.20	0.56	<0.03	2.02	<0.02	5.8	10	Ca-NO ₃
Site 1 071210	0.14	<0.13	2.40	0.60	0.08	2.00	0.10	7.3	11	Ca-HCO ₃
Site 2 071210	0.20	<0.13	3.40	0.94	<0.03	3.27	<0.02	11	17	Ca-HCO ₃
Site 6 071210	0.13	<0.13	3.80	0.79	<0.03	3.30	<0.02	10	14	Ca-HCO ₃
Site 8 071210	0.11	<0.13	<1.2	0.50	<0.03	1.79	<0.02	3.9	7.7	Ca-NO ₃
Site 401 071210	0.20	<0.13	3.70	1.03	<0.03	4.29	<0.02	12	19	Ca-NO ₃
S. Portal 080108	0.42	<0.13	1.50	1.84	<0.03	1.80	<0.02	9.3	17	Ca-SO ₄
Site 1 080108	0.27	<0.13	1.50	1.49	<0.03	1.74	<0.02	7.8	14	Ca-SO ₄
Site 2 080108	0.22	<0.13	<1.2	0.97	<0.03	1.38	<0.02	4.6	9.1	Ca-NO ₃
Site 6 080108	0.34	<0.13	<1.2	1.25	0.14	2.18	<0.02	7.8	16	Ca-NO ₃
Site 8 080108	0.36	<0.13	2.24	1.84	<0.03	2.22	<0.02	10	18	Ca-SO ₄
Site 401 080108	0.21	<0.13	<1.2	1.10	<0.03	2.65	<0.02	6.1	11	Ca-NO ₃
S. Portal 080128	0.10	<0.13	1.7	0.48	<2.0	1.03	<2.0	4.2	6.0	Ca-HCO ₃
Site 1 080128	0.14	<0.13	1.6	0.35	<2.0	1.02	<2.0	4.0	6.0	Ca-HCO ₃
Site 2 080128	0.12	<0.13	1.7	0.35	<2.0	1.01	<2.0	4.0	5.7	Ca-HCO ₃
Site 6 080128	0.10	<0.13	1.4	0.33	<2.0	0.99	<2.0	3.5	5.1	Ca-HCO ₃
Site 8 080128	0.10	<0.13	1.3	0.33	<2.0	0.88	<2.0	3.3	5.0	Ca-HCO ₃
Site 401 080128	<0.09	<0.13	1.7	0.38	<2.0	0.92	<2.0	3.7	5.0	Ca-HCO ₃
S. Portal 080225	2.61	<0.13	19	3.37	<2.0	4.06	<2.0	40	60	NH ₄ -HCO ₃
Site 1 080225	0.60	<0.13	13	2.98	<2.0	3.46	3.85	33	45	NH ₄ -HCO ₃
Site 2 080225	0.69	<0.13	3.4	1.74	<2.0	4.92	<2.0	15	26	Ca-NO ₃
Site 6 080225	1.14	<0.13	6.9	1.62	<2.0	3.88	<2.0	19	29	NH ₄ -HCO ₃
Site 8 080225	0.61	<0.13	3.6	1.69	<2.0	3.39	<2.0	13	22	Ca-HCO ₃
Site 401 080225	0.49	<0.13	2.2	1.43	<2.0	4.01	<2.0	12	21	Ca-NO ₃
S. Portal 080528	4.27	<0.13	23	8.65	<2.0	8.35	<2.0	64	99	Ca-HCO ₃
Site 1 080527	9.43	<0.13	121	33.7	<2.0	0.08	36.6	276	338	NH ₄ -HCO ₃
Site 2 080527	4.76	<0.13	20	10.5	<2.0	0.11	<2.0	57	90	Ca-HCO ₃
Site 6 080527	6.20	1.87	149	24.5	<2.0	0.96	20.2	285	355	NH ₄ -HCO ₃
Site 8 080527	4.09	0.45	31	12.4	<2.0	11.0	<2.0	84	124	Ca-HCO ₃
Site 401 080528	3.31	<0.13	14	4.36	<2.0	5.85	<2.0	40	63	Ca-HCO ₃
S. Portal 080714	0.72	0.13	9.3	1.45	<2.0	2.46	<2.0	20	30	Ca-HCO ₃
Site 1 080714	0.58	<0.13	8.5	1.35	<2.0	2.82	<2.0	19	29	Ca-HCO ₃
Site 2 080714	0.81	<0.13	14	2.22	<2.0	3.26	<2.0	29	44	Ca-HCO ₃
Site 6 080714	2.97	4.56	56	10.3	<2.0	3.13	17.2	133	167	NH ₄ -HCO ₃
Site 8 080714	1.14	<0.13	14	2.41	<2.0	4.16	<2.0	31	46	Ca-HCO ₃
Site 401 080714	5.19	5.38	23	11.4	<2.0	0.08	22.8	105	140	NH ₄ -PO ₄

8 Meteoric Precipitation at Yucca Mountain, Nevada: Chemical and Stable Isotope Analyses, 2006–09

Table 2. Major cation and anion concentrations for precipitation samples at Yucca Mountain, Nevada, December 2007 to January 2009.—Continued

[Abbreviations: mg/L, milligrams per liter; TDS, total dissolved solids; $\mu\text{S}/\text{cm}$, microsiemens per centimeter; NA, not available. TDS and conductivity are based on calculations from ion concentrations, not field measurements. Sample name contains collection date format "yy/mm/dd" (year/month/day)]

Sample name	Na mg/L	NH ₄ mg/L	Mg mg/L	K mg/L	Ca mg/L	F mg/L	Acetate mg/L	Formate mg/L	Propionate mg/L
S. Portal 080909	3.44	2.82	0.57	1.95	10.1	0.02	0.06	0.04	<0.15
Site 1 080909	2.25	1.79	0.46	1.49	8.91	0.02	<0.01	0.01	<0.15
Site 8 080909	1.12	1.46	0.19	0.63	5.02	<0.01	0.02	0.02	<0.15
Site 401 080909	1.56	2.16	0.33	0.79	6.99	0.01	0.02	0.01	<0.15
S. Portal 081006	1.77	2.01	0.61	1.89	9.25	0.01	0.08	0.01	<0.15
Site 1 081006	0.99	2.45	0.30	1.66	5.10	<0.01	0.03	<0.01	<0.15
Site 6 081006	0.41	0.71	0.07	0.60	2.72	<0.01	0.03	<0.01	<0.15
Site 8 081006	0.92	1.04	0.31	0.80	5.77	<0.01	0.07	0.02	<0.15
Site 401 081006	0.46	0.70	0.08	0.38	3.11	<0.01	0.06	0.01	<0.15
S. Portal 081103	0.14	0.25	<0.05	0.11	0.80	<0.01	0.07	0.03	<0.15
Site 1 081103	0.12	0.14	<0.05	0.08	0.68	<0.01	0.05	0.02	<0.15
Site 2 081103	0.20	0.46	<0.05	0.18	1.11	<0.01	0.05	0.01	<0.15
Site 6 081103	0.16	0.17	<0.05	0.11	0.99	<0.01	0.06	0.04	<0.15
Site 8 081103	0.13	0.15	<0.05	0.07	0.67	<0.01	0.03	<0.01	<0.15
Site 401 081103	0.16	0.19	<0.05	0.07	0.84	<0.01	0.06	0.04	<0.15
S. Portal 081201	0.06	0.13	<0.05	<0.04	0.24	<0.01	<0.01	0.03	<0.15
Site 1 081201	0.24	0.31	<0.05	0.17	0.29	<0.01	0.04	<0.01	<0.15
Site 2 081201	<0.05	0.12	<0.05	<0.04	<0.15	<0.01	<0.01	0.04	<0.15
Site 6 081201	<0.05	0.10	<0.05	<0.04	<0.15	<0.01	<0.01	0.02	<0.15
Site 8 081201	0.05	0.11	<0.05	<0.04	0.19	<0.01	0.02	0.01	<0.15
Site 401 081201	<0.05	0.10	<0.05	<0.04	<0.15	<0.01	<0.01	0.11	<0.15
S. Portal 081222	0.38	0.44	<0.05	0.05	0.69	<0.01	NA	<0.01	<0.15
Site 1 081222	0.49	0.37	<0.05	0.24	0.61	<0.01	NA	<0.01	<0.15
Site 2 081222	0.87	0.46	0.05	0.15	1.35	<0.01	NA	<0.01	<0.15
Site 6 081222	0.60	0.25	<0.05	0.06	0.93	<0.01	NA	<0.01	<0.15
Site 8 081222	0.34	0.40	<0.05	<0.04	0.70	<0.01	NA	<0.01	<0.15
Site 401 081222	0.59	0.29	<0.05	0.07	0.82	<0.01	NA	<0.01	<0.15
S. Portal 081229	0.73	0.61	0.06	0.05	0.52	<0.01	NA	<0.01	<0.15
Site 1 081229	0.69	0.55	0.07	0.05	0.80	<0.01	NA	<0.01	<0.15
Site 2 081229	0.74	0.66	0.08	0.07	1.42	<0.01	NA	<0.01	<0.15
Site 6 081229	0.80	0.73	0.10	0.07	1.41	<0.01	NA	<0.01	<0.15
Site 8 081229	0.70	0.50	0.07	0.05	0.96	<0.01	NA	0.01	<0.15
Site 401 081229	0.92	0.78	0.10	0.07	1.47	<0.01	NA	<0.01	<0.15
S. Portal 090126	0.23	0.70	<0.05	0.05	0.73	<0.01	<0.01	<0.01	<0.15
Site 1 090126	0.26	0.64	<0.05	0.05	0.75	<0.01	0.02	0.01	<0.15
Site 2 090126	0.20	0.57	<0.05	0.05	0.61	<0.01	<0.01	<0.01	<0.15
Site 6 090126	0.20	0.57	<0.05	0.04	0.53	<0.01	<0.01	<0.01	<0.15
Site 8 090126	0.23	0.66	<0.05	0.04	0.72	<0.01	<0.01	0.11	<0.15
Site 401 090126	0.21	1.10	0.05	1.42	0.60	<0.01	<0.01	<0.01	<0.15

Table 2. Major cation and anion concentrations for precipitation samples at Yucca Mountain, Nevada, December 2007 to January 2009.—Continued

[Abbreviations: mg/L, milligrams per liter; TDS, total dissolved solids; $\mu\text{S}/\text{cm}$, microsiemens per centimeter; NA, not available. TDS and conductivity are based on calculations from ion concentrations, not field measurements. Sample name contains collection date format "yy/mm/dd" (year/month/day)]

Sample name	Cl mg/L	NO ₂ mg/L	HCO ₃ mg/L	SO ₄ mg/L	Br mg/L	NO ₃ mg/L	PO ₄ mg/L	TDS mg/L	Conductivity $\mu\text{S}/\text{cm}$	Water-type
S. Portal 080909	2.24	<0.13	25	7.07	<2.0	17.3	<2.0	71	102	Ca-HCO ₃
Site 1 080909	1.23	0.20	25	4.86	<2.0	10.2	<2.0	56	78	Ca-HCO ₃
Site 8 080909	0.84	<0.13	14	3.56	<2.0	6.97	<2.0	34	49	Ca-HCO ₃
Site 401 080909	1.02	<0.13	18	4.83	<2.0	11.3	<2.0	47	68	Ca-HCO ₃
S. Portal 081006	1.06	<0.13	26	6.33	<2.0	13.5	<2.0	62	86	Ca-HCO ₃
Site 1 081006	0.70	<0.13	22	3.88	<2.0	7.76	<2.0	45	61	Ca-HCO ₃
Site 6 081006	0.31	<0.13	13	1.83	<2.0	3.10	<2.0	23	29	Ca-HCO ₃
Site 8 081006	0.55	<0.13	20	3.88	<2.0	7.30	<2.0	41	54	Ca-HCO ₃
Site 401 081006	0.25	<0.13	12	1.68	<2.0	3.70	<2.0	22	29	Ca-HCO ₃
S. Portal 081103	0.17	<0.13	4.9	0.41	<2.0	0.71	<2.0	7.5	9.1	Ca-HCO ₃
Site 1 081103	0.14	<0.13	6.0	0.40	<2.0	0.61	<2.0	8.1	8.8	Ca-HCO ₃
Site 2 081103	0.24	<0.13	7.8	0.50	<2.0	1.05	<2.0	12	14	Ca-HCO ₃
Site 6 081103	0.18	<0.13	6.3	0.43	<2.0	0.78	<2.0	9.1	11	Ca-HCO ₃
Site 8 081103	0.18	<0.13	5.0	0.37	<2.0	0.63	<2.0	7.2	8.2	Ca-HCO ₃
Site 401 081103	0.15	<0.13	4.2	0.36	<2.0	0.77	<2.0	6.7	8.4	Ca-HCO ₃
S. Portal 081201	<0.09	<0.13	<1.2	0.33	<2.0	0.66	<2.0	1.4	2.6	Ca-NO ₃
Site 1 081201	0.16	<0.13	2.2	0.41	<2.0	0.57	<2.0	4.4	6.1	NH ₄ -HCO ₃
Site 2 081201	<0.09	<0.13	<1.2	0.26	<2.0	0.51	<2.0	0.9	1.5	NH ₄ -NO ₃
Site 6 081201	<0.09	<0.13	<1.2	0.25	<2.0	0.44	<2.0	0.8	1.3	NH ₄ -NO ₃
Site 8 081201	<0.09	<0.13	<1.2	0.29	<2.0	0.61	<2.0	1.3	2.3	Ca-NO ₃
Site 401 081201	<0.09	<0.13	<1.2	0.26	<2.0	0.51	<2.0	0.9	1.4	NH ₄ -NO ₃
S. Portal 081222	0.29	<0.13	1.3	0.42	<2.0	1.67	<2.0	5.2	8.8	Ca-NO ₃
Site 1 081222	0.45	<0.13	2.9	0.53	<2.0	1.39	<2.0	7.0	10	Ca-HCO ₃
Site 2 081222	0.53	<0.13	3.8	1.16	<2.0	2.86	<2.0	11	17	Ca-HCO ₃
Site 6 081222	0.28	<0.13	2.3	0.76	<2.0	1.54	<2.0	6.7	10	Ca-HCO ₃
Site 8 081222	0.26	<0.13	1.7	0.44	<2.0	1.54	<2.0	5.4	8.6	Ca-HCO ₃
Site 401 081222	0.32	<0.13	1.6	0.76	<2.0	1.66	<2.0	6.1	9.8	Ca-NO ₃
S. Portal 081229	0.75	<0.13	<1.2	0.70	<2.0	2.62	<2.0	6.0	11	NH ₄ -NO ₃
Site 1 081229	0.68	<0.13	1.5	0.88	<2.0	2.42	<2.0	7.6	13	Ca-NO ₃
Site 2 081229	0.67	<0.13	2.2	0.93	<2.0	2.54	<2.0	9.3	16	Ca-NO ₃
Site 6 081229	0.76	<0.13	2.2	0.99	<2.0	2.68	<2.0	9.7	17	Ca-NO ₃
Site 8 081229	0.72	<0.13	<1.2	0.71	<2.0	2.27	<2.0	6.0	12	Ca-NO ₃
Site 401 081229	0.77	<0.13	2.3	1.21	<2.0	2.67	<2.0	10	18	Ca-NO ₃
S. Portal 090126	0.16	<0.13	5.5	0.97	<2.0	1.78	<2.0	10	13	NH ₄ -HCO ₃
Site 1 090126	0.19	<0.13	7.5	1.01	<2.0	1.70	<2.0	12	15	Ca-HCO ₃
Site 2 090126	0.14	<0.13	6.4	0.80	<2.0	1.59	<2.0	10	12	NH ₄ -HCO ₃
Site 6 090126	0.15	<0.13	6.3	0.93	<2.0	1.56	<2.0	10	12	NH ₄ -HCO ₃
Site 8 090126	0.18	<0.13	5.5	0.99	<2.0	1.69	<2.0	10	13	NH ₄ -HCO ₃
Site 401 090126	0.32	<0.13	6.9	1.25	<2.0	1.69	<2.0	14	19	NH ₄ -HCO ₃

Dilution of these samples likely is a function of the length of their collection period, typically spanning several days of rainfall. Generally, rain samples collected at the beginning of an individual storm contain most of the soluble material available in the atmosphere, and consequently, rain toward the end of a storm is more dilute (Friedman and others, 2002). This effect is compounded because samples often accumulated over a period of many days, with associated intermittent storms (causing increased dilution), before collection.

The collected rainfall is slightly acidic, commonly with a pH between 6 and 7. The relatively high values of pH (compared to pure water in equilibrium with the atmosphere, pH 5.6 [Drever, 1997]) likely are not due to a lack of acidity in the precipitation but to the buffering by local, naturally alkaline dusts that contain large calcium-carbonate fractions.

The precipitation samples, defined on the basis of dissolved ions (after Back, 1966), commonly are characterized by calcium-bicarbonate-type water (fig. 3). A small percentage of other water types also are recognized, including calcium-nitrate and ammonium-bicarbonate (23 percent and 16 percent, respectively, of the total samples analyzed). Eleven of the analyzed samples have low HCO_3^- values (<1.2 mg/L) and plot anomalously near the top-right part of the diamond on figure 3, accounting for almost half of the calcium-nitrate type waters identified.

Typical winter storm trajectories originating over the Pacific Ocean (Friedman and others, 1992) and tracking toward southern Nevada cross mountain ranges, playas, and alluvial fans. As these air masses move inland, terrestrial dust is entrained. That eolian dust, dominantly derived from arid soils, contains calcite (CaCO_3), salts (such as NaCl), and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) from pedogenic, authigenic, and playa settings (Reheis and Kihl, 1995) and is likely the main contributor of dissolved Na^+ , Ca^{2+} , Cl^- , and SO_4^{2-} to the meteoric-precipitation chemistry at Yucca Mountain. Elevated nitrate and ammonium concentrations may be both anthropogenic and natural (released by vegetation), but are more likely to be anthropogenic, linked to agricultural ammonium-nitrate fertilizers and animal urine (and to a lesser extent, vehicle emissions) in the nearby Amargosa River valley south and west of Yucca Mountain.

Oliver and Whelan (2006) reported the chemical characterization of the February 2005 seepage waters that triggered this study. They determined that those seepage waters, which traveled through the soil zone and through 40 to 80 m of Tiva Canyon Tuff, were of the calcium-sulfate-chloride type, which would plot in the top-center portion of the diamond in a Piper-type diagram (for example, see figure 3). Data presented here illustrate a marked shift in infiltration-water chemistry, from predominately calcium-bicarbonate type at the surface to calcium-sulfate-chloride type in the ESF, over a relatively short distance and percolation time. The Oliver and Whelan (2006) samples were collected from the floor of the ESF, on vents and rock bolts in the tunnel, and from exposed rock surfaces and fractures.

Stable Isotopes

The arid climate of Yucca Mountain has a mean annual precipitation of approximately 200 mm that occurs as convective precipitation in the summer monsoon period of July and August, or as lower-intensity, longer-duration periods of precipitation during the winter (Sharpe, 2007). Flint and others (2002) estimated that average net infiltration at Yucca Mountain is 3 percent of annual precipitation, or approximately 6 mm/year, and increases to approximately 20 mm/year at the exposed bedrock crest of Yucca Mountain. Precipitation and infiltration data at Yucca Mountain were used to estimate travel time, extent of water-rock interaction, and evaporative water loss during percolation through the unsaturated zone (Flint and others, 2002). Not only are estimates of infiltration important, but the stable-isotope chemistry of the precipitation also is needed to obtain baseline data for meteoric water prior to interaction with the soil or bedrock.

Thirty-six distinct precipitation events that occurred in 2006–09, with an average 3- to 4-day duration and an average 9.9 mm of accumulation, have been analyzed. Stable isotope data (more than 200 samples) from these events are summarized in table 3 and are represented on figure 4 as individual rainfall events designated by their date(s) of occurrence. Delta ^{18}O values range from 3.0 to -20.4‰ and δD values range from 10 to -147‰ and define a line of slope 6.4 on a $\delta\text{D} - \delta^{18}\text{O}$ plot, less than the slope of 8 of the Global Meteoric Water Line (GMWL). The GMWL, quantified by Craig (1961), is a relation between δD and $\delta^{18}\text{O}$ values of meteoric waters, expressed as $\delta\text{D} = 8(\delta^{18}\text{O}) + 10$. The defined slope of Yucca Mountain precipitation (6.4) is the result of evaporation of falling raindrops (Benson and Klieforth, 1989), typical of arid environments. The ESF seepage samples collected in February 2005 exhibit a slope of 4 (fig. 4) and demonstrate continued evaporation as the water percolated through the bedrock or after it seeped into the tunnel (Oliver and Whelan, 2006).

There is a distinct seasonal difference in oxygen and deuterium isotope values (fig. 5). Although precipitation was collected and analyzed continually over the course of a year, precipitation that fell from November through April was labeled as winter precipitation, and precipitation that fell from May through October as summer precipitation. The average winter values are -11.9 and -81‰ , and for summer are -5.9 and -51‰ , resulting in an average difference of 6.0 and 30‰ for oxygen and deuterium, respectively. Weighted average values, where more influence is given to precipitation events of greater volume, for winter precipitation are -12.9 and -93‰ and for summer precipitation are -9.9 and -69‰ for oxygen and deuterium, respectively. The weighted averages equate to a seasonal difference of 3.0‰ for oxygen and 24‰ for deuterium. It should be noted that during the collection period of this study, precipitation that fell as snow was not differentiated from precipitation that fell as rain. Snow precipitation was rare, however, even in winter, and limited to high-altitude sites (for example, Sites 2 and 401).

Table 3. Delta oxygen-18 ($\delta^{18}\text{O}$) and delta deuterium (δD) values, and amounts, of precipitation samples at Yucca Mountain, Nevada, February 2006 to January 2009.

[Sample name contains collection date format "yy/mm/dd" (year/month/day); ‰, per mil; cm, centimeter; Precip. Amt., precipitation amount]

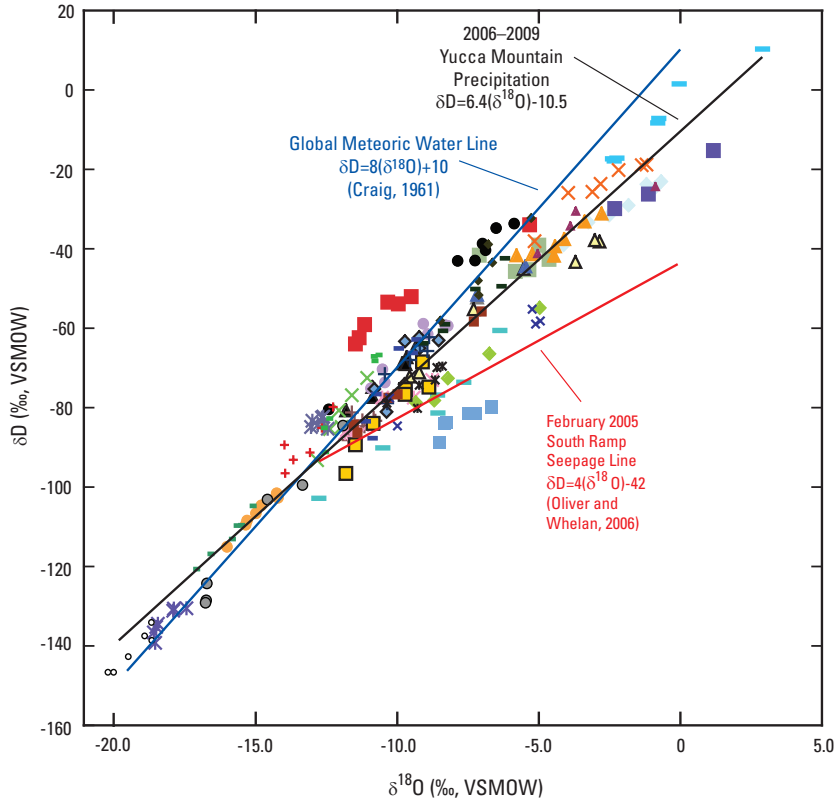
Sample name	$\delta^{18}\text{O}$ ‰	δD ‰	Precip. Amt. cm	Sample name	$\delta^{18}\text{O}$ ‰	δD ‰	Precip. Amt. cm	Sample name	$\delta^{18}\text{O}$ ‰	δD ‰	Precip. Amt. cm
S. Portal 060221	-11.4	-64	0.15	Site 2 061003	-8.4	-89	0.36	Site 6 071210	-13.3	-99	0.56
Site 1 060221	-11.3	-62	0.15	Site 401 061003	-8.3	-84	0.33	Site 8 071210	-16.7	-129	1.42
Site 2 060221	-5.3	-34	0.36	Site 418 061004	-7.4	-81	0.30	S. Portal 080108	-9.5	-68	1.07
Site 401 060221	-9.9	-54	0.30	Site 6 061003	-8.2	-84	0.28	Site 1 080108	-8.8	-62	0.84
Site 418 060221	-10.3	-53	0.43	Site 8 061003	-6.6	-80	0.15	Site 2 080108	-10.3	-79	1.50
Site 6 060221	-9.4	-52	0.46	S. Portal 061018	-11.5	-87	0.30	Site 401 080108	-10.4	-72	1.73
Site 8 060221	-11.1	-59	0.18	Site 1 061017	-11.8	-87	0.20	Site 6 080108	-9.1	-65	1.32
S. Portal 060301	-9.7	-69	1.45	Site 2 061017	-11.7	-86	0.20	Site 8 080108	-8.9	-66	1.07
Site 1 060301	-9.6	-67	1.75	Site 401 061017	-10.5	-78	0.18	S. Portal 080128	-15.7	-110	0.87
Site 2 060301	-10.8	-78	1.65	Site 418 061018	-8.7	-73	0.13	Site 1 080128	-15.5	-110	0.88
Site 401 060301	-11.7	-81	2.01	Site 6 061017	-9.3	-78	0.15	Site 2 080128	-16.6	-117	0.57
Site 418 060301	-9.6	-69	1.27	Site 8 061017	-10.9	-85	0.28	Site 401 080128	-17.1	-121	0.56
Site 6 060301	-10.8	-75	1.68	S. Portal 061211	-8.9	-62	0.36	Site 6 080128	-15.8	-113	0.64
Site 8 060301	-9.2	-64	1.60	Site 1 061211	-8.3	-59	0.43	Site 8 080128	-15.1	-105	0.98
S. Portal 060313	-12.7	-93	0.51	Site 2 061211	-10.5	-70	0.43	S. Portal 080225	-6.1	-42	0.18
Site 1 060313	-11.9	-85	0.46	Site 401 061211	-10.9	-75	0.58	Site 1 080225	-7.2	-50	0.25
Site 2 060313	-11.0	-73	0.84	Site 418 061213	-9.0	-59	0.30	Site 2 080225	-8.3	-59	0.19
Site 401 060313	-11.5	-77	0.97	Site 6 061211	-10.4	-74	0.58	Site 401 080225	-9.0	-64	0.33
Site 418 060313	-12.3	-86	0.79	Site 8 061211	-8.2	-59	0.41	Site 6 080225	-8.3	-61	0.31
Site 6 060313	-12.0	-81	0.81	S. Portal 061218	-7.2	-43	0.69	Site 8 080225	-6.3	-50	0.20
Site 8 060313	-11.7	-87	0.46	Site 1 061218	-6.8	-40	1.45	S. Portal 080528	-8.4	-58	0.15
S. Portal 060323	-18.5	-137	2.41	Site 2 061218	-12.4	-80	1.07	Site 1 080527	-6.6	-44	0.10
Site 1 060323	-18.5	-139	2.24	Site 401 061219	-7.8	-43	0.81	Site 2 080527	-5.2	-32	0.12
Site 2 060322	-17.8	-131	0.97	Site 418 061218	-6.4	-35	0.13	Site 401 080528	-6.7	-39	0.05
Site 401 060323	-17.4	-131	1.27	Site 6 061218	-5.8	-34	1.47	Site 6 080527	-7.1	-48	0.07
Site 418 060322	-18.4	-135	1.27	Site 8 061218	-6.9	-39	1.45	Site 8 080527	-7.0	-52	0.09
Site 6 060322	-17.8	-131	1.47	Site 401 070214	-7.1	-52	0.23	S. Portal 080714	-11.3	-86	0.46
Site 8 060323	-18.4	-135	2.29	Site 6 070214	-5.4	-45	0.20	Site 1 080714	-10.2	-78	0.47
S. Portal 060330	-14.9	-107	2.59	S. Portal 070220	-8.5	-77	0.30	Site 2 080714	-11.5	-84	0.30
Site 1 060330	-14.2	-103	3.00	Site 1 070220	-6.3	-61	0.20	Site 401 080714	-7.2	-58	0.09
Site 2 060330	-16.0	-115	2.49	Site 2 070220	-7.6	-74	0.25	Site 6 080714	-7.0	-56	0.06
Site 401 060330	-15.2	-108	3.00	Site 401 070220	-12.7	-103	0.18	Site 8 080714	-9.9	-77	0.15
Site 418 060330	-15.3	-109	2.36	Site 6 070220	-10.5	-90	0.20	S. Portal 080909	-0.8	-25	0.07
Site 6 060330	-14.7	-105	3.07	Site 8 070220	-8.5	-81	0.13	Site 1 080909	-3.8	-34	0.10
Site 8 060330	-14.2	-102	3.02	S. Portal 070417	-8.5	-63	0.53	Site 401 080909	-3.6	-31	0.09
S. Portal 060406	-11.6	-88	1.35	Site 1 070417	-9.1	-65	0.48	Site 8 080909	-5.0	-41	0.14
Site 1 060406	-10.7	-83	1.32	Site 2 070417	-10.7	-75	0.41	S. Portal 081006	-5.0	-59	0.05
Site 2 060406	-11.4	-84	1.32	Site 401 070417	-9.7	-74	0.36	Site 1 081006	-5.1	-55	0.06
Site 401 060406	-11.5	-81	1.63	Site 418 070417	-9.6	-63	0.56	Site 401 081006	-10.2	-78	0.15
Site 418 060406	-11.1	-85	1.19	Site 6 070417	-10.3	-81	0.43	Site 6 081006	-9.9	-85	0.11
Site 6 060406	-10.7	-83	1.55	Site 8 070417	-9.1	-62	0.48	Site 8 081006	-4.9	-58	0.05
Site 8 060406	-11.1	-83	1.40	S. Portal 070425	-9.0	-69	0.25	S. Portal 081103	-8.3	-70	0.45

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Table 3. Delta oxygen-18 ($\delta^{18}\text{O}$) and delta deuterium (δD) values, and amounts, of precipitation samples at Yucca Mountain, Nevada, February 2006 to January 2009.—Continued

[Sample name contains collection date format "yy/mm/dd" (year/month/day); ‰, per mil; cm, centimeter; Precip. Amt., precipitation amount]

Sample name	$\delta^{18}\text{O}$ ‰	δD ‰	Precip. Amt. cm	Sample name	$\delta^{18}\text{O}$ ‰	δD ‰	Precip. Amt. cm	Sample name	$\delta^{18}\text{O}$ ‰	δD ‰	Precip. Amt. cm
S. Portal 060418	-4.6	-43	0.25	Site 1 070425	-9.6	-75	0.23	Site 1 081103	-8.5	-70	0.44
Site 401 060418	-7.0	-42	0.51	Site 2 070425	-10.8	-84	0.20	Site 2 081103	-9.2	-80	0.33
Site 418 060418	-4.9	-39	0.28	Site 401 070425	-11.4	-89	0.15	Site 401 081103	-10.3	-79	0.33
Site 6 060418	-5.8	-46	0.33	Site 418 070425	-9.7	-77	0.28	Site 6 081103	-9.1	-75	0.35
Site 8 060418	-5.3	-45	0.23	Site 6 070425	-11.7	-97	0.38	Site 8 081103	-8.6	-73	0.44
S. Portal 060711	-2.2	-17	1.07	Site 8 070425	-8.8	-75	0.15	S. Portal 081201	-18.6	-139	0.73
Site 1 060711	-2.3	-17	0.97	S. Portal 070806	-4.0	-38	0.13	Site 1 081201	-18.9	-137	0.75
Site 2 060711	-0.7	-8	0.91	Site 1 070806	-4.4	-42	0.20	Site 2 081201	-20.1	-147	0.74
Site 401 060711	0.0	1	0.38	Site 2 070806	-4.3	-40	0.20	Site 401 081201	-20.4	-147	0.73
Site 418 060711	3.0	10	0.51	Site 401 070806	-5.7	-42	0.84	Site 6 081201	-19.4	-143	0.75
Site 6 060711	-2.3	-18	0.41	Site 418 070807	-2.7	-31	0.13	Site 8 081201	-18.6	-134	0.80
Site 8 060711	-0.7	-7	0.81	Site 6 070806	-5.1	-42	0.71	S. Portal 081222	-13.9	-90	0.42
S. Portal 060722	-2.4	-32	1.35	Site 8 070806	-3.3	-33	0.10	Site 1 081222	-13.6	-93	0.44
Site 1 060722	-0.6	-23	0.71	S. Portal 070829	-2.7	-24	0.36	Site 2 081222	-13.0	-92	0.18
Site 2 060722	-1.1	-24	0.79	Site 1 070829	-1.3	-19	0.28	Site 401 081222	-12.6	-85	0.28
Site 401 060722	-0.8	-25	0.46	Site 2 070828	-3.0	-26	0.28	Site 6 081222	-12.2	-80	0.33
Site 418 060722	-1.7	-29	1.60	Site 401 070828	-5.1	-38	0.43	Site 8 081222	-13.9	-97	0.46
Site 6 060722	-4.0	-39	0.91	Site 418 070829	-3.9	-26	0.15	S. Portal 081229	-12.6	-85	0.18
Site 8 060722	-3.2	-33	1.42	Site 6 070829	-1.1	-19	0.20	Site 1 081229	-12.5	-91	0.19
S. Portal 060808	-1.1	-26	0.05	Site 8 070829	-2.1	-20	0.28	Site 2 081229	-10.8	-68	0.17
Site 2 060808	-2.3	-30	0.15	S. Portal 070925	-12.5	-82	7.37	Site 401 081229	-10.8	-67	0.23
Site 418 060809	1.2	-15	0.08	Site 1 070924	-12.6	-83	7.49	Site 6 081229	-10.6	-67	0.21
S. Portal 060912	-2.8	-38	0.30	Site 2 070924	-13.0	-85	7.39	Site 8 081229	-12.4	-83	0.16
Site 1 060912	-3.6	-43	0.28	Site 401 070924	-12.9	-83	8.08	S. Portal 090126	-11.0	-83	0.23
Site 2 060911	-7.2	-55	0.30	Site 418 070925	-12.5	-84	6.81	Site 1 090126	-10.7	-77	0.21
Site 401 060912	-9.5	-72	0.64	Site 6 070924	-12.7	-84	8.13	Site 2 090126	-9.4	-66	0.25
Site 418 060911	-5.5	-45	0.25	Site 8 070924	-12.4	-86	7.37	Site 401 090126	-9.3	-63	0.28
Site 6 060912	-9.1	-71	0.58	S. Portal 071210	-16.7	-124	1.22	Site 6 090126	-9.9	-65	0.25
Site 8 060912	-2.9	-38	0.20	Site 1 071210	-16.7	-129	1.14	Site 8 090126	-10.8	-88	0.22
S. Portal 061004	-6.6	-80	0.23	Site 2 071210	-14.5	-103	0.79				
Site 1 061003	-7.2	-81	0.18	Site 401 071210	-11.9	-85	0.33				



Precipitation event interval and collection date are expressed as month/day-day/year or month/day/year.

EXPLANATION

(Duration of precipitation event expressed as month/day-day/year or month/day/year)

Event Interval	Collection Date	Event Interval	Collection Date
■ 2/18–19/06	2/21/06	■ 4/22–23/07	4/25/07
▲ 2/27–28/06	3/1/06	▲ 7/30–8/3/07	8/6/07
× 3/03–12/06	3/13/06	× 8/26–28/07	8/29/07
× 3/18–21/06	3/23/06	× 9/21–22/07	9/25/07
○ 3/28–29/06	3/30/06	● 11/30–12/9/07	12/10/07
+ 4/3–6/06	4/6/06	+ 12/18–1/5/08	1/8/08
■ 4/10–17/06	4/18/06	- 1/24–27/08	1/28/08
- 7/8–10/06	7/11/06	- 2/20–24/08	2/25/08
◇ 7/20–22/06	7/22/06	◆ 5/23–25/08	5/28/08
■ 8/3/06	8/8/06	■ 7/12–12/08	7/14/08
▲ 9/6–7/06	9/12/06	▲ 9/8/08	9/9/08
■ 10/1–2/06	10/4/06	× 10/4/08	10/6/08
× 10/13–15/06	10/18/06	× 10/31–11/1/08	11/3/08
○ 12/9–10/06	12/11/06	○ 11/26/08	12/1/08
● 12/16–17/06	12/18/06	+ 12/15–17/08	12/22/08
▲ 2/11/07	2/14/07	- 12/25–28/08	12/29/08
- 2/18–19/07	2/20/07	- 1/22–25/09	1/26/09
◇ 3/20/07	3/20/07		
◇ 4/15–16/07	4/17/07		

Figure 4. Delta deuterium plotted against delta oxygen-18, in per mil relative to Vienna Standard Mean Ocean Water, for 2006–2009 precipitation samples from monitoring stations at Yucca Mountain, Nevada.

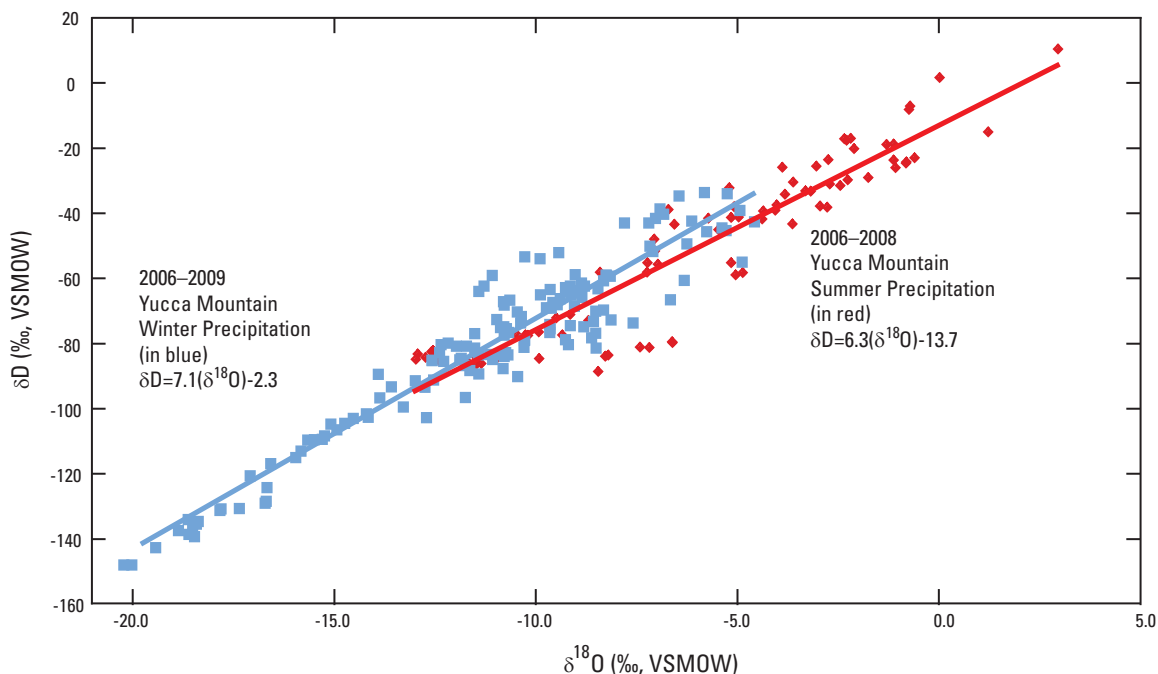


Figure 5. Delta deuterium plotted against delta oxygen-18, in per mil relative to Vienna Standard Mean Ocean Water, for 2006–2009 samples of winter (November–April) and summer (May–October) precipitation from monitoring stations at Yucca Mountain, Nevada.

The stable-isotopic composition of precipitation at and near Yucca Mountain has been measured intermittently over the past three decades by Ingraham and others (1990) for 1982–86, Milne and others (1987) and Benson and Klieforth (1989) for 1983–86, Whelan and others (1995) for 1993–95, and by Moscati and others (2008) for 2006–08. There also have been regional stable-isotopic studies of precipitation that encompassed southern Nevada by Friedman and others (1992; 2002) for 1982–89 and 1991–97. The stable-isotopic studies specific to the Yucca Mountain region yielded very similar results to data presented here; precipitation samples define an average line of slope of 6.7, and the seasonal range of $\delta^{18}\text{O}$ and δD is consistent with the data presented in figure 4. Specifically, Whelan and others (1995) reported a summer line of slope of 5.8 and for winter, 7.8. In the current work (fig. 5), the summer and winter lines of slopes are 6.3 and 7.1, respectively.

In general, the two data sets are complementary; however, the Whelan and others (1995) data locally contained incomplete data sets and analyses from multiple precipitation events (in some cases spanning over 8 weeks), due to locations inaccessible during winter and (or) due to a lack of resources to collect samples. Data in this report (table 3, fig. 4) also compare favorably with the precipitation data collected during

the mid-1980s by Benson and Klieforth (1989). Although Benson and Klieforth did not specifically compare summer and winter precipitation, they did compare precipitation that fell only as rain to that which fell only as snow. Their rain-only data defined a line of slope of 6.6, and their snow-only data defined a line of 8 (identical to the GMWL because snow does not fractionate due to evaporation). A compilation of 342 pairs ($\delta^{18}\text{O}$ and δD) of precipitation data collected by Whelan and others (1995) in the early 1990s with the data reported here provide an annual mean value of -10.3 and -76‰ ($\delta^{18}\text{O}$ and δD , respectively) for Yucca Mountain precipitation.

Seasonal isotopic variation principally is a result of temperature differences but also is affected by seasonal changes in moisture sources and storm-track trajectories. Friedman and others (1992) analyzed storm tracks and demonstrated that winter storms in the Yucca Mountain area typically originate from the Pacific Ocean and pass over high mountain ranges in California before reaching the Yucca Mountain area. The heavy isotopes in water, ^{18}O and D, are fractionated preferentially into the liquid phase during condensation. Therefore, precipitation (or rain-out) from moist, cooling air masses during adiabatic uplift over high terrain decreases $\delta^{18}\text{O}$ and δD values of remaining water vapor. In contrast, summer storms typically arrive from the south or east, obtaining

water vapor from the Gulf of California or the Gulf Mexico, without traversing substantial mountainous terrain. Hence, typical summer storm trajectories allow the air masses to reach Yucca Mountain with less fractionation of initial isotopic composition(s) and consequently have isotopic values that are higher than their winter counterparts. Winter precipitation, in the form of rain, undergoes only minor evaporation as it falls from cloud to ground. If winter precipitation falls as snow, the snow may sublimate as it falls, but without fractionation of the isotopic composition. As such, winter samples, in general, plot closer to, or even above, the GMWL (fig. 4), in contrast to summer precipitation, which is subject to more evaporation due to warmer air temperatures.

Conclusions

Monitoring of modern precipitation for stable-isotope and chemical compositions provides baseline hydrochemical data of Yucca Mountain precipitation, the major source of infiltration to the unsaturated zone and of recharge to the saturated zone. Those baseline data constitute an invaluable component for many types of studies, including characterization of potential seepage into the tunnels of a formerly proposed repository; groundwater origins, recharge, and movement through the unsaturated and saturated zones; infiltration and evaporation rates; and water/rock interaction.

Chemical analyses of the precipitation indicate that the samples are dilute, perhaps a function of the length of the collection period (typically spanning several days of rainfall). The precipitation has pH values of 6–7, slightly less acidic than most precipitation, likely due to buffering by local naturally alkaline dust that contains a large fraction of calcium carbonate. The cation composition of the precipitation generally is dominated by calcium, while the anion composition is marked by high sulfate and nitrate.

Stable isotopic and chemical analysis of samples of Yucca Mountain precipitation in 2006–09 has yielded a snapshot of baseline hydrochemical inputs of meteoric water that will provide greater understanding of potential future seepage events in the area. Over the 3 years of this study, sampled $\delta^{18}\text{O}$ and δD values ranged from 3.0 to -20.4‰ and 10 to -147‰ , respectively. The $\delta^{18}\text{O}$ and δD values plot on a line of slope of 6.4 (less than the slope of 8 of the GMWL), a result of evaporation of falling raindrops typical of arid environments. Winter-summer seasonal variation is readily apparent with average winter precipitation values of -11.9 and -81‰ and average summer precipitation values of -5.9 and -51‰ ($\delta^{18}\text{O}$ and δD , respectively). Although seasonal shifts principally are due to temperature, changes in moisture sources and storm track trajectories also play a role. A cumulative analysis of 342 available pairs ($\delta^{18}\text{O}$ and δD) of stable isotopic data generated by the U.S. Geological Survey from the early 1990s to the present (this work) yields an annual mean value

for $\delta^{18}\text{O}$ of -10.3‰ and for δD of -76‰ for Yucca Mountain precipitation.

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