Climate Change Effects on Yucca Mountain Region Groundwater Recharge

Arturo Woocay and John C. Walton

Environmental Science and Engineering, University of Texas at El Paso, 500 W. University Ave., El Paso, TX, 79968, awoocay@utep.edu, walton@utep.edu

Abstract – *Groundwater geochemical data from 211 sampling locations in the Amargosa Desert region are analyzed to better understand the general flow system and climate-induced changes in recharge around Fortymile Wash near Yucca Mountain. Major ion groundwater chemistry was examined using the multivariate statistical methods of principal component analysis and k-means cluster analysis. These analyses showed several groundwater signatures, or potential flowpaths; the most pronounced tracked the entire length of Fortymile Wash. Carbon-14 data from 98 sampling locations in the region, corrected with carbon-13 data, are presented. Corrected carbon-14 dating of groundwater beneath Fortymile Wash shows ages between 8,000 years BP in the upper canyon region and 14,000 years BP in the lower region near the Amargosa Desert. This range in ages corresponds to the end of the Pleistocene and early Holocene epochs, marking the end of Wisconsin glaciation and the start of the current interglacial period. In contrast, groundwater adjacent to Fortymile Wash appears to be older. The trend of increasing groundwater age beneath Fortymile Wash with increasing distance from the source suggests that the average reach of runoff events and recharge diminished over time as the climate became warmer and dryer. Stable isotopic hydrogen-2 data and oxygen-18 data from 115 and 118 sampling locations, respectively, from the same region are interpreted in relation to the global meteoric water line. The hydrogen-2 and oxygen-18 signatures are similar to carbon-14 corrected by carbon-13 and principal component analysis signatures, and are evidence of changes to the groundwater system as the climate became warmer and dryer during the past 14,000 years.*

I. INTRODUCTION

The Amargosa Desert is located in south-central Nevada in the southern portion of Nye County. Nye County is the third largest county in the continental U.S., with more than 11½ million acres, 93 percent of which are public land. The Amargosa Desert is separated from Death Valley to the southwest by the Funeral Mountains and bounded on the north and east by a series of mountain ranges. The ephemeral Amargosa River begins in the Oasis Valley, turns southeast to run through the Amargosa Desert, continues until it turns northwest, and enters Death Valley from its southeast extension.

Yucca Mountain, north of the Amargosa Desert, has been chosen as the site of a high-level nuclear waste repository and is expected to hold approximately 77,000 metric tons of waste. Fortymile Wash, an ephemeral drainage, originates in the uplands north of Yucca Mountain, flows southward along the east side of the mountain, and terminates in the northern part of the Amargosa Desert.

Since groundwater beneath Yucca Mountain is directly upgradient from populated areas in the Amargosa Desert, a determination of groundwater flow patterns in this region is important. Furthermore, understanding hydrologic response around Yucca Mountain to past climate changes may provide insight to future responses that may affect the waste isolation performance of the repository.

The present climate in the Amargosa Desert region is considered arid to semiarid, with average annual precipitation ranging from less than 130 millimeters (mm) at lower elevations to more than 280 mm at higher elevations [1]. In contrast, the climate at the end of the Tioga glacial maximum of Wisconsin glaciation in North America, at approximately 11,500 years before present (yr BP), was wetter and colder than the present [2] [3]. Other authors [3] have noted the existence of large lakes in California and Nevada in the late Pleistocene to early Holocene epochs related to precipitation with temperatures 3 to 8 degrees centigrade (°C) cooler and precipitation rates 60 to 300 percent greater than the current levels. These changes are attributed to a southward displacement of the jet stream, with resultant high winter precipitation.

The Holocene epoch is divided into the early, middle, and late parts; the middle Holocene, approximately 8,000 to 3,000 yr BP, is considered the warmer and/or drier part [2]. Evidence of a wetter transition from the Pleistocene to the Holocene epoch is found in black mats formed in the southern Great Basin by increased spring discharge, which extended from 11,800 to 6,300 yr BP, with the majority appearing at 10,000 yr BP [4].

The work presented in this paper adds to the understanding of the general groundwater flow system and climate-induced changes in recharge east of Yucca Mountain around Fortymile Wash. Groundwater chemistry data used herein were obtained from the Nye County Nuclear Waste Repository Project Office

(NWRPO) website as of March 2003 [5] and a Los Alamos National Laboratory report [6]. Data were compiled into a single database, covering the Amargosa Desert region, and analyzed as described in the following sections. Sampling locations are mainly composed of wells, some with multiple screened depths, while the remaining are fresh springs.

II. METHODS

II.A. Multivariate Statistical Methods

Multivariate statistical methods (MSMs) are powerful tools used to examine large, complex datasets in order to help identify parameters or dimensions that describe data and may thus provide new insight into their behavior [7]. The MSMs applied herein are principal component analysis (PCA) and *k*-means cluster analysis (CA). PCA is a factor analysis method and CA is a classification method.

Factor analysis methods calculate new descriptive variables from the original variables in an attempt to detect structure or similarities among the original variables. These methods allow a reduction in the number of variables that describe system behavior and the identification of new, homogeneous subgroups that are easier to identify [7]. The new variables are generally called factors, or "axes," in PCA and are the solution to an Eigenvalue problem of the correlation of the data or their covariance in the form of a square matrix. Together, all factors form a factor-space upon which the original variable space and dataset are projected. Each factor is orthogonal, or uncorrelated, to the others and measures, or explains, certain amounts of data variability.

PCA uses linear combinations of the variables to form the factors. The linear combinations permit PCA to retain as much as possible of the original data variation and spatial distribution in factor-space, and allows for the use of rotation schemes that better reveal similarities within variables or cases. The most common rotation is the normalized varimax rotation, which attempts to find the rotation that will maximize variability on the rotated axes while minimizing it everywhere else [7].

A *k*-means CA attempts to minimize the variability within each cluster while maximizing the variability between clusters. The mean of a cluster, or centoid, has its components specified by the average of each variable in the analysis. The algorithm uses one initial observation per cluster as the mean for that cluster, and then evaluates each of the remaining observations for inclusion into a particular cluster. Initial observations are selected to maximize initial Euclidean distances between clusters and the number of clusters (*k*) is predetermined. As each observation is included, or clustered, the mean of each cluster is recalculated and previously clustered observations are re-evaluated to check for correct clustering. Observations and *k* means are evaluated at each step until no further improvement can be achieved and all observations have been clustered.

Using a statistical software (i.e., STATISTICA 5 [8]), a PCA of the major ion data from 211 sampling locations in the Amargosa Desert region was performed, along with a rotation of the first four factors, to reduce the number of variables from 7 to 4 and to find relationships among the original variables.

From the rotated factors of the ion chemistry, factor scores were generated for each of the 211 sampling locations, thus producing a loading table indicating the decomposition of each of the samples into the 4 rotated axes. Using the same statistical software, the factor scores from the rotated PCA results were then evaluated with the *k*-means CA to cluster sampling locations with a similar genesis into seven separate sample groups, or chemical facies. The *k*-means CA variables evaluated are the four factor scores; the observations are the factor scores for each sampling location. Both empirically and from previous analysis, it was determined to use seven groups for the CA.

The resulting principal axes and sample groups are overlaid on a digital elevation model (DEM) of the region in order to reveal groundwater signatures.

II.B. Corrected Carbon-14 Data

The interpretation of carbon-14 (^{14}C) data to obtain groundwater age dates is complicated by the mixing of young (i.e., atmospheric) and old (i.e., carbonate-mineral) sources of carbon. Given the generally thick vadose zone and slow percolation rates in the region, vadose zone water can interact with the atmosphere and both older carbonate rocks and more recently formed carbonates (e.g., caliche) for extended periods before reaching the water table.

To correct for mineral sources of carbon, it is assumed that all carbon is of atmospheric origin and a correction factor based on estimates of the fraction of carbon from mineral carbonates is applied [9]. A correction factor (*q*) is applied to determine the corrected ^{14}C age dates as follows:

$$t = -8267 * \ln \frac{^{14}C_{pmc}}{q * 100} \tag{1}$$

where t is time in yr BP and $^{14}C_{pmc}$ is percent modern carbon. The correction is intended to compensate for the dissolution of older carbonates in the vadose zone water and groundwater.

None of the methods developed to determine q apply well to the compiled NWRPO [5] and LANL [6] dataset. For example, a common method is to base q on alkalinity, with the assumption that the alkalinity is caused by the carbonate weathering. However, an analysis of the

NWRPO data suggests that the weathering of silicate minerals, not the dissolution of carbonates, causes the alkalinity. The method used here to obtain an approximation of *q* consists of applying carbon-13 (^{13}C) data as follows [9]:

$$q = \frac{\delta^{13} C_{DIC} - \delta^{13} C_{carb}}{\delta^{13} C_{rech} - \delta^{13} C_{carb}} \tag{2}$$

where $\delta^{13}C_{DIC}$ is the dissolved inorganic carbon (DIC) $\delta^{13}C$ value, $\delta^{13}C_{carb}$ is the carbonate rock value, and $\delta^{13}C_{rech}$ is the value of old recharge. Limitations to this method arise from assumptions, particularly $\delta^{13}C_{rech}$; it is assumed that carbonate rocks have zero permil (‰) of $\delta^{13}C$, and $\delta^{13}C_{rech}$ is estimated to be –15 ‰ from weighed DIC-species-dependent fractionations corresponding to pH values of 6.5 to 9.5 [9, Figure 5-5]. The data present a range of pH values from 6.7 to 9.4, with an average of 7.9.

II.C. Stable Oxygen-18 and Hydrogen-2 Isotope Data

The stable oxygen-18 (^{18}O) and hydrogen-2 (^{2}H) composition of soil water and groundwater reflects the isotope composition of precipitation, which is correlated with mean annual temperature and may thus provide paleoclimate information [10]. In precipitation, ^{18}O and ^{2}H usually fall along a single line when plotted against each other, due to the process of fractionation at the moment of condensation; this line is referred to as the global meteoric water line (GMWL) [9] [10] and is given by the equation [11]:

$$\delta^{2} H = 8(\delta^{18} O) + 10\,‰ \tag{3}$$

The location of precipitation along the GMWL depends primarily on temperature during precipitation; lighter waters are associated with cold temperatures and fall in the lower left portion of the line; heavier waters are associated with warmer temperatures and fall in the upper right portion. Initial precipitation composition is also influenced by relative humidity. Precipitation that occurs in an environment with humidity below approximately 85 percent [9] will be plotted above the GMWL, due to evaporation during its fall, and is said to have an excess of ^{2}H, although still depleted compared to the standard mean ocean water (SMOW) value. Precipitation that occurs in a humid environment (i.e., above approximately 85 percent humidity) falls below the GMWL.

Precipitated water that accumulates at the earth surface and then evaporates (i.e., in a lake or along a river) will deviate from its initial composition. Accumulated water values will deviate along a line with a slope lower than the GMWL (8) towards a less depleted ^{18}O. The deviation is proportional to the extent of evaporation, and the slope of the deviation depends on the relative humidity of the environment. Deviation slopes of 4.5, 5.2, and 6.8 correspond approximately to relative humidity values of 50, 75, and 95 percent, respectively [9].

This paper uses stable isotopic groundwater ^{18}O and ^{2}H data from 118 and 115 sampling locations, respectively; interprets these data compared to the GMWL; and presents data that follow the trace of Fortymile Wash until it mixes with groundwater under the Amargosa River.

III. RESULTS

III.A. Multivariate Statistical Methods

PCA of the major ion data was performed to reduce the number of variables to four. PCA results were rotated to find relationships among the original variables and classify them. The first four PCA axes, or factors, were able to explain 96 percent of the system variation. Table 1 presents the amount of total variation explained by each rotated axis, along with the loading distribution of the ion chemistry.

TABLE 1 Normalized Varimax Rotated Factor Loadings

Parameter	Axis 1	Axis 2	Axis 3	Axis 4
Calcium (Ca^{2+}) (mg/L)	0.866	0.322	0.036	0.315
Magnesium (Mg^{2+}) (mg/L)	0.922	0.055	0.289	0.135
Sodium (Na^{+}) (mg/L)	-0.004	0.727	0.659	0.148
Potassium (K^{+}) (mg/L)	0.299	0.265	0.199	0.893
Chloride (Cl^{-}) (mg/L)	0.202	0.924	0.129	0.195
Sulfate (SO_4^{2-}) (mg/L)	0.541	0.667	0.260	0.318
Alkalinity ($CaCO_3$) (mg/L)	0.514	0.232	0.769	0.246
Explained Variation	2.287	2.059	1.235	1.137
Proportional Total	32.6%	29.4%	17.6%	16.2%

Axis 1 is dominated by magnesium (Mg^{2+}) and calcium (Ca^{2+}) ions, which are typically associated with the dissolution of carbonates. Axis 2 is primarily composed of chloride (Cl^{-}), sodium (Na^{+}), and sulfate (SO_4^{2-}). High levels of these ions are generally associated with elevated amounts of the water evaporation that caused their concentration. Axis 3 is dominated by alkalinity and sodium, and is most likely related to the weathering of silicate minerals with the generation of alkalinity and the concomitant release of sodium. Finally, Axis 4 is mostly composed of potassium (K^+).

The factor scores from the rotated PCA results were evaluated with *k*-means CA to group sampling locations with a similar genesis into seven separate groups, or hydrochemical facies. The names of the groups are intended to be descriptive of either general sampling locations and/or dominant ions. The Axis 1 contours overlaid on the DEM of the region are shown on Figure 1, along with the sample groups; a red arrow shows the trace of the Amargosa River and a dark blue arrow shows the trace of Fortymile Wash and its convergence with the Amargosa River.

The four resulting principal axes and seven sample groups reveal groundwater signatures. The best-defined of these signatures is shown on Figure 1 along Fortymile Wash. Concentration contours of total dissolved solids (TDS) data from sampling locations in the vicinity of the wash, not shown on Figure 1, correspond closely with the Axis 1 contours. That is, values of TDS are lower directly beneath the wash and higher in areas adjacent to the wash.

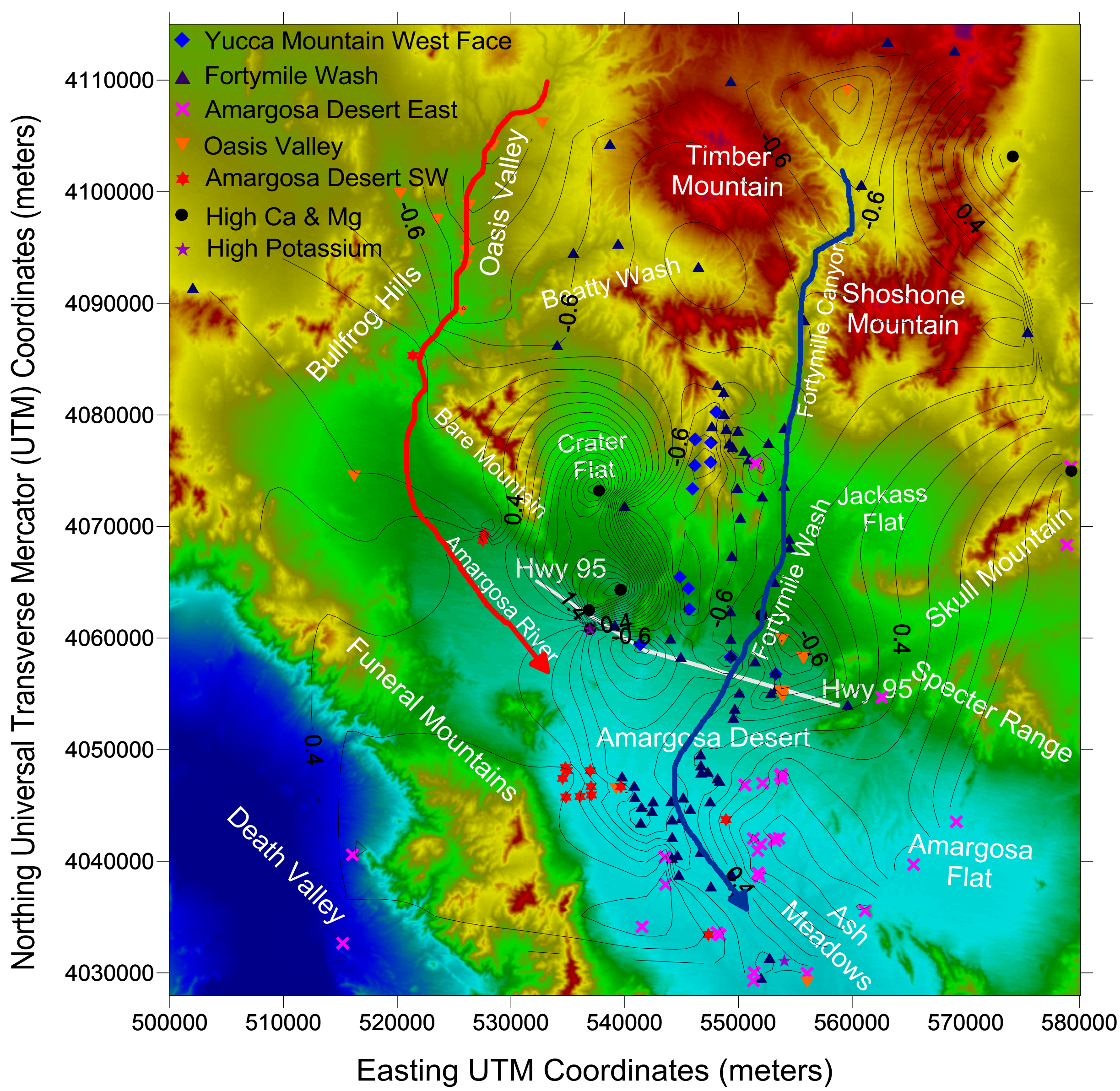

FIGURE 1 Principal Component Analysis Axis 1 Calcium and Magnesium Contours
with Sampling Locations and Sample Groups, and Two Suggested Flowpaths Overlain on a Digital Elevation Map

III.B. Corrected Carbon –14 Data

Figure 2 shows contours of corrected ^{14}C age dates based on ^{14}C and $\delta^{13}C$ data for groundwater from 98 sampling locations. Groundwater ages beneath Fortymile Wash range from 8,000 yr BP in the upper region to 14,000 yr BP in the lower region near the Amargosa Desert. This range corresponds to the end of the Pleistocene and early Holocene epochs, marking the end of Wisconsin glaciation and the start of the current warmer interglacial period [2]. Figure 2 also shows that groundwater beneath the wash is younger than that of adjacent highlands.

III.C. Stable Oxygen-18 and Hydrogen-2 Isotope Data

Figure 3 presents a plot of regional ^{2}H versus ^{18}O values that fall close to and below the GMWL, with ^{2}H values between –117 and –86 ‰, and an average of -103 ‰ and a slope of 6.1. In contrast, isotopic ^{2}H

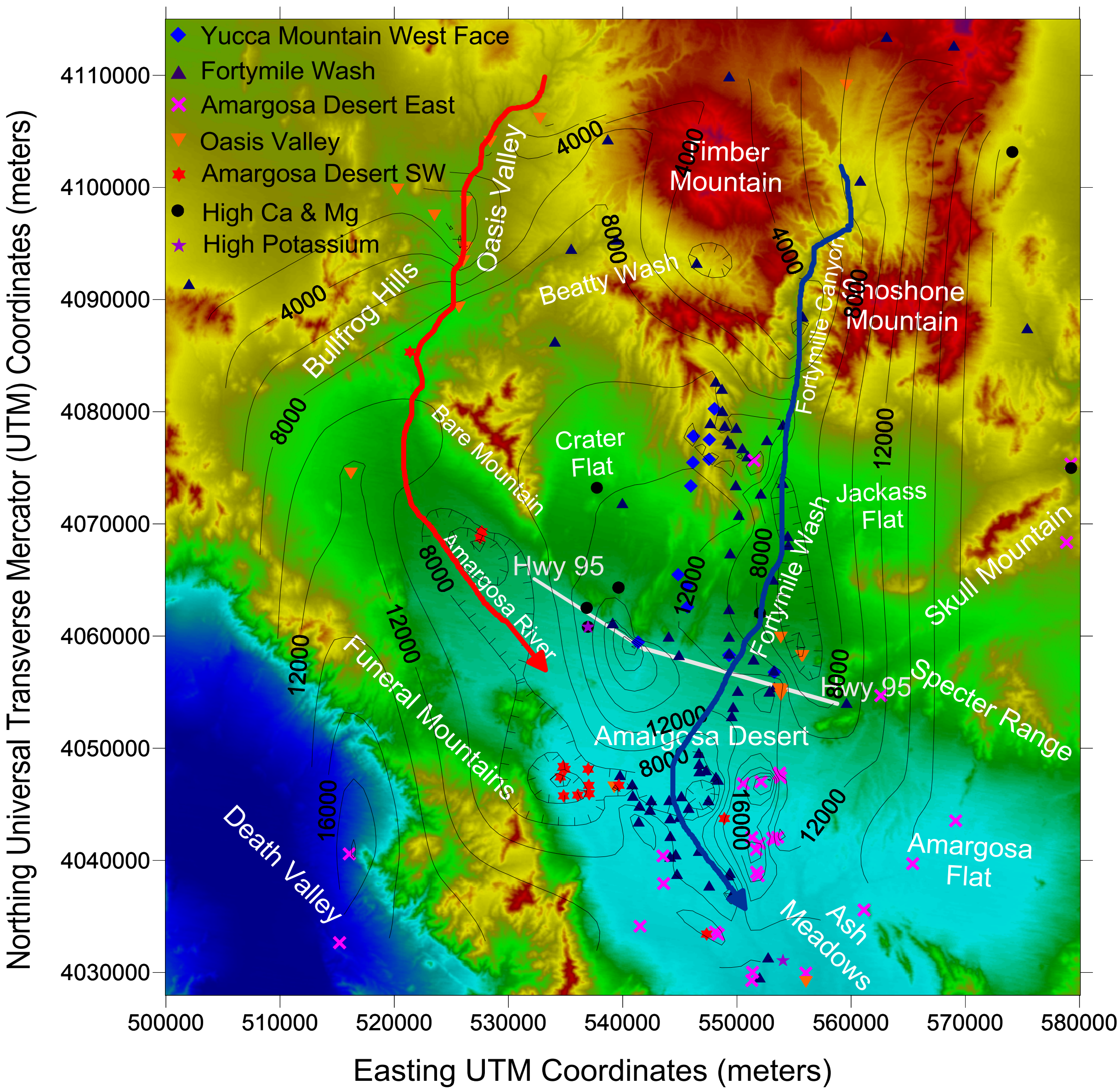

FIGURE 2 Groundwater Carbon-14 Age Contours
with Sampling locations and Sample Groups Overlain on a Digital Elevation Map, Corrected with Carbon-13 Data

values of contemporary precipitation present a wider range due to seasonal variations, with an approximate average of –101 ‰, and fall on the GMWL [12], as opposed to below it.

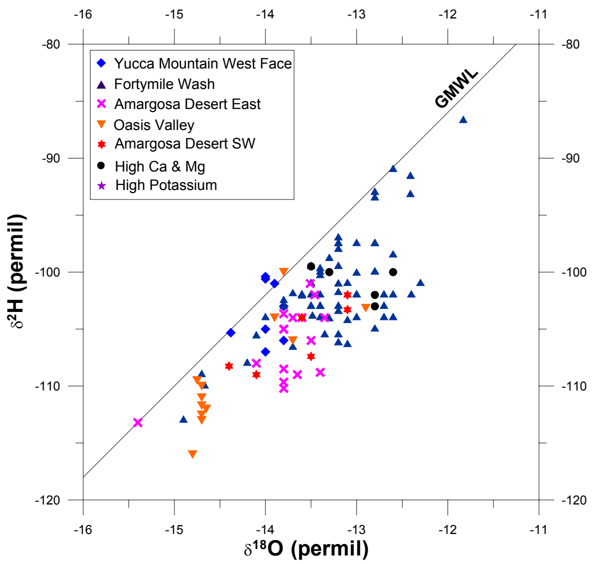

FIGURE 3 Groundwater Stable Isotope Data by Sample Groups Compared to the Global Meteoric Water Line

Figure 4 shows ^{2}H versus ^{18}O groundwater values beneath Fortymile Wash, the Amargosa River (i.e., the Oasis Valley and Amargosa Desert southwest), and the junction of the two, plotted against the GMWL; data from each of these areas correspond to one of the marked sections on the figure. The royal blue arrow indicates the

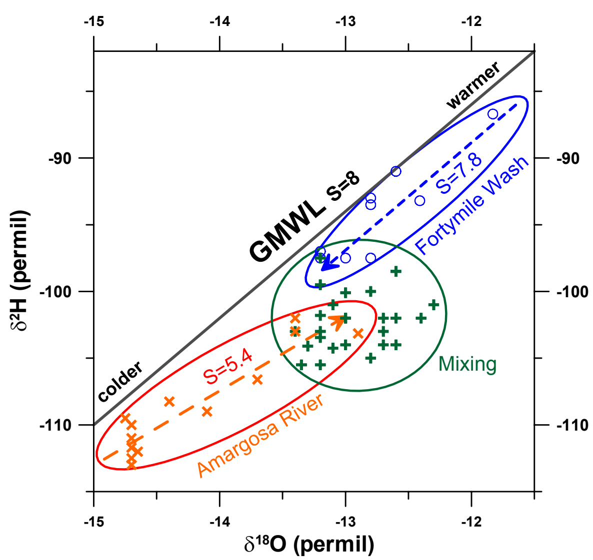

FIGURE 4 Groundwater Stable Water Isotope Data Compared to the Global Meteoric Water Line

approximate downslope direction of the wash; it can be noted that the values of ^{2}H and ^{18}O beneath the wash (i.e., the blue circles) are plotted approximately parallel to the GMWL with a slope of 7.8. Groundwater ^{2}H values in the upper part of Fortymile Wash correspond to the portion of the cold climate range that is warmer but still cold relative to the present, whereas values found in the middle portion of the wash correspond to the colder portion of the cold climate range, with more isotopic depletion.

The ^{2}H values (i.e., the orange diagonal crosses) beneath the Amargosa River from the Oasis Valley until it merges with the fan of Fortymile Wash range from –113 to –102 ‰, and show a slope of 5.4 (i.e., the orange arrow, which indicates the approximate downslope direction of the Amargosa River). If the groundwater age range differed in the order of days and not thousands of years, the slope of the orange arrow would match the evaporation of a river in an atmosphere with relative humidity slightly above 75 percent

On Figure 4, the data in the mixing section (i.e., with green crosses) correspond to sampling locations in the fan of Fortymile Wash, the junction of the Amargosa River with the fan, and slightly beyond the fan of Fortymile Wash near Ash Meadows. These data are associated with groundwater mixing beneath the river and wash; a clear difference can be noted from the unmixed groundwater beneath the wash: ^{2}H versus ^{18}O values are plotted further below the GMWL and in a more depleted ^{2}H range (i.e., -97.5 and -105.5 ‰).

Figure 5 presents ^{2}H data with a signature similar to the one found by the PCA results and corrected ^{14}C dating. Following Fortymile Wash southward to the Amargosa Desert, ^{2}H values become more depleted; furthermore, ^{2}H values of groundwater adjacent to the wash are also more depleted.

IV. CONCLUSIONS

The geochemical data presented herein suggests that groundwater beneath Fortymile Wash follows the surface of the wash until it appears to merge and mix with groundwater beneath the Amargosa River. Corrected and uncorrected ^{14}C values from groundwater beneath Fortymile Wash are younger and fresher (i.e., with lower TDS values) than those on adjacent highlands, which indicates that the highlands are not the source for the groundwater below the wash. The ^{2}H and ^{18}O signatures are similar to ^{14}C and PCA signatures and are evidence of changes to the groundwater system as the climate became warmer and dryer during the past 14,000 years. Beginning at the source of Fortymile Wash in the north and following south along the wash, groundwater becomes sequentially older, suggesting that the average reach of runoff events and recharge have diminished over time. Regional ^{2}H versus ^{18}O values suggest a humid-climate

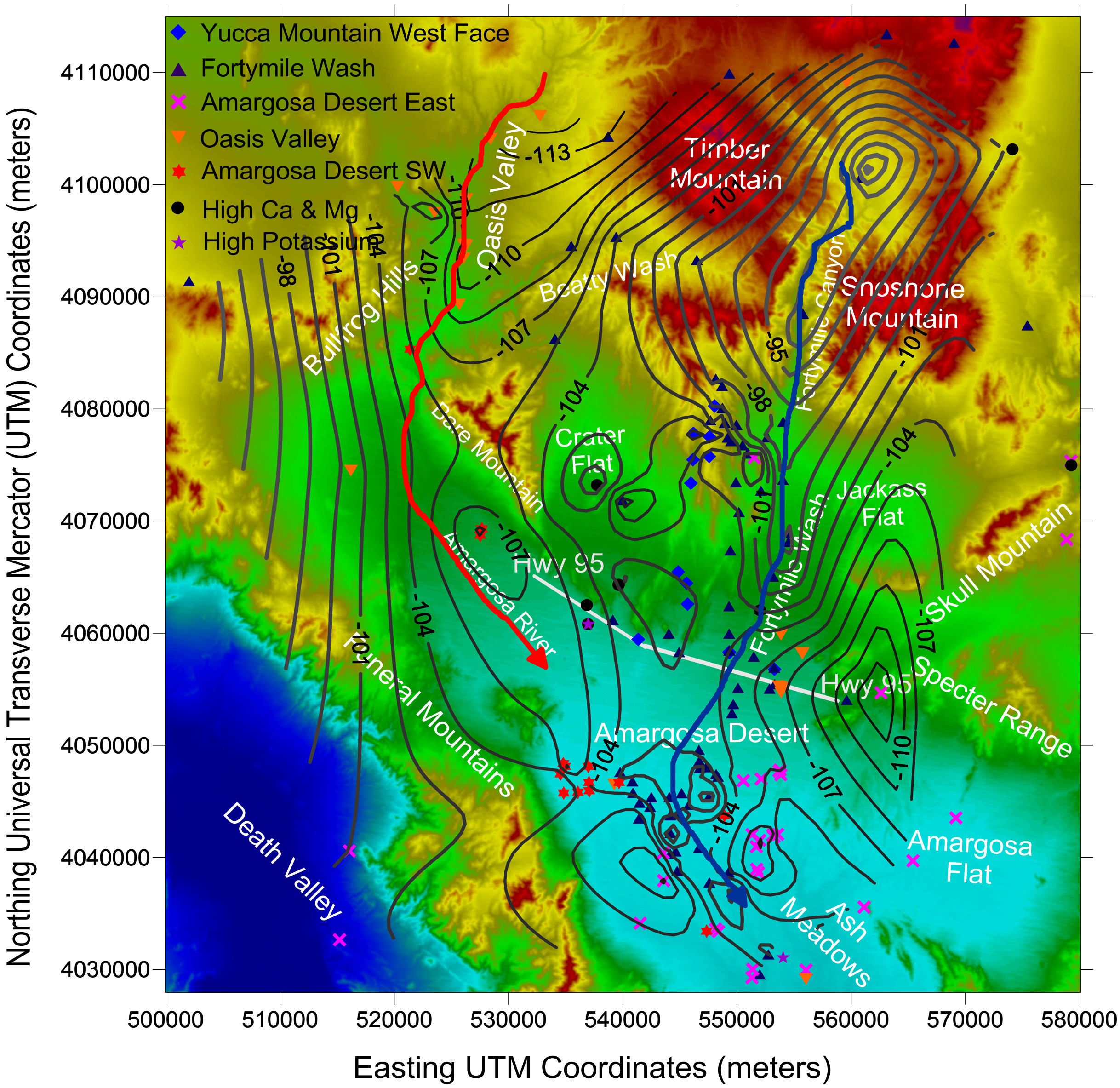

FIGURE 5 Groundwater δ^2H Concentration Contours in Permil Overlaid on Digital Elevation Map

precipitation, with little surface evaporation before infiltration. The stable isotope values beneath the wash fall parallel to the GMWL, with successive depletion of ^2H and ^{18}O values suggesting not an evaporation curve but evidence of climate change from cold to warm, although still colder than the present. The signature from Fortymile Wash is believed to represent the relic of focused infiltration of surface runoff along the course of the wash during past pluvial periods, when the climate was colder and wetter than the present and the amount of runoff in the wash was significantly greater.

ACKNOWLEDGMENTS

The Nye County NWRPO funded this work through the U.S. Department of Energy Office of Civilian Radioactive Waste Management cooperative research grant DE-FC28-02RW12163.

We would like to thank Dr. Dale Hammermeister, Nye County NWRPO Director, for his numerous suggestions, revisions, and corrections.

REFERENCES

1. Flint, A.L., Flint, L.E., Bodvarsson, G.S., Kwicklis, E.M. and Fabryka-Martin, J.T., 2001. "Evolution of the conceptual model of unsaturated zone hydrology at Yucca Mountain, Nevada." *Journal of Hydrology*, 247, 1-30.
2. Benson, L., Kashgarian, M., Rye, R., Lund, S., Paillet, F., Smoot, J., Kester, C., Mensing, S., Meko, D., and Lindström, S., 2002. "Holocene Multidecadal and Milticentennial Droughts Affecting Northern California and Nevada." *Quaternary Science Reviews*, 21, 659-682.
3. Harvey, A.M., Wigand P.E. and Wells, S.G., 1999. "Response of Alluvial Fan Systems to the Late Pleistocene to Holocene Climatic Transitions: Contrasts between the Margins of Pluvial Lakes Lahontan and Mojave, Nevada and California, USA." *Catena*, 36, 255-281.
4. Quade, J., Forester, R.M., Pratt, W.L. and Carter, C., 1998. "Black Mats, Spring-Fed Streams, and Late-Glacial-Age Recharge in the Southern Great Plains." *Quaternary Research*, 49, 129-148.
5. NWRPO (Nuclear Waste Repository Project Office). 2003. Geochemistry data files. Nye County, Nevada. http://www.nyecounty.com. Accessed June 2004.
6. LANL (Los Alamos National Laboratory), 2003. *Regional Groundwater Hydrochemical Data in the Yucca Mountain Are Used as Direct Input to ANL-NBS-00021*, Revision 01. LA0309RR831233.001, May, 2003.
7. Mellinger, M., 1987. "Multivariate Data Anlysis: Its Methods." *Chemometrics and Intelligent Laboratory Systems*, 2, 29-36.
8. StatSoft, Inc. 1984-2005. SATISTICA for Windows [Computer program manual]. Tulsa, OK. Kernel release 5.5. www.statsoft.com.
9. Clark, I., and Fritz, P., *Environmental Isotopes in Hydrogeology*, Lewis Publishers, Boca Raton, 1997.
10. Liu, B., Phillips, F., Hoines, S., Campbell, A.R. and Sharma, P., 1995. "Water movement in desert soil traced by hydrogen and oxygen isotopes, chloride, and chlorine-36, southern Arizona." *Journal of Hydrology*, 168, 91–110.
11. Craig, H., 1961. "Isotopic variations in meteoric water." *Science*, 133, 1702-1703.
12. Friedman, I., Smith G.I., Johnson, C.A., and Moscati, R.J., 2002. "Stable Isotope Composition of Waters in the Great Basin, United States 2. Modern Precipitation." *Journal of Geophysical Research*, 107(D19), 4401, doi:10.1029/2001JD000566, 2002.