

Soil-water flux in the southern Great Basin, United States: Temporal and spatial variations over the last 120,000 years

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Abstract. The disposal of hazardous and radioactive waste in arid regions requires a thorough understanding of the occurrence of soil-water flux and recharge. Soil-water chemistry and isotopic data are presented from three deep vadose zone boreholes (>230 m) at the Nevada Test Site, located in the Great Basin geographic province of the southwestern United States, to quantify soil-water flux and its relation to climate. The low water contents found in the soils significantly reduce the mixing of tracers in the subsurface and provide a unique opportunity to examine the role of climate variation on recharge in arid climates. Tracing techniques and core data are examined in this work to reconstruct the paleohydrologic conditions existing in the vadose zone well beyond the timescales typically investigated. Stable chloride and chlorine 36 profiles indicate that the soil waters deep in the vadose zone range in age from approximately 20,000 to 120,000 years. Secondary chloride bulges that are present in two of the three profiles support the concept of recharge occurring at or near the last two glacial maxima, when the climate of the area was considerably wetter and cooler. The stable isotopic composition of the soil water in the profiles is significantly more depleted in heavy isotopes than is modern precipitation, suggesting that recharge under the current climate is not occurring at this arid site. Past and present recharge appears to have been strongly controlled by surface topography, with increased incidence of recharge where runoff from the surrounding mountains may have been concentrated. The data obtained from this detailed drilling and sampling program shed new light on the behavior of water in thick vadose zones and, in particular, show the sensitivity of arid regions to the extreme variations in climate experienced by the region over the last two glacial maxima.

Introduction

In recent years, investigations into the hydrogeology of arid regions have focused on the flow and transport processes of the vadose zone. Much of this work has been driven by the need to find safe disposal sites for hazardous and radioactive wastes and by the search for water resources to feed the growth of urban areas. In this work, data collected during characterization of the Area 5 Radioactive Waste Management Site (RWMS), located on the Nevada Test Site (NTS), in the southern portion of the Great Basin geographic province, are examined (Figure 1). The Area 5 RWMS is approximately 95 km

northwest of Las Vegas, Nevada [Sully *et al.*, 1993]. The current climate at the study site is arid, with a mean precipitation of 124 mm/yr for 30 years of record (1963–1992) at a National Weather Service station 6 km south of the RWMS. There is great variability in the amount of precipitation from year to year, with a recorded minimum of 29 mm/yr, maximum of 230 mm/yr, and standard deviation of 55 mm/yr. The southern Great Basin experiences two distinct precipitation periods: a winter season characterized by cyclonic frontal systems originating in the Pacific Ocean off the western coast of the United States, and a summer monsoon of high-intensity convective thunderstorms carrying moisture originating in the Gulf of California. About 25% of the annual precipitation falls during this summer monsoon season.

Seven shallow (ST series) and three deep (PW series) boreholes were drilled and cored to characterize the thick vadose zone in the vicinity of the radioactive waste disposal site. The PW series boreholes were drilled to the water table approximately 230 to 270 m below land surface. In this work we focus on the paleoclimate response of the vadose zone as inferred from the distribution of environmental tracers in the soil water. These data clearly show the response of the vadose zone to major climatic variations over the last 120,000 years and represent a unique opportunity to study the paleohydrology of the southern Great Basin.

The Role of Tracers in Vadose Zone Studies

In this work we define net infiltration as the soil-water flux below the active rooting zone and define recharge as that flux

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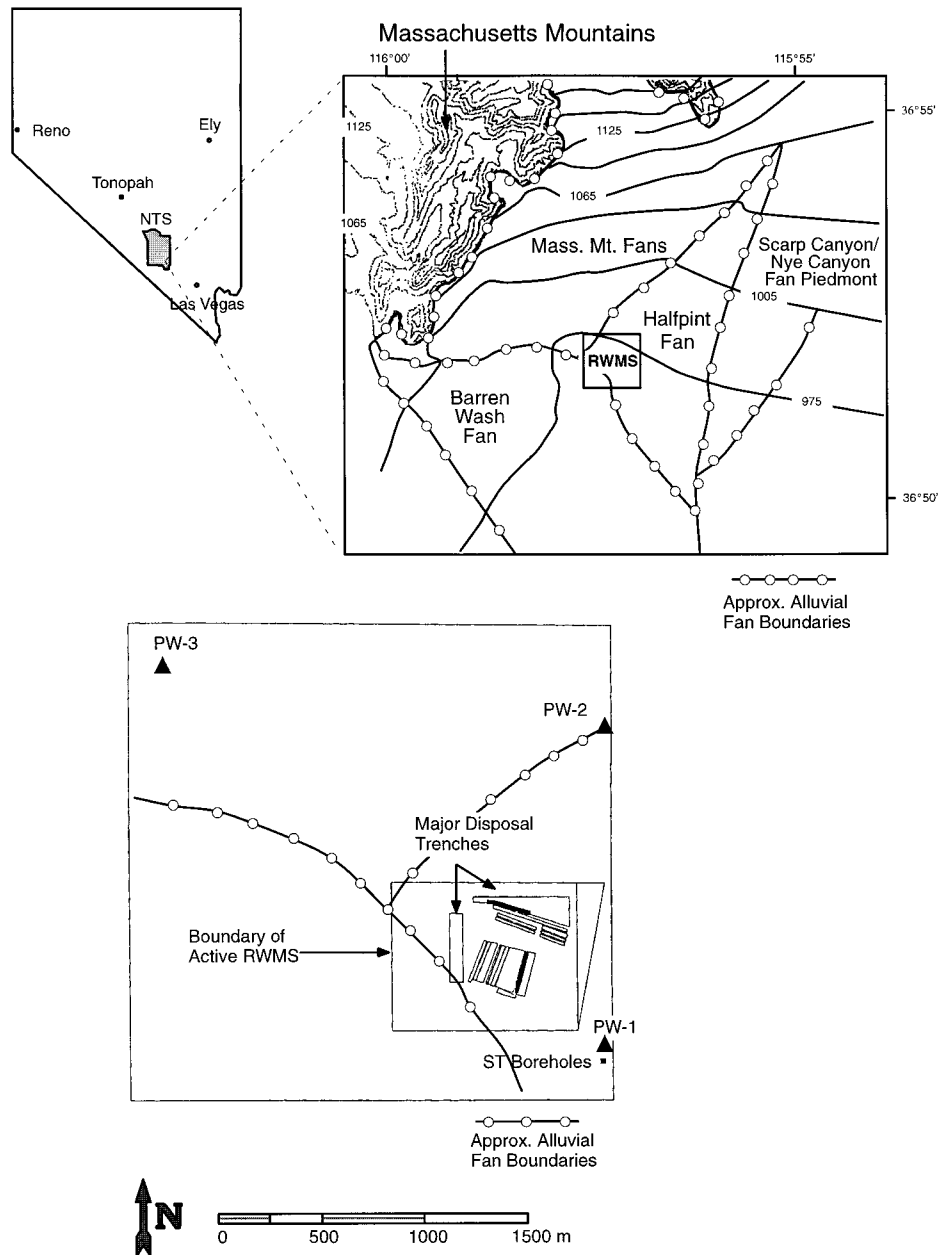


Figure 1. Locations of wells and boreholes discussed in the text relative to the Area 5 Radioactive Waste Management Site (RWMS). Contour interval is 30 m.

reaching the saturated zone. In vadose/groundwater systems at steady state, these terms are interchangeable; however, the response time of these systems may be much longer than the shifts in climate and it is necessary to differentiate these fluxes.

Study of environmental tracers in net infiltration and groundwater recharge investigations began in the early 1960s, when tracking of tritium (^3H) from atmospheric nuclear weapons testing was used to examine movement of soil water [Zimmermann *et al.*, 1967]. Use of radiotracers was subsequently expanded to include chlorine 36 (^{36}Cl) by Phillips *et al.* [1988]. As the fallout of these tracers is well documented, the rate of movement and dispersion of soil water can easily be estimated by noting the location of these tracers in the vadose zone. Scanlon [1992] and Phillips *et al.* [1988] present comparisons of both tritium and ^{36}Cl in arid portions of the western United

States. Since tritium may travel as both liquid and vapor, whereas ^{36}Cl is limited to the liquid phase, both Scanlon [1992] and Phillips *et al.* [1988] were able to estimate the relative proportion of vapor and liquid fluxes, which suggest that vapor flux at these arid sites accounted for 37 to 80% of the total water flow.

Radiogenic decay of ^{36}Cl has also been used to date groundwater, yet its long half-life (301,000 years) makes it of limited use in most vadose zone studies. Of considerable hydrologic interest, however, are the variations in isotope production resulting from shifts in strength and orientation of the Earth's magnetic field [Mazaud *et al.*, 1991]. Shifts in the field have resulted in a time-varying cosmic ray bombardment of the upper atmosphere. Tric *et al.* [1992] used cores of marine sediments to construct a continuous estimate of the geomag-

netic field strength over the last 80 kyr and found three periods of significantly reduced field strength, between 15 and 25 ka, between 35 and 45 ka, and between 60 and 67 ka ("ka" denotes a date before present; "kyr" denotes a time period). Because both carbon 14 (^{14}C) and ^{36}Cl are produced by cosmic ray bombardment, their concentration in their respective reservoirs has not remained fixed. This variation in production was first noted by discrepancies between ^{14}C and uranium-thorium age dates in corals [Bard *et al.*, 1990] and was subsequently extended to ^{36}Cl [Phillips *et al.*, 1991]. Because of the long half-life of ^{36}Cl , these variations may provide a chronological dating technique if preserved in the soil water.

Decay of ^{14}C is the most commonly applied radioactive dating method for groundwaters with residence times beyond the point when tritium is useful (>40 years). With a half-life of 5,730 years, ^{14}C can be used to date carbon which has been isolated from the atmosphere for up to 30,000 to 50,000 years. With the development of accelerator mass spectrometry, ^{14}C measurements can be performed with great accuracy on small volume samples. Despite complications presented by geochemical reactions and diffusion of carbon dioxide (CO_2) in the gas phase [Thorstenson *et al.*, 1983], thick unsaturated sections in arid regions may offer the possibility of dating successive infiltration events from hundreds to thousands of years in age.

Nonradiogenic isotopes, principally deuterium (^2H) and oxygen 18 (^{18}O), have also been extensively used in studying processes in the vadose zone. Barnes and Allison [1983] developed models of both liquid and vapor flow based on the fractionation that occurs under evaporation to estimate vertical water fluxes in the vadose zone. Under evaporating conditions the profiles of ^2H and ^{18}O can be divided into three general regimes. In the uppermost portion of the soil profile, where vapor flow is dominant, the isotopic composition of the soil water is influenced by the atmospheric concentration which is always more depleted in heavy isotopes than the liquid phase. Moving deeper into the profile, the composition of the soil water becomes enriched in heavy isotopes selectively left behind by the evaporation process. At the point in the profile, where liquid flow begins to dominate (often within 10 to 20 cm of the land surface), the isotopic composition reaches its maximum enrichment [Barnes and Allison, 1983]. Below this point the isotopic composition tends toward that of the underlying source water as a result of downward diffusion against the upward advective flux. Barnes and Allison [1983] developed simple expressions to estimate the rate of evaporation based on the depth of the vapor transmission zone as well as the shape of the lower, liquid-dominated profile.

One of the simplest techniques proposed for net infiltration and recharge estimation is the chloride mass-balance method [U.S. Department of Agriculture, 1954; Allison and Hughes, 1978]. By noting that in most environments, the major source of chloride in the soil solution is from atmospheric deposition, either in precipitation or as dry deposition, a simple mass-balance expression of chloride may be developed to predict net water flux at any point in the profile.

The chloride mass-balance method has gained wide acceptance and has been applied to a wide variety of sites to estimate recharge. It suffers from several assumptions (e.g., all fluxes are steady and there are no additional sources of chloride present in the soil) and data limitations (e.g., the chloride flux to the soil surface is both variable and difficult to accurately measure); however, it has proven to be a robust estimator, particularly for low rates of net infiltration [Allison *et al.*, 1994].

Under steady flow the ratio of the net infiltration or recharge to the precipitation flux is given as

$$PC_P/C_R \quad (1)$$

where P is the precipitation rate and C_P and C_R are the chloride concentrations in the precipitation and soil water, respectively.

It is convenient to consider C_P to be an "effective chloride concentration," which accounts for both wet and dry deposition. The concentration of chloride in precipitation is strongly controlled by the distance to its oceanic source [Junge and Werby, 1957] and is therefore unlikely to vary significantly over the timescales of most hydrologic interest. In arid settings a significant component of chloride input is also derived from dry deposition and dust [Dettenger, 1989]. In a study of chloride and groundwater recharge in the Great Basin of Nevada and Utah, Dettenger [1989] suggested that dry deposition may contribute as much as 33% of the total influx of chloride. For low rates of flux, errors introduced by the uncertainty of the effective chloride concentration and/or precipitation may have to be tolerated, as other tracers also suffer uncertainties at low flux rates.

In many arid systems where the net infiltration may be less than 0.1 mm/yr, the assumption of a steady state flux of water throughout the vadose zone required in the chloride mass-balance method may not be appropriate. For example, under a flux of 0.1 mm/yr, a vadose zone 20 m deep at an average water content of 10% by volume will contain soil water as old as 20,000 years at the bottom of the profile. Particularly in North America, where the last 20,000 years have been a time of significant climate change, we cannot expect the net infiltration rate to have remained steady over such a period. In such cases the chloride concentration deep in the vadose zone will not reflect the current conditions. To overcome this difficulty, the chloride mass-balance method can be modified to develop a chloride age of the soil water. If we assume that the chloride input has remained constant over time and that no additional sources of chloride are present in the soil, the chloride age, $A(z)$, at any depth in the soil profile, z , is simply taken as the ratio of the cumulative chloride concentration (mass Cl/unit volume of soil) from the soil surface to the depth of interest divided by the annual chloride deposition:

$$A(z) = \frac{\int_{\text{surface}}^z \theta_e C_R dz}{PC_P} \quad (2)$$

where θ_e is the volumetric water content.

Rather than yielding a direct measure of net infiltration, (2) provides an estimate of age of the soil-water chloride (and by assumption, the age of the water) at any depth in the profile. The only major assumption in this technique is that the rate of chloride deposition (PC_P) to the surface is constant. While this will certainly vary, it is unlikely to vary greatly for the following reasons. Because the concentration of chloride in precipitation is most strongly controlled by the proximity to its ocean source, the wet deposition flux should be linearly proportional to the precipitation assuming the source of the precipitation has remained constant. Paleoclimatic reconstructions for southern Nevada suggest that the two major sources of precipitation through the late Pleistocene have been the Pacific Ocean and the Gulf of California, both at approxi-

mately equal distances. At the same time, the dry deposition component may have varied significantly due to both local and regional sources.

Recent data from Greenland [Mayewski *et al.*, 1994] have shown that chloride concentrations preserved in Greenland ice cores were almost an order of magnitude higher during the last glacial maximum. Extrapolation of this record to the southern Great Basin may not be appropriate, however, given the major differences in factors controlling the region's climate and wind patterns and Greenland's proximity to oceanic sources of chloride. Consistency in the local chloride deposition rate is, however, supported by correlation between climatic variation and chloride ages calculated from modern accumulation rates in the vicinity of the study area, as shown by Fouty [1989] and Phillips [1994]. Correlations between major climatic shifts and chloride age found by these workers support the assumption of consistency in chloride deposition and therefore support the dating of soil waters based on chloride. Based on the above discussion, it is clear that care must be used in assigning chloride age dates in the absence of other evidence for the timing of recharge and climate change.

The Role of Paleoclimate in Recharge

Acceptance of tracers and the increasing awareness and interest in the nature and extent of climate change have led several workers to investigate thick vadose zones as sources of climate change information. Because many of the arid zones of the world have seen dramatic climate changes over the last 10,000 to 15,000 years, the relationship of climate to recharge may be inferred from the distribution of tracers in the vadose zone. Low flow velocities and water contents found in arid vadose zones significantly reduce the effects of diffusion and should help to preserve information in the soil water concerning the geochemical signature of precipitation and root zone processes.

The first research to recognize the potential for paleoclimate reconstruction from vadose zone chemistry was that by Edmunds and Walton [1980]. Stone [1992] used chloride profiles from Australia and suggested that shifts in the slope of the chloride-age-versus-depth relationship reflected changes in net infiltration in the region. These ages were shown to be correlated to paleoclimate changes inferred from other independent sources including paleolake levels, pollen analysis, and packrat midden data. Scanlon [1991] showed similar results for profiles from west Texas. Cook *et al.* [1992] analyzed vadose zone chloride data from north Africa and found very good agreement between recent (<400 year) climatic events and the rate of residual flux based on chloride mass balance. Cook *et al.* [1992] also presented analyses that century-scale fluctuations in climate might be preserved for >1000 years under recharging conditions.

Phillips [1994] presented an encompassing study of chloride profiles from the southwestern United States, where chloride ages suggest that soil water is as old as 16,000 years. Many of the chloride profiles showed a characteristic maximum in chloride concentration just below the root zone, with decreasing concentrations below the maximum. This chloride "bulge" was suggested to be the result of a cessation of recharge to the water table between 13,000 and 15,000 years ago, when the climate of the western United States began to shift from a cooler and wetter climate to the current arid conditions. As will be shown in this work, even this most recent pluvial period may

not have been sufficient to induce recharge in one of the most arid portions of the southwestern United States.

Paleoclimate of the Southern Great Basin

In contrast to the present arid climate, evidence from a variety of sources clearly indicates that the paleoclimate in the southern Great Basin over the last 100,000 to 150,000 years (100–150 kyr) has been dramatically different and at times significantly less arid. Smith [1984] identified paleohydrologic regimes in the southwestern Great Basin on the basis of lacustrine deposits at Searles Lake (located 160 km southwest of the study site) and found reasonable correlation with global ice sheet histories. Jannick *et al.* [1991] found evidence for a shallow lake at Searles between 290 and 150 ka, with evidence for the last major highstand and overflow event at 150 ka, lasting through 120 ka. They interpret a sequence of fluctuating shallow lakes from 100 to 24 ka with an additional overflow event between 24 and 10 ka. For the last 10 kyr, with the exception of one unspecified brief Holocene pluvial period, Searles has been a small- to moderate-sized saline lake.

Winograd *et al.* [1988, 1992] present a detailed examination of the oxygen isotope record of spring deposits at Devils Hole, located approximately 60 km southwest of the study site in the major discharge zone for the groundwater flow basin encompassing the RWMS. These paleohydrologic reconstructions identified the periods of 250 to 160 ka and 120 to 60 ka before present as relatively wet periods. There are differences in the timing of the end of Isotope Stage 6 between the Devils Hole and Searles records, with Winograd *et al.* [1992] favoring 160 ka, whereas Jannick *et al.* [1991] record Searles overflowing until 120 ka. A major stadial at 65 ka is the last pluvial event recorded by Devils Hole because the last 50 ka are missing from the record. Szabo *et al.* [1994] combined calcite morphology with uranium series dating to create a record of water table fluctuations in Browns Room at Devils Hole. They identified at least two major episodes of wetter conditions during the period 10 to 160 ka: between 116 and 53 ka and between 44 and 20 ka. For after 17 ka they found the water level continued to decline to its present level.

Persistent pluvial-period lakes did not exist in the vicinity of the RWMS; the closest were in Groom and Kawich playas, approximately 60 km to the north [Mifflin and Wheat, 1979]. Marsh deposits have been identified 50 to 70 km south of the RWMS in an area characterized today by isolated springs [Quade, 1986]. The more moist, marsh-forming periods occurred between 40 to 60 ka and between 30 and 15 ka (the most widespread period of standing water). Between 14 and 7.2 ka, surface water gradually decreased, whereas after 7.2 ka there was a lowering of the water table accompanied by widespread erosion [Quade, 1986], though conditions remained more moist than today until as late as 8.6 ka. Similar chronologies have been found at other locations south of the RWMS [Quade and Pratt, 1989; Haynes, 1967].

Plant macrofossils from ancient packrat middens have been used to reconstruct vegetation and climatic conditions over the last 50 kyr, with several intensive studies conducted at and near the Nevada Test Site [Wells and Jorgensen, 1964; Wells and Berger, 1967; Spaulding, 1985; Spaulding and Graumlich, 1986]. Juniper woodlands and steppe shrubs were widespread in the area from at least 45 to 10 ka, but the development of desert vegetation in the lowlands had begun by around 15 ka. The period from 45 to 35 ka was marked by plants adapted to

rainfall amounts similar to present, but more of that rain occurred during the winter season and temperatures may have been slightly cooler (1° to 3°C). This was followed by a progressive increase in available moisture up to about 25 ka. The latest period of major continental ice sheet expansion is recorded as beginning around 22 ka in the Mojave Desert, based on major biotic turnover marking the initiation of a stadial climatic regime. Maximum (full glacial) conditions may have occurred locally between 19 and 16 ka and were marked by plants adapted to relatively cold, dry environments, suggesting a large decrease in winter temperatures (up to 7°C), a pronounced absence of summer rain (making up less than 10% of the total), and a relative increase in winter precipitation by as much as 70% above current values. The change to postglacial vegetation took place earlier at some NTS sites than as recorded elsewhere. At elevations comparable to the RWMS, woodlands gave way to desert scrub prior to 14 ka. The transformation took time to spread across the elevational range, but was nearly complete by 9 ka. Between 12 and 10 ka, the number of plants dependent on summer rainfall increased so that by 10 ka, it is estimated that summer and fall precipitation around the NTS may have been 50% more than that at present. Current plant communities were not established until after 5 ka, presumably owing to migration times for warm-weather species. There is also evidence of a mid-Holocene increase in effective moisture and summer precipitation probably exceeded present amounts until 3 or 4 ka [Spaulding and Graumlich, 1986].

In summary, the paleoclimate of the region was significantly different than the modern climate. Various paleoclimatic indicators, each with a different spatial and temporal resolution, suggest periods of extensive groundwater and surface water discharge were associated with glacial maxima at approximately 120–150 ka and 15–35 ka. In the following sections we examine the response of the vadose zone to these two periods of documented pluvials.

Results From the Nevada Test Site

Ten core holes were drilled adjacent to the RWMS facility to characterize the vadose zone. Three of these boreholes (PW-1, PW-2, and PW-3) were drilled to the water table, with the remaining boreholes (ST-1 through 7) limited to the upper 40 m. The ST series boreholes were drilled using either casing advance, under ream, or hollow stem auger techniques to provide preliminary data for the deep drilling efforts. The PW series boreholes were drilled and cored using a casing advance, under ream drilling method, and air percussion coring [Detty *et al.*, 1993; Sully *et al.*, 1993]. Air was used as the drilling fluid to minimize disturbance of the in situ water contents, water potentials, and tracer signatures.

The ST boreholes were drilled and sampled in January and February 1992, with shallow sampling completed prior to the onset of unusually heavy rainfall in February (monthly total precipitation of 3.3 cm). Drilling and sampling from PW-1 were conducted from March through June 1992, coinciding with additional heavy precipitation in March (monthly total of 3.8 cm). PW-2 was sampled from June through September 1992, and PW-3 was drilled and sampled from September through November 1992, with no marked excursions from normal precipitation patterns.

As part of the drilling program, intact core and cutting samples were analyzed for both geochemical and radiotracers

as well as for a suite of hydraulic properties [Sully *et al.*, 1993; Reynolds Electrical and Engineering Company (REECo), 1994]. Cores were collected in 76-cm lengths. At each core depth, subcores (7.6 cm in length) were collected in plastic liners, sealed, and sent to the laboratory for hydraulic and geochemical analysis. Tracer analysis included chloride, bromide, sulfate, ^{36}Cl , ^{18}O , ^2H , and ^{14}C . In addition to these tracers, core splits were analyzed for water potential, water content, saturated hydraulic conductivity, water retention, porosity, and grain size distribution. Cuttings samples from the drilling were also collected at 0.76-m intervals for textural and chloride analysis. Groundwater samples from each of the PW boreholes were also analyzed for the tracers listed above. Core data from the shallow boreholes (ST series) were similar to those found in the upper portions of the deep boreholes, and we therefore focus our attention on these deep boreholes.

Boreholes PW-1, PW-2, and PW-3 are located within 3 km of each other at surface elevations of 968.7, 989.4, and 1004.9 m above mean sea level (AMSL), respectively [REECo, 1994] (Figure 1). The vegetation is similar at each borehole, consisting predominantly of *Larria tridentata*, *Atriplex canescens*, and *Ephedra nevadensis* [Wallace *et al.*, 1974]. Sediments encountered in each of the boreholes consisted of sandy-textured alluvial deposits, with generally less than 10% acid soluble inorganic carbon. At PW-3, volcanic tuff was encountered at a depth of 188 m. Groundwater was intersected in PW-1, PW-2, and PW-3 at 235.2, 256, and 271.6 m below land surface at elevations of 733.5, 733.4, and 734.3 m AMSL, respectively, indicating that the water table beneath the RWMS has little or no gradient.

Alluvial sediments exposed in the existing waste pits and trenches show considerable bedding and limited soil development; however, the hydraulic properties from each of the three deep boreholes show less variation in water retention, saturated hydraulic conductivity, and in situ water content with depth [Sully *et al.*, 1993] than would be expected from visual inspection of these outcrops. In the tuffaceous units encountered below 188 m in PW-3, the saturated hydraulic conductivity measured on the few available cores from this unit is several orders of magnitude lower than that of the alluvium.

Soil-Water Chloride

Soil-water chloride was measured on core samples from selected intervals and from cutting samples on 0.76-m intervals. Analysis by ion chromatography was performed on 1:2 soil-water extracts (50 g of dried soil diluted with 100 g of distilled water). Owing to the alluvial nature of most sediments, it was assumed that the extracts represented soil water only and that no additional chloride was leached from the soil matrix. Concentrations were then reported as milligrams of chloride per kilogram of dried soil. Figure 2 shows the chloride concentration from both cores and cuttings from PW-1, PW-2, and PW-3. Because of limited recovery in the upper portions of PW1, core chloride concentration from borehole ST-1, 61 m to the south, has been used to represent the chloride concentrations in the upper 8 m of PW-1. Good correlation between the core concentrations and adjacent cuttings was found at most depths, suggesting that measured concentrations in the cuttings can be used where core data are sparse or missing. This is particularly important when analyzing the data from PW-2 and PW-3, where core sample density was less. The apparent lack of agreement in the upper portion of PW-1 is primarily

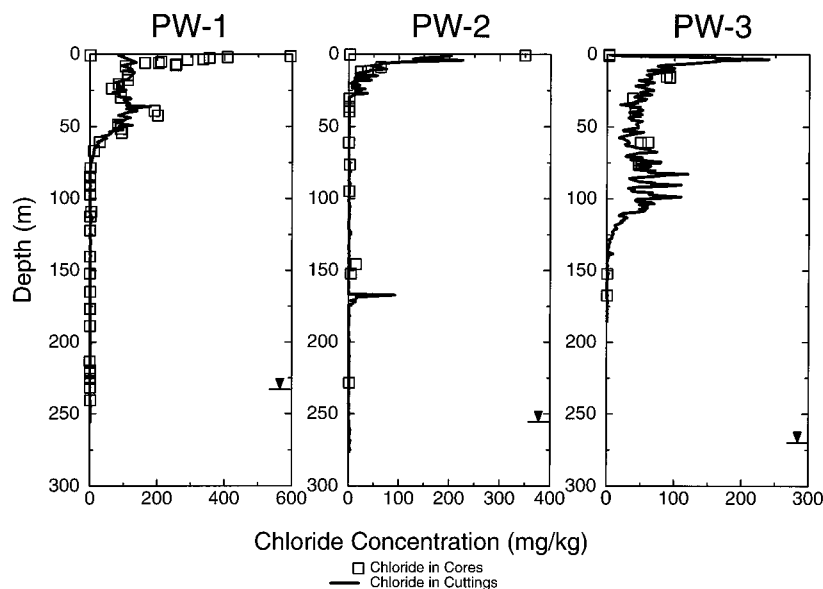


Figure 2. Chloride concentration in cores and cuttings from boreholes PW-1, PW-2, and PW-3. Chloride concentrations from the upper 8 m of ST-1, 61 m to the south, are used to augment the core record from PW-1. All concentrations are reported as milligrams of chloride per kilogram of dry soil.

attributable to the limited core available in this high-chloride zone and to difficulties in obtaining representative cutting samples in the shallow parts of the borehole. As both water content and bulk density varied over only a narrow range, soil-water concentration (as milligrams per liter) versus depth profiles were essentially identical in shape to those shown in Figure 2.

Each of the boreholes shows similar characteristics. In the upper 1 to 2 m of the vadose zone the chloride concentration is very low, reflecting repeated flushing by precipitation. This is also the zone of active rooting, based on observations from the waste pits and trench walls. Below 2 m, each of the profiles quickly reaches a maximum concentration of between 250 and 600 mg/kg. Such a peak concentration is typical in many chloride profiles in arid regions [Phillips, 1994] and indicates either a net infiltration rate that has changed over time, significant nonpiston flow, or a combination of these two processes.

Below this characteristic bulge the profiles differ somewhat. In both PW-1 and PW-3 the chloride profile shows a second bulge at 40 and 85 m, respectively. These bulges are not as pronounced as the first peak, and both show considerable spreading. The secondary bulges show evidence of diffusion or dispersion and may represent a previously developed chloride bulge in the near surface that has been advected downward under a subsequent, more pluvial condition. Below these secondary bulges the chloride concentration quickly drops, ranging from 0.5 to 2.0 mg/kg. Using the measured gravimetric water contents of core samples, the calculated soil-water concentration ranges from 10 to 30 mg/L in the deeper portions of each borehole. Groundwater samples collected from the boreholes showed slightly lower concentrations of chloride.

In contrast, PW-2 shows a very rapid decrease in chloride concentration to a depth of 25 m, with low chloride concentrations throughout the rest of the profile. A small spike does appear in several cutting samples at a depth of approximately 175 m. This may be the result of contamination of the cuttings during drilling, although no core data are available from the interval to confirm this. Using the cuttings data, the total mass

of chloride stored in the PW-2 profile is roughly 70% lower than the mass stored in either PW-1 or PW-3, suggesting either a shorter time of chloride accumulation or a significantly smaller input flux of chloride at the soil surface. Given the geographic proximity of the boreholes, it is unlikely that differences in the input flux could be responsible for this large difference.

The chloride profiles show that the profiles are not at steady state and are accumulating chloride in the upper 125 m. Two possible explanations are plausible for the profile shapes: a water table much higher than that which currently exists or a period of significantly wetter surface conditions that resulted in significant net infiltration and a flushing of the vadose zone. Given the coarse texture of the soil, the water table would have to be very near the land surface to maintain the significant evaporation rate needed to accumulate the chloride found in the boreholes. It has been suggested [Winograd and Doty, 1980] that the water table in Frenchman Flat may have risen by as much as 30 m in the late Pleistocene; however, simple evaporation from this depth could not produce the secondary bulges found in both PW-1 and PW-3. In addition, Jones [1982] suggests that the water table has remained relatively stable throughout the Pleistocene, based on the uniformity in clay hydration found in a borehole (U11g) 5 km north of the study site. It is more probable that at some time in the past, the regional climate was sufficiently wet to induce a significant recharge with resulting low chloride concentrations in the lower portion of the vadose zone.

While it is not appropriate to estimate a recharge rate from the upper portions of the boreholes where chloride is currently accumulating, it is possible to use the deeper data (>100 to 150 m) to estimate the paleorecharge rate. The very low and uniform chloride concentrations at depth indicate that at some time in the past, the vadose zone was in equilibrium and significant recharge must have occurred. An estimate of the recharge represented by the low chloride concentrations at depth in each of the boreholes requires knowledge of the chloride

flux at the surface at the time recharge was occurring. Although the magnitude of the precipitation when the recharge occurred is unknown, it must have been greater than present conditions (124 mm/yr; from French [1986]), under which recharge and net infiltration are negligible [Detty *et al.*, 1993; Tyler *et al.*, 1994]. At this time, data are not available for chloride fluxes at the site. Junge and Werby [1957] and Dettenger [1989] report chloride concentrations in precipitation in the general area averaging 0.4 mg/L and also reported dry deposition measurements from several stations. On the basis of these measurements, Dettenger [1989] suggested using an “effective” concentration of 0.6 mg/L to account for the additional flux due to dry deposition. Chloride concentrations in bulk precipitation samples (both wet fall and dry deposition combined) collected in 1985 from several sites across the NTS ranged from a minimum of 0.2 mg/L to a maximum of 1.3 mg/L (unpublished data, 1985). These samples showed no apparent trend attributable to elevation. In addition to these data, several authors [Phillips, 1994; Fouty, 1989; Fabryka-Martin *et al.*, 1993] have estimated chloride flux in the region to range from 80 and 150 mg/m²/yr, with most estimates close to 100 mg/m²/yr.

The calculated chloride flux based on average annual precipitation (124 mm/yr) and Dettenger's [1989] estimate of effective chloride concentration is 74.4 mg/m²/yr, somewhat lower than those used in other studies. The paleoclimate record clearly shows that more mesic conditions prevailed through much of the Pleistocene, and it is therefore logical to assign a higher value of precipitation (and therefore chloride flux) when estimating paleorecharge. Packrat midden data suggest that precipitation over the last 35 ka was often 20 to 50% higher than present precipitation. Prior to these dates, other paleoclimatic indicators in the region also suggest a more pluvial period than at present. Using an assumed 50% increase in precipitation, the estimated paleochloride flux is 105 mg/m²/yr, similar to the estimated chloride paleoflux used by Fouty [1989] and Fabryka-Martin *et al.* [1993]. While the paleochloride flux remains an open question, it is important to point out that calculated recharge rates are linearly related to this estimate and are therefore less sensitive to uncertainties than traditional soil physics methods used to estimate recharge.

An estimate of the paleorecharge preserved in the deeper portions of each of the three boreholes can be made based on their average deep chloride concentrations ($C_R = 13.9$ mg/L in PW-1, 23.7 mg/L in PW-2, and 17.9 mg/L in PW-3). Using the above estimated chloride flux, the calculated paleorecharge rates from deep in the profiles range from 7.6 mm/yr at PW-1 to 4.4 mm/yr at PW-2 to 5.9 mm at PW-3. These rates of recharge are currently found at much higher elevations in the southern Great Basin. Modern recharge of this magnitude is associated with areas with cooler average temperatures and higher annual precipitation. Increased precipitation and cooler temperatures characterized glacial climates of the region and suggest that conditions at the site during recharging periods were similar to those found only at higher elevations today.

The combination of low chloride concentrations at depth, of large differences in stored chloride between the boreholes, and of the presence of secondary bulges suggests that a series of recharging events have occurred and that the profiles have responded in different ways. At PW-1 and PW-3 significant recharge was interrupted by a long period of chloride accumulation in the near surface. This accumulation was presumably the result of a climatic shift from a more pluvial period. During this same period PW-2 may have also experienced chloride

accumulation (and hence little or no recharge); however, this signal is no longer present. At some more recent time a return to pluvial conditions initiated deep infiltration at all three boreholes. This infiltration was of sufficient magnitude or temporal length to induce infiltration to the water table at PW-2, carrying with it most of the accumulated chloride. At PW-1 and PW-3 the infiltration was not sufficient to reach the water table but, rather, advected the near-surface chloride bulges deeper into the profile. The results of this “aborted” recharge are witnessed by the presence of the secondary bulges in both PW-1 and PW-3. Following this paleorecharge period, the profiles show the beginning of another period of chloride accumulation that is still occurring today.

Timing the age of these postulated periods may be estimated from (2), provided the input chloride flux is known. As shown in the discussion of paleorecharge rates, above, the input flux requires knowledge of both the chloride concentration of the precipitation and the precipitation rate, both of which have clearly varied over recent geologic time. Figures 3a–3c show the estimated chloride ages from the three boreholes under an assumed chloride flux of 105 mg/m²/yr. The use of constant flux in the chloride age calculations is at best a simplification of the climatic conditions over the last 100 kyr; as discussed above, the choice of a flux slightly higher than that presently occurring appears appropriate given the known changes in climate over the period of interest. The chloride ages shown in Figures 3a–3c show the significant differences between the PW-1, PW-3, and PW-2 profiles. Age estimates at both PW-1 and PW-3 suggest that these profiles have accumulated chloride for at least 100 to 120 kyr. In contrast, the chloride age calculated at PW-2 (Figure 3b) is 25 to 35 kyr, with almost all of the chloride contained in the upper 25 m. As will be discussed later, these ages may represent the last two major pluvial periods in the paleoclimatic history of the region.

If the secondary bulges in PW-1 and PW-3 represent a more pluvial period in which recharge was occurring in PW-2, the chloride age of the bulges should be commensurate with the age at the bottom of the chloride bulge in PW-2. From Figures 3a and 3c the break in slopes of the chloride ages represents the secondary bulges and clearly shows an apparent age of approximately 60 to 70 kyr, much older than that estimated for the timing of recharge at PW-2. This apparent discrepancy may be the result of dispersive mixing, rather than of the simple piston displacement assumed by the chloride age model. The secondary bulges clearly show spreading, reflecting additional mixing during the advective phase of transport from the near surface. The accumulated chloride above the secondary peaks at 40 and 85 m in PW-1 and PW-3, respectively, therefore represents not only chloride added since the aborted recharge, but also a significant amount of chloride that was initially present but that has spread, owing to the transport. By assuming a simple piston model of displacement the calculated age of the peak will overestimate the actual age.

To address the effect of the dispersed chloride, a two-step modeling process was conducted. In the first step a simple Gaussian model was fit to both secondary bulges in PW-1 and PW-3. The initial conditions assumed a Dirac distribution of chloride centered on the current peak of the respective secondary bulges. The only parameter which was allowed to vary to obtain a best fit was the variance of concentration. In the second step the actual age of the chloride peak was calculated from the chloride accumulated above the peak, after subtracting that portion of the chloride which resulted from dispersion

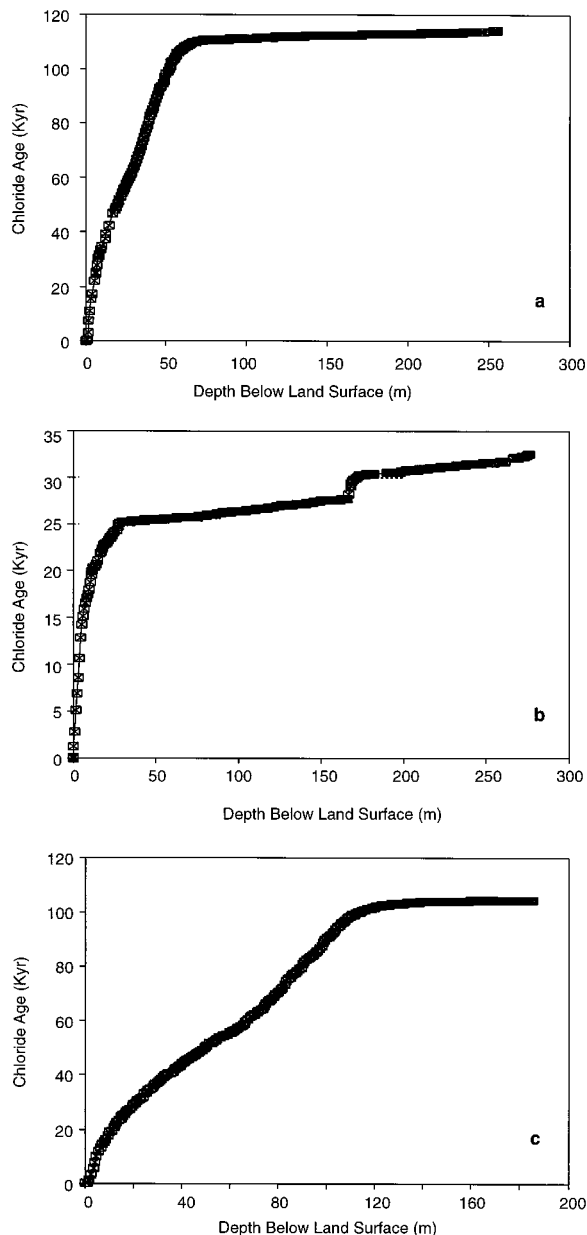


Figure 3. Estimated soil water age based on chloride accumulation for (a) borehole PW-1, (b) borehole PW-2, and (c) borehole PW-3. In each case a chloride accumulation rate of $0.105 \text{ gr/m}^2/\text{yr}$ was assumed.

of the original peak. This age also corresponds to the trough between the primary and secondary bulges. The average velocity of the secondary bulge was then calculated by dividing the peak depth by the adjusted age. The best fit simulated results are compared with the measured concentrations in Figures 4a and 4b. The solid line represents the distribution of chloride that would be present if no further chloride had been input to the soil following the advective phase of the transport. The Gaussian model fits the leading (deeper) edges of the secondary bulges very well, but it is not possible to assess the accuracy along the trailing edge since it is obscured by more modern chloride.

At PW-1 the Gaussian model reduces the age of the secondary bulge from 82 kyr to 53 kyr, while at PW-3 the age was reduced from 75 kyr to approximately 46 kyr. These ages are

closer to the total age at PW-2 but are still much older and indicate different timing for recharge. There are several other possible explanations for this apparent lack of consistency. The secondary bulge ages represent the time when the aborted recharge events began, while the accumulated chloride age at PW-2 represents the amount of time since recharge ceased. It is quite plausible that recharging conditions continued to prevail at PW-2 for an additional 20 to 30 kyr, well after the aborted recharge had been initiated at PW-1 and PW-3. The paleoclimatic indicators clearly demonstrate that throughout much of the late Wisconsin, conditions were conducive to recharge. Another explanation for the difference may be due to nonpiston or nonuniform flushing of the accumulated chloride by the aborted recharge at PW-1 and PW-3. Incomplete removal of chloride has been reported by Jolly *et al.* [1989] in studies of land clearing and chloride flushing in Australia. Complete flushing would only occur after several pore volumes of recharge had moved through the profile, such as what may have occurred at PW-2. This phenomenon leaves accumulated chloride behind, resulting in a skewed upward distribution (long tail) of chloride. While the leading edge of secondary bulges is well defined by the advection dispersion model (Figures 4a and 4b), the tails cannot be modeled with any certainty, as they intersect the primary bulges in both cases. If the leaching of the chloride was not complete, this older chloride left behind would increase the apparent age of the recharging period. If tailing is the major source of the disparities in estimated timing, the calculated leaching efficiency needed to reconcile the timing of the aborted recharge was approximately 75% for both boreholes, with 25% of the initial mass of chloride remaining outside of the calculated Gaussian distribution. From the chloride data alone it does not appear possible to resolve which, if either, of these explanations is most appropriate.

The modeling of the secondary bulges can also be used to investigate the magnitude of the average dispersion coefficient. Average in this sense represents both spatial and temporal variations. In the spatial sense the dispersive characteristics are assumed to be homogenous from the land surface to the bulge position. The chloride profiles shown in Figures 2a and 2c display significant scatter attributable to both sample collection methods (primarily drill cuttings) and small-scale heterogeneity in the flow velocities. The dispersion coefficient therefore represents a profile-scale measure of dispersion. From a temporal framework the dispersive process has varied from an advective case under past recharging conditions to one dominated by diffusion today. The dispersion coefficients which best fit the secondary bulges in PW-1 and PW-3 are 4×10^{-11} and $1 \times 10^{-10} \text{ m}^2/\text{s}$, respectively. The ratio of the dispersion coefficients is very close to the ratio of the depths of the maximum concentration of the secondary bulges, suggesting that the difference may be attributable to differences in advective velocity rather than to differences in the intrinsic dispersivity. The magnitude of the dispersion coefficient is only somewhat higher than that expected for molecular diffusion, indicating that the advective velocity was small and supporting the small estimated recharge rates of 7.6 and 5.9 mm/yr deeper in the profiles of PW-1 and PW-3, respectively.

It is important to note that the secondary bulge velocity in PW-3 is almost twice that of PW-1, while the deep chloride concentrations imply a higher rate of recharge in PW-1. The soil textures in PW-1 are coarser, which would result in slower wetting front velocities during displacement of the secondary

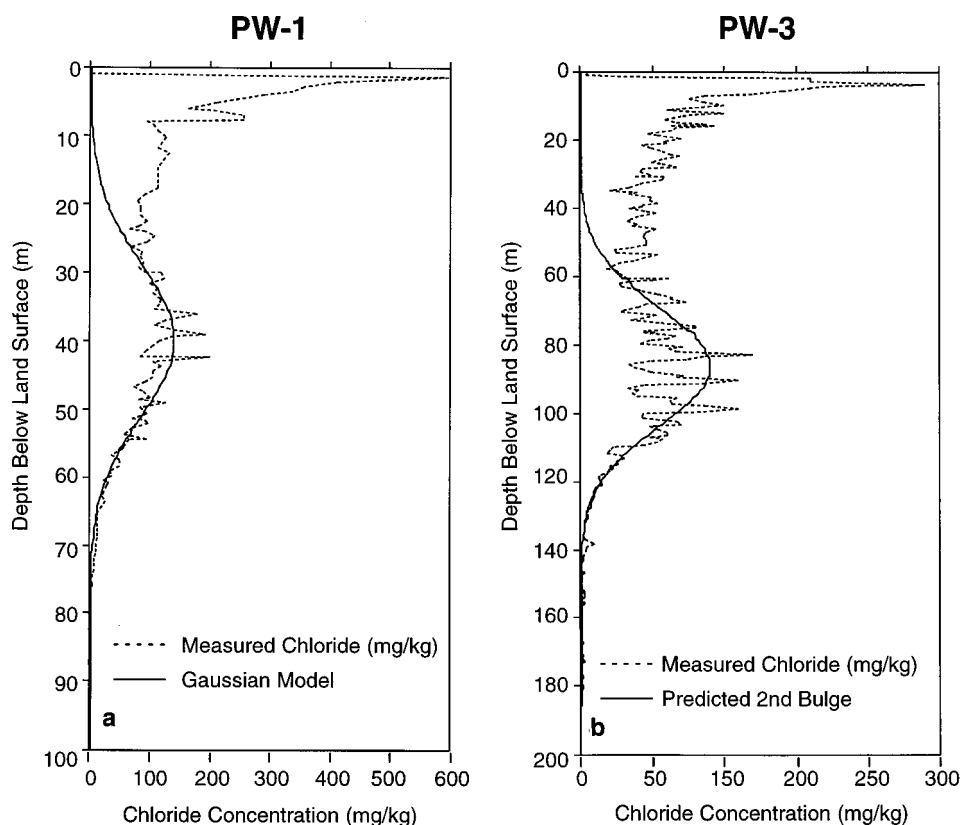


Figure 4. Gaussian model fit to the secondary chloride bulge in (a) borehole PW-1 and (b) borehole PW-3.

bulges yet higher overall recharge rates. It is also possible that surface conditions, particularly vegetation communities, may have differed between recharging periods at these two boreholes. PW-3 is located at a slightly higher elevation and further up the fan surface. These factors may have resulted in different conditions during these two recharging periods separated by almost 100 kyr.

Chlorine 36 in Soil Water

Analysis of ^{36}Cl from the near-surface soils in the vicinity of the RWMS has shown the ^{36}Cl from nuclear weapons testing to be restricted to the upper 2 m of the soil profile [REECO, 1994]. This is consistent with the chloride mass-balance results (presented above) and hydraulic data [Detty *et al.*, 1993], which indicate that infiltration is recycled in the root zone.

Isotopic ratios for ^{36}Cl were measured on 27 core samples from the PW series boreholes. The chloride content of the soil was precipitated in the form of AgCl using standard procedures [Mattick *et al.*, 1987]. The ratio of ^{36}Cl to chlorine 35 (^{35}Cl) was measured using tandem accelerator mass spectroscopy [Elmore *et al.*, 1979]. Between the land surface and the water table, 14 samples were analyzed from borehole PW-1, four samples were analyzed from borehole PW-2, and nine samples were analyzed from borehole PW-3.

Chlorine-36 ratios versus depth are shown in Figure 5. The solid symbols represent raw data, that is, the ^{36}Cl ratio as measured by the accelerator mass spectrometer. The open symbols show ^{36}Cl ratios corrected for decay and represent the estimated ^{36}Cl ratios at the time of deposition. Decay corrections were calculated using chloride mass-balance ages corresponding to the depth from which the sample was taken. The

corrected ^{36}Cl ratios from all three boreholes are significantly higher than the modern ratio of approximately 500×10^{-15} ($^{36}\text{Cl}/^{35}\text{Cl}$) for the region measured at Yucca Mountain by Fabrika-Martin *et al.* [1993] from samples taken just beneath the ^{36}Cl peak. According to Tric *et al.* [1992], the beginning of the first period of reduced field strength occurred approximately 15 ka, suggesting that even the most shallow soil-water samples must be at least 15 kyr old. An age estimate of at least 15 ka is consistent with the chloride mass-balance results.

The PW-1 profile shows one anomalously low ratio of 184×10^{-15} at a depth of 91 m. This ratio is much lower than what would be expected from the geomagnetic fluctuations. If this low ratio was attained by decay of ^{36}Cl , the decay age is 433 kyr, significantly older than the water above it or beneath it in the profile and inconsistent with their chloride ages. Two samples deeper in the profile (152 m and 213 m) show much higher ratios as well as excellent agreement in ^{36}Cl ratio. All three samples were taken from beneath the chloride bulge in the region of low chloride concentrations where chloride was added as a carrier during analysis, and therefore the likelihood of analytical error was significantly increased. It is most likely that this anomalously low ratio does not represent very old water but, rather, analytical error.

Figure 6 shows the decay-corrected ^{36}Cl data as a function of their calculated chloride ages from all three boreholes plotted along with the estimated atmospheric fallout at the site over time following the method of Mazaud *et al.* [1991]. Here, the data presented previously in Figure 5 have been normalized relative to the modern ratio of 500×10^{-15} so that they may be compared against the curve of ^{36}Cl production. Figure 6 shows three peaks of ^{36}Cl production corresponding to the three

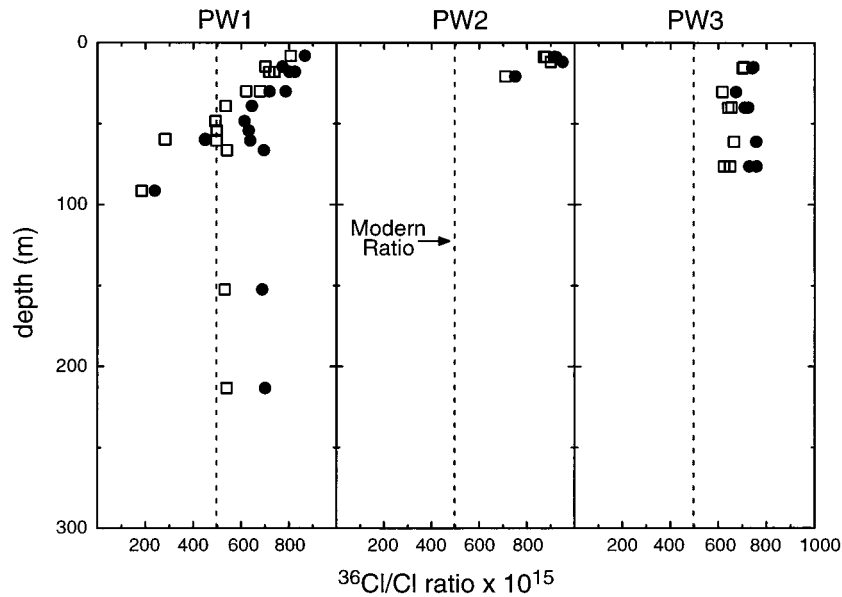


Figure 5. Chlorine 36 concentrations in soil water from PW-1, PW-2, and PW-3. Open symbols represent decay-corrected concentrations based on chloride ages estimated for the sample depth. Dashed line represents approximate modern ratio of $^{36}\text{Cl}/\text{Cl}$ deposition at the site.

periods of significantly reduced strength in the magnetic field. Over these time periods of increased ^{36}Cl production, the soil-water samples are also elevated in ^{36}Cl relative to the modern ratio. However, during periods of reduced ^{36}Cl production, the ^{36}Cl ratios of soil water remain elevated rather than decreasing toward the modern ratio, as predicted. This lack of lower concentration of observed ^{36}Cl may be the result of dispersion during transport or nonpiston displacement through the vadose zone. However, the elevated levels of ^{36}Cl are consistent with waters infiltrated during the late Pleistocene.

Stable Isotopes in Soil Water

The stable isotopes of hydrogen and oxygen provide an excellent indicator for evaluating paleofluxes, as their ratios in precipitation are sensitive to changes in both temperature and origin of moisture. Thus changes in the net infiltration and recharge are likely to be directly recorded in the isotopic ratios of the soil waters [Fontes, 1981]. Stable isotopic analysis was performed on core samples from both the ST series and the PW series boreholes. Subsamples (7.6 cm in length) from each core run were collected in plastic liners, sealed in the field, and

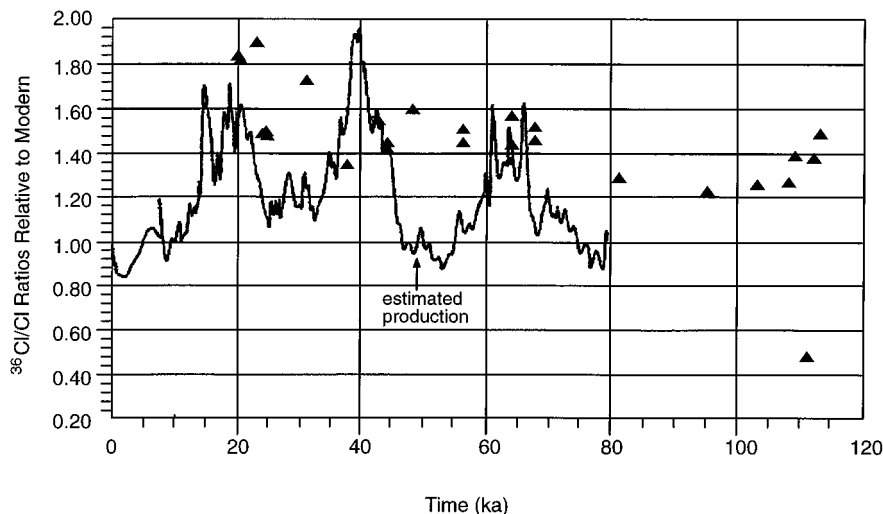


Figure 6. Decay corrected ^{36}Cl ratios relative to the modern ratio at the site (500×10^{-15} atoms of $^{36}\text{Cl}/\text{atoms of } ^{35}\text{Cl}$) from all three deep boreholes. The solid line represents the estimated fallout from cosmic production as influenced by variations in the geomagnetic field intensity.

sent to the laboratory for soil-water extraction. After completion of the PW series boreholes beneath the water table, groundwater samples were collected for isotopic analysis.

Drilling techniques may have a significant impact on the quality of subsurface samples. This is particularly true of the stable isotopic samples if drying of the core occurs. Although all core samples were collected by percussion coring, compressed air was used to drill all of the PW series boreholes and some of the ST series boreholes. Significant amounts of drilling air were often injected into the formation during several stages of drilling the deeper boreholes, which could cause drying of the formation and possibly the core samples. The potential magnitude of this problem was tested by comparing the isotopic composition between two ST boreholes drilled 1.5 m apart; one drilled by a hollow-stem auger and the other using the air casing advance, under the ream-drilling method. Three sample pairs, where core depth was within 2 m of each other vertically, were available for comparison. For these three pairs the greatest difference in $\delta^{18}\text{O}$ is 0.3‰ and the greatest difference in δD is 2‰, in both cases just slightly greater than the analytical reproducibility (discussed below). Minor drying at depth is evidenced by small (<2.5 MPa) excursions in the water potential at depth [Dettly *et al.*, 1993]. The coarse texture of the material suggest that had significant drying occurred during drilling, the water potential excursion would have to be much larger to also be reflected in the isotopic composition of the soil water.

The isotopic content of precipitation was not collected as part of this study. In a study of precipitation and springs in southern Nevada, Ingraham *et al.* [1991] operated 14 precipitation sampling stations, including a station located 450 m from the RWMS. The station elevation was 960 m AMSL, only 10 m lower than the land surface at PW-1. The station was designed only to collect monthly averaged precipitation chemistry and isotopic ratios. Ingraham *et al.* [1991] reported the results of 40 samples collected from 1982 to 1986, although 13 of the samples report ^{18}O only. An additional 19 samples (from January 1987 through October 1988) were archived and analyzed as part of this study. These samples had been stored in glass, and several samples analyzed shortly after collection were compared to their archived duplicates. These checks on sample integrity showed the archived samples to be within the standard analytical error of the previously analyzed precipitation.

Laboratory analysis of cores began with a toluene extraction [Ingraham and Shadel, 1992] on approximately 100 g of moist soil from the cores. The extractions were run to completion, with generally 3 to 4 mL of water being derived from each extraction. For the oxygen analysis, approximately 10 μL of water was completely converted to carbon dioxide using guanidine hydrochloride, and the CO_2 was directly introduced into a Delta E Finnigan-Matt triple collector mass spectrometer. Hydrogen analyses were conducted after quantitative conversion of 5 μL of water to hydrogen gas using uranium as the reducing agent and direct injection into a Nuclide 3-60 HDD double collector mass spectrometer. All data are reported in standard delta notation, with respect to standard mean ocean water (SMOW). The reproducibility of the ^2H is $\pm 1\%$, while the oxygen results are $\pm 0.2\%$.

Isotope Composition of Precipitation and Soil Water

A total of 46 analyses of precipitation isotope pairs are available covering the period from January 1984 through October 1988. The $\delta^{18}\text{O}$ value of precipitation ranged from

+2.9‰ to -19.7‰, while the δD values ranged from -15‰ to -152‰. The annual mean composition, weighted by the volume of precipitation, is -10.5‰ for $\delta^{18}\text{O}$ and -80‰ for δD . An important factor is the relative proportion and isotopic composition of the seasonal component. Considering the summer season to include precipitation from May through October, the weighted mean summer precipitation is -7.1‰ and -57‰ for $\delta^{18}\text{O}$ and δD , respectively. The weighted mean for winter precipitation is -12.5‰ and -93‰, respectively, reflecting the cooler temperatures. The winter δD mean agrees well with that reported by Smith *et al.* [1992] of -95‰ for recharge in the Amargosa Desert area, just southwest of the study site.

A local meteoric water line (LMWL) can be defined by a linear regression through the precipitation data and is shown in Figure 7 along with the weighted average values. This line is described by $\delta\text{D} = 6.26 \cdot \delta^{18}\text{O} - 15.3$. The difference between this locally derived line and the global water line is small over the range of isotopic values encountered at the study site.

The measured ^2H and ^{18}O content of soil waters and groundwater from PW-1, PW-2, and PW-3 are plotted against depth in Figures 8a-8c and 9a-9c, respectively. In the upper portions of each borehole, both oxygen and hydrogen are enriched in heavy isotopes. This enrichment is maximum near the soil surface and decreases rapidly with depth. Below 50 m the isotopic composition is fairly consistent with depth in PW-1 and PW-3; however, PW-2 shows some differences, including its minimum isotopic value at approximately 50 m and several excursions of enriched water at depths of 150 and 225 m. As the water table is approached, the soil water isotopic signature resembles the groundwater signature in all three wells.

The relation of the soil-water, precipitation, and groundwater isotopic signatures is shown in Figure 7. Two populations can be clearly identified in the soil-water isotopic compositions: samples collected from the land surface to about 16 m (and to almost 40 m in PW-1) that exhibit evaporative enrichment of ^{18}O relative to ^2H (defined here as "shallow soil water") and deeper samples that trend on a line parallel to the LMWL (defined here as "deep soil water"). As a group, the shallow soil waters define a line described by $\delta\text{D} = 3.6 \cdot \delta^{18}\text{O} - 65$ ($n = 45$, $R^2 = 0.99$). The isotopic enrichment of this sample group is inversely related to depth (Figures 8 and 9). The deep soil waters define a line described by $\delta\text{D} = 6.64 \cdot \delta^{18}\text{O} - 22$ ($n = 41$, $R^2 = 0.90$). The maximum and minimum along this deeper trend are defined by samples from PW-2, which has more variation in the composition of the deeper samples than either PW-1 or PW-3.

Shallow Soil-Water Isotopic Composition

The isotopic composition of recharge water is generally believed to be reasonably represented by the isotopic composition of the mean precipitation in an area [Gat, 1981]. For example, Yonge *et al.* [1985] found that the isotopic ratios measured in cave seepage water approximately reflected the mean annual precipitation for the region, weighted by the volume of individual storms. Groundwaters in some arid regions, however, have been shown to deviate from the isotopic composition of mean precipitation, with either enrichment or depletion in heavy isotopes. Enriched compositions generally plot along evaporation lines from the local precipitation, indicating that evaporative enrichment occurs during the recharge process, either from precipitation or surface water prior to infiltration or by evaporative loss from the soil zone. Depleted

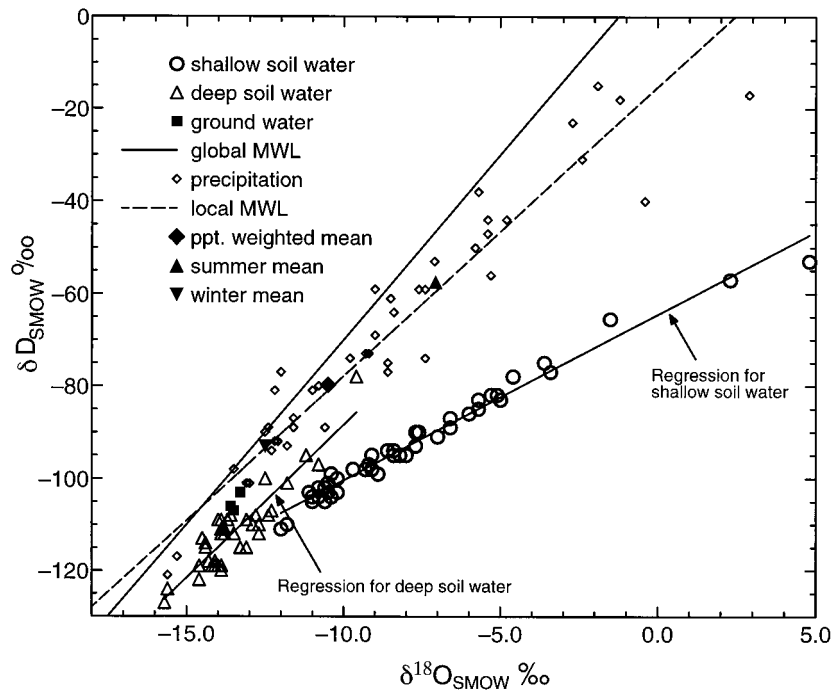


Figure 7. Stable isotopic concentrations of soil water, groundwater, and precipitation. Precipitation chemistry data consist of reported data from *Ingraham et al.* [1991] as well as additional samples analyzed during the present study.

groundwater relative to mean precipitation was found by *Vogel et al.* [1963] and *Vogel and Van Urk* [1975] and attributed to selective infiltration of rainfall from intense, large-volume, isotopically light rainfall events. Depleted values can also indicate infiltration of primarily cooler season precipitation. By com-

paring precipitation values and spring discharge in a desert range in California (Providence Mountains), *Smith et al.* [1992] concluded that most summer precipitation evaporates before reaching the groundwater and that recharge occurs mainly in winter. A study of southern Nevada precipitation and springs

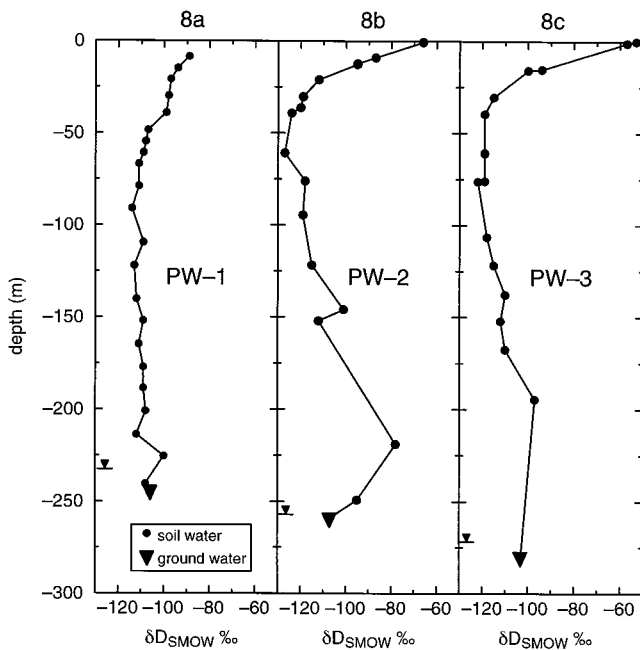


Figure 8. Soil water ^2H concentrations from boreholes PW-1, PW-2, and PW-3. Note the isotopic enrichment in the upper 25–35 m of each borehole, suggesting long-term evaporation. Solid triangle represents isotopic composition of groundwater.

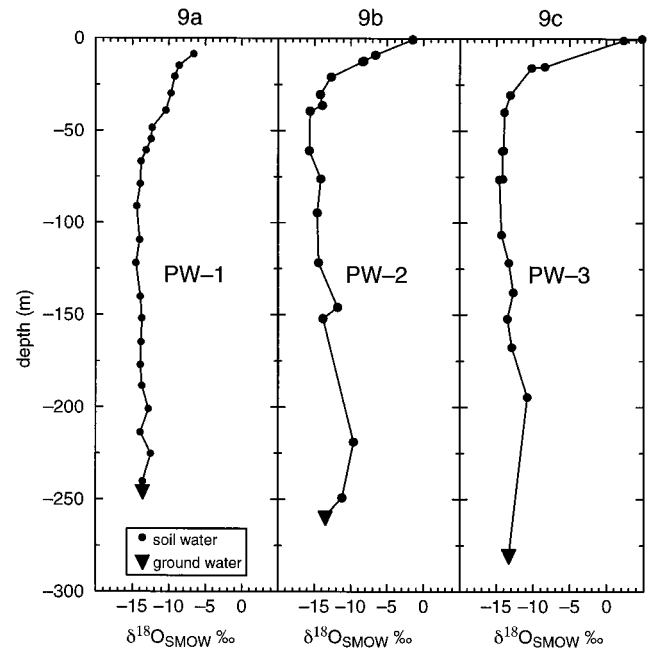


Figure 9. Soil water ^{18}O concentrations from boreholes PW-1, PW-2, and PW-3. Note the isotopic enrichment in the upper 25–35 m of each borehole, suggesting long-term evaporation. Solid triangle represents isotopic composition of groundwater.

[Ingraham *et al.*, 1991] concluded that both winter and summer precipitation events contributed to spring discharge in the NTS area, but that summer recharge occurred only as a result of exceptionally large precipitation events. One of the springs in the study is located approximately 13 km from our study area.

Several workers have established that direct rain infiltration and recharge is widespread in arid regions [Mazor *et al.*, 1974; Gat and Issar, 1974; Dincer *et al.*, 1974], but localized infiltration from runoff events, which may possess a different isotopic signature, can also be expected. Runoff from higher elevations, such as the adjacent Massachusetts Mountains (elevation 1,600 m), may introduce water of different isotopic signatures to lower elevation areas. Isotopic variation due to orographic effects on the NTS are generally small, however. An isotopic sampling station located 25 km north of the site at an elevation of 1,590 m had a mean weighted $\delta^{18}\text{O}$ composition of -11% , very similar to that measured at the site. Runoff events have been documented during all seasons, which, combined with the similar isotopic composition of precipitation at higher elevations, implies that modern infiltration can be represented by the weighted mean of the local precipitation ($\delta^{18}\text{O} = -10.5\%$, $\delta\text{D} = -80\%$).

The progressive enrichment in heavy isotopes near the land surface (Figures 8 and 9), coupled with the low slope of the shallow soil data (Figure 7), indicates that the enrichment is due to evaporation occurring in the shallow soil zone. Low slopes were determined by Allison [1982] to be typical for the isotopic relationship developed by evaporation from relatively dry soils. The evaporation line defined by the shallow soil data joins the deeper samples as well as the meteoric water line at an isotopic composition much more depleted than both the modern precipitation mean and the mean of modern winter precipitation. This implies that the soil water, as well as groundwater, was infiltrated under previous climatic conditions, in concurrence with the soil chloride and ^{36}Cl results. The only evidence of current infiltration may be found in the three samples collected within 1 m of the surface at PW-2 and PW-3. A line formed by the samples from 7.5 cm and 91 cm in PW-3 and 60 cm in PW-2 intersects the LMWL between the weighted mean precipitation value and the weighted mean for winter precipitation. It is logical that these three very shallow samples represent current infiltration affected by evaporation under the present climate. This is also supported by the high water potentials, abundant root distribution, low chloride concentration found in the upper 1 to 2 m of the soil profile, and the shallow penetration of ^{36}Cl bomb pulse [REECO, 1994]. The timing of sampling of the PW series boreholes also coincided or directly followed the unusual wet spring of 1992, further supporting the conclusion that the shallowest soil water isotope samples are derived from modern precipitation. This infiltration does not penetrate to 3 m, the next most shallow sample available.

The effects of evaporation on the soil water isotopic composition can be seen to a depth of 39 m in PW-1, 8.5 m in PW-2, and 16 m in PW-3. However, it is not possible to distinguish between enrichment caused directly by evaporation and enrichment attributable to mixing between shallow, evaporated water and deeper soil water. Downward movement of the evaporative signature will occur under diffusive gradients but could also be accelerated by advective movement during brief periods of infiltration. In a diffusion-dominated system the isotope profile reaches a steady state, balanced by downward diffusion and upward evaporation. The characteristic

depth of the diffusion profile is defined by the ratio of the combined liquid and vapor diffusivity to the evaporation rate. The great depth of the evaporative signature suggests a low evaporation rate, ranging from 0.2 to 1.0 mm/yr, using the approach of Barnes and Allison [1983], considering both liquid and vapor phase diffusion [Walker *et al.*, 1988; Cook *et al.*, 1992]. The diffusion calculations assumed a liquid-phase tortuosity of 0.2 and a gas-phase tortuosity of 0.45, resulting in an effective diffusion coefficient ($D_e + D_v$) ranging from 0.0025 to 0.003 m^2/yr , depending on water content. The total porosity used was 0.37, and a soil humidity of 0.99 was assumed for the vapor diffusivity. The upward evaporation rate is higher than that calculated for the geothermally driven vapor flux (0.019 mm/yr, from Detty *et al.*, [1993]) and may reflect enhanced drying owing to seasonal temperature gradients and an upward liquid flow component in addition to the geothermal gradient.

The depth of the observed isotopic enrichment implies a very long time of development. A simple estimate of the time required for these profiles to develop can be obtained by assuming a purely diffusional transport of isotopes from the evaporating front at the land surface through the underlying vadose zone and neglecting any advection due to evaporation. The upper boundary is taken to be constant and equal to that of the observed enriched concentration found at the soil surface while the rest of the profile initially has the concentration currently found at the water table. Solution of the diffusion equation for these boundary and initial conditions was calculated using the diffusion parameters described above. For borehole PW-2 these calculations result in an estimate of 20 to 30 kyr needed for the development of the observed isotope profile in PW-2. This time period agrees well with the chloride age dates of the soil water, suggesting that the soil profile has not experienced any significant infiltration events since the last time of groundwater recharge at the end of the Pleistocene. Calculations for PW-3 yield larger estimates of up to 60 kyr for diffusional profile development due to the deeper penetration of the enriched isotopic signature. The isotope profile at PW-1 does not exhibit the exponential shape expected for diffusion-dominated profiles, nor were sufficient shallow samples available to accurately fit the diffusion solution.

Although the above calculations provide a general range of time needed to develop such deep enriched profiles, application of a diffusion model is a simplification. Deep infiltration events may occur in response to short-term periods of increased rainfall and runoff that are not necessarily associated with major climate changes. Such infiltration would tend to carry the enriched water to depth, resulting in a diffuse profile. Occasional deep infiltration would increase the depth of enriched isotopes in the profile, and the estimated diffusion times would represent a maximum time of development.

Deep Soil-Water Isotope Profile

Soil-water data below the zone of evaporative enrichment record infiltration that must have occurred under past climate conditions. Similarity of the slopes of the current LMWL and the trend of the deep soil data suggests that recharge in the past was from moisture sources the same as those at present, although at a cooler temperature. The displacement of the soil trend to the right of the LMWL may reflect slight evaporation during infiltration, as suggested by Allison *et al.* [1984]. The spread in composition of the deep soil water data as shown in Figure 7 may be due to the preservation of "packets" of water infiltrated under slightly different, but still pluvial, climates.

Three packets are definable in the PW-2 profile: one containing the most depleted water in the soil profile, located just below the enriched zone and extending to at least 61 m below land surface; a section containing soil water with an intermediate composition (δD of -112 to -119‰) from 61 to 152 m; and then a more enriched bulge deeper in the profile containing water with an isotopic composition comparable to the current precipitation weighted mean. All of the profiles share the presence of enriched water to varying degrees at depth. These enriched values do not deviate from the deep soil water trend and are therefore not suggestive of evaporation from drying by the low-humidity air used during drilling, although this cannot be ruled out conclusively. Because they do not appear evaporated, their enrichment may be indicative of recharge under warmer climatic conditions or precipitation patterns dominated by summer precipitation.

The presence and persistence of these deep isotopic variations are somewhat surprising, given the estimated ages of the soil water deep in the vadose zone. However, these variations, or lack thereof, can be used to support the relative ages of soil water in the three boreholes. Both PW-1 and PW-3 show only modest variation in the distribution of ^2H and ^{18}O below approximately 100 m (see Figures 8 and 9). The chloride age dates for these deep waters are up to 110 ka. In contrast, PW-2, with its chloride age of only 20 to 35 kyr, shows significant departures at depths of approximately 150 m and 225 to 250 m, as well as a much more pronounced minimum at 50 to 60 m. The persistence of these departures is consistent with the chloride data, as the soil water in PW-2 may be much younger with less time to diffuse these pulses than both PW-1 and PW-3.

Direct age dating can be done only if the diffusive and advective constants (vapor diffusivity, thermal vapor diffusivity, liquid diffusivity, etc.) are known. However, by using reasonable estimates of diffusion constants, recharge rates, and input time periods, estimates of persistence times for pulses of isotopically different water can be made. Using the approach of Cook *et al.* [1992], the persistence time, t_p , can be calculated as

$$t_p \approx \frac{t_i^2 R^2}{D \pi^2 \theta_e^2} \ln \left[\frac{4f}{\pi} \right] \quad (3)$$

where t_i is the timescale of the isotopically different recharge; R , the recharge rate during that time; D , the effective diffusion coefficient (including both vapor and liquid components); θ_e , the water content; and f , a factor chosen to express the reduction in concentration over the persistence period. For the calculation of persistence time the reduction factor used was 5.0 [Cook *et al.*, 1992]. A single value for volumetric water content (0.10), representative of the deep soils at the site and the other parameters were as described previously, was used, resulting in an effective diffusion coefficient of $0.003 \text{ m}^2/\text{yr}$ for combined liquid and vapor diffusion. Using a recharge rate of $10 \text{ mm}/\text{yr}$ (roughly the rate suggested by the chloride concentrations at depth) and an input signal lasting 200 years (reflecting a short-term climate shift), the persistence time for the resulting 20-m-wide isotope pulse is 25,000 years. Such a signal could reasonably be preserved in the PW-2 profile, but would be lost from PW-1 and PW-3 if the waters are as old as predicted by the chloride profiles. The small isotopic variations seen deep in the PW-1 and PW-3 profiles may be the remnants of larger pulses, either recharged during periods of higher recharge rates or for longer periods of time (>500 years).

The groundwater collected from the PW series boreholes is significantly depleted in the heavy isotopes as compared to

both the weighted mean of current precipitation and the weighted mean of winter-only precipitation. The depletion is large enough ($>10\text{‰}$ in δD even as compared to the winter values) to strongly indicate that the groundwater was recharged under previous climatic conditions. Either these conditions would have been cooler, or more precipitation would have fallen in the cooler months, or both. This coincides with estimates of conditions in the southern Great Basin during the last glacial interval and that prior to Termination II. The source of much of the aquifer recharge may not have been derived from the overlying vadose zone, however, as the chloride concentrations in the soil water are elevated slightly over the groundwater.

Carbon 14 Age Dating of Groundwater and Soil Water

Carbon 14 was used to date both groundwater and soil water from the site. Groundwater sampling was conducted with a low-volume piston pump to collect a large-volume sample (100 L), with the carbon precipitated within 24 hours as strontium carbonate. Two samples each were collected from PW-1 and PW-2, separated by several months, and one sample from PW-3. The samples from PW-1 differed markedly from one another at $21.2 \pm 1\%$ and $14.4 \pm 0.4\%$ modern carbon (PMC) (12,800 and 16,000 radiocarbon years, respectively). The two samples from PW-2 agreed closely with each other at 27.1 ± 0.4 and 28.4 ± 1.6 PMC. This gives an uncorrected ^{14}C age of approximately 10,500 radiocarbon years. The hydrogeologic setting and repeatability of the PW-2 samples argue against a temporal change in ^{14}C in PW-1 between samplings. Given that sample contamination by atmospheric CO_2 is more likely than contamination by dead carbon, the older age is considered more accurate. PW-3 contained 17.1 ± 0.4 PMC, yielding a radiocarbon age of approximately 14,500 years. These ages are consistent with ages reported from other wells in Frenchman Flat [Byer, 1991]. Carbon 13 (^{13}C) varied from δ values (as referenced to PDB) of -7.9 to -7.3‰ .

All of the groundwater ages imply recharge during the late Wisconsinan, contrary to the chloride ages of soil water in PW-1 and PW-3. The discrepancy may be evidence that groundwater recharge in the Frenchman Flat basin is not always evenly distributed spatially. Recharge to the aquifer is likely to have occurred in the surrounding highlands and along ephemeral streams where conditions are most conducive to recharge.

Age dating of arid-zone soil water via ^{14}C is only recently possible due to the small sample sizes that can be analyzed with a tandem accelerator. Samples were collected and stored in the identical fashion as the stable isotope samples. Soil water was extracted by washing the soil with a CO_2 -free water, created by boiling ultrapure distilled water. The washing and subsequent filtering and addition of strontium carbonate and sodium hydroxide were performed under a nitrogen atmosphere. The resultant precipitate was split, with part retained for ^{13}C determination, and part sent with an aliquot of wash water to Lawrence Livermore National Laboratory for ^{14}C analysis. The wash water was found to retain 0.5 to $1 \text{ mg}/\text{L}$ HCO_3^- . This bicarbonate was assigned a ^{14}C concentration of 111 PMC and corrected from the soil wash analysis. Of greater concern is the possibility for contamination from the drilling air. For the deeper PW boreholes, generally more drilling air and difficulties were encountered which could have led to significant con-

tamination of the samples. As with the stable oxygen and hydrogen isotopes, there is no systematic difference between the samples collected during auger drilling at ST-1 and those collected during drilling with air in the PW holes (in both cases, the samples were collected by driving a core barrel ahead of the drill bit). However, ^{14}C is expected to be more sensitive to contamination problems than the stable isotopes because it is present in trace quantities. If contamination were to have occurred, the ^{14}C composition of the soil water would be shifted toward the modern value.

A total of five soil-water samples were analyzed; however, the results are not consistent with piston flow from the surface to the water table. For example, the sample collected at 30 m from PW-2 had 13 PMC, while a sample from 146 m in the same well had 19 PMC. The highest ^{14}C concentration, 25 PMC, was found in a sample from 54 m in PW-1. Two samples collected from near the same depth in ST-1 (at 30.8 and 33.5 m) agreed fairly well with 17 and 19 PMC, respectively.

The ^{14}C concentrations in PW-1 and ST-1 lead to soil-water ages (11,000 to 15,000 radiocarbon years) much younger than those indicated by the chloride accumulation, but the ages at PW-2 are in general agreement (14,000 to 17,000 radiocarbon years), well within the uncertainty of the chloride method. Though the discrepancy at PW-1 could be a result of inappropriate assumptions for the chloride calculations such as the presence of nonpiston flow, it is also likely that the ^{14}C content is not an accurate indicator of soil-water residence time. Diffusion of gaseous CO_2 through the unsaturated zone was shown to be an important transport mechanism by *Thorstenon et al.* [1983] and results in apparent ^{14}C ages much younger than the actual soil-water residence time. Calculations for ^{14}C diffusion in these soils using representative diffusion and exchange coefficients indicate that significant addition of atmospheric ^{14}C is likely. The interpretation of the soil-water ^{14}C data with respect to the other chemical and isotopic indicators must await continued research into the processes controlling gaseous carbon diffusion in the unsaturated zone.

Relation Between Paleoclimate and Borehole Tracers

The tracer data from the three boreholes show distinct similarities as well as major differences in their response to climatic changes. Each of the boreholes displays the characteristic chloride "bulge" and enriched isotopes found in many arid vadose zones having little or no current recharge [*Phillips*, 1994]. Prior to the beginning of the accumulation phase, the vadose zone appears to have experienced a period of areally widespread recharge to the water table to produce the low concentrations currently found at depth. Boreholes PW-1 and PW-3 both show a long duration of chloride accumulation (approximately 100 to 120 kyr) broken by a period of downward advective transport represented by a secondary chloride peak centered at 40 and 85 m, respectively. Based on chloride age dating and a simple model of dispersive transport, the timing of onset of the advective phase was approximately 40 to 50 ka. Stable isotopic profiles from these boreholes indicate net upward movement in the shallow soil zone (ranging from 8.5 to 39 m), owing to evapotranspiration and thermal gradients. The depletion of the isotopic composition of the deep soil water as compared to the current precipitation indicates that the soil waters infiltrated during a colder period when the precipitation was depleted in heavy isotopes. The only soil

water resembling current precipitation is found in the upper 0.9 m of the vadose zone. The ^{36}Cl in all soil waters below the root zone shows enrichment compared to modern values, indicative of water infiltrated during times of a weaker geomagnetic field.

In contrast to these boreholes, PW-2 shows a much shorter duration of chloride accumulation, representing only the last 20 to 30 kyr. Chloride concentrations deep in the profile indicate a previous period of recharge. The isotopic profile is similar to the other boreholes, although once below the upper enriched section, the profile exhibits greater variation in isotopic concentration than either PW-1 or PW-3. These major differences in hydrologic responses and timing of events cannot be logically assigned to any climatic differences, as the boreholes are within 3 km of one another and differ in elevation by less than 40 m. Other evidence must be investigated to explain the tracer distributions. We first develop a simple chronology of events based on the inferred climatic history of the region over the last 150 kyr.

Figure 10 summarizes the general climatic trends in moisture as inferred from the paleoclimatic indicators in the region. Between 150 and 120 ka, the global climate record indicates a major transition (Termination II) from a full glacial maximum. Locally, the period was marked by a general warming, an increase in pluvial lake areas [*Smith*, 1987; *Jannick et al.*, 1991], and a period of significant groundwater recharge. From this time to the next glacial maximum at 18 ka the region experienced a general cooling. Several records (Browns Room and marsh deposits) also indicate moist conditions predominating up to 40 ka. Precipitation along with maximum cooling culminated at around 18 ka. As in the previous glacial maximum, pluvial lakes reached their maximum at or slightly after this termination.

The implications to vadose zone flux from these broad climatic regimes are significant and correlate well with the tracer data presented. At the time of Termination II (approximately 120 ka), precipitation was high and vegetation may have been in a transition phase. Opportunity for recharge at all three boreholes would have been high. This is the approximate age calculated for the accumulations of chloride found in both PW-1 and PW-3. After this period, recharge significantly decreased or ceased through the vadose zone at PW-1 and PW-3 with chloride beginning to accumulate. The flux conditions at PW-2 cannot be determined, owing to complete flushing of the profile at a much later time.

The period of advective transport responsible for the secondary bulges at PW-1 and PW-3 has been calculated to begin at 40 and 50 ka, respectively, based on the chloride ages of the soil water, but the data were not sufficient to estimate when this phase ended. Several of the paleoclimatic indicators suggest that this period was moist, although not to the same magnitude as the period from 15 to 35 ka. This aborted recharge event through the vadose zone was then followed by a chloride accumulation phase (that continues to this time), indicating an ending to recharge. The timing of the cessation of recharge at PW-2 is later, in the range of 20 to 30 ka. This period is recognized by all of the paleoclimate indicators as a major pluvial period. The disparity in timing of these events in the vadose zone may indicate that the recharging event lasted from 50 to 20 ka, and/or the age difference may be due to residual chloride in the upper portions of the vadose zone in both PW-1 and PW-3.

If the above hypothesis is correct, then the timing of re-

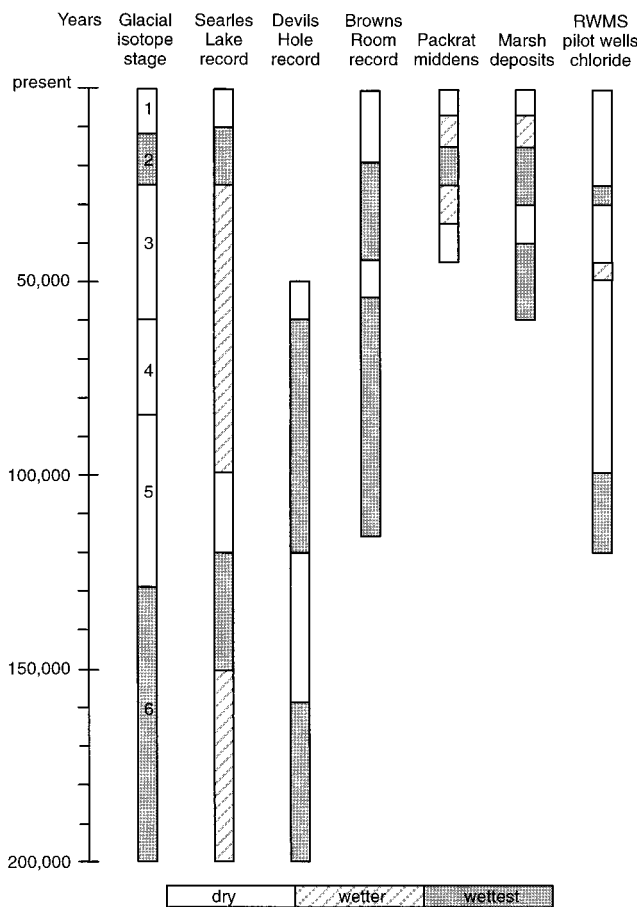


Figure 10. Summary of interpretations from paleoclimatic indicators. Glacial isotope stages are those from the marine $\delta^{18}\text{O}$ record. Our assignment of “wettest” corresponds to glacial maximum stages, when regional climates are often interpreted as cooler and wetter. The Searles Lake record is as reported by Jannick *et al.* [1991]. Periods of overflow are designated here as “wettest,” with fluctuating lake levels designated as “wetter” than present. The Devils Hole record is from Winograd *et al.* [1988], with “wettest” periods corresponding to their periods of short groundwater residence time. The Browns Room record shows the water table fluctuations in a room of Devils Hole reported by Szabo *et al.* [1994]. The packrat midden record includes the plant fossil interpretations of Spaulding [1985], with “wettest” corresponding to his interpretation of late Wisconsin full glacial conditions and “wetter” coinciding with periods of increasing and decreasing effective moisture before and after. The marsh deposit record is from Quade [1986], with “wettest” periods coinciding with widespread standing water at groundwater discharge locations south of the RWMS. The RWMS pilot well record summarizes the chloride results presented in this paper. “Wettest” periods correspond to the flushing of chloride from PW-1 and PW-3 profiles (100 to 120 ka) and from PW-2 (24 to 30 ka). “Wetter” corresponds to the aborted flushing of the secondary chloride bulge in PW-1 and PW-3, assumed to have occurred at approximately 50 ka.

charge and aborted recharge corresponds to the period of pluvial conditions in the mid-Wisconsinan to late Wisconsinan glaciation between 15 and 30 ka. Following this period, the vadose zone at each borehole responded to the more xeric environment, and the evapotranspiration requirements utilized most of the precipitation. Recharge continued in favorable

environments, perhaps along washes and at upland margins, as indicated by the younger ^{14}C ages of the regional groundwater; however, the vadose zone sampled at this lower elevation became effectively isolated from the underlying groundwater. Szabo *et al.* [1994] also found reasonable correlation between Great Basin paleoclimate records and water level fluctuations at Browns Room. Similar to the record from Browns Room, our vadose zone record contains no indication of increased infiltration subsequent to the last glacial maximum, despite records of intermittent high lake levels in other parts of the Great Basin near the Pleistocene-Holocene boundary.

While the timing of events can be reasonably correlated between the boreholes, the issue of the apparent spatial variability in recharge remains. During the last glacial maximum, significant recharge to the water table appears to have occurred only at PW-2. At the other two boreholes, infiltration was only able to move 40 to 80 m. Although the boreholes are close in proximity, there are several differences that may have led to different responses to the same climatic forcing.

Textural and hydraulic properties measured on cores from the three boreholes show slight but consistent differences. Of the three boreholes, cores and cuttings from PW-1 have the lowest average percentage of <200 mesh (74 μm) size particles, while PW-2 contains the highest percentage [REECO, 1994]. The difference is not readily explained, as PW-1 is located on the more distal portion of the Halfpint alluvial fan than is PW-2. However, the vadose zones of all three boreholes are derived from several alluvial fan systems with some significant differences in catchment size and in source rock, ranging from Tertiary volcanics to Paleozoic carbonates [Snyder *et al.*, 1994]. During the deposition of the vadose zone material, the relative dominance of any one of these sources has undoubtedly shifted with time. As a result, the underlying sediment sorting and distribution may not follow the current surface topography.

These slight differences in texture are also manifested in the differences in saturated conductivity measured on cores from the various boreholes. The saturated hydraulic conductivities from the upper 60 m of PW-2 are generally less than those found at similar depths in PW-1 [Sully *et al.*, 1993]. While the saturated conductivities may be greater at PW-1, this may indicate that the unsaturated conductivity in PW-1 may be less than that in PW-2 at the same water potential. Under these conditions, infiltrating water would move more slowly at PW-1 and could remain near the surface, where evapotranspiration may remove much of the water. As a result, net infiltration could be significantly reduced. In contrast, the higher unsaturated conductivity at PW-2, under the conditions of a wetter climate, may have allowed a deeper penetration of surface moisture beyond the reach of vegetation and evaporation.

Perhaps a more significant influence on recharge mechanisms in arid regions is surface topography [Allison *et al.*, 1994]. In arid regions, local ponding or concentration of runoff can be a major factor in controlling the magnitude of recharge. In particular, channelization of flow across the alluvial surfaces may lead to increased recharge. Surficial mapping and aerial photography of the fan surfaces have revealed the presence of a major lineament that crosses the PW-2 drill site from northeast to southwest [Carr *et al.*, 1967; Miller *et al.*, 1993]. Detailed trenching across this lineament in several locales has revealed no evidence of fault control, however. The likely explanation for the formation of this lineament is that it is associated with the alluvial fan morphology. At present, the western edge of

the Halfpint alluvial fan is coincident with this lineament. Coalescing alluvial fans emanating from the Massachusetts Mountains to the west intersect the western edge of the Halfpint alluvial fan, concentrating overland flow within a well-defined channelized zone along the lineament. At the PW-2 drill site a small confined active channel is presently located within 20 m of the PW-2 borehole. Field evidence also suggests that the edge of a series of older fans from the north also delineated this feature in the past [Snyder *et al.*, 1994], implying a consistency in enhanced runoff. During times of increased runoff it is probable that this feature would result in more frequent flooding of the area adjacent to borehole PW-2 and therefore increase the likelihood of recharge.

In contrast, no such flow-concentrating mechanism currently exists at either PW-1 or PW-3. The drill site of PW-1 lies on the more distal portions of the Halfpint alluvial fan and shows no evidence of channelized flow. The drill site of PW-3 lies on coalescing alluvial fans emanating from the Massachusetts Mountains. The drainage areas for these fans are smaller than that for the Halfpint fan and therefore does not supply the same volume of water for runoff and recharge. As at PW-1, there is no evidence of recurrent channel flow at the PW-3 drill site.

The importance of topography and channel control on recharge is further supported by recent shallow drilling around the perimeter of the RWMS. Boreholes drilled to depths of 80 m in clearly defined channels showed significantly less accumulated chloride and enriched isotopic concentration than those boreholes drilled in the interfluvial areas. Such topographic features may be contributing recharge under the modern climate and are important hydrologic features to be considered in the design of waste disposal facilities.

Conclusions

The data presented represent the first use of very deep (>230 m) vadose zone borehole data to reconstruct paleohydrologic behavior. The results presented suggest that a variety of soil-water tracers are needed to reconstruct the paleohydrology of the vadose zone. Both soil-water chloride and ^{36}Cl clearly show that the soil waters were infiltrated during the late Pleistocene. The stable isotopic composition of the soil water demonstrates that recharge is not occurring under present climatic conditions at the deep boreholes and that the timescales needed for isotopic profile development are consistent with late Pleistocene recharge. Carbon 14 analysis of ground-water supports this conclusion, while soil-water ^{14}C shows the effect of gaseous diffusion. Local-scale heterogeneity in topography and soil texture also play a role in the magnitude of the vadose zone response to climate change. The vadose zone at the study site has responded to the major climatic shifts of the last 120 ka. Recharge is evident under more pluvial climates, most likely prior to full glacial maximum conditions at approximately 20 and 120 ka, when other indicators suggest general pluvials. The nature and extent of the pluvial at 120 ka were sufficient to induce recharge even in the lowest portions of the basin. The most recent pluvial, however, may not have been sufficient to induce deep infiltration everywhere, and recharge to the water table was not widespread. During this last period, recharge was controlled not only by climate, but also by surface geomorphology in which a drainage channel may have brought more surface water to the area above borehole PW-2. Soil textural differences which define the unsaturated hydraulic

conductivity may also have played a role in determining the spatial distribution of recharge.

The strong correlation between climate and recharge in arid settings is clearly shown in the data from this site. Borehole profiles document up to 120,000 years of climate history and vadose zone response. The secondary chloride bulges represent the first known observations of aborted recharge during this period. Preservation of these responses is due to the low rates of diffusion and dispersion of the tracers in the extremely dry soil, the deep water table and the continuity of the sedimentary sequence. Such attributes are similar to those found in the deep ice core records. These data represent the first use of deep vadose zones to infer climatic histories over timescales commensurate with the detailed ice core records from Greenland and the Antarctic. The site drilled represents one of the more shallow vadose zones in the southern Great Basin [Wingrad, 1981] and clearly opens the possibility for other records to be developed using the drilling and tracer technologies developed in this current effort.

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