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ISOTOPIC INVESTIGATION OF RECHARGE TO A REGIONAL GROUNDWATER FLOW SYSTEM, GREAT BASIN, NEVADA, USA

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Abstract

Groundwater recharge processes were investigated in central Nevada by examining the relationships between the stable isotope (δD and $\delta^{18}O$) compositions of snowfall, snowmelt, alpine spring waters, and regional groundwaters. Snowmelt infiltration is inferred to be the dominant source of groundwater recharge in this region. Bulk snow cores collected throughout central Nevada near the time of maximum accumulation have δD-$\delta^{18}O$ pairs that plot subparallel to the global meteoric water line (GMWL), but have negative *d*-values, implying kinetic isotope enrichments. Heavy isotope enrichments occur at the base of snowpacks due to fractionation during snow metamorphism, sometimes resulting in remarkably systematic isotopic variations. Ice crystals in the soil immediately beneath the snowpack can be strongly depleted in heavy isotopes relative to the overlying snow, implying fractionation or exchange with the snowpack. Late season ablation processes tend to homogenize isotopic variations between snowpack layers, and cause the bulk isotopic composition of the snowpack to become enriched in ^{18}O by 2-3‰ relative to the composition during peak accumulation. The dynamic evolution of the snowpack and snowmelt isotopic compositions over time makes it difficult to directly ascertain groundwater recharge compositions without careful mass balance measurements. Preliminary evidence suggests that small local springs may be reasonable indicators of the integrated isotopic value of the snowmelt recharge in a particular area. Springs and snowmelt runoff samples collected throughout central Nevada during the peak runoff plot along a least squares regression line with the equation $\delta D = 7.3\delta^{18}O - 7$, which is similar to the line obtained for 28 metamorphosed snow cores collected during peak accumulation ($\delta D = 7.5\delta^{18}O - 3$). These results suggest that kinetic fractionation processes during snow metamorphism and ablation may largely account for the low *d*-values that are widely observed in groundwaters from both local and regional flow systems in Nevada.

1. INTRODUCTION

The state of Nevada receives the lowest annual amount of precipitation of the fifty United States, but currently has the highest rate of population growth. The lack of reliable surface water supplies in Nevada implies that future development will depend largely on the extraction of deep groundwater from desert basins. For this reason, it is of vital interest to develop an understanding of the sources and mechanisms for groundwater recharge in this region. Summer convective storms account for approximately one third of the annual precipitation in central and southern Nevada. However, these storms are typically of short duration and limited areal extent. High evapotranspiration

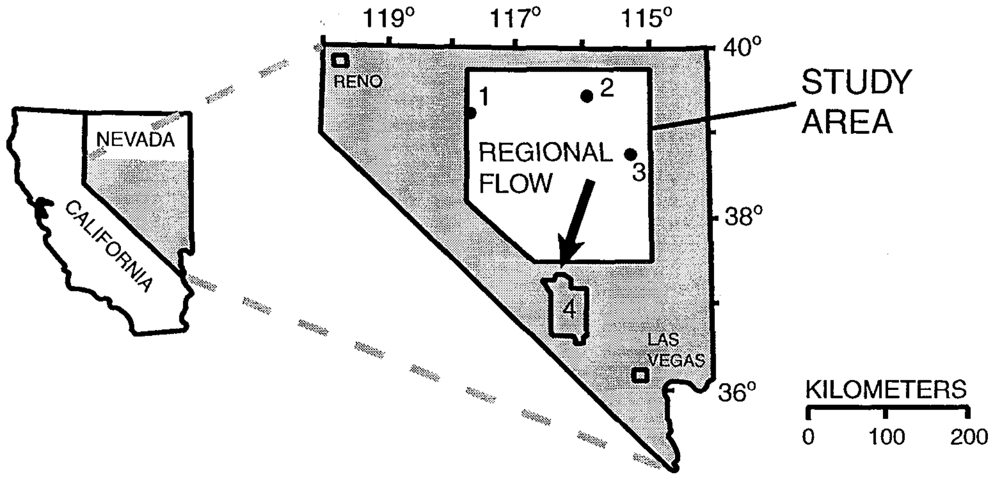

Fig. 1. Location of study area. Numbered features correspond to locations discussed in the text: (1) Carroll Summit; (2) Pinto Summit; (3) Currant Summit; (4) Nevada Test Site.

rates during the summer coupled with long infiltration pathways to the water table generally limit summer recharge contributions. In contrast, winter frontal systems normally deposit more than half of the annual precipitation as snowfall, producing relatively large accumulations in alpine areas. The alpine snowpacks are rapidly melted in the spring and early summer, accounting for a majority of the annual groundwater recharge budget. A recent study [1] comparing the stable isotope signatures of spring water and precipitation in the mountains near Las Vegas, Nevada concluded that spring snowmelt accounts for up to 90% of all groundwater recharge in this region. A comparable study in Arizona drew similar conclusions regarding the importance of recharge from snowmelt [2].

This paper discusses the results of a regional survey of the stable isotope compositions of winter snowpacks in central Nevada. The study area is inferred to be the principal recharge center for a regional aquifer system that extends >200 km from mountainous regions in central Nevada to the low desert along the Nevada-California border (Fig. 1). We focus in this report on (1) understanding the processes that influence the isotopic composition of the snowpack over time; (2) comparing the δD and $\delta^{18}O$ compositions of the snowpack with those of alpine spring waters, snowmelt runoff and regional groundwaters; and (3) relating the low deuterium excess values (or *d*-values) observed in groundwaters to processes that occur during snow metamorphism and ablation.

2. HYDROGEOLOGIC SETTING

The Great Basin province encompasses a 360,000 km^2 area, largely in Nevada and western Utah, characterized by subparallel north-south trending mountain ranges separated by alluvial and fluviolacustrine basins [3]. The arid nature of this hydrologically closed basin is largely a result of the rain shadow effect of the Sierra Nevada range, which inhibits the prevailing westerly winds from carrying large amounts of moisture inland from the Pacific Ocean. Regional groundwater flow systems of the Great Basin are typified by fracture-dominated flow through thick sequences of carbonate and volcanic rocks, driven by hydraulic gradients that are laterally continuous over hundreds of kilometers [3-5]. Davisson et al. [6] observed that these regional flow systems are characterized by systematic increases in $\delta^{18}O$ values with decreasing latitude, in the direction of southward regional flow. The increase in $\delta^{18}O$ along the flow path was interpreted to indicate gradual mixing with ^{18}O-enriched recharge at progressively lower latitudes. At latitudes south of ~38°N, annual precipitation rates in Nevada are low (generally <25 cm yr^{-1}) and regional groundwaters typically have $\delta^{18}O$ values that are 2-3‰ depleted in heavy isotopes relative to local recharge. Most of these regional groundwaters also exhibit low *d*-values relative to the global meteoric water line (GMWL; $\delta D = 8\delta^{18}O + 10$) [7], and thus plot below the line. The low *d*-values, coupled with the conspicuous difference between the stable isotope values of deep groundwater and local precipitation, led several researchers to conclude that the isotopically-depleted groundwaters in southern Nevada were locally recharged under cooler paleoclimatic conditions [e.g., 8, 9].

From a practical standpoint, determining the relative abundance of recharge from these different sources is a critical issue with regard to interpreting groundwater flow patterns through the U.S. Department of Energy's Nevada Test Site (NTS). The NTS was the location for more than 800 underground nuclear tests conducted by the United States between 1956 and 1992 [10]. The recent discovery of colloidal transport of actinides in NTS groundwater [11] has underscored the need for a more comprehensive understanding of the flow system in this region. For this reason, a research program has been initiated to evaluate recharge processes and flowpaths related to regional groundwater flow. Precipitation patterns in Nevada suggest that most of the significant recharge to the regional flow system occurs between latitudes 38 and 40°N, primarily in alpine areas that may receive over 50 cm yr^{-1} of precipitation [12]. A majority of this precipitation occurs during the winter months as snowfall.

3. STABLE ISOTOPE VARIATIONS IN SNOW PACKS

Snow core samples were collected at 28 locations over a broad region of central Nevada (latitude 37°30' to 39°45'N; longitude 115° to 117°45'W) during early March 1998, and from selected locations in late April 1998 and early March 1999. The 1997-1998 winter season was characterized by a strong El Niño-Southern Oscillation influence that produced heavier than average precipitation rates in Nevada [13]. In contrast, winter storms were less frequent during the 1998-1999 season, and snowpack depths measured in March 1999 were typically less than half that of the 1997-1998 season.

3.1 Isotope effects during snow metamorphism

At the time of peak accumulation (March), most Nevada snowpacks showed physical evidence of snow metamorphism, such as the development of depth hoar and grain clusters [14]. Heat transfer from the ground to the overlying snowpack creates both temperature and vapor pressure gradients within the snowpack [15]. Under these conditions, mass transport and recrystallization processes are accompanied by isotopic fractionation effects [16] that can attenuate the initial isotopic variability of individual snow layers [17]. Recrystallization was especially pronounced in samples collected below 2,000 meters elevation, where the snowpacks tended to be thinner. The least-squares regression line

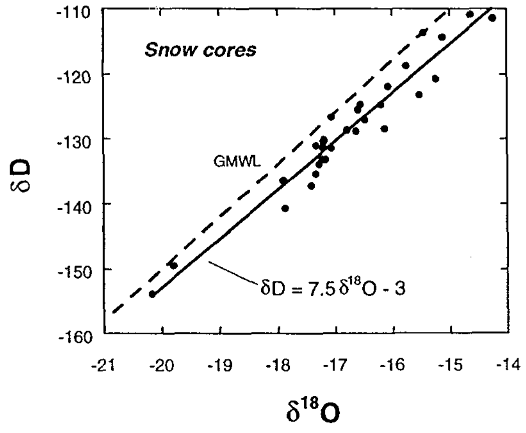

Fig. 2. Plot of δD-$\delta^{18}O$ pairs for snow core samples collected in central Nevada, March 1998.

for 28 bulk snow cores collected in March 1998 is $\delta D = 7.5\delta^{18}O - 3$ (Fig. 2). The negative *d*-value indicates the relative significance of kinetic isotope fractionation effects during aging of the snowpack. The effects of snow metamorphism are well illustrated by the isotopic results for the Currant Summit snowpack (38°49'N, 115°17'W, elevation 2130 m) sampled in March 1999 (Fig. 3). The $\delta^{18}O$ values of individual layers decrease systematically from -11‰ at the base to -18‰ at 19 cm above the base, then abruptly shift toward isotopically heavier values in the top 4 cm of the snowpack (Fig. 3a). On a plot of $\delta^{18}O$ versus δD (Fig. 3b), samples from the base of the snowpack are enriched in both $\delta^{18}O$ and δD and lie along a slope of 3.8, whereas samples from the upper part of the snowpack plot relatively close to the GMWL.

Isotopic enrichment effects associated with snowpack aging and depth hoar formation have been widely documented [e.g., 18-20]. Friedman et al. [16] suggested that isotopic fractionation during snow metamorphism is related to two processes: the change of state from solid to vapor, and molecular diffusion during vapor transport. The fractional condensation of water vapor derived from sublimation onto growing snow crystals favors enrichment in the molecules with the lowest vapor pressure (i.e. the heavier molecules), possibly resulting in δD-$\delta^{18}O$ slopes >8 when this process is dominant [16]. In contrast, molecular diffusion during simple loss of water vapor will result in kinetic fractionations with low slope δD-$\delta^{18}O$ trajectories near 2. The results in Fig. 3 suggest these fractionation processes operate simultaneously, and that one process may dominate over the other in different parts of the snowpack. The presence of a dense ice layer near the top of the Currant Summit snowpack (Fig. 3a) probably reflects partial melting and refreezing from solar heating, or possibly a rain-on-snow event. If this ice layer created a barrier to atmospheric vapor exchange, it may help to explain the remarkably systematic isotopic variations observed in the lower part of the snowpack.

It is notable that ice crystals collected from the soil immediately beneath the snowpack are nearly 6‰ depleted in $\delta^{18}O$ relative to the basal snow layer (Fig. 3b). This effect was also observed at other locations. Friedman et al. [16] demonstrated that the transfer of water from the soil to the base of

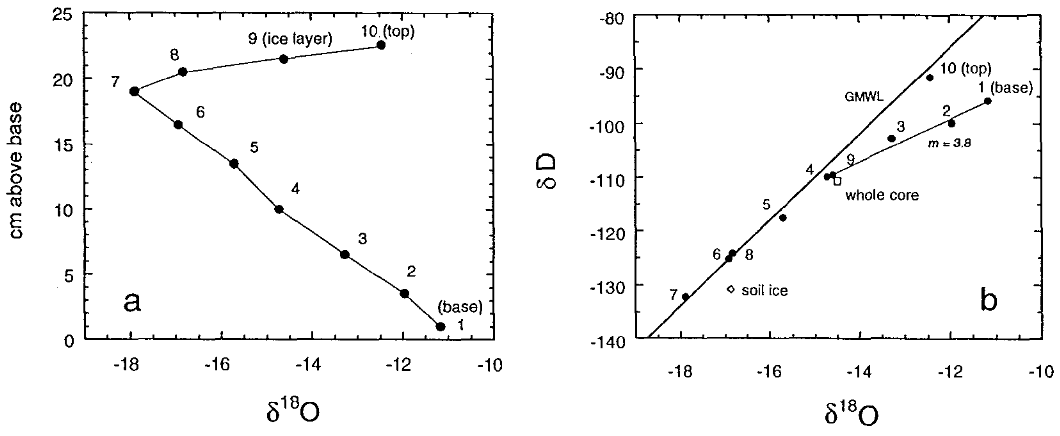

Fig. 3. Stable isotope data for Currant Summit snowpack, March 1999: (a) variation in $\delta^{18}O$ with stratigraphic position; (b) plot of δD versus $\delta^{18}O$ values.

the snowpack plays a part in enriching the snow in heavy isotopes. Our results indicate that the moisture remaining in the upper soil zone is isotopically fractionated during this process, or that the upper soil zone exchanges vapor with the base of the snowpack.

3.2 Isotope effects during snowpack melting

To investigate snowpack aging over time, five of the high elevation locations (2,100-2300 m) that were sampled in March 1998 were revisited during an intense melting period in late April 1998. Whereas the March snowpacks showed up to 5‰ variations in $\delta^{18}O$ between different layers, the variations in the April snowpacks were frequently less than 2‰. This homogenization of the snowpack probably reflects interactions between the percolating meltwater and snow [21, 22]. It was found that the top of the April snowpack was often slightly enriched in heavy isotopes relative to the base. This is in contrast to the March snowpack, when the base invariably had the heaviest isotopic values. The fractionation of stable isotopes between coexisting water and ice favors enrichment of the solid phase in heavy isotopes [23]. Given that snowpack ablation proceeds from the top downward, the isotopic enrichment at the top of the snowpack may in part reflect the preferential removal of light isotopes in the liquid phase during melting.

In general, the integrated (bulk) isotopic values for the April snowpacks were 2 to 3‰ heavier in $\delta^{18}O$ relative to their March counterparts. This enrichment process follows a δD-$\delta^{18}O$ trajectory with a slope that varies between 7 and 10. The observed isotopic enrichment in the residual snowpack must therefore be balanced by prior losses of light isotopes. It has been previously demonstrated that the light isotopes predominate in the initial stages of runoff, whereas the heavy isotope content of the runoff steadily increases with time [22, 24].

4. STABLE ISOTOPE VARIATIONS IN SURFACE RUNOFF AND GROUNDWATER

4.1 Isotope relationships between melting snow, local springs and runoff

During the April 1998 melting event, particular attention was given to obtaining samples of snowmelt runoff and spring water near the snowpack sampling locations. The objective was to determine the extent to which the meltwater inherits kinetic isotope enrichments from snow metamorphism and ablation. The δD-$\delta^{18}O$ results from two different sample locations are shown in Fig. 4. At Carroll Summit (39°16'N, 117°44'W, elevation 2270 m), the bulk composition of the snowpack evolved along a δD-$\delta^{18}O$ slope of 8.7 between March and April 1998 (Fig. 4a). Samples of snowmelt runoff, spring discharge and soil water collected in April are all shifted to the right of the GMWL relative to the snowpack, but plot on a colinear trend with a slope of near 8. This implies that each sample experienced a similar degree of kinetic isotopic enrichment.

The soil water sample from Carroll Summit was obtained by coring the upper 5 cm of water-saturated bare ground directly adjacent to the melting snowpack (Fig. 4a). The close proximity of the soil sample to the melting snowfield suggests the moisture was derived from recent snowmelt infiltration. The sample was stored in an airtight container, and moisture was subsequently extracted in the laboratory by centrifuging the sample. The slope of the line between the April snowpack and soil water isotopic values is ~5, indicating a kinetic enrichment process. In this case, the kinetic isotope enrichment in the meltwater does not appear to be related to the isotopic composition of the residual snow itself, but rather to evaporation processes occurring during ablation and infiltration. Evaporative losses of >10% were previously estimated by isotope mass balance calculations for meltwater directly intercepted by a snow lysimeter [20]. Additional evaporation probably occurs during the final stages of melting, when the snowfields tend to lie in discontinuous patches, and the soil surrounding the melting snow is completely saturated.

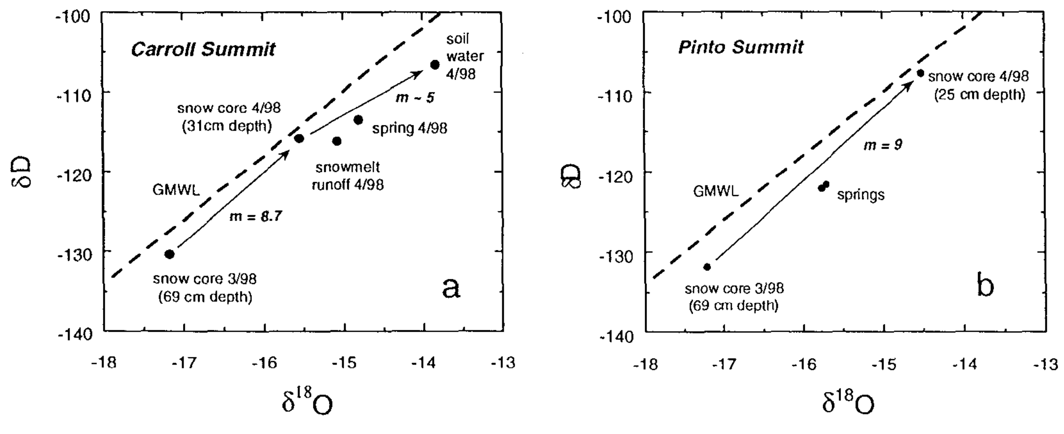

Fig. 4. Temporal variations in snowpack δD and $\delta^{18}O$ values compared to local meltwater and spring water isotope values: (a) Carroll Summit; (b) Pinto Summit.

Unlike the soil water sample, the runoff and spring water samples from Carroll Summit were not sampled immediately adjacent to the snow coring location, and cannot be directly related to the composition of the snowpack at that time. If these samples evolved along a kinetic enrichment slope similar to that of the soil water, they would be related to an earlier bulk snow isotopic composition lying on the evolution trend between the March and April snowpacks (Fig. 4a). We cannot rule out the possibility of an "older" groundwater component in the runoff and spring samples. However, the spring lies within 20 m of the summit elevation, and its ephemeral (seasonal) nature suggests that most of the discharge is probably related to recent infiltration.

Fig. 4b shows a δD-$\delta^{18}O$ plot for the March and April 1998 snow cores and two different springs from the Pinto Summit area (39°27'N, 115°56'W, elevation 2250 m). In this case, the snow core collected in March 1998 had a bulk isotopic value that was isotopically depleted relative to nearby springs, whereas the April 1998 snowpack was enriched relative to the springs. The spring waters were sampled during two different years, and from two different springs, yet they have remarkably similar isotopic values. Similar relationships were observed at other locations. These results suggest that small local springs may be the best indicators of the integrated recharge isotopic value in a particular location, particularly given of the dynamic evolution of the snowpack isotopic composition with time.

4.2 Regional implications for snowmelt recharge

Alpine springs and snowmelt-derived runoff collected from high elevation ranges throughout central Nevada (north of 38° latitude) plot along a least-squares regression line with the equation $\delta D = 7.3\delta^{18}O - 7$ (Fig. 5). All of the spring water and runoff samples were collected in April or early May, during the peak period of snowmelt. It is noteworthy that the spring water/runoff regression line is similar to the line obtained for the 28 snow core samples collected in March 1998 ($\delta D = 7.5\delta^{18}O - 3$) (Fig. 2). This result suggests that kinetic fractionation processes occurring during snow metamorphism and ablation may largely account for the negative *d*-values observed in Nevada groundwaters.

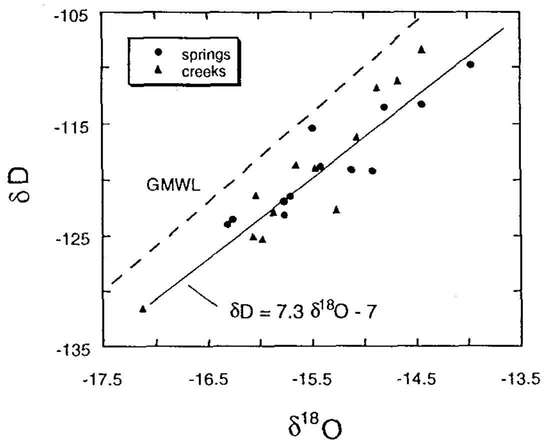

Fig. 5. Plot of δD-$\delta^{18}O$ pairs for alpine springs and snowmelt runoff in central Nevada.

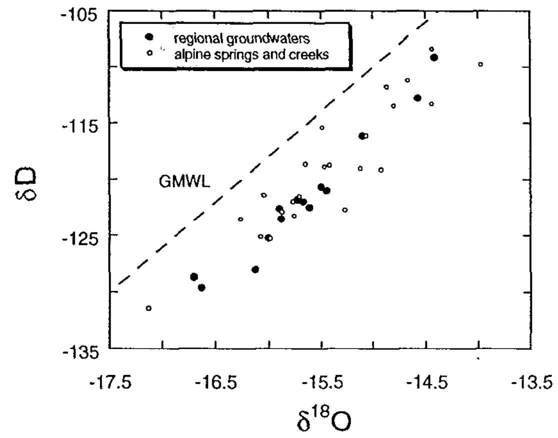

Fig. 6. Plot of δD-$\delta^{18}O$ pairs for central Nevada regional groundwaters, compared to alpine springs and snowmelt runoff from the same region.

Lastly, it is of interest to compare the δD-$\delta^{18}O$ compositions of the alpine springs and runoff with those of groundwater from regional aquifers underlying the central Nevada basins (Fig. 6). All of the regional groundwaters (shown as solid circles in Fig. 6) were sampled from springs, most of which originate from the regional carbonate aquifer and have warm temperatures indicative of a deep flowpath history. The regional groundwaters exhibit a shift to the right of the GMWL that is comparable to that of the alpine springs and creeks from which they are inferred to be derived (Fig. 6). The regional groundwaters typically exhibit $\delta^{18}O$ values that are 0.2 to 0.4‰ lower than alpine springs from adjacent ranges in central Nevada. However, this is interpreted to show that the recharge is predominantly derived from the highest elevation parts of the ranges (up to 3500 m), which also receive the highest amounts of winter snowfall.

To summarize, the results of this study indicate that regional groundwater flow systems in central Nevada are locally recharged, and that much of this recharge is derived from melting of the winter snowpack. The apparent link between this recharge area and regional groundwater transport into southern Nevada [ref. 6] suggests that low *d*-values previously attributed to recharge under paleoclimatic conditions in southern Nevada may be simply related to isotopic enrichment processes occurring during modern recharge.

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