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STABLE ISOTOPIC STUDY OF PRECIPITATION AND SPRING DISCHARGE IN SOUTHERN NEVADA

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ABSTRACT

Ingraham, N.L., Lyles, B.F., Jacobson, R.L. and Hess, J.W., 1991. Stable isotopic study of precipitation and spring discharge in southern Nevada. J. Hydrol., 125: 243–258.

Precipitation was collected in southern Nevada on a semi-regular monthly basis at 14 locations for 6 years for stable isotopic analysis. The total elevational range of the collection sites was 1270 m and the total geographic range was 65 km. The average yearly difference in $\delta^{18}O$ of precipitation from all sites was smallest and amounted to only 2.3‰, whereas the average difference based on location (elevation) was only 3.7‰. The largest difference in $\delta^{18}O$ was between enriched summer and depleted winter precipitation and amounted to more than 13‰.

The precipitation record shows two time-based regimes. For the first 3 years of collection, the precipitation was highly variable with several large events and several dry periods. During the last 3 years of collection, the precipitation was much more even with no large events. However, there is no correlation between the variability of the amount of precipitation and the stable isotopic composition of precipitation.

In addition, the $\delta^{18}O$ composition and discharge of two springs, Whiterock Spring and Cane Spring, issuing from perched water tables, were monitored for 5 years on a similar basis as for the precipitation. During the first 2.5 years of collection, both volume of discharge and $\delta^{18}O$ responded to large precipitation events. However, during the last 2.5 years of collection when precipitation moderated in amounts, but not in stable isotopic composition, the springs displayed not only less variation in discharge, but in stable isotopic composition as well.

Summer precipitation may be involved in groundwater recharge, as during the first 3 years of collection, some of the events to which the springs responded were summer events. Moreover, the average $\delta^{18}O$ of winter precipitation is less than that of the spring discharge, even when the water from large summer events is absent from the spring discharge.

The stable isotopic composition of precipitation has been used to determine the season most responsible for infiltration and groundwater recharge. By using stable isotopic ratios of precipitation, lysimeter water and ground water, Darling and Bath (1988) were able to discern that recharge through a chalk aquifer was occurring throughout the year. Winograd and Riggs (1984), using isotopic data from snow, rain and springs, concluded that groundwater

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recharge to the Spring Mountains in southern Nevada occurs primarily from winter precipitation, and that water from summer precipitation is rarely involved in recharge. These researchers also stated that significant recharge events may be as much as 5 years apart. These conclusions were supported by Hershey et al. (1987) who also compared the stable isotopic composition of snow with that of spring discharge on the Spring Mountains.

The stable isotopic composition of precipitation has been shown to be highly variable, even in regions of single precipitation periods. Ingraham and Taylor (1991) found differences in δD contents of 40‰ at one location during one season, whereas Smith et al. (1979) found variations of δD in precipitation of up to 37‰ between individual storms in northern California. Milne et al. (1987) reported on 3 years of record on the isotopic composition of precipitation in southern Nevada. Their data also show large variations; however, these researchers offered no interpretations or conclusions concerning the results.

Southern Nevada, as with most of the southwestern United States, has dual precipitation periods: a winter period and a summer period. Winter precipitation is produced from frontal systems migrating eastward off the Pacific Ocean and is colder than the summer precipitation. The summer rains occur primarily as localized high-intensity convective storms (French, 1983, 1985) that are a result of subtropical disturbances moving northward from the Gulf of California (Hales, 1972, 1974). Simpson et al. (1972) have demonstrated a substantial and predictable difference in the stable isotopic composition of precipitation during these two periods. Winter precipitation is isotopically more depleted than summer precipitation, which is a result of differences in storm origin, history, temperature and degrees of evaporation during descent. Thus, to interpret the stable isotopic results of spring discharge, especially in areas of dual precipitation periods, numerous samples of precipitation must be collected.

This research reports on a network of 14 precipitation sampling stations that was initiated in late 1982 in southern Nevada and continuously operated until the end of 1986. The purpose of the network was to establish baseline information on the stable isotopic composition of precipitation in southern Nevada. The variations in the isotopic ratios of precipitation are interpreted in terms of differences in location, elevation, season, and year, and are compared with the stable isotopic ratios in the discharge waters of two springs.

The two sampled springs, Whiterock Spring and Cane Spring, issue from perched waters in volcanic tuffs. The stable isotopic ratios of the spring waters allowed interpretations concerning the response of the spring discharge to large precipitation events, and the precipitation period most responsible for infiltration and recharge.

Sample collection

Precipitation was collected at 14 sites, between February 1982 and December 1986, for stable isotopic analysis. It was collected by a simple device consisting of a catchment area of 0.22 m^2 placed over a barrel. The catchment area was

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connected to a collection vessel by a tube with a U-shaped trap. The U-trap was designed to remain filled with water after a precipitation event, thus protecting the water sample in the collection vessel from evaporation and associated isotopic enrichment. The barrel was then partially buried for stability. Sample collection was performed on a semi-regular basis that was designed to determine the average year and seasonal stable isotopic ratios of precipitation. The resulting schedule of sample collection was usually between 3 and 6 weeks.

The two springs, Cane Spring and Whiterock Spring, were monitored for their discharge and stable isotopic composition on a schedule similar to the precipitation collection. The discharges of both springs are small and, thus, the orifices have been developed by the digging of adits. The water slowly seeps out of the rock and collects in a pool in the adit before flowing out. Several tritium analyses of both springs and one ^{14}C analysis of Cane Spring were also performed. In addition, precise measurements of precipitation were obtained from rain gages located close to the springs. The locations and elevations of the precipitation collection sites, Whiterock Spring, Cane Spring, and precipitation gages are shown on Fig. 1.

Sample analysis

All samples were collected in glass bottles and sealed with plastic tape to prevent leakage or evaporation. The oxygen isotopic analyses were performed by the complete conversion of water to carbon dioxide by guanidine hydrochloride (Dugan et al., 1985). The hydrogen isotopic ratios were determined by the quantitative conversion of water to hydrogen gas using uranium as a reducing agent (Bigeleisen et al., 1952). The hydrogen and carbon dioxide gases were then each introduced directly into mass spectrometers.

The hydrogen gas was analyzed in a Nuclide 3-60 HD double collector mass spectrometer, whereas carbon dioxide was analyzed in a Delta E Finnigan–Matt triple collector mass spectrometer. The reproducibility of the δD values are $\pm$ 1‰, whereas the $\delta^{18}O$ values have a reproducibility of $\pm$ 0.2‰. All data are reported in the standard δ notation with respect to standard mean ocean water (SMOW).

RESULTS

Over 400 precipitation samples and nearly 100 spring samples were analyzed for their oxygen isotopic ratios, and about 275 of the precipitation and 70 of the spring samples were also analyzed for their hydrogen isotopic ratios. Therefore, the conclusions presented here are primarily based on interpretations made from the oxygen isotopic ratios.

Precipitation

All available pairs of stable isotopic data (δD and $\delta^{18}O$) of precipitation are plotted on Fig. 2. The data produce a regression line with the equation:

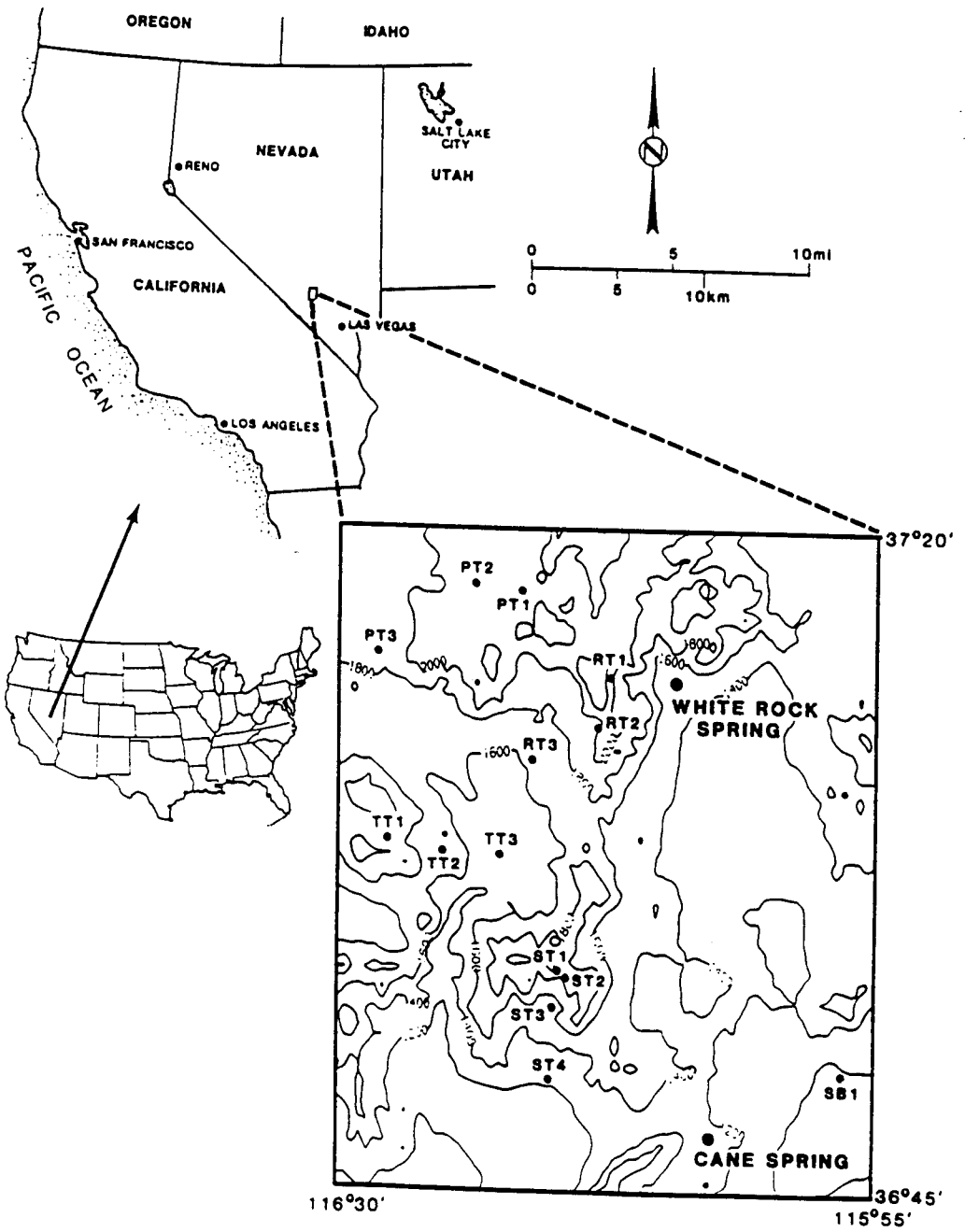
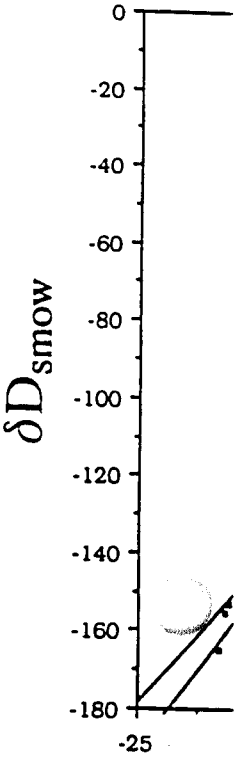


Fig. 1. Location of the springs and precipitation collection sites used in this study.

STABLE ISOTOPIC STUDY



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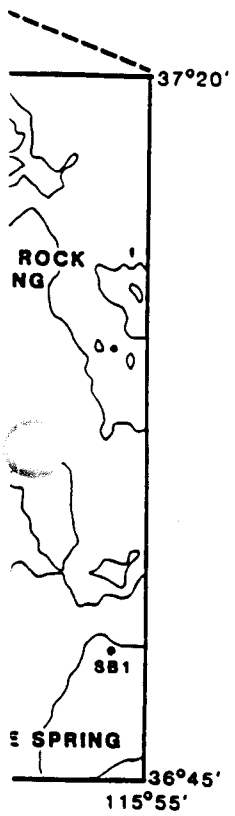

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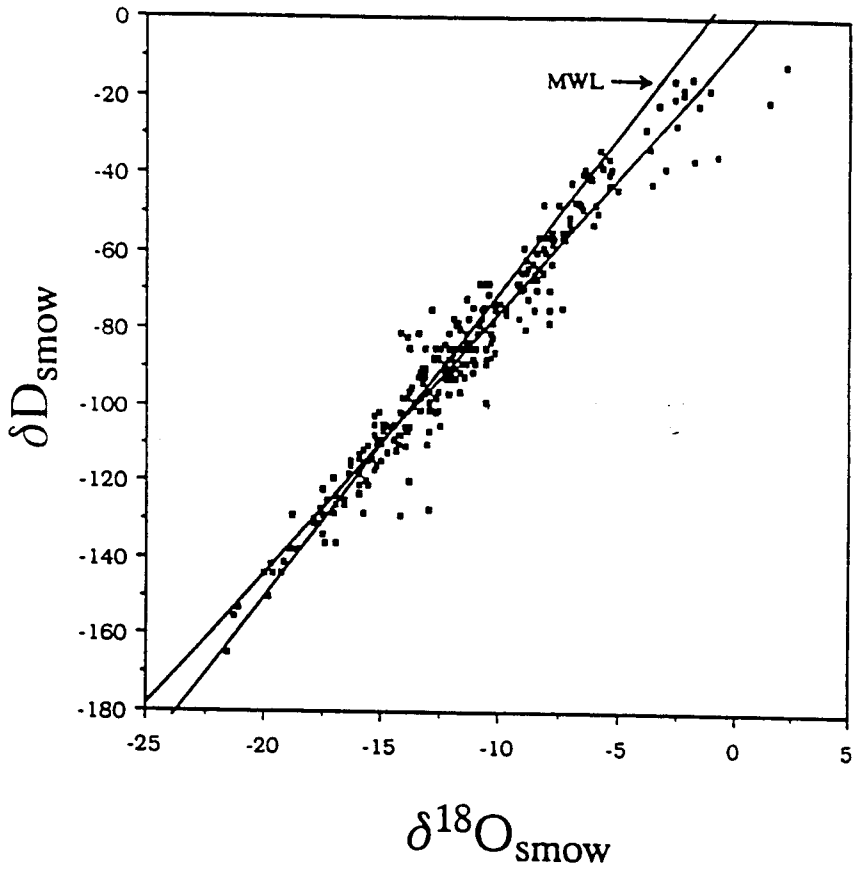


Fig. 2. Available pairs of the stable isotopic composition of precipitation from all collection sites regardless of amount. Also shown are the local mean water line (LMWL) ($\delta D = 6.87\delta^{18}O - 6.5$) and the meteoric water line (MWL) ($\delta D = 8\delta^{18}O + 10$; Craig, 1961).

$\delta D = 6.87\delta^{18}O - 6.5$ with a correlation coefficient of 0.97. This local meteoric water line (LMWL) represents the stable isotopic ratios of both summer and winter precipitation (regardless of amount) from all stations. This local line differs from the global meteoric water line (MWL: $\delta D = 8\delta^{18}O + 10$; Craig, 1961); however, as shown on Fig. 2, most of the data also plot close to the global line.

Isotopic variation

All of the collection sites are in reasonably close geographic proximity. The variations in the stable isotopic ratios of the precipitation samples are therefore not thought to be geographic. Instead, they are limited to differences in elevation of the collection sites, year, and season of collection. The smallest total average difference in $\delta^{18}O$, 2.3‰, was observed between the 5 years of

TABLE 1

The weighted averages of $\delta^{18}O$ of precipitation for each year of collection

Year	Weighted average ($\delta^{18}O$)
1982	− 10.3
1983	− 11.2
1984	− 10.4
1985	− 10.0
1986	− 12.3

collection, with most of the difference being produced by depleted precipitation collected during 1986 (Table 1). However, the total average difference between all sites is only 3.7‰ in $\delta^{18}O$, much of which can be attributed to differences in elevation (Table 2).

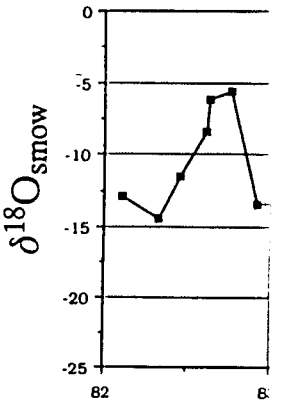
Most of the variation in the stable isotopic composition of precipitation can be attributed to season and inter-storm variation. Figure 3 shows the weighted average of $\delta^{18}O$ in precipitation from all collection sites versus time over the period of collection (1982–1986). Differences of as much as 15‰ are observed over the 5-year period between the depleted winter precipitation and enriched summer precipitation.

This seasonal variation is readily apparent on Fig. 4, which shows the weighted average of the $\delta^{18}O$ of precipitation for each month (from all stations). The $\delta^{18}O$ of precipitation decreases slightly between January and March,

TABLE 2

The weighted averages of $\delta^{18}O$ of precipitation for each sampling location and the elevations for each collection site

Station	Weighted average ($\delta^{18}O$)	Elevation (m)
SB1	− 9.5	960
ST4	− 11.6	1225
TT3	− 11.4	1400
ST3	− 11.7	1520
RT3	− 11.0	1590
TT2	− 11.3	1630
ST2	− 12.4	1830
TT1	− 10.3	1840
PT3	− 12.2	1890
RT2	− 12.9	1900
PT2	− 13.2	2060
ST1	− 12.5	2133
PT1	− 12.5	2200
RT1	− 12.7	2230



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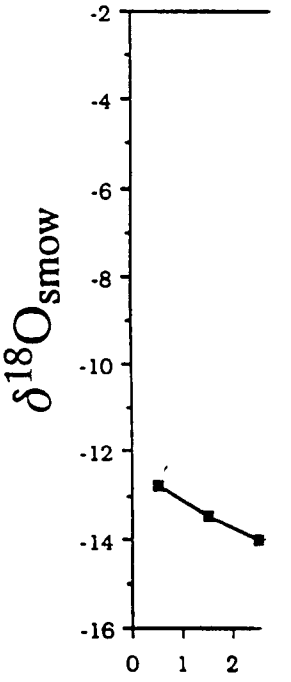

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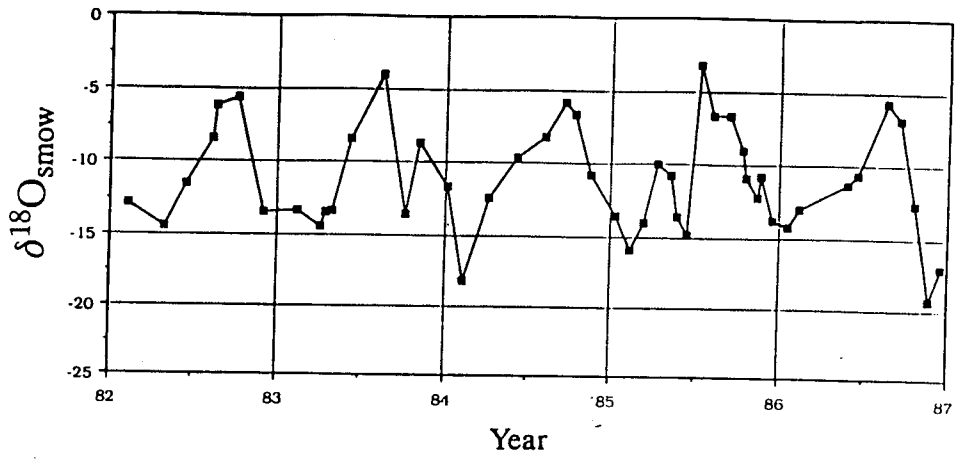


Fig. 3. Time series of the weighted average of the $\delta^{18}O$ of precipitation from all stations during the period of collection.

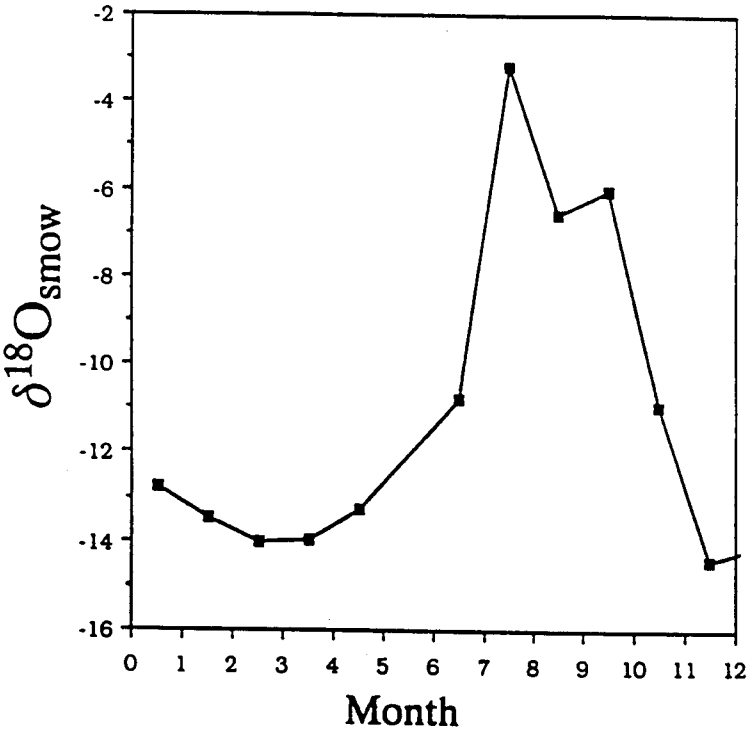


Fig. 4. The weighted average of the $\delta^{18}O$ of precipitation for each month from all stations.

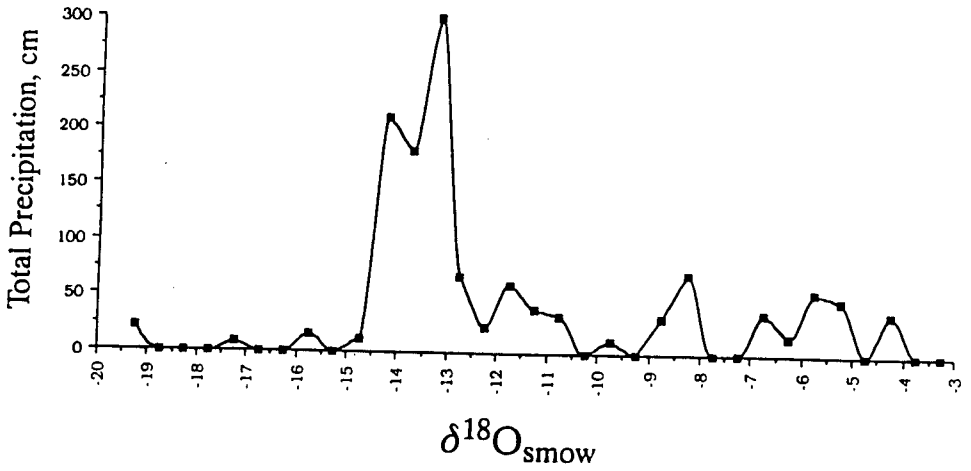


Fig. 5. The total amount of precipitation collected within each 0.5‰ interval in $\delta^{18}O$. The weighted mean of the $\delta^{18}O$ of all precipitation samples collected is -11.9‰, whereas the mode is between -13.0 and -14.5‰.

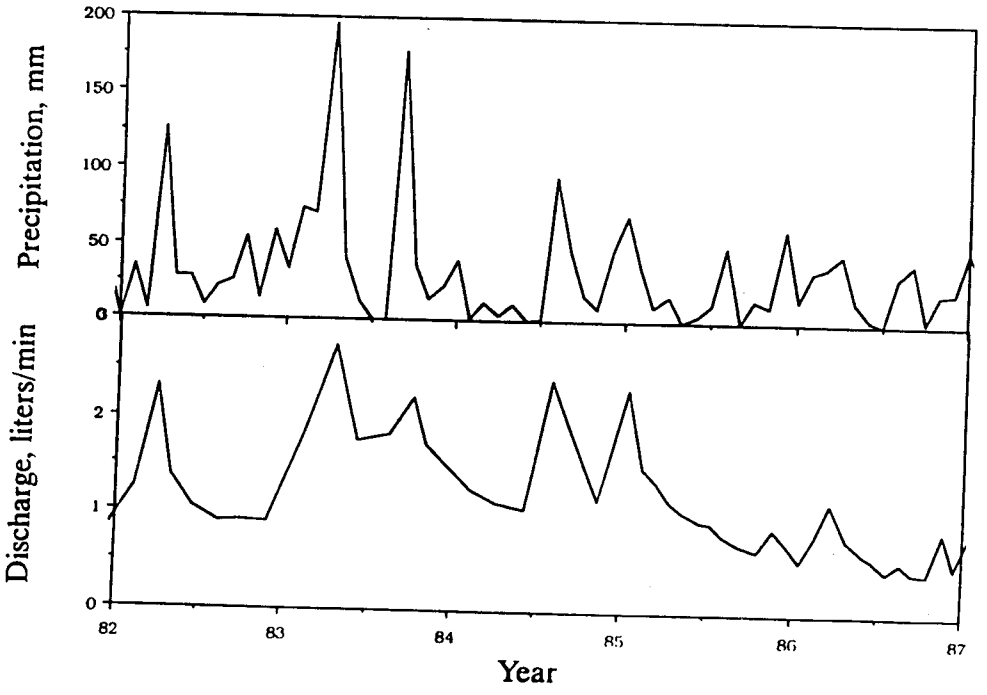
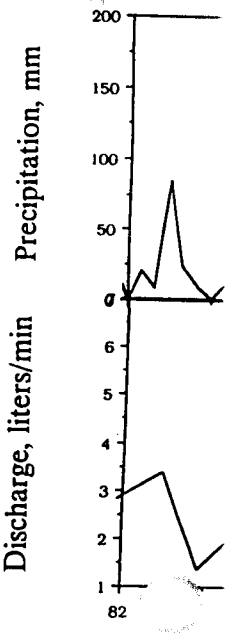


Fig. 6. Discharges from Whiterock Spring and amounts of precipitation collected nearby.



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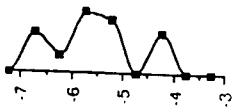

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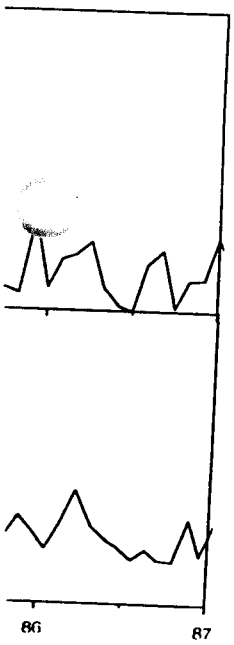

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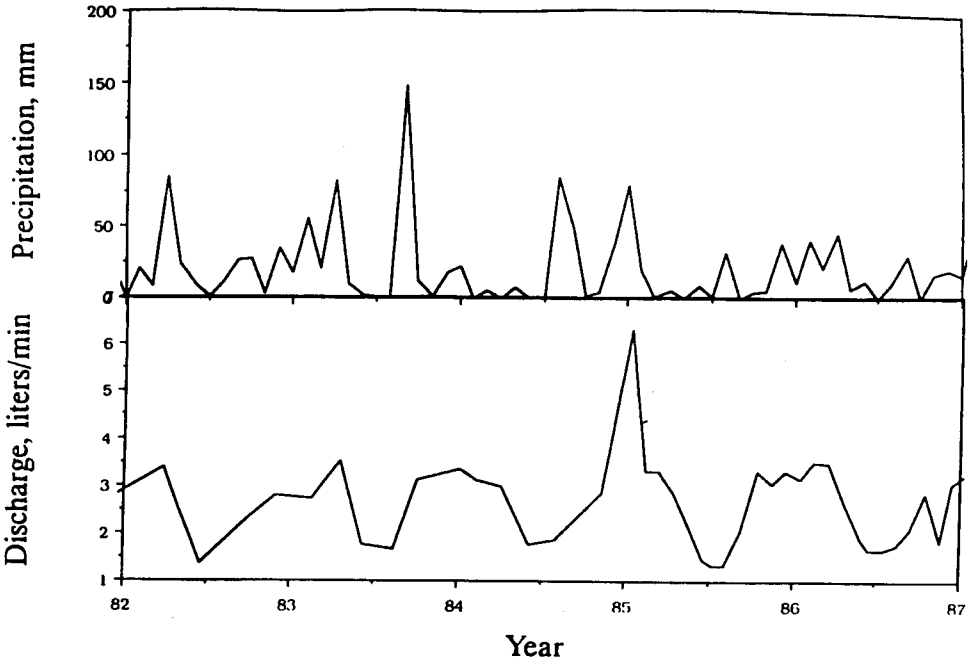

Fig. 7. Discharges from Cane Spring and amounts of precipitation collected nearby.

followed by a sharp increase of nearly 11‰ by July. However, over the 5-year period, there has only been one sampling run in July, leaving the true composition of precipitation in mid-summer uncertain. After July, the $\delta^{18}O$ of precipitation decreases sharply until it averages about −14‰ in December.

The total amount of precipitation collected within each 0.5‰ interval in $\delta^{18}O$ are compared in Fig. 5. The weighted mean of all precipitation samples collected is −11.9‰, whereas the mode is between −13.0 and −14.5‰. This plot also shows a rather flat plateau between −4 and −12‰ for the summer rain (June–October), and a very sharp peak between −12.5 and −14.5‰ for the winter rain (November–May).

Spring discharge

The discharges (l min^{-1}) from Whiterock Spring and Cane Spring are plotted in Figs. 6 and 7 respectively, along with the precipitation amounts collected nearby. Whiterock Spring displays considerable variation in discharge, which was first noted by Thordarson (1965), who related increases in discharge from Whiterock Spring to large precipitation events. Whiterock Spring shows a much more direct response to the peaks in precipitation than Cane Spring. This is especially evident for the five peaks in the discharge of Whiterock Spring during early 1986. However, after early 1985, the discharge of Whiterock Spring

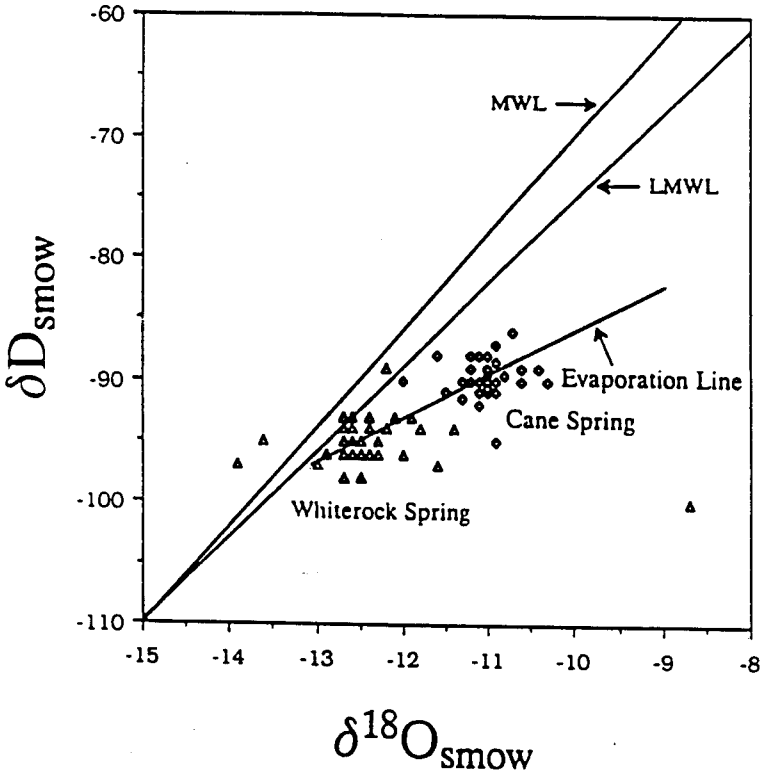

Fig. 8. The available stable isotopic pairs (δD and δ^{18}O) of discharge water from Whiterock Spring and Cane Spring. Also shown are the meteoric water line (MWL: $\delta D = 8\delta^{18}O + 10$; Craig, 1961) and the local meteoric water line (LMWL: $\delta D = 6.87\delta^{18}O - 6.5$) of this research. The spring waters plot in two separate fields and appear to have undergone evaporation following an evaporation line as shown.

appears to moderate, apparently in response to the moderation of precipitation commencing in late 1983. Similar correlations between precipitation peaks and discharge peaks are observed for Cane Spring; however, they are not as obvious. As with the precipitation records for Whiterock Spring, the variation in precipitation near Cane Spring also moderates commencing in late 1983.

Cane Spring and Whiterock Spring, were monitored for their stable isotopic composition as well as for discharge. In addition, several samples from each spring were collected and analyzed for tritium, which was detected in the discharge water of Whiterock Spring (14–25 TU; 10 January 1985 and 26 March 1982, respectively), but not in Cane Spring (less than 5 TU; 26 March 1982, 6 June 1984, 15 November 1984 and 10 January 1985). This prompted a ^{14}C analysis of Cane Spring (14 March 1982) which resulted in an uncorrected age of about 600 years for the water.

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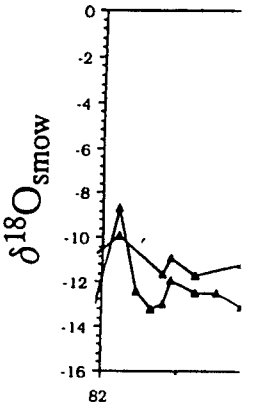

Fig. 9. Time series of the
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Whiterock Spring and Cane Spring are shown in Fig. 8, along with the meteoric water line (MWL) (Craig, 1961) and the local meteoric water line (LMWL: $\delta D = 6.87\ \delta^{18}O - 6.5$) of this research. The waters plot in two separate fields; waters from Cane Spring are generally a little more enriched in both deuterium and ^{18}O than those from Whiterock Spring. The enrichment observed in the water from both springs is probably due, in large part, to evaporation while the water is impounded in the adit. The larger shift in the waters from Cane Spring represents a longer residence time in the pool in the adit. Thus, the true stable isotopic composition of the discharge water of these springs is unknown. Nevertheless, large stable isotopic variations are observed in the discharge water that are thought to represent the stable isotopic fluctuation in precipitation.

The $\delta^{18}O$ values of the water from Cane Spring and Whiterock Spring, for the period of collection, are shown in Fig. 9. Both springs show considerable fluctuation, but display the fluctuation in unison. However, Whiterock Spring appears to fluctuate to a much greater degree than Cane Spring.

DISCUSSION

The stable isotopic composition of summer and winter precipitation is observed to differ by about 13‰ in $\delta^{18}O$, which represents differences in storm origin, history, and temperature between the seasons. In addition, occasional large summer precipitation events enriched in ^{18}O are observed. These seasonal variations and the occasional events allow the stable isotopic ratios of spring discharge to be studied in terms of infiltration and recharge.

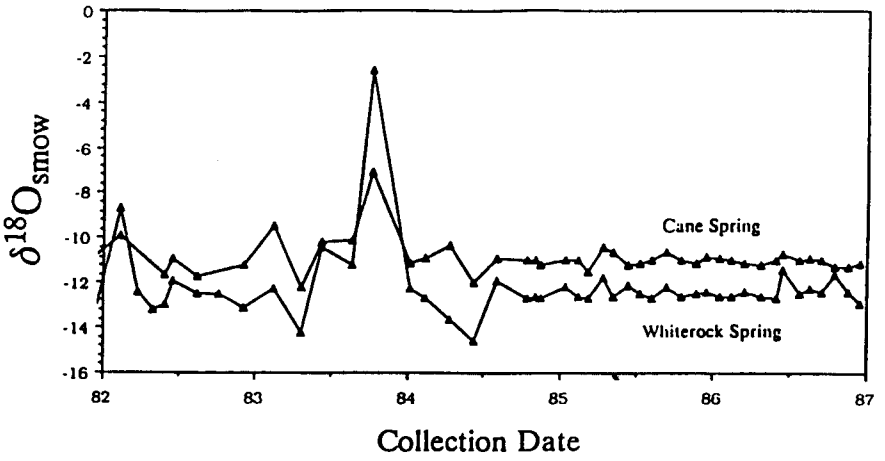


Fig. 9. Time series of the stable oxygen isotope compositions of discharge water from Cane Spring and Whiterock Spring, for the period of collection. Both springs show considerable fluctuation, but display the fluctuation in unison.

$\delta^{18}O$ of spring discharge and source water

Discharge water from Cane Spring, and to a lesser extent that from Whiterock Spring (Fig. 8), has undergone evaporation and associated isotopic enrichment. The samples fall along an evaporation line (drawn by eye) that intersects the local meteoric water line at a $\delta^{18}O$ value of a little less than $-13‰$. The two springs do not have the same recharge areas, and may not be produced by precipitation of the same isotopic ratio. Nevertheless, a $\delta^{18}O$ value of about $-13‰$ represents a reasonable value for recharging precipitation, but requires a total of 0.5‰ enrichment by evaporation for water discharging at Whiterock Spring, and a 2‰ enrichment for water discharging at Cane Spring. Most of the isotopic enrichment by evaporation is thought to occur at the discharge point in the adits, but some evaporation may be occurring in precipitation prior to infiltration.

Relationship between precipitation and spring discharge

The precipitation collection sites RT2 and RT3 are close to Whiterock Spring and are thought to collect precipitation representing the pre-evaporated water recharging the spring. Similarly, ST3 and ST4 are thought to collect precipitation representative of pre-evaporated water recharging Cane Spring. The $\delta^{18}O$ values of discharge water from Whiterock and Cane Springs are shown over the period of sampling on Figs. 10 and 11, respectively, along with the $\delta^{18}O$ of precipitation for the same period of record from the nearest collection sites for each spring (RT2 and RT3 for Whiterock Spring, and ST3 and ST4 for Cane Spring).

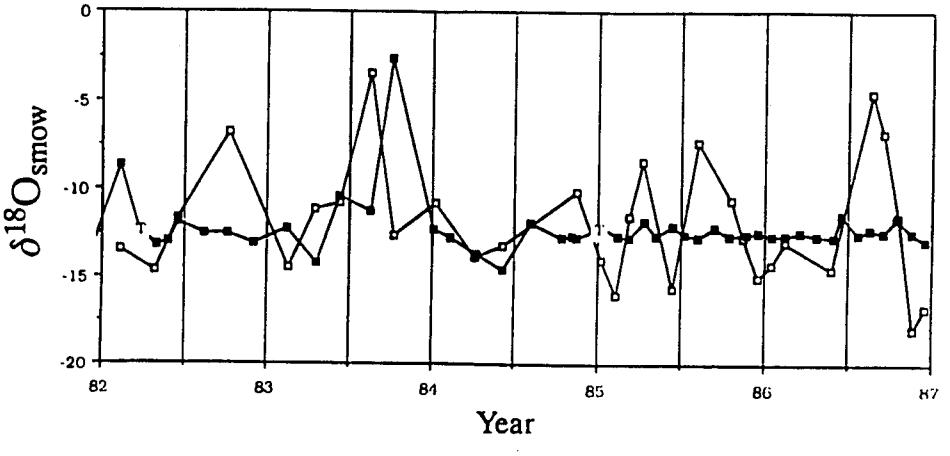
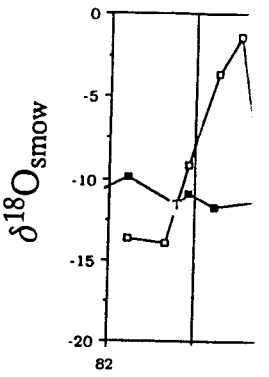


Fig. 10. Time series of the stable oxygen isotope compositions of discharge water from Whiterock Spring (solid squares) and those of the nearest precipitation collection sites (RT2 and RT3) (open squares) over the period of collection. The samples also analyzed for tritium are designated with a T.



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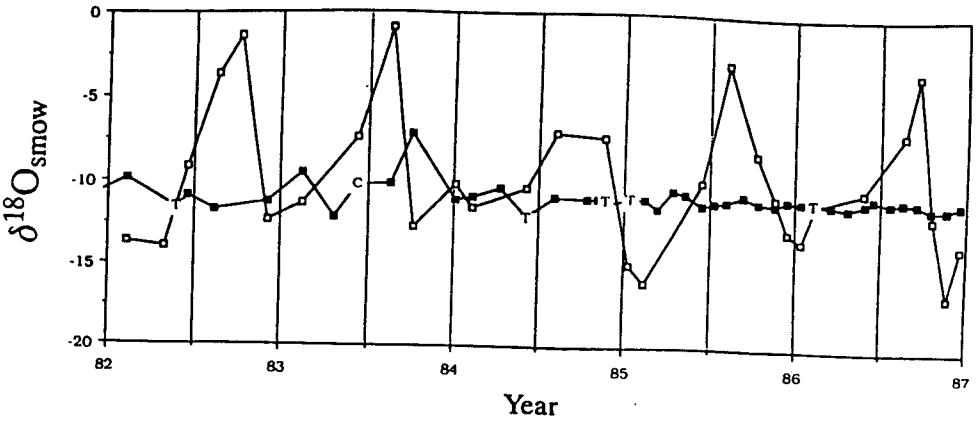

Fig. 11. Time series of the stable oxygen isotope compositions of discharge water from Cane Spring (solid squares) and those of the nearest precipitation collection sites (ST3 and ST4) (open squares) over the period of collection. The samples also analyzed for tritium are designated with a T, and that analyzed for ^{14}C is designated with a C.

For the first 2.5 years of record, between 1982 and mid-1984, there appears to be a good correlation between the $\delta^{18}O$ of precipitation and the $\delta^{18}O$ of discharge of Whiterock Spring, with a time lag of about 2–3 months as shown in Fig. 10. This is especially apparent in the data for 1983, when Whiterock Spring responded isotopically to the enriched nature of a large (see Fig. 6) summer precipitation event. After mid-1984, however, the $\delta^{18}O$ of discharge from Whiterock Spring does not appear to be affected by large fluctuations in the $\delta^{18}O$ of precipitation. Cane Spring (Fig. 11) shows a similar relationship between the $\delta^{18}O$ of local precipitation and the $\delta^{18}O$ of spring discharge during 1982 and 1983, although the relationship is not as direct as for Whiterock Spring. Nevertheless, this is especially notable considering the apparent age (approximately 600 years) of the Cane Spring waters. Since 1984, however, the $\delta^{18}O$ of Cane Spring, as with Whiterock Spring, does not appear to be affected by large fluctuations in the $\delta^{18}O$ of precipitation.

During the period of collection before 1984, Whiterock Spring appeared to be in fairly direct isotopic and hydrologic (Figs. 6 and 10) connection with precipitation, and to a lesser extent so did Cane Spring (Figs. 7 and 11). However, after 1984, the $\delta^{18}O$ of precipitation continued to fluctuate, but the $\delta^{18}O$ of the discharge of the two springs did not respond. The 3-year period after 1984 is characterized by more moderate precipitation amounts. From 1984 through 1987, the precipitation peaks were fewer and not so extreme, and the troughs were not as prolonged. This observation indicates that the water of large precipitation events of unique isotopic composition may be observed in spring discharge, but a unique isotopic composition of precipitation alone is not enough to alter the stable isotopic composition of that discharge.

This interpretation requires that large precipitation events must infiltrate rapidly and flush through the hydrologic system without extensive mixing with

the perched ground water; that is, the large precipitation events must 'short-circuit' the main body of the perched water table during infiltration. However, in the absence of large precipitation events, the residence time of the recharging water increases, and affords more complete mixing of the precipitation inputs which produces a more isotopically homogenized discharge at the spring. This 'short-circuiting' of the perched water table by infiltrate from large precipitation events may be explained by the nature of water movement in the unsaturated zone.

Matric versus fracture infiltration

Fluid flow in unsaturated fractured rock involves two mechanisms, slow flow through matrix blocks and rapid flow through intervening fractures. Both mechanisms appear to be important in a similar environment at Yucca Mountain in southern Nevada (Sinnock et al., 1987). These researchers proposed that under low water flux (small amounts of infiltration), the flow will be exclusively matrix flow and travel times will be long. As the flux increases, permeability of the fractures increases much more rapidly than for the matrix, and water will move by both matrix and fracture flow. Montazer and Wilson (1984) suggested that this process may be complicated by air being trapped in the pores during the wetting phase, and that fracture flow may dominate much earlier owing to the longer time of matrix wetting. The magnitude of the effects depends upon the rate at which water is introduced into the system and appears to be greatest for large precipitation events after prolonged dry spells. After large summer storm events, conditions may favor infiltration by fracture flow allowing the water a 'short-circuit' path to the springs, thus affording little mixing with the matrix infiltrate.

Seasonal effects and the $\delta^{18}O$ of spring discharge

The oxygen isotopic ratios of the homogenized discharge water from Whiterock Spring (as well as for Cane Spring), as observed between 1984 and 1987 and shown on Fig. 10 (Fig. 11), may have, prior to isotopic enrichment by evaporation, represented the ratio of recharge between enriched summer and depleted winter precipitation. The estimated oxygen isotopic composition of pre-evaporated recharge water to Whiterock Spring ($\delta^{18}O = -13‰$) is more enriched than the winter mode of between -13 and $-14.5‰$ (Fig. 5). However, it is more depleted than the weighted mean of all precipitation samples collected ($\delta^{18}O = -11.9‰$). As observed during the large summer precipitation event of 1983, the springs do respond isotopically (and hydrologically) to enriched summer precipitation, indicating that, at least under some conditions, summer precipitation is responsible for some infiltration.

As large summer precipitation events with enriched stable isotopic ratios effect large spring discharges that reflect the enriched nature of the precipitation, summer precipitation cannot be discounted as supplying water to the isotopically homogenized ground water. Thus, it is thought that both summer

and winter precipitation are responsible for recharging the ground water. However, for summer precipitation, recharge may only be accomplished by large precipitation events, some of which 'short-circuit' the perched water table.

CONCLUSIONS

The total average difference in $\delta^{18}O$ of precipitation for a 5-year period in southern Nevada amounted to only 2.3‰ year to year, whereas differences based on location were only 3.7‰. The largest difference was between enriched summer and depleted winter precipitation and amounted to more than 13‰. In addition, several large summer precipitation events of enriched isotopic composition were observed. This seasonal difference, and those of the large events, were compared with the $\delta^{18}O$ of discharge of two springs issuing from perched water tables.

During the first 2–2.5 years of collection, the springs responded in both volume, and $\delta^{18}O$, of discharge to large precipitation events. However, during the last 2–2.5 years of collection when precipitation moderated in amount, but not stable isotopic composition, the springs displayed not only less variation in discharge, but also in stable isotopic composition.

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ABSTRACT

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