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ABSTRACT: Many hydrothermal systems are dominated by water of meteoric origin, the stable isotopic composition of which is, in part, a function of climate extant at the time the hydrothermal system was active. Therefore, measurement of stable isotopic parameters in fossil hydrothermal systems provide a signal averaged over relatively large time scales that potentially can yield insights into longer-term climate changes. Two excellent indicators of the H isotope composition of meteoric waters from hydrothermal systems include fluid inclusions and hydrous minerals. In the Great Basin of western North America, hydrothermal systems have been active intermittently since at least Jurassic time. Data from the last half of the Tertiary in the Great Basin correlate well with existing data from weathering-related minerals of known age (e.g. alunite, kaolinite) and parallel global paleoclimate curves. A few data exist for older hydrothermal systems and can be utilized to constrain meteoric water back to the Jurassic, but with relatively large uncertainties. Additional data are required to better define this older portion of the secular curve for the Great Basin.

1 ORIGIN AND ISOTOPIC COMPOSITION OF METEORIC FLUIDS

The stable isotopic composition of meteoric fluids has been shown to reflect a number of parameters, including differences in paleolatitude, differences in paleoaltitude, or changes in paleoclimate (e.g. Taylor, 1979; Arehart and O'Neil, 1993). Changes in latitude required to affect the δD values are much larger than those known for western North America over the time span (~50 Ma) represented by most of the samples described below [Denham and Scotese, 1988]. Stable isotope compositions of precipitation can vary significantly with altitude, but in most cases groundwaters are long-term averages such that local variations due to altitude, as well as seasonal variations, are minimized or eliminated [e.g. Thordsen et al., 1992]. In the Great Basin, Arehart and O'Neil (1993) showed that if local altitude effects were dominant, the data for their sample set would be expected to be more random. This is supported by the fact that deuterium analyses of present-day springs across Nevada are broadly similar for any given latitude, regardless of the altitude of the spring [O'Neil and Silberman, 1974; Mariner et al., 1983; G. Arehart, J. O'Neil, S. Poulson, unpub. data]. However, it is shown below that the variation in spring composition

is clearly not strictly a function of latitude, as originally postulated by Arehart and O'Neil (1993). Rather, there is a broad band of lowest values that runs in a NE direction from Reno (Figure 1a). However, once this regional trend is taken into consideration, the stable isotopic composition of meteoric fluids is expected to reflect primarily paleoclimatological variations over the past ~50 Ma in the Great Basin, rather than reflecting changes in local altitudinal or latitudinal conditions.

2 HYDROTHERMAL SYSTEMS AND METEORIC WATER

Many hydrothermal systems that develop in the upper crust of the earth are dominated by meteoric fluids. Meteoric fluid circulation is driven by thermal anomalies in the upper crust, often associated with elevated geothermal gradients from shallow intrusive activity.

The oxygen isotope composition of hydrothermal fluids may reflect the oxygen isotope composition of the parent fluid (meteoric, metamorphic, magmatic) with modifications from water-rock interaction at depth and elevated temperatures. Although some geothermal fluids are essentially unexchanged (e.g. Wairakei, NZ;

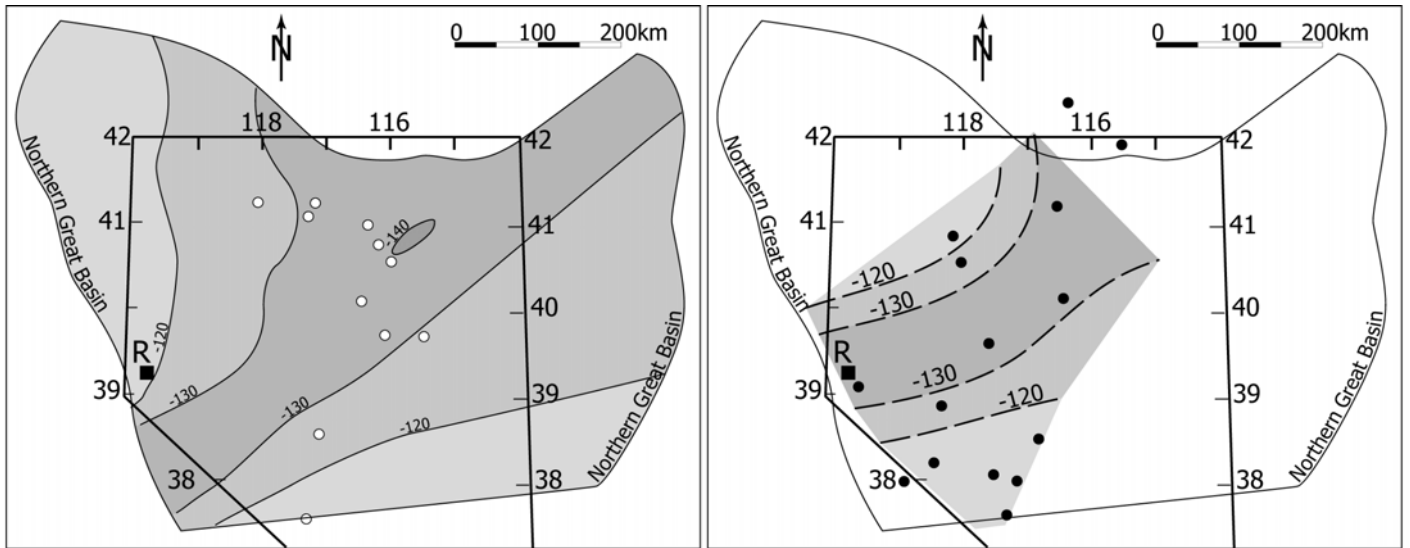


Figure 1a (left). Present-day contour map of the northern Great Basin for δD values of warm and hot springs. Data modified and updated from Mariner et al., 1983. White dots are locations for which alunitic paleoclimate data are available. 1b (right). Paleo-isotopic contour map of the northern Great Basin for δD values at ca. 16 Ma. Data from O'Neil and Silberman, 1974; Arehart and O'Neil, 1993; and this study. Black dots are locations for which fluid inclusion paleoclimate data are available. R = Reno

Truesdell, 1984) and have O isotope compositions identical to local meteoric water, other geothermal fluids (e.g. Iceland; Truesdell, 1984) show isotopic evidence of extensive exchange of oxygen between local meteoric waters and the rocks through which they have circulated. Therefore, measurement of oxygen isotopes in hydrothermal fluids is not useful as an indicator of the isotopic composition of the local meteoric fluid at the time of hydrothermal activity unless it is clear how much exchange has taken place with the rocks during hydrothermal circulation.

In contrast to exchange of oxygen between water and rock and consequent modification of the isotopic composition of a geothermal fluid, minimal effects are expected on the hydrogen isotopic composition of most geothermal fluids. Because rock contains very small amounts of hydrogen, fluids passing through most rocks will not be modified significantly in their hydrogen isotope composition unless they have passed through large volumes of rock and interacted extensively. This effect is well-known in the literature (e.g. Taylor, 1979). Therefore, the hydrogen isotope composition of meteoric-hydrothermal systems should be reflective of the isotopic composition of local meteoric water at the time the geothermal system was active.

Magmatic, metamorphic, and seawater fluids also may contribute water to hydrothermal systems. Such fluids are likely to have stable isotopic signatures significantly different from meteoric water-dominated systems. However, in most cases, these fluids can be recognized by other chemical tests and can be

eliminated from any data set that relates to meteoric water. In particular, seawater and magmatic fluids usually have much higher salinities (>5 wt. % NaCl equivalent) than meteoric-hydrothermal (<5 wt. % NaCl equivalent) systems. Metamorphic fluids often can be recognized by the geologic environment (deeper crustal) and the presence of significant (>~3%) CO_2 . None of the samples included in this study have demonstrable components of magmatic, metamorphic, or seawater.

3 DETERMINATION OF METEORIC FLUID COMPOSITIONS IN FOSSIL SYSTEMS

In most cases, hydrothermal activity is evanescent, but may leave behind some mineralogical record of its former presence. These mineralogical proxies commonly comprise vein material containing quartz, phyllosilicates (sericite, clays), pyrite and/or other minerals. Presuming that these minerals formed in equilibrium with the hydrothermal fluids, the isotopic composition of the former hydrothermal fluid can be calculated from equilibrium fractionation equations (Kyser, 1986; Gilg and Sheppard, 1996 and others) provided the temperature of deposition (equilibration) is known or can be estimated. Oxygen-bearing minerals can, therefore, provide an accurate measure of the oxygen isotope composition of the hydrothermal fluid. However, because of the problem of water-rock exchange described above, oxygen generally cannot be utilized as a measure of the meteoric fluid composition.

In contrast, hydrogen-bearing minerals are much more likely to provide a reasonable estimate of the hydrogen isotope composition of the parent meteoric fluid because of the larger fraction of H in the water relative to H in the rock. Therefore, this paper focuses exclusively on the H isotope signature of fossil geothermal systems.

In addition to mineral proxies, direct measurements of the isotopic composition of the (now vanished) hydrothermal fluid can be made on fluid inclusions in hydrothermal minerals. Both O and H measurements can be made, but as with the mineral proxies, O isotope measurements may not reflect the parent meteoric fluid composition. In addition, there is the possibility of post-entrapment exchange of O with any mineral (e.g. quartz) that contains O in its structure. This post-entrapment exchange should not affect H isotopes in anhydrous minerals.

There also are problems with fluid inclusion measurements that must be addressed before the data are accepted as representative of parent meteoric fluids. Fluid inclusions must be determined to be of the same age as the host mineral (or at least very closely related in time). Secondary inclusions could form in the vein minerals at some later date and not necessarily be representative of meteoric fluids at the time the system was active. Often this problem can be resolved by microscopic inspection and determination of the approximate temperature of deposition.

4 GREAT BASIN PALEOCLIMATE DATA

Given the caveats above, we have assembled the extant data from hydrothermal systems in the Great Basin since ~75 Ma (Table 1). Insights into the variability in the δD values of meteoric water in both time and space can be obtained from these data by:

1. Comparison of paleo-isotope data to present-day spring isotope data; and
2. Construction of a secular curve for meteoric water using paleo-isotope data combined with age data.

Figure 1a is a contour map of δD values for present-day geothermal springs and wells, based on the data of Mariner et al. (1983) modified to include several new data. Because of the mixing effect of subsurface flow, this map is generally representative of the δD values of average meteoric waters. (In the present dry climate, the majority of subsurface waters are more truly representative of winter precipitation because most summer precipitation evaporates before getting into the groundwater system. However, the relative amount of summer precipitation is small relative to the amount of winter precipitation, therefore, the groundwater is very

nearly representative of total meteoric water.) Generally, there are both altitude and latitude effects that appear to influence the meteoric water isotopic patterns, resulting in a NE-trending zone of lowest δD values with higher values in N-S and E-W belts adjacent to the zone of lowest δD .

Figure 1b is a more areally restricted contour map drawn for the period 13-19 Ma, based on alunite (Arehart and O'Neil, 1993) and fluid inclusion (O'Neil and Silberman, 1974; Arehart and O'Neil, 1993; this paper) data from several localities. The number of data for this time period are significantly less than for the present day, and there are a few data outliers (as there are with present-day data). However, in general, the paleo-isotopic data result in patterns of isotopic contours very similar to those of the present day. Our interpretation of this pattern is that the altitudinal and latitudinal effects on meteoric water isotopic composition were very similar at ca. 16 Ma to those extant today.

From these paleo-isotopic data, then, we can construct a temporal pattern of isotopic variation for the Great Basin (Figure 2). A similar figure (Arehart and O'Neil, 1993) was originally based primarily on alunite data for which a latitudinal correction only was applied (i.e. all data were normalized to 41°N with a 5‰/degree latitude correction). Figure 2 is a modification of the secular curve of Arehart and O'Neil for paleoisotopic composition of water in the Great Basin between 0 and 75 Ma, based on data from fluid inclusions and hydrous silicates (kaolinite, sericite) from hydrothermal systems combined with the original alunite data set. Although the curve has been extended to 75 Ma, the constraints on the data beyond ca. 40 Ma are considerably less than for the younger data. These data (Table 1) have been normalized to a location of 41°N and 116°E, based on the contour maps of Figure 1. We believe that such a normalization is

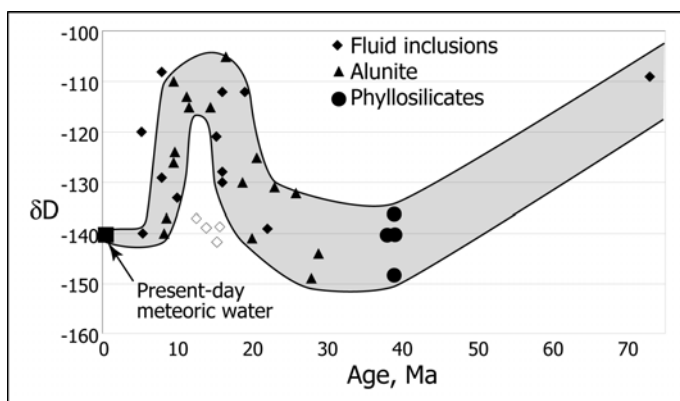


Figure 2. Secular δD curve for meteoric fluids normalized to 116°W longitude, 41°N latitude. White diamonds are data which do not appear to fit this curve (see text). Data from Table 1.

Table 1. Paleo-isotopic data for alunite (A), fluid inclusions (F) and kaolinite (K) samples.

Location	Type	Age	*D	corr *D
Roberts Mtns	A	5.3	-112	-120
Sleeper	A	5.4	-128	-140
Bodie	F	8.0	-98	-108
Gilbert	F	8.0	-111	-129
Alligator R	A	8.3	-129	-140
Post	A	8.6	-137	-137
Round Mtn	A	9.5	-94	-110
Post	A	9.5	-126	-126
Round Mtn	A	9.8	-107	-124
Aurora	F	10.0	-124	-133
Preble	A	11.3	-104	-113
Goldfield	A	11.6	-90	-115
Comstock	F	13.0	-133	-138
Jarbidge	F	14.0	-139	-139
Rabbit Creek	A	14.4	-106	-115
Trade Dollar	F	15.0	-136	-141
Eastern Star	F	15.3	-121	-121
Midas	F	15.3	-139	-139
Rawhide	F	16.0	-120	-128
Tenmile	F	16.0	-97	-112
Manhattan	F	16.0	-116	-130
Buckhorn	A	16.6	-102	-115
Rain	A	18.8	-130	-115
Tonopah	F	19.0	-90	-112
Rain	A	20.0	-141	-141
Rain	A	20.7	-125	-125
Wonder	F	22.0	-139	-139
Preble	A	23.0	-122	-131
Gold Quarry	A	25.9	-132	-132
Gold Quarry	A	27.9	-149	-149
Gold Quarry	A	28.9	-144	-144
Lone Mtn	K	38.0	-140	-140
Carlin trend	K	39.0	-145	-140
Getchell	K	39.0	-153	-148
Tuscarora	K	39.0	-136	-136
Humboldt	F	73.0	-95	-109

accurate than applying a simple latitudinal correction. It is clear from Figure 1 that patterns of isotopic distribution in meteoric waters were similar in the Great Basin at least during the late Tertiary. Extension of these patterns to earlier Tertiary times is probably more valid than the simple latitudinal correction.

Both weathering-related alunite, which can be dated directly (Arehart and O'Neil, 1993) and fluid inclusion data (O'Neil and Silberman, 1974; this study) yield similar patterns through time. Generally, *D values of meteoric fluids are fairly constant from 0-12 Ma, rise to a maximum at ca. 13-17 Ma, decrease between 17-40 Ma, and slowly rise between 40-75 Ma. Four fluid inclusion data at ca. 15 Ma fall off of this general trend and may represent either secondary inclusions (age younger than 15 Ma); an incorrect age for the inclusions; or possibly local climate variability. Additional examination of these anomalous data is warranted.

5 SUMMARY AND CONCLUSIONS

Stable isotope measurements from hydrothermal systems that were dominated by meteoric waters (primarily epithermal systems, but other systems as well) in the Great Basin of North America provide important insights into both spatial and temporal variations in the composition of paleo-meteoric water. From these water compositions, inferences about paleoclimates can be drawn. Isotopic composition of meteoric waters across the Great Basin at ca. 16 Ma appear to have been broadly similar to present-day patterns. Temporal variability in the isotopic composition of meteoric waters in the Great Basin yields a secular curve (Figure 2) that probably reflects changes in paleoclimate over the time period from late Cretaceous to present. Similar curves could be drawn for other areas of the world that have experienced significant hydrothermal activity. Extension of such secular curves to the more distant past is possible, but with decreasing accuracy.

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