OXYGEN ISOTOPIC EVIDENCE OF WATER-ROCK INTERACTIONS IN THE COSO GEOTHERMAL SYSTEM

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ABSTRACT

The Coso geothermal system, located on the Naval Air Weapons Station, China Lake, California, is developed on a suite of whole rock samples from wells 33A-7, 68-6 and 73-19 in a high temperature section of the Coso system have revealed varying degrees of δ¹⁸O depletion from primary igneous δ¹⁸O values of 7.5 ‰ down to δ¹⁸O values of -4.6 ‰. Near surface whole-rock δ¹⁸O values range from +3.7 to +7.6 ‰. Whole-rock δ¹⁸O values decrease with depth in all three wells analyzed, with wells 33A-7 and 68-6 having more systematic trends. Whole-rock δ¹⁸O values for 33A-7 decrease from 7.6 ‰ near the surface to a minimum of -3.0 ‰ at a depth of 2530 m, then rapidly increase to values between 4 and 5 ‰ down to the base of the well at 3295 m. In well 68-6, whole-rock δ¹⁸O values decrease from 7.6 ‰ near the surface to a minimum value of -4.6 ‰ at a depth of 1411 m. In well 73-19 δ¹⁸O depletion is generally less (minimum δ¹⁸O = 2.4 ‰) and δ¹⁸O values decrease less systematically with increasing depth. The lowest δ¹⁸O values in these wells are interpreted to represent alteration zones with higher water/rock ratios, most likely resulting from fracture-controlled increases in rock permeability. In the zones of maximum δ¹⁸O depletion in wells 33A-7 and 68-6, measured δ¹⁸O fractionations are smaller than equilibrium δc-r fractionation factors at current temperatures, suggesting that these portions of the Coso geothermal system were hotter and/or characterized by higher permeability in the past. However in well 73-19, measured δc-r is larger than equilibrium δc-r at current temperature conditions and the extent of δ¹⁸O depletion in whole-rock samples is generally smaller than in 33A-7 and 68-6. These differences suggest that isotope exchange in well 73-19 was more limited, either from kinetic barriers or lower permeability (less fluid access) or both.

INTRODUCTION

The Coso geothermal system, located on the Naval Air Weapons Station, China Lake, California, is a high temperature geothermal field developed in a series of dioritic to granodioritic intrusions of Mesozoic age. Two episodes of Cenozoic volcanism erupted basaltic and rhyolitic material throughout the field at 4.0-2.5 mya and 1.1-0.3 mya. Crustal thinning from Basin and Range extension has produced a silicic magma reservoir between 5-20 km depth; this has generated the necessary heat for current geothermal activity (Duffield et al., 1980). Over 150 wells, with many extending 3km in depth, have provided extensive geologic, geochemical and geophysical data. Potential geochemical measures of broad-scale reservoir permeability include the degree of water-rock interaction, as defined by oxygen isotope analysis of whole rock samples and mineral separates, and the extent of hydrothermal alteration.

Oxygen isotope analyses have been made on a preliminary suite of whole-rock samples and feldspar mineral separates taken from sample cuttings in three wells. These wells are located within a north-south trending zone of high temperature, and preliminary oxygen isotope data suggest that these wells intersect zones of significant fluid-rock interaction (unpublished data, Terra-Gen Operating Company). The results are utilized to identify zones of significant δ¹⁸O depletion that would indicate large amounts of fluid infiltration and isotopic exchange (high water to rock ratio and inferred high permeability) and to better understand water-rock interaction as a function of temperature and permeability.
Oxygen isotopic measurements were conducted at the University of Wisconsin-Madison, on 74 whole-rock and five hand-picked feldspar separates from three wells: 33A-7, 68-6 and 73-19. The locations of these wells are shown in figure 1. All samples were analyzed by laser fluorination using a sample chamber outfitted with an airlock sample chamber to prevent pre-fluorination of reactive rock powders (Spicuzza et al., 1998). Oxygen isotope values were standardized using UWG-2 garnet standard (Valley et al., 1995) and are reported in the standard δ\(^{18}\)O notation, relative to SMOW, in table 1. In well 33A-7 δ\(^{18}\)O values generally decrease with depth from a maximum value of +7.62 ‰ at 33 meters depth to a minimum of -3.08 ‰ at 2530 meters (Fig. 2a). Immediately below, δ\(^{18}\)O values are significantly higher, ranging between +3 to +4.9 ‰. For well 68-6 whole-rock values range from a maximum of +6.02 ‰ at 722 meters to a minimum of -4.60 ‰ at a depth of 2941 meters (Fig. 2b). Decreases in well 73-19 are less systematic, ranging from a maximum value of +7.57 ‰, at a depth of 777 meters to a minimum of +2.38 ‰ at 1408 meters depth (Fig. 2c). The highest measured δ\(^{18}\)O values from samples in these wells overlap the primary δ\(^{18}\)O values of +7.5 to 8.0 ‰ reported for the dioritic to granodioritic rocks in the region (Masi et al., 1981). Hydrothermally altered plagioclase is visible in cuttings (gray grain cores with distinctly whiter rims) and thin section (turbid grains and grain rims). To determine the extent of isotopic exchange that the whole rock sample has undergone in comparison to these feldspar grains, δ\(^{18}\)O measurements have been made on five feldspar separates. Plagioclase separates were prepared from cuttings at three depths (1372, 2792 and 2941 m) in well 68-6; rocks at two of these intervals exhibit moderate \(^{18}\)O/\(^{16}\)O depletion and the third sample exhibits extensive \(^{18}\)O/\(^{16}\)O depletion (table 1). A bulk plagioclase separate was prepared from the sample at 1792 m and has a δ\(^{18}\)O value of +2.73‰ compared to the whole rock δ\(^{18}\)O value of +2.83‰. A hand-picked concentrate of altered plagioclase from the sample at 1372 m yields a δ\(^{18}\)O value of +2.44‰ compared to the whole rock δ\(^{18}\)O value of +2.06‰. Bulk plagioclase (δ\(^{18}\)O = -4.44‰) was also separated from the sample at 2941 m depth that has the lowest whole rock δ\(^{18}\)O value (-4.60‰). Two hand-picked concentrates of altered feldspar from this bulk plagioclase separate have δ\(^{18}\)O values of -5.06 and -5.39‰.
## Table 1: Measured δ¹⁸O values of whole rock and plagioclase samples, current temperatures and calculated W/R ratios (closed and open system) at specific depths in wells 33A-7, 68-6 and 73-19 from Coso geothermal system, California. Asterisks next to a depth indicate the sample to be a mineral separate.

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## Discussion

### Fluid-Rock Interaction

The δ¹⁸O values of the whole rock samples range from -4.60 ‰ to 7.62 ‰ (table 1), and thus exhibit variable degrees of ¹⁸O/¹⁶O depletion relative to primary igneous δ¹⁸O values. These ¹⁸O/¹⁶O depletions result from isotopic exchange between the igneous host rock and the reservoir fluid derived from low δ¹⁸O local meteoric water. Assuming equilibration, the extent of ¹⁸O/¹⁶O depletion in any given rock will be a function of the amount of reservoir fluid with which the rock has interacted. Estimates of the amounts of fluid involved in hydrothermal alteration have often been made using
box models of mass balance to compute water (W) to rock (R) ratios (Taylor, 1971). Alternatively, use of reactive transport models (Baumgartner and Rumble, 1988; Bowman et al., 1994; Cook et al., 1997; Baumgartner and Valley, 2001) have potential to constrain fluid fluxes, but these models require knowledge of flow path and distances for the Coso system that are not available in this study. Two separate endmember box models have been used to calculate W/R (atomic oxygen) ratios following the mathematical formulations discussed in Criss and Taylor (1986). First, calculations relating to closed-system conditions were made using the following equation:

$$\frac{W}{R_c} = \frac{\delta^{18}O_{rf} - \delta^{18}O_{ri}}{\delta^{18}O_{wi} - \delta^{18}O_{wf}}$$  (1)

where $\delta^{18}O_{rf}$ is the measured $\delta^{18}O$ value of the exchanged rock in the geothermal system, $\delta^{18}O_{ri}$ is the initial $\delta^{18}O$ value of the igneous rock (in practice, the highest measured $\delta^{18}O$ value in the well of interest), $\delta^{18}O_{wi}$ is the oxygen isotopic composition of local meteoric water and $\delta^{18}O_{wf}$ is the $\delta^{18}O$ value of the reservoir fluid. Actual $\delta^{18}O$ values for reservoir fluids have been determined by calculating a steam fraction (based on enthalpy data) and utilizing measured $\delta^{18}O$ values of both separated vapor and liquid water (unpublished data, Terra-Gen Operating Company). The mass and heat balance relationships used for these calculations are described in detail by
The calculated $\delta^{18}O$ values of the reservoir fluid for wells 33A-7, 68-6 and 73-19 are -7.3‰, -8.7‰ and -4.8‰, respectively. The second set of W/R calculations assumes an open-system in the sense that water does not recycle within the system (one-pass), as described by Criss and Taylor (1986). This value is determined using the following equation:

$$W/R_o = \ln((W/R)_o + 1) \quad (2)$$

Values of W/R ratio calculated with the open-system endmember are lower, for a given amount of $^{18}O/^{16}O$ depletion in the rock.

Calculations of box model W/R ratios involve several assumptions, and it is important to understand how these assumptions place limitations on their interpretation. Both box model endmembers assume attainment of exchange equilibrium between rock and fluid. Incomplete exchange yields less $^{18}O/^{16}O$ depletion in a rock; this will result in lower calculated W/R ratios. Departures from equilibrium may be important in the shallow, lower temperature parts of geothermal systems. A second limitation is that box model W/R calculations do not account for the isotopic modification that the fluid undergoes along segments of its flow paths leading to the local site of hydrothermal alteration and isotopic exchange (Baumgartner and Rumble, 1984; Bowman and Willett, 1991; Bowman et al., 1994; Baumgartner and Valley, 2001). The impact from this prior exchange history of the fluid is that box model W/R ratios will underestimate actual W/R ratios. As a result, calculated box model W/R ratios should be regarded as minimum estimates of the amounts of fluid involved in hydrothermal alteration and isotopic exchange at specific sites within hydrothermal flow systems. However as long as the infiltrating fluid is chemically (isotopically) reactive, and therefore capable of inducing $^{18}O/^{16}O$ depletions in the infiltrated rocks, then the extent of $^{18}O/^{16}O$ depletion in the rock will reflect relative fluid fluxes. Under these circumstances, differences in calculated W/R ratios would also be qualitative guides to the relative amounts of fluid involved in alteration and isotopic exchange at specific sites within hydrothermal systems.

The results of both sets of W/R calculations are presented in table 1. As calculated W/R ratio increases with the extent of $^{18}O/^{16}O$ depletion, the most highly depleted $\delta^{18}O$ values for each well also correspond to the highest calculated W/R ratios (both closed and open). The $\delta^{18}O$ measurements (and W/R ratio calculations) show that there are a limited number of discrete intervals in these wells with large $^{18}O/^{16}O$ depletions that identify zones in the rock reservoir that have interacted and exchanged isotopically with significant quantities of geothermal fluid (high calculated W/R ratios) at some point in time. Well 33A-7 has three intervals of high calculated W/R ratio: 1.86 (closed system conditions) and 1.05 (open system) at 2530 meters; 1.30 (closed) and 0.83 (open system) at 872 meters; and 0.68 (closed) and 0.52 (open) at 110 meters. Well 68-6 has one interval at 2941 meters that is characterized by much higher W/R ratio (1.41 and 0.88 for closed and open system, respectively) than elsewhere in the well. In general, calculated W/R ratios for well 73-19 are lower than for the other two wells. However locally higher W/R ratios (closed system) are computed for depths of 1709 (0.33), 1411 (0.71) and 546 (0.28) meters in well 73-19.

It is plausible that these zones of significant $^{18}O/^{16}O$ depletion—and high W/R ratio—in the three wells are characterized by higher permeability during geothermal activity currently or in the past. In contrast, the great majority of the rock in these wells has experienced considerably less or even no significant $^{18}O/^{16}O$ depletion, and calculated W/R ratios (and permeability) for these extensive intervals are much lower. This spatial pattern is consistent with fluid flow and resulting fluid-rock interaction focused along discrete zones, likely fractures, and therefore large-scale permeability within the rock reservoir is likely fracture-controlled.

**Thermal and oxygen isotope evolution of geothermal fluids in the Coso system**

The measured difference in $\delta^{18}O$ value between the reservoir fluid and the most $^{18}O/^{16}O$ depleted whole-rock sample (measured $\Delta_{r,w}$) in two of the three wells is considerably less than the equilibrium rock-water fractionation factor (equilibrium $\Delta_{w}$) at current measured temperature in these wells. The equilibrium $\Delta_{r,w}$ has been estimated using the experimental calibration for oxygen isotope fractionation between plagioclase ($X_{An} = 0.4$) and water from O’Neil and Taylor (1967). Measured $\Delta_{r,w}$ in well 33A-7 at 2530 m (depth of the most $^{18}O/^{16}O$ depleted whole rock sample; table 1) is 4.18 ‰, whereas equilibrium $\Delta_{w}$ for the current measured temperature of 228°C at this depth would be 7.13 ‰. In well 68-6, the measured $\Delta_{r,w}$ at 2941 m (depth of the most $^{18}O/^{16}O$ depleted whole rock sample; table 1) is 3.4 ‰, whereas the equilibrium $\Delta_{w}$ is 6.88 for the current measured temperature of 234°C at this depth. It is clear that the measured $\Delta_{r,w}$ values for these $^{18}O/^{16}O$ depleted zones in wells 33A-7 and 68-6 are smaller than the equilibrium $\Delta_{w}$ values at current temperatures. This discrepancy is not the result of incomplete oxygen isotope exchange.
between the geothermal fluid and the rocks at these intervals. Incomplete isotopic exchange would produce measured $\Delta_{w}$ values greater than equilibrium $\Delta_{w}$ values; hence isotopic exchange kinetics is not the explanation for these differences. These discrepancies require either that temperature for this fluid-rock isotopic exchange was higher than current temperatures or that the $\delta^{18}O$ values of the geothermal fluids were lower, or a combination of both. Temperature would need to increase to 318° and 352°C in wells 33A-7 and 68-6, respectively, for the measured $\Delta_{w}$ values in these wells to correspond to equilibrium $\Delta_{w}$ values. Alternatively, the $\delta^{18}O$ values of the reservoir fluids in wells 33A-7 and 68-6 would have to decrease by 2.91 %o and 3.49 %o, respectively. A decrease in the $\delta^{18}O$ value of the reservoir fluid implies an increase in the W/R ratio (and permeability) for the geothermal system as a whole. The implication is that these portions of the Coso geothermal system represented by wells 33A-7 and 68-6 were hotter and/or characterized by higher permeability during the fluid-rock exchange recorded by the most $^{18}O/^{16}O$ depleted intervals in these two wells.

The situation for well 73-19 is opposite that in wells 33A-7 and 68-6. Measured $\Delta_{w}$ in well 73-19 at 1411 m (depth of the most $^{18}O/^{16}O$ depleted whole rock sample; table 1) is 8.03 %o, whereas equilibrium $\Delta_{w}$ for the current measured temperature of 282°C at this depth would be smaller, 4.13 %o, the reverse of the situation in wells 33A-7 and 68-6. This discrepancy reflects incomplete isotopic exchange between rock and reservoir fluid, either from kinetic barriers to isotopic exchange or limited physical contact between reservoir fluid and rock owing to lower permeability, or both. The extent of $^{18}O/^{16}O$ depletion measured in whole rock samples in well 73-19 is smaller in comparison to $^{18}O/^{16}O$ depletion in the other two wells (table 1, fig. 2), compatible with either of these effects.

CONCLUSION

Oxygen isotope measurements on a suite of whole rock samples from wells 33A-7, 68-6 and 73-19 have revealed varying degrees of $^{18}O/^{16}O$ depletion from primary igneous $\delta^{18}O$ values of 7.5 %o down to $\delta^{18}O$ values of -4.60 %. In general $^{18}O/^{16}O$ depletion increases with increasing depth in wells 33A-7 and 68-6. In well 73-19 $^{18}O/^{16}O$ depletion is generally less, and $\delta^{18}O$ values decrease less systematically with increasing depth.

The $\delta^{18}O$ results and associated estimates for minimum values of W/R ratio show that there are a limited number of discrete intervals in these wells with large $^{18}O/^{16}O$ depletions that identify zones in the rock reservoir that have interacted and exchanged isotopically with significant quantities of geothermal fluid (high calculated W/R ratios). In the zones of maximum $^{18}O/^{16}O$ depletion in wells 33A-7 and 68-6, measured $\Delta_{w}$ fractionations are smaller than equilibrium $\Delta_{w}$ fractionation factors at current temperatures. These discrepancies suggest that these portions of the Coso geothermal system represented by wells 33A-7 and 68-6 were hotter and/or characterized by higher permeability in the past. The oxygen isotope data from well 73-19 however reveal a different situation. Measured $\Delta_{w}$ is larger than equilibrium $\Delta_{w}$ at current temperature conditions and the extent of $^{18}O/^{16}O$ depletion in whole-rock samples is generally smaller than in 33A-7 and 68-6. These differences suggest that the $^{18}O$ exchange in well 73-19 is opposite that in wells 33A-7 and 68-6.

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