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Evidence for Deep-Flowing Cool Recharge Solutions at the NE Part of the Coso Geothermal Field from Clay Minerals and Fluid Inclusion Gas Analysis

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Keywords

Coso geothermal field, fluid inclusion gas analysis, clay mineral geothermometry, geothermal recharge solutions, geothermal reservoir seal

ABSTRACT

Wells 58A-10 and 76-27 drilled northeast of the Coso geothermal reservoir were studied by clay mineral analysis and fluid inclusion gas chemistry. These analyses indicate the common presence of low temperature meteoric fluids. Kaolin is a common alteration mineral in both wells. Reaction modeling of kaolin formation indicates this best occurs by action of solutions of 100°C or less and requires water/rock ratios of 60 or more. A remarkable change in fluid inclusion gas chemistry at 6200 ft in well 58A-10 indicates the presence of a seal at that depth. The fluid inclusion, gas, and clay data are consistent with the area of wells 76-27 and well 58A-10 providing recharge fluid to the Coso system and with Coso being a prograding geothermal system. The highest concentration of kaolin occurs at depths thought to be fracture zones.

Introduction

This paper reports fluid inclusion and clay mineral analyses on wells peripheral to the Coso geothermal system. Our goal is to characterize hydrothermal activity in wells 58A-10 and 76-27, drilled north of the eastern Coso production area. Well cuttings were analyzed by petrography, fluid inclusion microthermometry, fluid inclusion gas analysis, and clay mineral analysis; only the latter two types of analyses are reported here.

Well 58A-10 is located near the Eastern Coso geothermal field. Well 76-27 is more distal (Figure 1). Both wells intersect a Jurassic suite of intermediate composition intrusives that range from diorite to quartz monzonite in composition (Striegler 1995). These intrusives have been altered by low-grade regional metamorphism. Meta-igneous rocks are intruded by basalt, rhyolite, and granite pegmatites that exhibit little of the alteration observed in the plutonic rocks. The upper 1800 ft of well 58A-10 is comprised of sands, gravel, tuff, and a basalt flow about 650 ft thick. Spectrum $^{39}Ar/^{40}Ar$ dating indicates an age of ~ 73 Ma (Kurilovitch 2003) for Coso basement rocks that we interpret as the cooling age after regional metamorphism. Chlorite and illite occur ubiquitously from the top to the bottom of both wells.

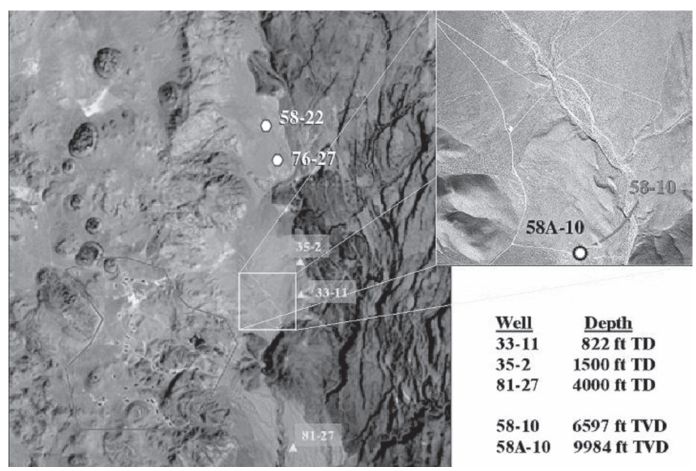

Figure 1. The location of wells 58A-10 and 76-27 is shown on an aerial photograph. The outlined area in the SW corner of the photo is the approximate outline of the Coso geothermal field.

Methodology

Well 58A-10 cuttings were sampled at 100 ft intervals; well 76-27 cuttings were sampled at 200 ft intervals starting below 1000 ft. Samples were split for gas analysis and clay mineral analysis. Clay minerals analysis was performed following the methods outlined using standard methods in Moore (1997). Bulk fluid inclusion gas analysis was performed at New Mexico Tech on both wells. In addition, well 58A-10 fluid inclusion volatiles were analyzed by a commercial laboratory, Fluid Inclusion Technologies (FIT), which principally serves the oil and gas industry. At the NMT laboratory, chip samples of about 0.2 gm are crushed in a vacuum and the volatiles that are released are analyzed by quadrupole mass spectrometry. The NMT system is calibrated with gas mixtures and fluid inclusion standards to maintain an analytical precision of at least 5%. Several mass spectrometer peaks are monitored in order to increase analytical precision. This method is detailed in (Norman 1996). FIT's analytical procedures are proprietary. Analyses are made for mass peaks 2 to 4 and 12 to 180; there is no calibration for individual gaseous species. FIT analytical replicate precision was determined to be +/- 27% for mass 44, which is the principal mass spectrometer peak for CO_2, by analyzing 27 replicate samples. FIT analyses can be used to determine fluid inclusion density. Each sample is given a blow with a small piston, which opens more inclusions in inclusion-rich material. Therefore, fluid inclusion density is best monitored using the water peak (mass 18) because fluid inclusions contain mostly water.

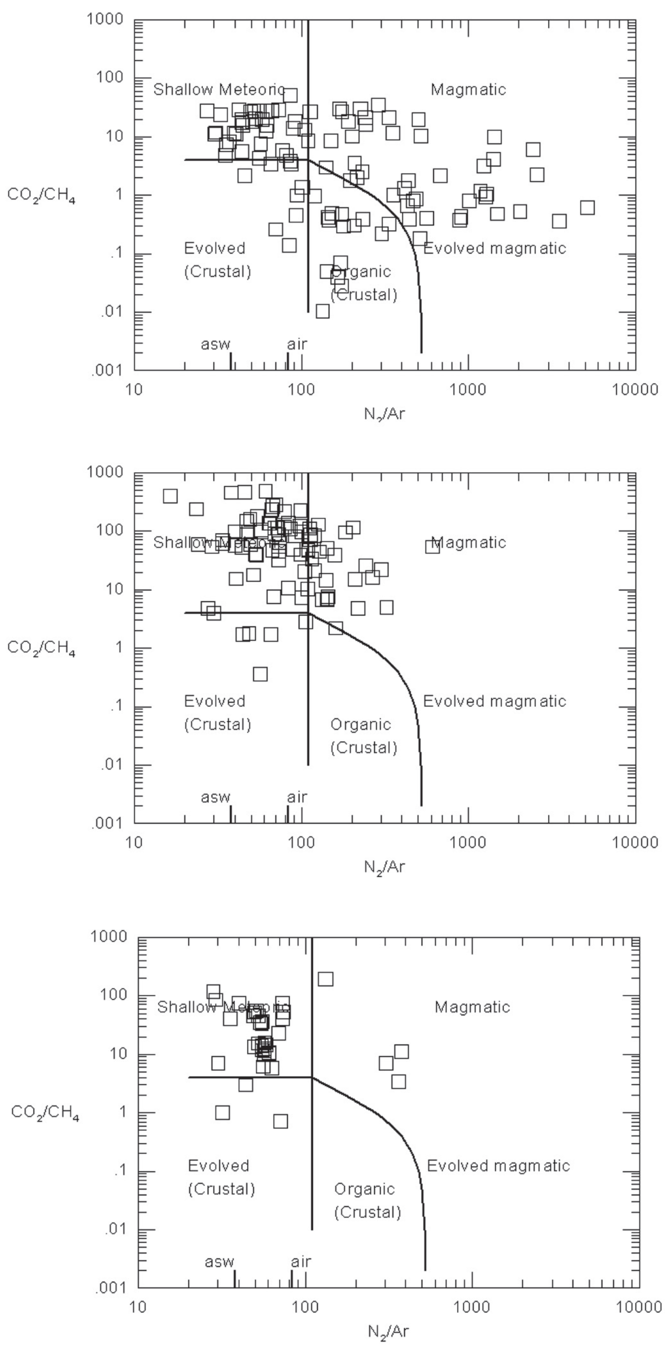

Figure 2. The top diagram shows Coso reservoir fluid inclusion gas analyses, the middle diagram shows well 58A-10 fluid inclusion gas analyses, and the bottom diagram shows well 76-27 fluid inclusion gas analyses.

Results

The fluid inclusion gas analyses performed at NMT are plotted on the N_2/Ar-CO_2/CH_4 discrimination diagrams shown in Fig. 2**.** We compare these analyses to 113 analyses performed on Coso reservoir wells, including wells 34a-9, 68-6, 33b-19, 51a-16, 84-30, 72-19, 64-16, and 73a-7. The depth of the reservoir fluid inclusion samples ranges from 531 to 9710 ft. Reservoir fluid inclusions show a broad range in chemistry with many exhibiting N_2/Ar ratios > 500 and CO_2/CH_4 ratios <1. Near-field well 58A-10 shows less variation in the gas ratios and far-field well 76-27 has the most homogenous gas compositions. For both wells, the majority of the analyses plot in the meteoric field.

NMT and FIT fluid inclusion gas ratios and the ratio of alkane-to-alkene organic species are plotted versus depth in Figures 3-5**.** For FIT analyses, the N_2/Ar is approximated by the ratio of mass peak 28 to mass peak 40; 28 is the principal mass spectrometer peak for nitrogen gas and 40 is the principal peak for argon. The ratio of peaks 44/15 is used to approximate the ratio of CO_2 to CH_4. The ratio of peaks 41/39 is used to approximate the ratio of propane, an alkane compound, to propene, an alkene compound.

Well 58A-10 shows remarkable changes in the gas ratios at a depth of about 6200 ft. These changes are clearly seen in both the NMT and the FIT analyses. Below 6200 ft, there are a significant percentage of the N_2/Ar ratios > 100 in the NMT analyses. The FIT analyses show similar higher ratios for the bottom portion of the well. The $C0_2$/CH_4 ratio changes remarkably (by two orders of magnitude) across the 6200 ft

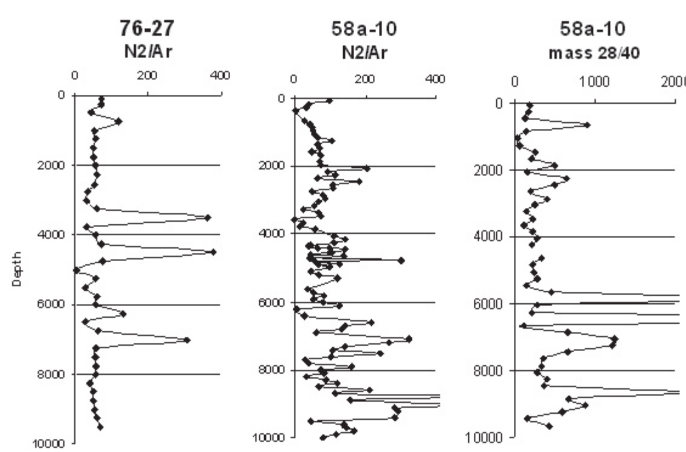

Figure 3. N_2/Ar ratios plotted versus depth in feet for fluid inclusion gas analyses of wells 76-27 and 58A-10. The right-most graph shows FIT analyses (See text for explanations).

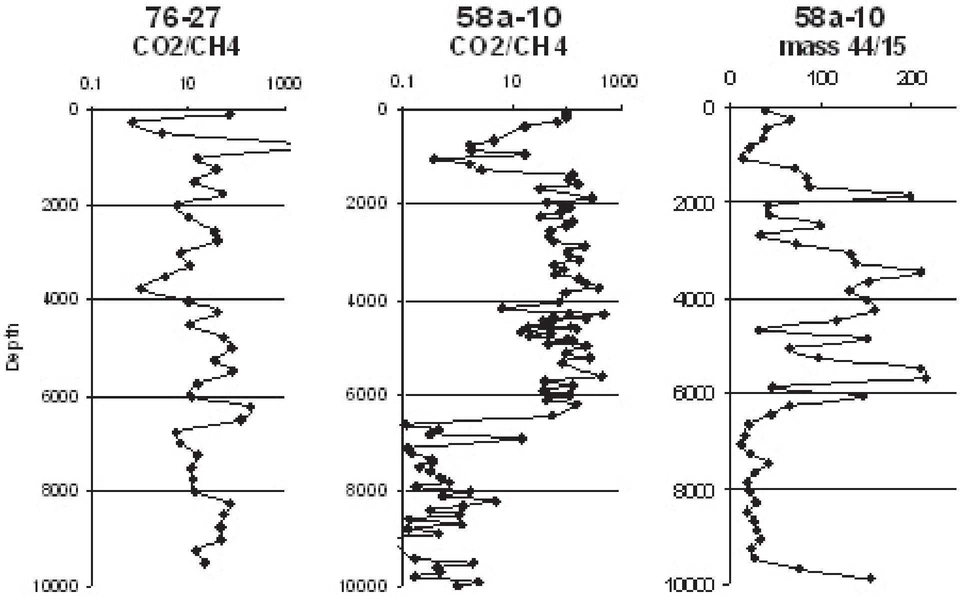

Figure 4. CO_2/CH_4 ratios plotted versus depth in feet for fluid inclusion gas analyses of wells 76-27 and 58A-10. The right-most graph shows FIT analyses (See text for explanations).

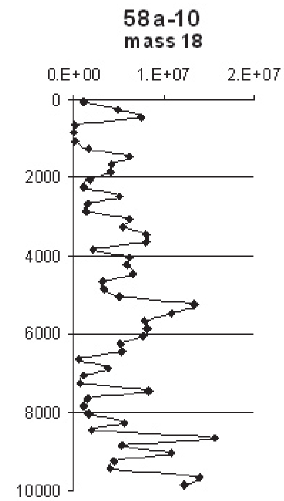

Figure 6. FIT fluid inclusion water analyses plotted versus depth. High FIT fluid inclusion water analyses indicate a high density of fluid inclusions.

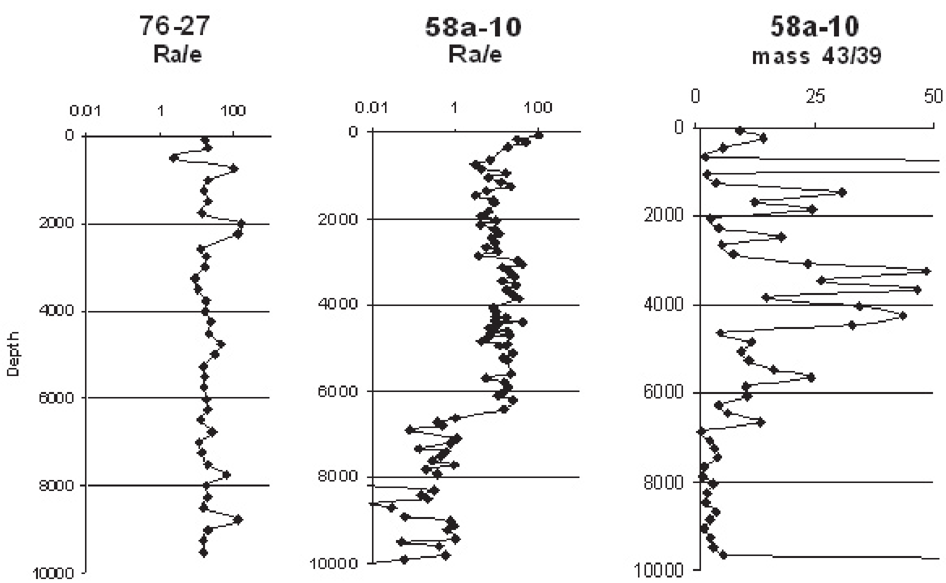

Figure 5. Alkane/alkene ratios plotted versus depth in feet for fluid inclusion gas analyses of wells 76-27 and 58A-10. The right-most graph shows FIT analyses (See text for explanations).

depth. Above 6200 ft, inclusions have CO_2-dominated fluids. Below 6200 ft, fluids are generally methane-dominated. Also, at a depth of 6200 ft, light hydrocarbon compounds in the fluid inclusions change from being dominated by the alkane compounds ethane, propane and butane, to being dominated by the alkene compounds ethylene, propene, and butene. Not shown are CO_2 analyses that have values mostly between 2 and 8 mol % for depths < 6200 ft and values < 2 mol % in deeper inclusions. FIT mass 18 analyses are plotted (Figure 6) using the same scale used for FIT analyses performed on 3 Coso reservoir wells and on one non-producing well (Norman 2004). Peak 18 shows significantly lower values than we observed in reservoir wells. A higher concentration of fluid inclusion water occurs at depths of 5000 to 5500 ft, 7700 ft and below 8500 ft.

Clay minerals identified and quantified include kaolinite, smectite, illite-smectite, illite, and chlorite. For simplicity, we have only plotted the amounts of kaolinite, smectite and illite (Figure 7, overleaf). Illite is a clay mineral generally stable at temperatures > 225°C. It occurs from top to bottom in both wells, which strongly suggests that it represents a long-past thermal event. Smectite, a clay mineral that generally is stable below about 125°C, occurs in the highest concentrations near the top and bottom of well 58A-10. The percentage of smectite decreases with depth in well 76-27, but some smectite is present at all depths. Kaolinite is very low temperature clay, yet kaolinite is present in significant amounts throughout both wells. It occurs in high abundance in well 58A-10 at depths of 4500 to 5500 ft and again at 7700 ft. The kaolinite analyses done at NMT were verified by the laboratory at the Energy and Geoscience Institute (EGI) at the University of Utah. EGI confirmed this highly unlikely occurrence of low temperature clay at depths > 4500 ft. Remarkably, kaolinite also occurs throughout well 76-27.

Discussion

Kaolinite

Kaolinite is typically the product of an acid attack on silicate minerals when fluids form advanced argillic mineral assemblages (Henley and Ellis 1983; Henley, Hedenquist et al.

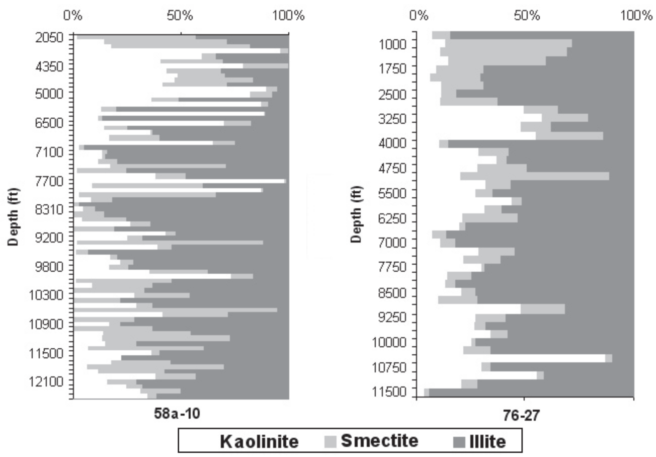

Figure 7. Relative abundances of kaolinite, smectite and illite are plotted for wells 58A-10 and 76-27.

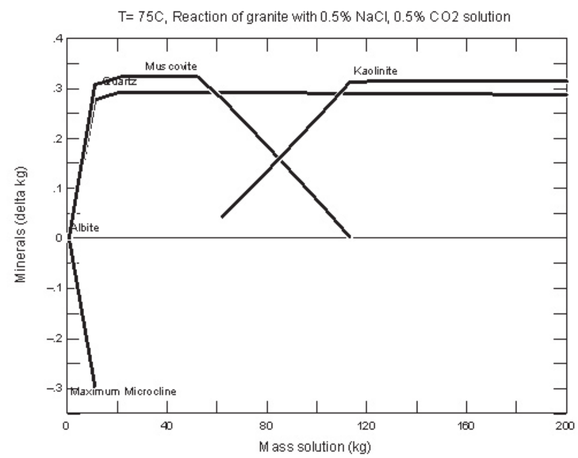

Figure 8. A reaction-transport model for a 75ºC solution with 0.5% CO_2 and 0.5% NaCl flowing through 1 kg of granite. The x-axis values of kg of solution are equal to the water-to-rock ratio. See text for modeling details.

1989; Hedenquist, Aoki et al. 1996). However, advanced argillic alteration in geothermal systems occurs either near the surface where H_2S oxidizes or it is associated with a high-sulfidation environment. There is no evidence of such an environment in either well. Kaolinite can also form in response to low temperature water flow through rock.

In order to try to understand how kaolinite formed, we modeled the formation of kaolinite in granitic rock using reaction-path modeling (Bethke 1996). A fluid composition of 0.5 wt% NaCl and 0.5 mol % CO_2 was used based on fluid inclusion analyses from Coso wells 58A-10 and 76-27. That fluid was reacted with granite consisting of equal parts of K-feldspar, albite and quartz at temperatures of 50, 75, 150, and 200ºC. The starting pH value was set at 7; using a different starting fluid pH has little affect on the results. During fluid flow, pH is controlled by water-rock reactions. A rock mass of one kilogram was assumed so that the models would show mineral changes versus kilograms of fluid, and thus kilograms of fluid are equal to the water-to-rock ratio. Models for 75ºC solutions predict that muscovite or illite form first; then, after all the feldspar is consumed, the water chemistry evolves and kaolinite forms (Figure 8). Kaolinite appears at water/rock ratios of about 60. For 150ºC fluids, kaolinite appears at a water/rock ratio ~ 140, and at 200ºC kaolinite appears at water/rock ratios >220. These are the minimum water/rock ratios that would form kaolinite because the models assume equilibrium that is seldom attained in geothermal systems (Norman 1998). We expect that smectite actually would form before kaolinite at temperatures >125ºC. Smectite, however, contains Mg and Fe, and no Fe and Mg-bearing minerals were included in the model. Therefore, the modeling could not predict smectite formation. We conclude from the modeling that large volumes of water passed through parts of the rocks penetrated by wells 58A-10 and 76-27, and that kaolinite is best formed by fluids at 100°C or less.

Reservoir Margin

Fluid inclusion gas analysis shows that wells 58A-10 and 76-27 are influenced by the Coso geothermal system, but were not subjected to current reservoir fluids. For comparison, we use production-well fluid inclusion gases in vein material and well cuttings (Lutz 1999; Lutz, Moore et al. 1999; Dilley 2004; Norman 2004). Coso bed-rock has metamorphic fluid inclusions unless overprinted by later fluid activity. Dilley (2004) analyzed chips from well BLM 84-30, which lies outside the Coso geothermal system, and from three wells within the geothermal field. Fluid inclusion gas ratios show little variation from top to bottom of well BLM 84-30, and this well shows little alteration. The constant gas ratios are consistent with a metamorphic origin of these fluids, because during regional metamorphism, large volumes of rock are subject to the same physical and chemical conditions. The most remarkable features of BLM 84-30 gas analyses (performed by FIT) are the low amounts of water that on a graph like Fig. 6 plot along the y axis, N_2/Ar ratios of about 50, and ratios of alkane to alkene species less than 1. The lack of alteration in well BLM 84-30 also suggests no geothermal- or groundwater flow. Fluid inclusions in wells 58A-10 and 76-27 are different from those in well BLM 84-30, and those wells show significant alteration. Well 58A-10 and 76-27 gas analyses are not similar to what we believe is the signature of metamorphic fluid inclusions, and as shown in Figure 2, these analyses differ from those of Coso production wells.

Fluid inclusion gas chemistry varies progressively from well 76-27, to well 58A-10, to the Coso reservoir wells. The gas analyses plotted in Figure 2 indicate that well 58A-10 was influenced by Coso reservoir fluids. The higher N_2/Ar ratio analyses occur near the bottom of well 58A-10, suggesting that this area of the well was most affected by geothermal fluids with a magmatic origin. However, there is no evidence suggesting that well 58A-10 was within the reservoir in the near past. The CH_4/CO_2 ratios that contrast with the low amounts of methane in Coso reservoir waters and reservoir fluid inclusions (Dilley 2004) plus the presence of low-temperature alteration minerals indicates that well 58A-10 does not record a significant flux of reservoir fluids.

Well 76-27 shows even less evidence for magmatic fluids, which is abundant in the producing wells. However, the inclusion gas chemistry for this well does not resemble what we believe to be that for pristine Coso basement rock. The ubiquitous presence of low temperature clay minerals indicates well 76-27 was subject to low temperature fluids. The fluid inclusion gas chemistry is consistent with low temperature ground water fluxing through the rock.

A Seal and Fluid Stratigraphy

We assume that fluid inclusion gas chemistry preserves samples of the fluids that have occupied well 58A-10. The sharp and significant change in fluid inclusion chemistry across the 6200 ft level in well 58A-10 indicates that different fluids occupied the pore space above versus the pore space below that depth. The lack of mixing between these two fluids is evidenced by the sharp differences in organic species at 6200 ft and indicates that there was no communication across this boundary. Thus the evidence is quite strong that there is a permeability seal at about 6200 ft in well 58A-10.

The chemistry of the upper fluid suggests that it is a low-temperature, shallow meteoric fluid with significant concentrations of CO_2. The N_2/Ar ratios of the upper fluid plot mostly in the meteoric field, suggesting that the fluid is not a deep-basin evolved water (Norman 1994). The high concentrations of CO_2 suggest fluid boiling (Norman 1996). However, "boiling" can result from heating low-temperature, CO_2-saturated waters, because CO_2 has a reverse solubility in water below 180°C (Giggenbach 1980).

The fluid from well 58A-10 appears to be a composite solution below 6200 ft. It has a greater magmatic component and much higher methane content than the fluid trapped above 6200 ft. Analyses plot mostly in the evolved and magmatic fields on the diagrams in Fig. 2. The dominance of alkene species indicates that the deep fluid is either a more oxidized or a higher temperature fluid than the shallow fluid. The high concentrations of methane in the deep fluid suggest quite reduced fluids; hence the deep fluids were at a higher temperature than the shallow fluids.

Recharge

The best explanation for a high flux of low-temperature waters on the margin of a geothermal system is that low-temperature fluid flow represents recharge. The high amounts of kaolinite in well 76-27 suggest that area had experienced a high flux of cool water to depths of at least 11,000 ft. Fluid inclusion gas analysis indicates these fluids are little-evolved meteoric fluids. Higher concentration of kaolinite locally over narrow depth intervals, for example at 7700 ft in well 58A-10 and 10,500 ft in well 76-27, indicate areas of higher fluid flow. High fluid flow locally is explained by the occurrence of major fractures at those depths. This agrees with the occurrence of high fluid inclusion densities (See Figure 6), which presumably record hydrological channel ways in well 58A-10 at the same depths that shows elevated kaolin content.

Our data indicates that well 58A-10 is in a zone where geothermal fluids are intermingling with meteoric fluids. All the data on well 76-27 suggests that it has seen mainly cool ground waters. Our analyses on well 58A-10 show some influences of geothermal waters on the well, as well as evidence for waters similar to those recorded by well 76-27 inclusions. An interface of Coso thermal fluids and recharge waters near well 58A-10 explains our analyses and the indications of fluid "boiling". The more evolved fluids recorded in the lower part of well 58A-10 must be a second influx of recharging fluid. Reservoir fluid inclusions also show the evidence of a meteoric fluid, a magmatic fluid, and an evolved meteoric fluid.

Conclusions

Fluid inclusion gas analysis indicates that wells 58A-10 and 76-27 are affected by the Coso geothermal system, but there is no evidence that they have seen fluids like those described from the production areas.

Wells 58A-10 and 76-27 have kaolinite alteration to depths of 10,000 ft and below. Modeling indicates that this kaolin was formed by a flow of large volumes of water that had temperatures well below 100°C.

Fluid inclusion gas chemistry indicates that well 78-27 and well 58A-10 experienced flow of shallow meteoric waters above 6,200 ft.

The highest amounts of kaolin are associated with major fractures.

Some recharge fluids enter the Coso geothermal system from the NE of the field.

There are two recharge fluids, one is shallow meteoric water and a second an evolved basin fluid. Contact between these fluids has formed a seal.

Well 58A-10 is on the extreme margin of the Coso geothermal system. Because there is no indication that this well has seen significant reservoir fluid in the past, the Coso geothermal systems is prograding.

Acknowledgment

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