ASSESSMENT OF FLUID-MINERAL EQUILBRIA IN THE COSO GEOTHERMAL RESERVOIR

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ABSTRACT

We evaluated the state of fluid-mineral equilibria in the Coso geothermal reservoir, based on deep reservoir fluids sampled in the early stage of production. These fluids are near neutral pH, chloride waters with minor to moderate concentrations of aqueous CO_2. The reservoir is entirely hosted in fractured crystalline plutonic and metamorphosed rocks, and the reservoir temperatures range from 190-300ºC.

The results of chemical speciation show the deep fluids are in equilibrium with quartz or chalcedony, Na-feldspar, K-feldspar, K-mica, and probably Mg-chlorite. These fluids are slightly under-saturated with respect to calcite, and we presume the widespread occurrence of epidote is a major control on aqueous calcium concentrations.

The Na/K cation ratios conform to equilibria involving Na-feldspar-K-feldspar, but they predict temperatures that exceed the resource temperature suggesting equilibrium is established beneath current drilled depths.

1. INTRODUCTION

The Coso geothermal field, Coso Range, is located in east central California, where geothermal power (≥240 MWe) has been produced since 1987. The geothermal resource is situated within the Naval Air Weapons Station, China Lake, and the power station is owned and operated by Terra-Gen. Coso ranks third among geothermal power producers in the USA, after the Geysers and the Salton Sea, and like these, the high-temperature resource is related to magmatic intrusion and volcanism (Duffield et al., 1980; Monastero et al., 2005; Kennedy and van Soest, 2007).

Geologically, the field is located in the southwestern edge of the Great Basin, inside a triangular shaped province of basin and range extension bounded by the Sierra Nevada to the west, the Garlock fault zone to the south, and the Walker Lane to the northeast (Monastero et al., 2005). In its natural state, the high temperature geothermal resource was liquid-dominated and entirely hosted by fractured plutonic and metamorphosed rocks of Mesozoic age (e.g. Fournier et al., 1980; Adams et al., 2010). Permeability and fluid flow are controlled by faults and fractures (e.g., Duffield et al., 1980; Monastero et al., 2005; Davatzes and Hickman, 2010), and despite an arid setting (<120 mm annual rainfall), the water table was close to the surface. Wells in the vicinity of 74A-19 and 81-19 (Fig. 1) are located within the upflow zone where the temperature exceeds >300ºC at <1500 m depth. An outflow plume extends northward, and wells 78-6 and 34-9 lie on the periphery of the resource.

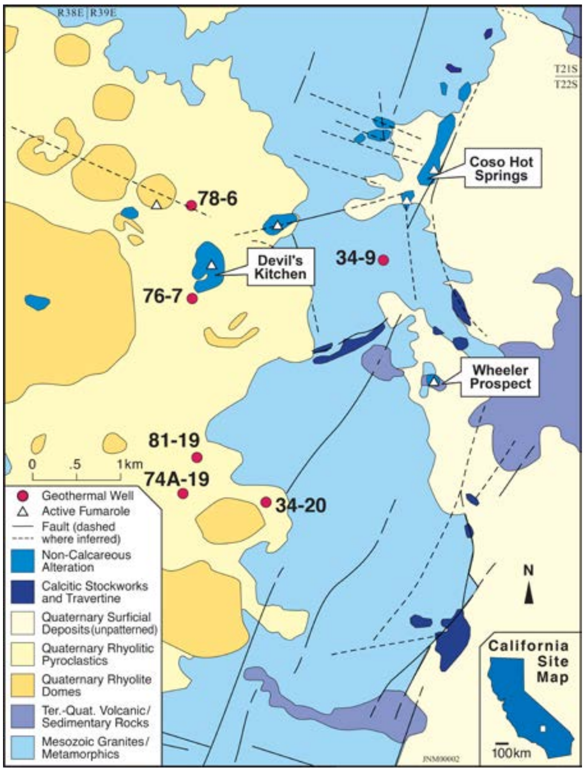

Figure 1: The geological setting of the Coso geothermal field, and the locations of wells discussed in this paper.

Chemical data for fluids from more than 140 wells were made available to us to evaluate water-rock interaction and to assess fluid-mineral equilibria. For brevity, we report preliminary results on just six wells, which span the range of chemical and thermal conditions for the resource, as represented in the Cl-enthalpy plot (Fig. 2.). Geothermal fluid production over the last 25 years, combined with evaporative steam loss and low rainfall has caused the reservoir to dry out, and many of the wells produced excess enthalpy by the early 1990s (Fig. 3). Accordingly, the data that are evaluated in this paper were collected shortly after the wells were drilled and tested, in the period 1987-1992.

2. FLUID-MINERAL EQUILIBRIA

In order to assess the state of fluid mineral equilibria, a distribution of aqueous species calculation was undertaken using WATCH 2.0 (Iceland Geosurvey; http://geothermal.is/software/software), which is modified and updated from the software that was initially written by Stefán Arnórsson, Sven Sigurđsson and and Hörđur Svararson (e.g., Arnórsson et al., 1982, 1983a, 1983b). Water and gas analyses were combined to a reservoir condition to compute the pH and the free ion activities of the major cations. These data were then plotted on phase diagrams, showing the stabilities of common secondary

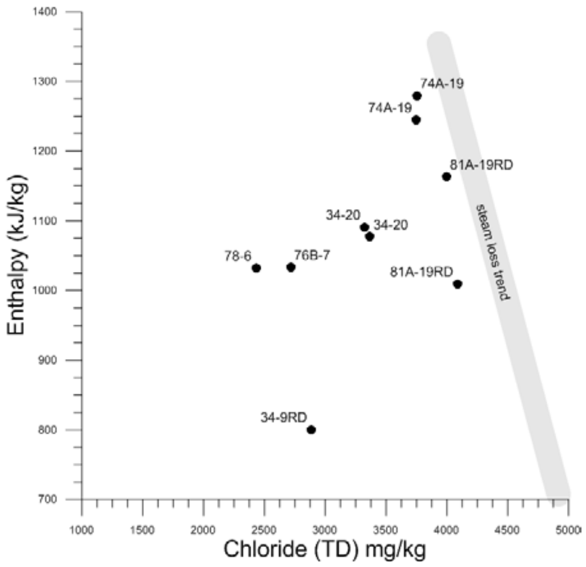

Figure 2: Chloride-enthalpy plot of production fluids.

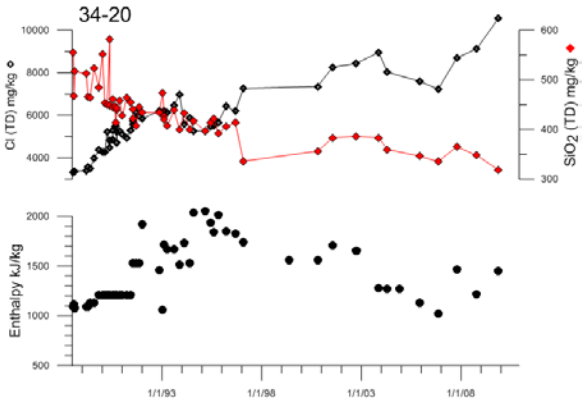

Figure 3: Time series plot for well 34-20 showing the onset of excess enthalpy production in the early 1990s.

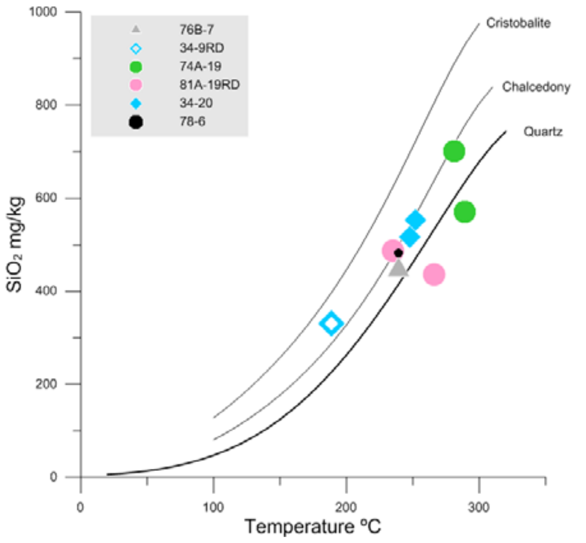

Figure 4: Aqueous silica concentrations plotted as a function of temperature and with respect to quartz, chalcedony, and cristobalite solubility curves

minerals, computed using Geochemists Workbench (Bethke, 1996) and the SUPCRT thermodynamic database (Johnson et al., 1992).

The states of fluid-mineral equilibria are presented in graphs (Figs. 4-8). All of the deep thermal waters are near neutral pH, with chloride concentrations of 2500 to 4200 mg/kg, aqueous CO_2 concentrations of 1000 to 8000 mg/kg (0.02 to 0.2 mol/kg), and aqueous SO_4 concentrations <70 mg/kg.

The concentrations of aqueous silica as a function of reservoir temperature (Fig. 4) show considerable scatter, but they cluster close to chalcedony and quartz solubility curves. Some of the scatter in silica values may be related to errors in sampling. Nonetheless, it is clear that silica concentrations were controlled by the least soluble silica polymorphs as is commonly seen in high temperature reservoirs.

The Log Na/H vs Log K/H activity diagram (Fig. 5) shows that most waters plot along the Na-feldspar-K-feldspar boundary and its meta-stable extension into the K-mica field. This trend is also typical of high temperature geothermal reservoirs and accounts for the widespread applicability of the Na-K geothermometer. A cross check of Log K/H vs temperature (Fig. 6) suggests that most fluids are in equilibrium with K-mica, but the position of the K-feldspar-K-mica boundary is sensitive to quartz versus chalcedony saturation.

Finally to assess the reliability of applying conventional Na-K and K-Mg cation geothermometers (Giggenbach, 1988), we plotted Log Na/K and Log Mg/K^2 ratios vs well enthalpy temperatures in two separate graphs. In Figure 7, numerical values form a coherent linear trend that plot below but parallel to the Na-feldspar-K-feldspar tie line. As a result, computed equilibration temperatures are as much as 50ºC hotter than the well enthalpy temperature. Presumably, this points to equilibration at levels deeper and hotter than those accessed by wells.

In Figure 8, numerical values form a linear trend coincident with the equilibrium expression:

$$0.8 \text{ K-mica} + 0.2 \text{ Mg-chlorite} + 5.4 \text{ quartz} + 2 K^+ = 2.8 \text{ K-feldspar} + 1.6 H_2O + Mg^{2+}$$

but with considerably more scatter than the Log Na/K data. The lowest ratios underestimate reservoir temperatures, and these results also suggest that equilibration occurred at levels deeper and hotter than those accessed by wells.

For calcium phases, the speciation computations indicate the reservoir waters were slightly undersaturated with respect to calcite, as might be expected from fluids with moderate to low CO_2 concentrations.

3. COMPARISONS WITH ALTERATION MINERALOGY

A comprehensive study of hydrothermal alteration in the reservoir is lacking, but detailed thin section studies of drill core and cuttings from a few wells demonstrates that a large portion (>80%) of the reservoir rock lacks significant evidence of hydrothermal alteration. Secondary minerals are mainly found filling veins and veinlets; to much a lesser extent they occur as replacement along the fracture and vein selvedges. Metamorphic mineral phases comprise

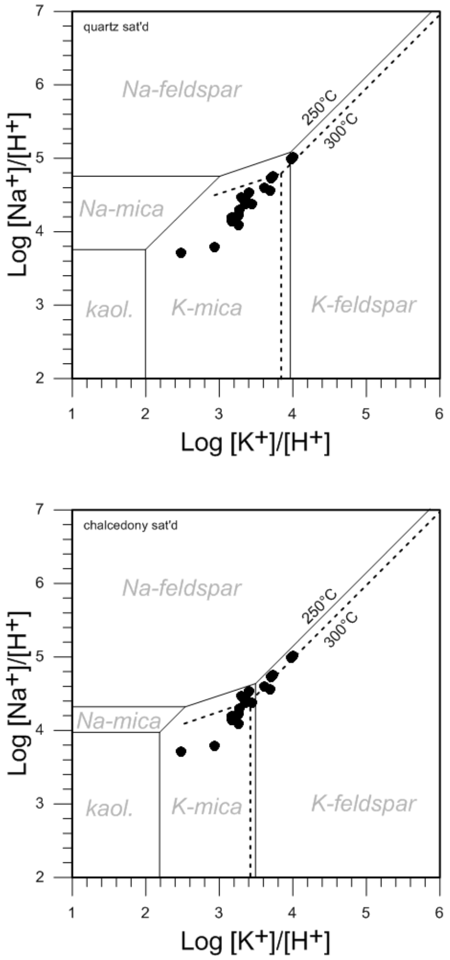

Figure 5: Log Na/H vs Log K/H activity phase diagrams as a function of quartz and chalcedony equilibria. Dots represent Coso reservoir water compositions.

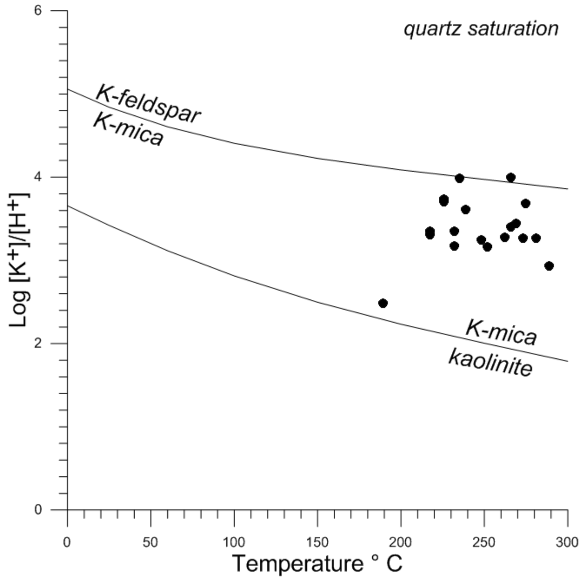

Figure 6: Log K/H activity vs temperature phase diagram as a function of quartz equilibria. Dots represent Coso reservoir water compositions.

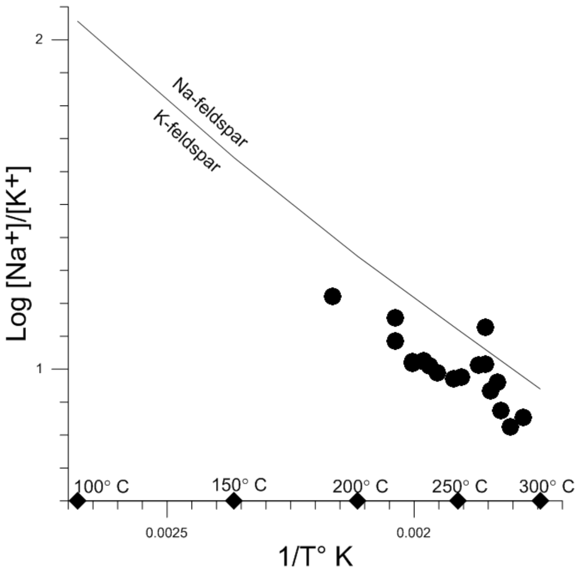

Figure 7: Log Na/K activity ratio vs temperature, and the Na-feldspar-K-feldspar stability fields.

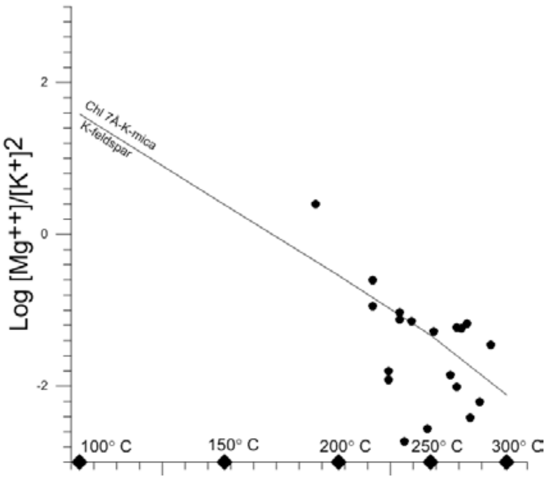

Figure 8: Log Mg/K^2 activity ratio vs temperature, and the K-feldspar-Mg-Chlorite-K-mica stability fields.

plagioclase, hornblende, epidote, and biotite, whereas young hydrothermal alteration is made up of quartz, calcite, chlorite, epidote, adularia, illite, and trace wairakite (Moore, unpub. data). These observations are consistent with the interpretations of fluid-mineral equilibria (Figs. 4-8). The widespread occurrence of epidote makes it the most likely candidate for a control on calcium ion activities.

4. PRELIMINARY FINDINGS

The reservoir fluids in the Coso geothermal resource share characteristics in common with many high temperature geothermal fields in terms of the state of fluid-mineral equilibria. This is in spite of the fact that hydrothermal alteration is poorly developed because of the very low porosity in the crystalline reservoir rocks. Fluid-mineral equilibria appear to be controlled by minerals exposed along fracture selvedges and filling open spaces. Silica concentrations are controlled by equilibrium with quartz or chalcedony solubility, whereas Na/K ratios are controlled by equilibrium with Na-feldspar and K-feldspar. Mg/K^2 ratios are probably influenced by equilibria involving K-feldspar, K-mica, Mg-chlorite and chalcedony (or quartz). The deep fluids are slightly undersaturated in calcite due low to moderate CO_2 concentrations, and the widespread occurrence of epidote in the reservoir rocks suggests it is an important influence on aqueous calcium concentrations. Na/K cation geothermometer over-estimates the resource temperature, while the Mg/K^2 cation geothermometer gives a range of equilibration temperatures that hover around reservoir conditions.

ACKNOWLEDGEMENTS

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