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USE OF NATURALLY-OCCURRING TRACERS TO MONITOR TWO-PHASE CONDITIONS IN THE COSO EGS PROJECT

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ABSTRACT

A dramatic decrease in the ratio of chloride to boron was observed in the liquid discharge of a well proposed for EGS development in the Coso geothermal field. The decrease appears to be related to the transformation of some feed zones in the well from liquid-dominated to vapor-dominated. High concentrations of boron are transported to the wellbore in the steam, where it fractionates to the liquid phase flowing in from liquid-dominated feed zones. The high-boron steam is created when the reservoir liquid in some of the feed zones boils with a steam fraction greater than 90%. Combination of boron from both phases into the liquid phase results in the Cl;B ratio dropping from 40 to as low as 20.

INTRODUCTION

The Coso geothermal field is the site of a U.S. Dept. of Energy engineered geothermal system project (EGS; ROSE et al., 2002). The goal of this project is to improve the connection between an injection and a production well on the eastern periphery of the field (Figure 1). The feasibility of using naturally-occurring tracers to detect permeability changes between the injection and production wells was examined in support of the Coso EGS project. This project was initiated because condensate was frequently used in the injection well being considered. Condensate has a composition that is distinctly different than brine. One of these differences is the Cl/B ratio, which is much lower in condensate. Using Cl and B as tracers appeared ideal because they are both generally considered to be conservative in geothermal waters.

The time trends of Cl/B for the nearest production wells were examined to determine if the ratio was stable enough to be used as a tracer. In contrast to expectations, it was found that the ratio had dropped from a reservoir value of around 40 down to 20 over the period 1998-2001 (Figure 2). This was unexpected because Cl/B ratios are thought to be generally stable in liquid reservoirs. Further exploration of the Coso geochemical database demonstrated that several wells had shown this behavior at various times since production began at the field. This paper presents an explanation for the ratio decrease and the results of calculations on the systematics of Cl/B behavior in a two-phase geothermal system.

CHLORIDE AND BORON IN THE COSO GEOTHERMAL SYSTEM

Geochemists have long used the ratio of chloride to boron to determine the origin of waters (Arnorsson and Andresdottir, 1995). The basis for its use is that boron and chloride are among the most conservative aqueous species, as demonstrated by the close resemblance of the aqueous and host rock ratios (Ellis and Mahon, 1964; Ellis and Mahon, 1967) and the homogeneity of the ratio in fluids derived from a common reservoir (Shaw and Sturchio, 1992). An example of chloride and boron from two Icelandic geothermal systems is shown in Figure 3. It can be seen that the ratios for each system are constant despite the varying concentrations.

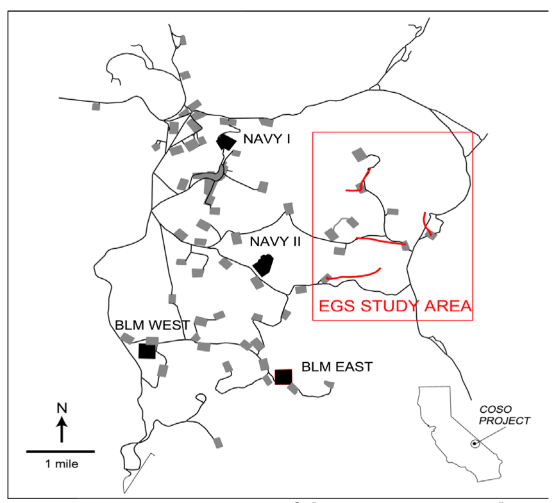

Figure 1. Location map of the Coso EGS study area.

The initial state concentrations at Coso were relatively constant with respect to location within the system, although they varied from 37 to 60. Figure 4 shows the boron and chloride concentrations in the Coso initial state. It can be seen that Navy I and East Flank waters average around 40, while those from BLM East and West range from 50 to 60. Waters

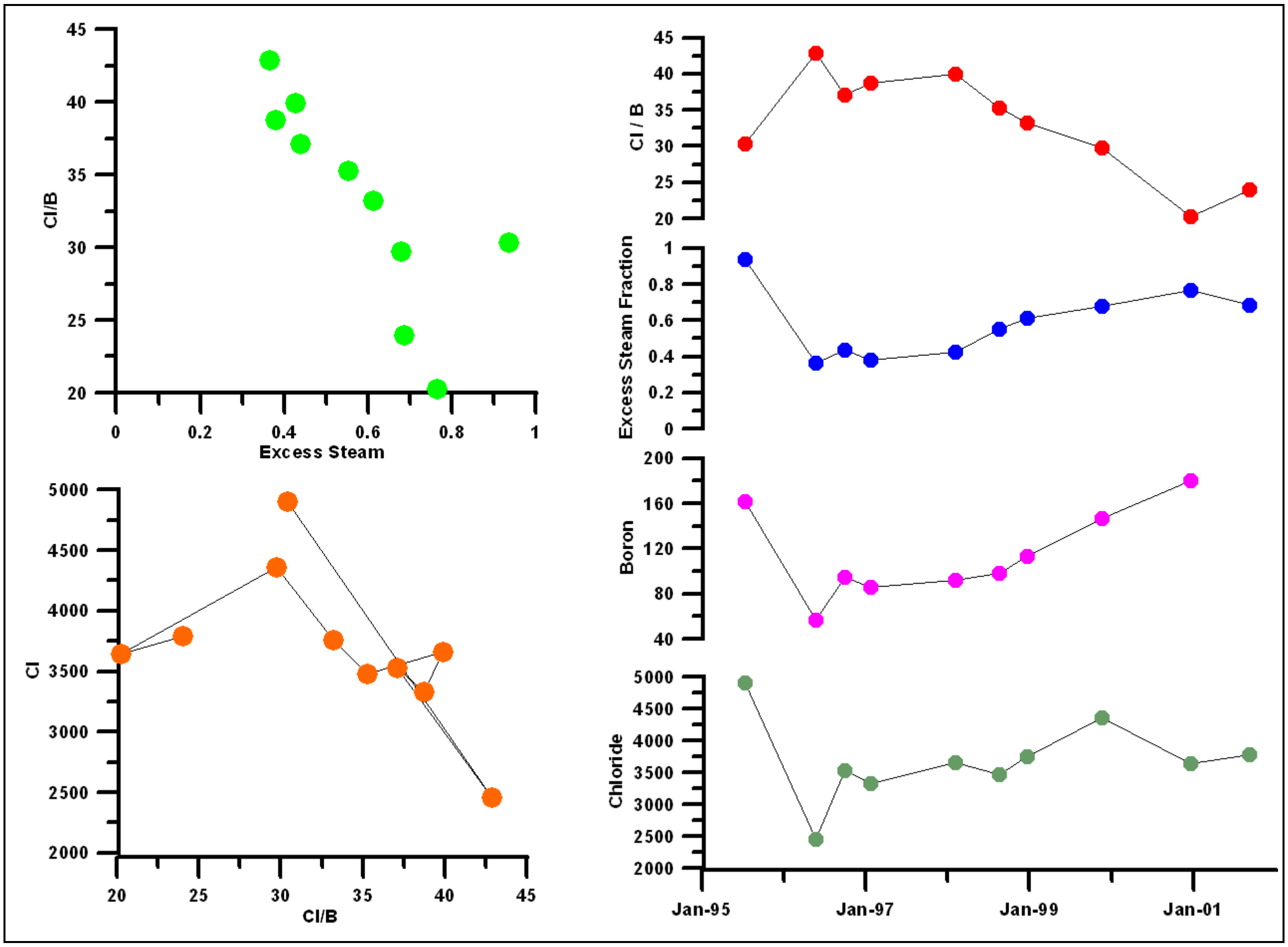

Figure 2. Chemical time trends from well 38-9 in the Coso system. Note the inverse relationship between Cl/B and the excess steam fraction

from western Navy II bridge the gap between the southern and northern averages.

All of the Coso production data were examined to determine if this was an isolated incident. It was found that while the majority of data fell with the range 37-60, quite a few data were found to fall below 37 (Fig. 5). Time trends for many of the wells were also examined, and several clear examples of Cl/B excursions were found.

The ratios were then plotted against the chemical parameters that are generally monitored to see if any correlations could be made. It was immediately apparent that excess steam (steam from reservoir boiling) is a nearly perfect inverse of the Cl/B ratio in well 38-9 (Fig. 2). This leads to the speculation that steam released during reservoir boiling might be responsible for transporting the excess boron to the production well.

VAPOR TRANSPORT OF BORON

Boron has long been known to have low but significant solubility in the steam phase at geothermal temperatures (Styrikovich et al., 1960). It has been speculated that boron could move through natural two-phase reservoirs and perturb the Cl/B ratios in the fluids, but only under unique, rarely occurring conditions (TONANI, 1970). (GLOVER, 1988) quantified the steam-liquid distribution using published data and liquid and steam from separators in New Zealand geothermal fields. This relationship is illustrated in Figure 6, which shows the boron concentration expected in steam versus the boiling fraction for a liquid that was initially 50 ppm B. It can be seen in this figure that a steam fraction of greater than 90% is required before significant boron concentrations of boron occur in the steam phase.

Although the calculations indicate that there must have been significant boiling occurring away from the well to provide the high boron concentrations, the remnant, highly concentrated liquid that resulted does not appear to be produced by the wells. Examination of chloride concentrations associated with low Cl/B ratios show no anomalous increases. This could be due the low relative permeability of liquid at high vapor fractions. The steam could exist some distance away from the well bore, since steam can travel much faster than liquid in a vapor-dominated zone (Adams et al., 1991).

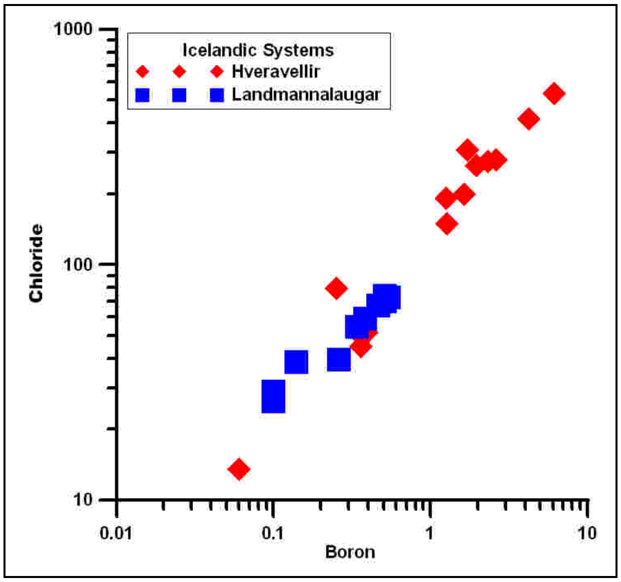

Figure 3. An illustration of the "normal" linear relationship between chloride and boron within a geothermal system. Data taken from (ARNORSSON and ANDRESDOTTIR, 1995).

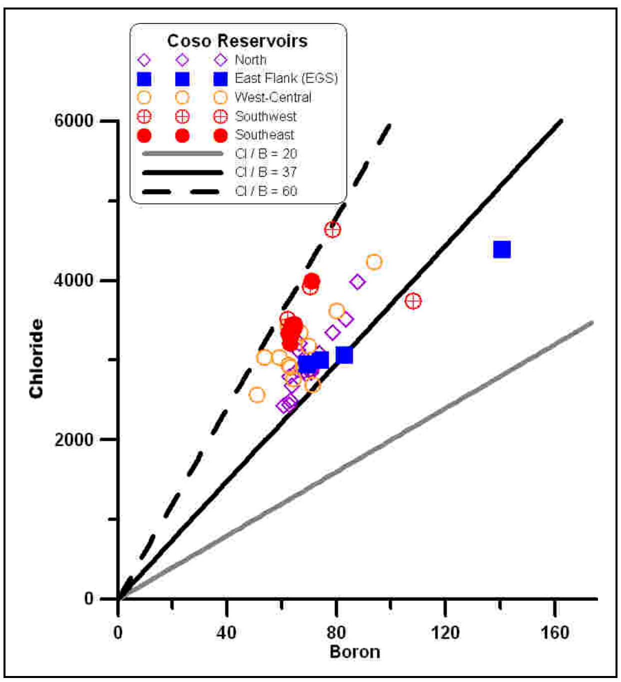

Figure 4. Initial state concentrations of chloride and boron in waters from the Coso geothermal system.

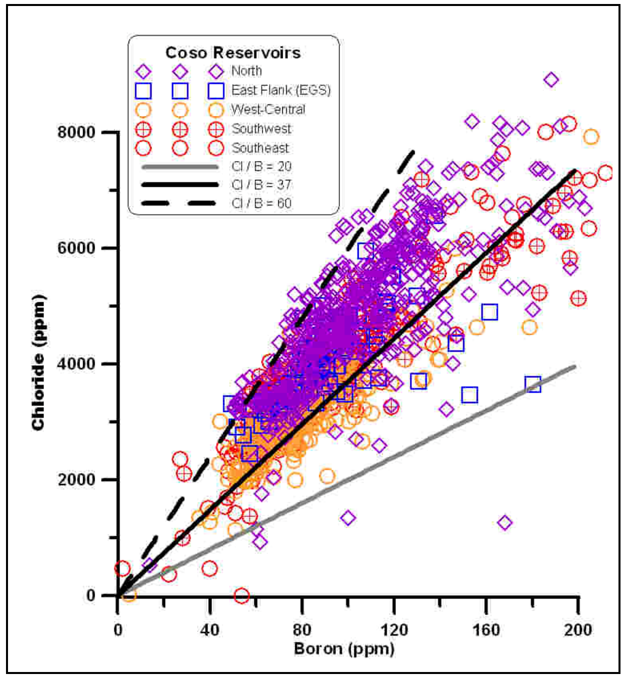

Figure 5. Post-exploitation concentrations of chloride and boron in the Coso production waters. There have been many excursions below the initial state Cl/B minimum of 37.

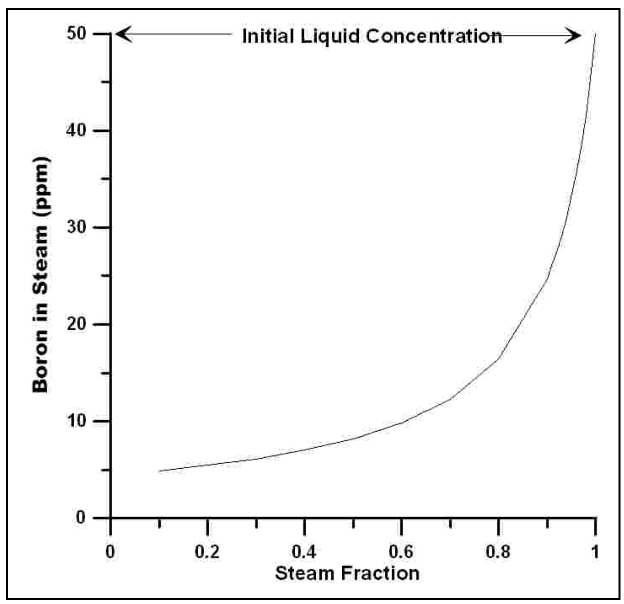

Figure 6. Concentration of boron in steam from water with an initial concentration of 50 ppm boron. Note that a steam fraction of greater than 0.9 is required to transport significant quantities of boron

Some special circumstances must occur in order for the liquid Cl/B ratio to be decreased significantly. First, the liquid must be boiled nearly dry to transfer enough boron to the steam. Then the steam must be transported through the reservoir without coming in contact with liquid to avoid loosing the boron back to the liquid. Once it reaches the two-phase zone near or in the well bore the steam concentration is

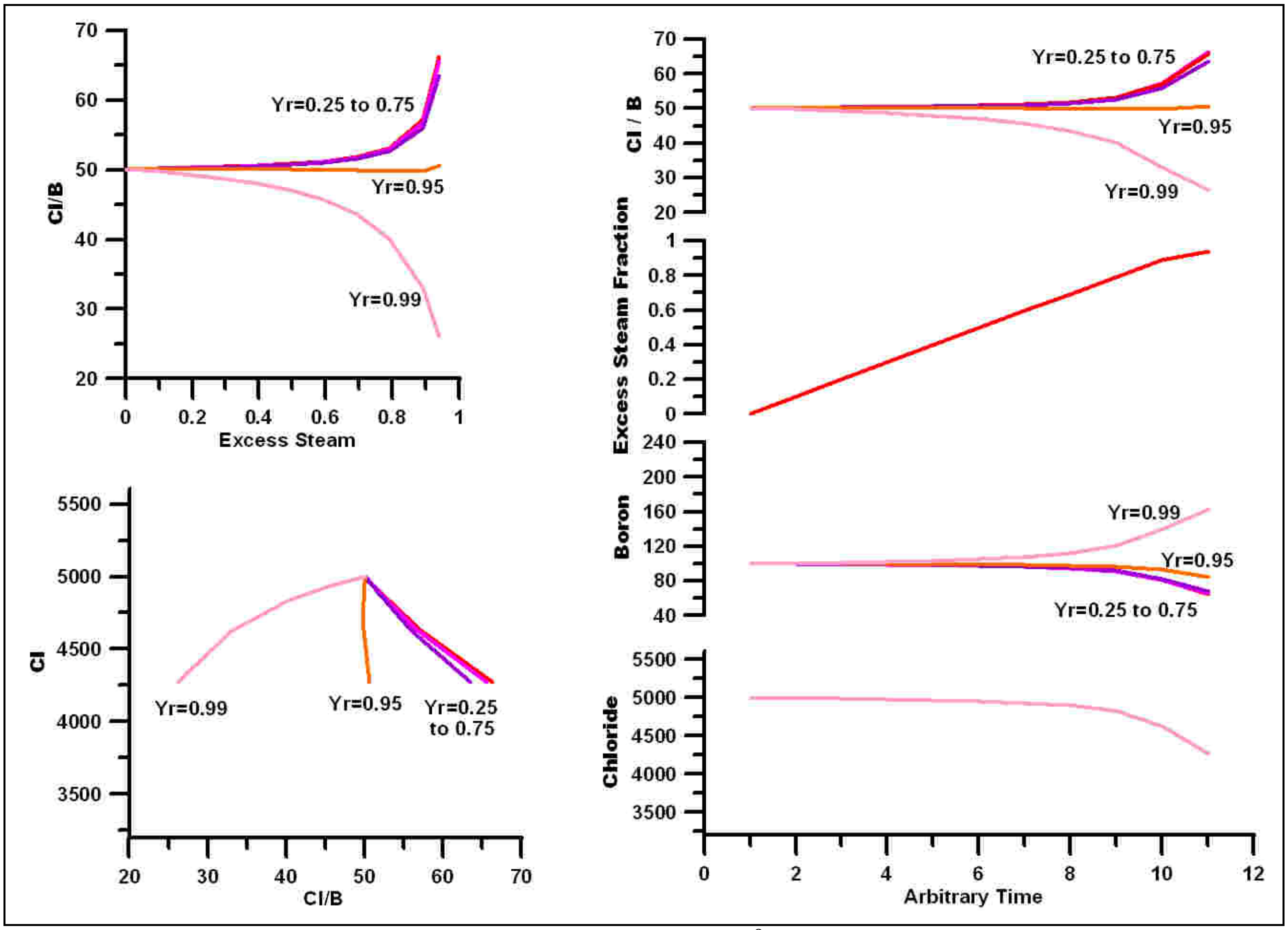

Figure 7. Summary of the results from the boiling model for the 275°C case.

again ruled by the distribution coefficient and the most of the boron will be transferred back to the liquid. These conditions are very similar to those that produce HCl in steam at The Geysers (FOURNIER and THOMPSON, 1993). The distribution coefficients derived from the work of Glover (1988) and the feasibility of transporting boron by reservoir boiling were tested by examining the results of a geochemical survey.

The survey was conducted during 1991and 1992 to determine if HCl existed in wells at Coso that had recently begun to produce dry steam. Analysis of the gas from these wells before and after the dry-out indicated that the steam was produced by a boiling fraction of less than 70%. In other words, the steam was produced from a two-phase zone and the boron concentration should have been similar to the product of the reservoir B concentration and the distribution coefficient of (GLOVER, 1988). At 300°C the distribution coefficient (C_{vap}/C_{liq}) calculated from Glover is 0.089. The liquid concentration of boron prior to the dry steam episode was 75 to 100 ppm, although the boron concentrations and the salinity doubled after two-phase conditions were restored to this well. Applying the distribution coefficient of 0.89 to these values gives steam concentrations ranging from 7 to 17 ppm, which agrees well with the measured steam concentrations of 10 to 13 ppm. This shows that the relationship published by Glover (Glover, 1988) and used in the simulations discussed below is appropriate for the Coso field.

CALCULATION OF FAR-FIELD BOILING

A simple model was created to mimic the transfer of boron to the steam during boiling, the mixing of this steam with local reservoir water around the well bore, the mixing of injectate, and the final boiling before sampling. The output (boron and chloride concentrations) has been corrected for excess steam, duplicating the data reduction used for the Coso chemical database. This allows the model output to be compared with the historical geochemistry data. However, it should be noted that an assumption is made that the higher enthalpy of the excess steam is retained as it approaches the wellbore. This produces a salinity change in the corrected analysis that would not exist if the far-field steam equilibrated to the temperature around the well bore.

The model uses a reservoir fluid with 5000 ppm Cl and 100 ppm B, which equates to an initial Cl;B ratio of 50. "Excess steam" is produced by single-step boiling of this reservoir fluid with a user-specified steam fraction. This steam, with its elevated Cl and B, is combined with unboiled reservoir liquid at a temperature (T_L) 25^oC less than the reservoir boiling (T_R), although the excess steam is assumed to retain its higher temperature until mixed. The combined fluid is then boiled to discharge conditions (175^oC) using a single-stage calculation and the boron is distributed according to the distribution coefficients of Glover (1988). The liquid composition is then corrected for boiling using calculations based on the quartz adiabatic geothermometer. This correction is identical to that used for the Coso data.

A model was prepared for a temperature of 275^oC. The reservoir steam fraction (Yr) and the excess steam mixing fraction (Xr) were varied from 0.25 to 0.99. The purpose behind the modeling was to determine if the effect is significant enough to be responsible for the observed change, and if there are characteristic patterns produced on cross-plots that could be used to identify the dominant process during routine geochemical monitoring.

A summary of the results is shown in Figure 7. It can be seen in this figure that the effect is indeed significant enough to show up on cross-plots (compare to Figure 2). It should be noted again, however, that the change in chloride concentration is dependent on there being a difference between the temperature of the boron-enriched steam and the "local" reservoir water. This will not necessarily occur, and in that case the pattern will consist of changing Cl;B ratio with increasing excess steam.

CONCLUSIONS

The decreased Cl;B ratio noted in the liquid discharge of well 38-9 in the Coso geothermal field is related to the development of vapor-dominated feed zones. The boron is transported in the vapor phase to the wellbore in dry steam, where it fractionates to the liquid phase flowing in from liquid-dominated feed zones. The steam in the vapor-dominated feed zone must have been produced by a boiling fraction greater than 90%, rendering the remaining liquid immobile.

ACKNOWLEDGEMENTS

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