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GEOLOGIC HISTORY OF THE COSO GEOTHERMAL SYSTEM

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ABSTRACT

The Coso geothermal system is developed within a Plio-Pleistocene volcanic field. At least three episodes of geothermal activity have affected the area during the last 300,000 years. Travertine deposits that formed at 307 ka represent the earliest thermal activity. These deposits may have been related to a large low- to moderate-temperature geothermal system. The second episode produced sinter at 238 ka. Fluid inclusions document a large high-temperature system with an upflow zone in the southern part of the present-day geothermal field. Temperatures up to 328°C and N_2/Ar ratios of inclusion fluids provide evidence of magmatic activity during this episode. Fluid originating within this upwelling zone was progressively diluted by low-salinity groundwater as it flowed laterally and upward to the north. The modern geothermal system consists of several weakly connected or isolated reservoirs that are being heated by young intrusions. At least three reservoirs can be distinguished based on the relationships between the production fluid compositions and temperatures. These relationships indicate that flow between the north and south had all but ceased in the pre-exploitation system, and that heating of the East Flank has been so recent that the salinity of the fluid has not yet increased. Both the production chemistry and the fluid-inclusion data indicate that the low-salinity water that once blanketed the system and provided a low-temperature mixing end-member has disappeared, presumably due to lower recharge rates.

1. INTRODUCTION

Coso is the largest of the geothermal systems in the U.S. Basin and Range province related to young volcanic activity. The field covers an area of approximately 30 sq. km in the Mojave Desert, on the eastern side of the Sierra Nevada Mountains (Fig. 1). Since 1989, when the field became fully operational, the reservoir has sustained production of 240 MWe from fractured Mesozoic intrusive and metamorphic rocks.

Over the course of the last two decades, various aspects of the geology (Echols et al., 1986; Hulen, 1978), geophysics (Wright et al., 1985), fluid chemistry (Adams, 1994-1999; Nimz et al., 1997), fluid inclusions (Moore et al., 1990), mineralogy (Bishop and Bird, 1987; Lutz et al., 1996), and fluid-inclusion gas compositions (Lutz et al., 1999) have been investigated. Integration of these studies has revealed that the geothermal system at Coso has had a much longer and more complex history than previously thought. In this paper we discuss the evidence for some of the changes that must have taken place.

2. GEOLOGIC SETTING

The Coso geothermal system lies within the eastern part of a major volcanic center containing 38 rhyolite domes and a slightly smaller volume of basalt (Fig. 1). The dome field and associated volcanics erupted between 1.0 Ma and 40 ka (Duffield et al., 1980). The youngest of these domes, Sugarloaf Mountain, is located immediately west of the active thermal system. An adjacent dome, just north of the system, is surrounded by a relatively fresh phreatic explosion crater. Both the rhyolite and the geothermal system are believed to be related to a partially molten magma body located 5 to 20 km beneath the field (Duffield et al., 1980; Reasenberg et al., 1980).

The modern reservoir is characterized by well-defined heat flow, dipole-dipole resistivity, and magnetic anomalies (Wright et al., 1985). Its northern edge appears approximately coincident with a northeast-trending belt of active and fossil fumaroles that include the Devil's Kitchen and Coso Hot Springs. Fossil sinter and travertine deposits occur along a northerly trending fault zone on the eastern margin of the field (Fig. 1) known as the East Flank. A minimum date of 307,000 years was obtained on the travertine using the U-Th method (Leslie, personal communication, 1991). At the Wheeler Prospect, opaline sinter both underlies and coats a basalt flow that has yielded a K-Ar age of 238 ka (Duffield et al., 1980; Echols et al., 1986). Although the reservoir has been extensively disrupted by faults, there are no thermal manifestations over the highest temperature portions of the field.

3. THE EARLY GEOTHERMAL SYSTEM: DATA FROM FLUID INCLUSIONS

Fluid inclusions in rocks from the Coso geothermal system record a broad range of temperatures and salinities. Analysis of the data presented by Moore et al. (1990) indicates that fluid inclusions related to geothermal activity had homogenization temperatures that ranged from 76° to 328°C and salinities of 0 to 3.4 weight percent NaCl equivalent (Fig. 2). The highest temperatures and salinities are found near the southern end of the field, where they define a shallow upflow zone in an area that contains no apparent surface manifestations. These hot saline waters formed a narrow plume that extended laterally to the north. Variations in the temperatures and salinities of the data suggest that the high-temperature fluids were diluted by a low-temperature water with essentially nil salinity. Figure 2 shows that this diluent occurs primarily at the top of the system where it was trapped in the secondary minerals as 1 and 2-phase liquid-rich inclusions. Although no low-salinity ground waters overlie the geothermal today, the data imply that nonthermal waters were present in the past.

Selected samples of the fluid inclusions were analyzed for major and minor gaseous species to determine their origins (Moore et al., 1999; Norman and Moore, 1999). The CO_2/CH_4 and N_2/Ar ratios of inclusion fluids from 4 wells, 64-16 TCH, 64-16 RD, 72-19, and 84-30, are presented in Figure 3. For comparison, the compositions of the modern fluids are also shown. Based on the ratios of these gaseous species, Norman and Moore (1999) were able to distinguish fluids containing meteoric, crustal, and magmatic components. An important conclusion of their study was that fluids with high N_2/Ar ratios (>1000) were indicative of a magmatic component, irrespective of the CO_2/CH_4 ratio, which for magmatic fluids typically exceeds 45,000 (Giggenbach, 1997). The data in Figure 3 suggest that fluids containing a magmatic component were trapped in inclusions in 64-16 TCH and 64-16RD. However, their CO_2/CH_4 ratios require mixing with a second component. In 64-16 TCH, this component was apparently derived from crustal sources, as indicated by the distribution of CO_2/CH_4 and N_2/Ar ratios. A possible mixing trend between the crustal and magmatic components is shown by the arrow. Similarly reduced gases are found in 72-19 (1606.3 m) and in 84-30 at (1895.9 m), which is located outside the productive portion of the field. We interpret the latter ratios as representing very early geothermal background values. The samples from 72-19 (1606.3 m) are from a modern-day production interval where fluid-inclusion temperatures (328^{o}C) and mineral relationships indicate boiling occurred in the past. Although the past and present temperatures are similar, the inclusion fluids have CO_2/CH_4 ratios that are lower than those of the discharged waters. Moore et al. (1999) concluded that such low ratios may typify geothermal systems before extensive degassing and the deep incursion of meteoric fluids has occurred. A meteoric influence is reflected in the gas compositions of the inclusions from 64-16 TCH (694.9 m), 64-16 RD (1606.3 m) and 72-19 (1609.3 m). In 64-16 RD, meteoric fluids appear to have accumulated various proportions of magmatic gases.

4. THE MODERN GEOTHERMAL SYSTEM: DATA FROM WELL BORE DISCHARGES

The Coso geothermal field produces power from more than one hundred production wells. Since production began in 1987, thousands of high-quality chemical analyses have been collected. The raw chemical data (unpublished) have been corrected for reservoir and local boiling using the quartz geothermometer and the measured enthalpy (Fournier, 1981; Henley, 1984). Chloride concentrations and NaKCa geothermometer temperatures that represent the initial state of the system were extracted from this database and are shown in Figure 4. Examination of this figure shows that strong thermal and salinity gradients existed in the field prior to exploitation. Salinities increased from north to south by a factor of two, and temperatures increased in the same direction by up to 100^{o}C.

The relationships between the temperature and salinity data are shown in Figure 5. This enthalpy-chloride plot shows what appears to be a mixing trend that extends from north to south across the field. However, there are two problems with this simple interpretation. The first is that Cl/B ratios are distinctly different in the north and the south, opposite the direction that would be expected from the temperature difference. Specifically, the northern, southern, and eastern portions of the reservoir had initial state Cl/B weight ratios of 43, 52, and 38, with standard deviations of 5.9, 2.5, and 4.5, respectively. Second, the low-temperature end-member extrapolated from the mixing trend would be between 150^o and 200^{o}C, but no low-salinity water in this temperature range has been encountered at Coso. These discrepancies can be resolved if it is assumed that flow between the reservoirs decreased and that the low-temperature water disappeared at some point in the past. This would allow time for the reservoirs to produce different Cl/B ratios. Once the low-temperature mixing end-member disappeared, the low-salinity end of the mixing trend would heat up and the trend would rotate around the high-temperature end-member, producing a more horizontal trend. The enthalpy-chloride plot also shows that the waters from the East Flank lie above the mixing trend, i.e., they have similar salinities but much higher temperatures. This relationship implies that the waters have been recently heated but have not had time to scavenge more solutes from the reservoir rocks. As discussed below, this agrees well with the fluid-inclusion data.

5. HISTORY OF THE GEOTHERMAL SYSTEM

The earliest recorded geothermal activity at Coso is represented by the 307,000 year old travertine deposits (Leslie, personal communication, 1991) on the east side of the field. Little is known about the extent or character of this system. However, the presence of calcite, rather than sinter, suggests that these deposits may have formed above a moderate-temperature system centered to the east of the modern reservoir. Subsequent geothermal activity is represented by the sinter deposits that formed at 238 ka at the Wheeler prospect (Duffield et al., 1980; Echols et al., 1986). The long time span between these events suggest that they are not related to the same thermal pulse.

The presence of sinter, rather than travertine, at the Wheeler prospect is important because it implies reservoir temperatures in excess of 200^o-225^{o}C. It is likely that much of the hydrothermal alteration found in the reservoir rocks is also related to this episode of activity. This conclusion is supported by the fluid-inclusion data, which indicate that a high-temperature system developed and cooled prior to the present-day thermal regime. Although the maximum temperatures of the early system were similar to those found today, the lowest fluid-inclusion temperatures are frequently lower than the present-day measured values, particularly within the central parts of the field. These temperatures, and the high N_2/Ar ratios of some inclusions indicate that the system was related to a magmatic pulse.

The gas compositions of the inclusion fluids suggest that the initial waters in the system were crustal or connate, with salinities up to 3.4 weight percent NaCl equivalent. The incursion of meteoric water and gases may have occurred as the system began to convect. Fluid-inclusion gas compositions indicate that these waters still had lower CO_2/CH_4 ratios than those of the modern fluids.

The modern geothermal system reflects renewed magmatic activity beneath the Coso dome field, as indicated by high temperatures, which exceed 325^{o}C, and the high $^3He/^4He$ ratios (Welhan et al., 1988). Attempts have been made to date the water and its solutes in the modern geothermal system. The concentration of tritium is generally less than 0.05 tritium units, demonstrating that the rain or snow precipitated less than 50 years ago do not play a part in the geothermal hydrologic cycle at Coso (MCA, unpublished data). Chloride-36 has also been used to bracket the source and age of chloride in the waters at Coso. Investigations by Nimz et al. (1997) shows that the chloride was derived from an outside, and in all likelihood, a sedimentary source. Furthermore, the chloride has been present in the geothermal system for no more than 100,000 to 200,000 years.

The most dramatic change between the early and modern geothermal systems was the disappearance of the low-salinity groundwater, as indicated by both the production chemistry and the fluid-inclusion data. Coso is located in the Mojave Desert, and receives only a few inches of rain a year. However, the abundance of rainfall in the region has varied in the past as a function of glaciations. The last pluvial, or wet, period in this area occurred around 10,000 years ago. Thus, the disappearance of the groundwater must have occurred since that time.

The segregation of the reservoir into compartments may have occurred when the groundwater disappeared. It is probable that recharge decreased at that time. The effects of the lack of dilution would be an increase in steam outflow and surficial acid alteration, which is a dominant feature of the current northern reservoir.

6. CONCLUSIONS

The Coso geothermal system has existed, at least intermittently, for more than 300,000 years. Three episodes of thermal activity can be recognized within the reservoir rocks. The earliest cycle was associated with the formation of travertine deposits on the eastern side of the field approximately 307,000 years ago. A large, low to moderate temperature system may have existed at this time, but little is known of its character. The second episode was triggered by magmatic activity beneath the dome field. This event produced a large, high-temperature geothermal system centered in the eastern and southern part of present-day field. Fluids that discharged from this system deposited sinter at 238 ka. The most recent event heated up the East Flank by at least 100^oC and reactivated the high temperature center beneath the southern part of the field.

The isotopic composition of chloride in the modern waters and the chemical composition of fluid inclusion gases indicate the original waters in the system were crustal, possibly connate waters from nearby sedimentary formations. Once the system began to convect, bringing in other waters, the thermal fluids flowed laterally and upward to the north for much of the system's life. A dilute, nonthermal groundwater system capped the system, mixing with the outflowing thermal water. The salinity and temperature gradients that developed as a result of mixing are still present in the modern system. However, the outflow itself has largely ceased and the low-temperature mixing end-member is gone. The present-day geothermal system is partitioned into at least two reservoirs that are weakly connected and one that is isolated.

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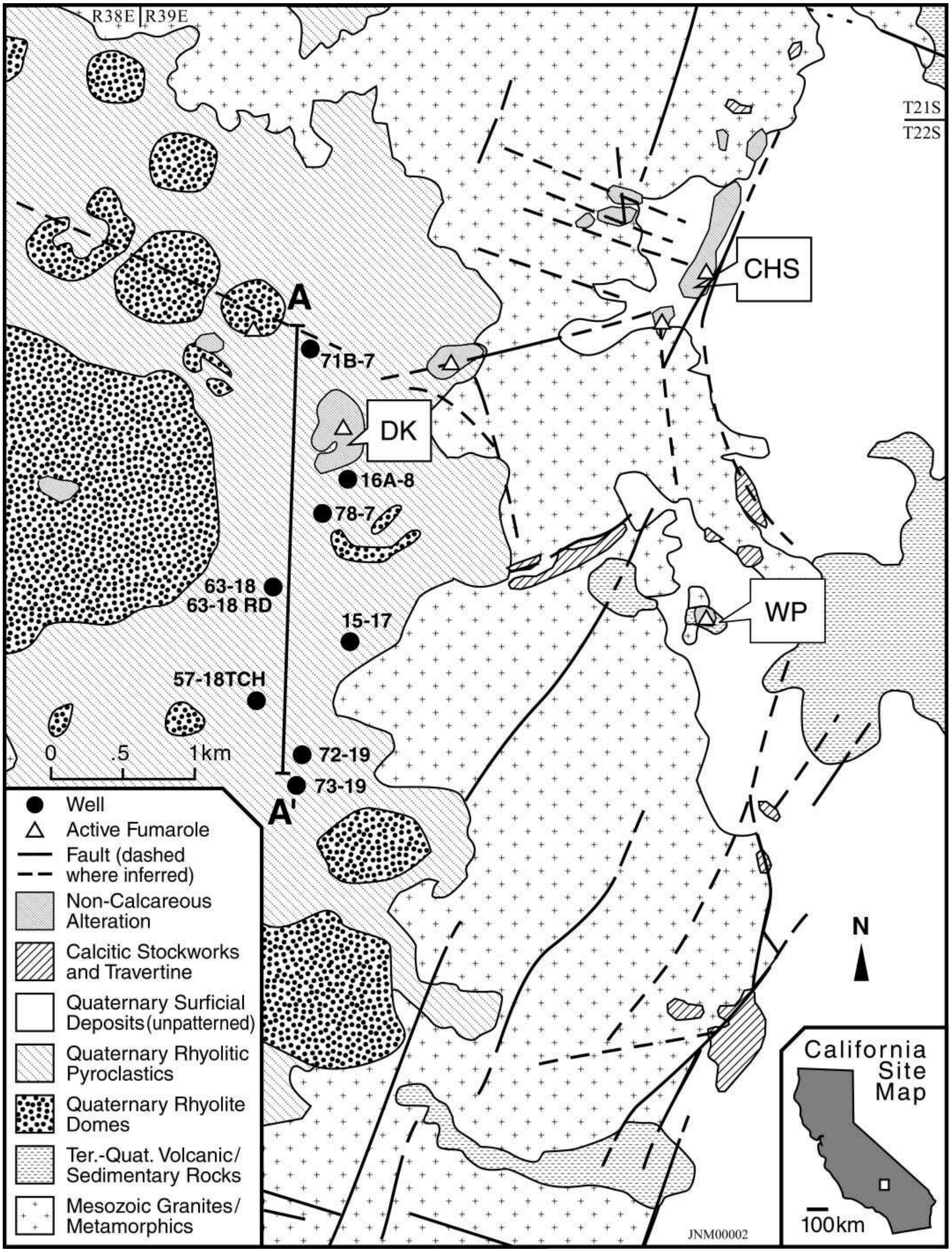

Figure 1. Map of the Coso geothermal field showing the locations of the major surface features and wells discussed in the text (Hulen, 1978). Abbreviations: CHS = Coso Hot Springs; DK = Devil's Kitchen; NP = Nicol prospect; RD = redrill; TCH = thermal core hole; WP = Wheeler prospect. A-A[1] is the cross sectional line shown in Figure 2. Only fumaroles are active today.

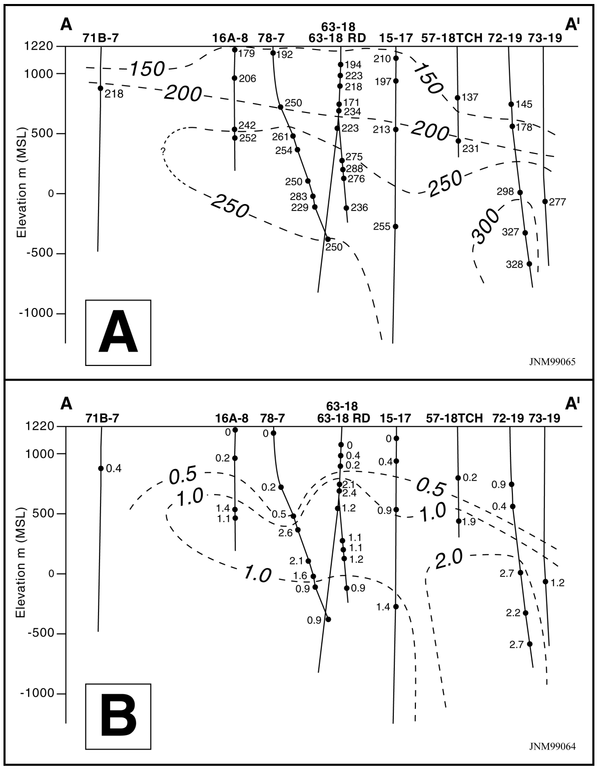

Figure 2. North-south cross sections of the reservoir. Elevations are relative to mean sea level (MSL). Well-head elevations range from 1235 to 1338 m. No data was obtained above 1200 m MSL. A) Maximum fluid-inclusion homogenization temperatures (°C) of inclusions related to geothermal activity. B) Maximum salinities of these inclusions in weight percent NaCl equivalent. See Figure 1 for location of cross section.

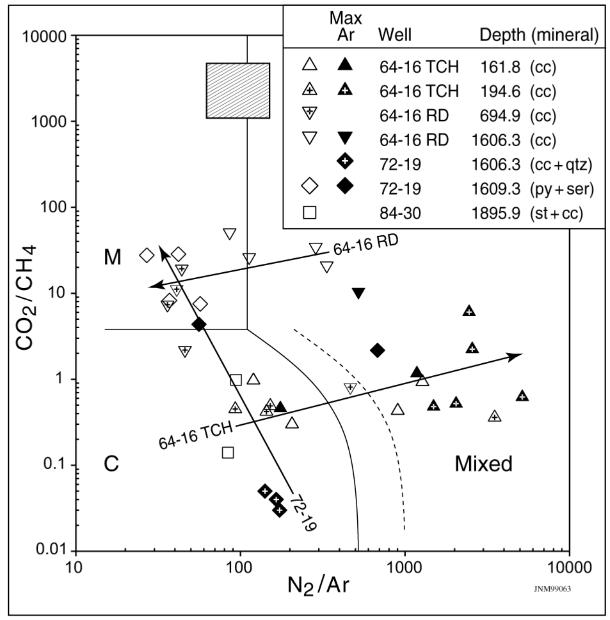

Figure 3. Plot of CO_2/CH_4 vs N_2/Ar of fluid inclusions from wells 64-16 TCH, 64-16 RD, 72-19, and 84-30. Sample depths are in meters. Mineral (min.) abbreviations; cc = calcite; qtz = quartz; py = pyrite; ser = sericite; st = stilbite. The hachured box represents the compositions of the modern fluids. The fields within the diagram show the compositional ranges of meteoric (M), crustal (C) and mixed meteoric/crustal/magmatic gases. The solid and dashed curves were drawn for gas contents of 1 and 2 mole percent, respectively. See Norman and Moore (1999) for the derivation of this diagram. Arrows show possible mixing trends.

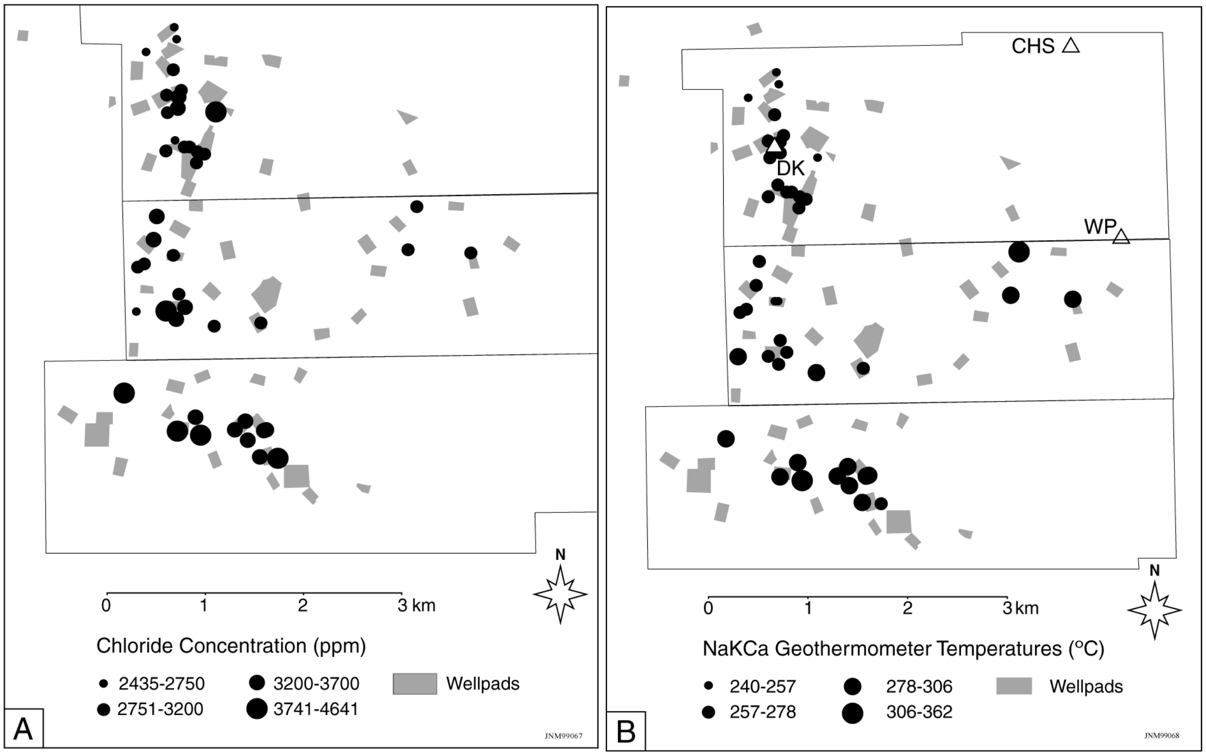

Figure 4. Initial state characteristics of the Coso reservoir fluids. The fluids are derived from depths of approximately 3000 m in the east, 2000 m in the south, and 1000 m in the north. The solid lines are lease boundaries. See Figure 1 for abbreviations. The three wells near WP are located in the East Flank. West of the East Flank, the lease boundaries separate the north, central, and southern parts of the field. (A) Initial reservoir chloride concentrations. (B) NaKCa geothermometer temperatures (Fournier and Truesdell, 1973).

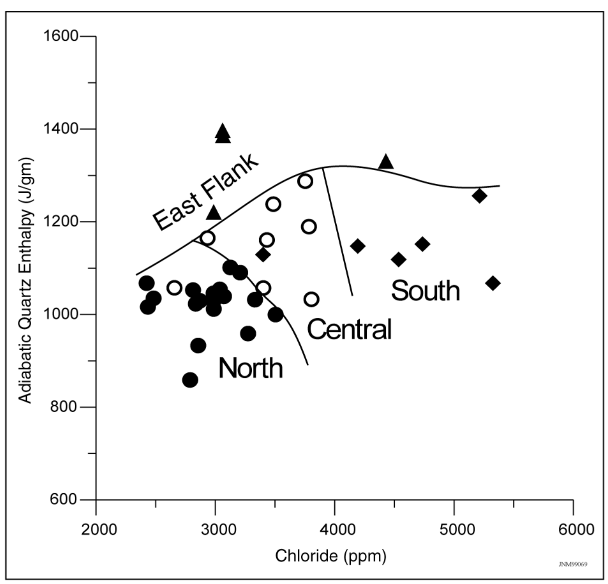

Figure 5. Enthalpy-chloride diagram showing relationships among the reservoir fluids from different parts of the field. The adiabatic quartz geothermometer (Fournier, 1981) was used to derive the fluid enthalpies and to correct the raw chloride concentrations for boiling. See figure 4 for well distributions