GL00618

PROCEEDINGS, Twenty-First Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 22-24, 1996
SGP-TR-151

INTEGRATED MINERALOGICAL AND FLUID INCLUSION STUDY OF THE COSO GEOTHERMAL SYSTEM, CALIFORNIA

Susan J. Lutz[1], Joseph N. Moore[1], and John F. Copp[2]

[1]Earth Sciences and Resources Institute
Department of Civil and Environmental Engineering
University of Utah
Salt Lake City, Utah

[2]California Energy Company
Ridgecrest, California

ABSTRACT

Coso is one of several high-temperature geothermal systems on the margins of the Basin and Range province that is associated with recent volcanic activity. This system, which is developed entirely in fractured granitic and metamorphic rocks, consists of a well-defined thermal plume that originates in the southern part of the field and then flows upward and laterally to the north.

Fluid inclusion homogenization temperatures and salinities demonstrate that cool, low salinity ground waters were present when the thermal plume was emplaced. Dilution of the thermal waters occurred above and below the plume producing strong gradients in their compositions. In response to heating and mixing, clays and carbonate minerals precipitated, sealing the fractures along the margins of the reservoir and strongly influencing its geometry.

The alteration mineralogy varies systematically with depth and temperature. Based on the clay mineralogy, three zones can be recognized: the smectite zone, the illite-smectite zone, and the illite zone. The smectite zone thickens from the north to south and is characterized by smectite, kaolin, stilbite and a variety of carbonate minerals. The illite-smectite zone contains mixed-layer clays and also thickens to the south. The deepest zone (the illite zone) contains illite, chlorite, epidote, and wairakite. Quartz and calcite veins occur in all three zones. Comparison of mineral and fluid inclusion based temperatures demonstrates that cooling has occurred along the margins of the thermal system but that the interior of the system is still undergoing heating.

INTRODUCTION

Coso is the largest and most extensively developed of the active hydrothermal systems in the Basin and Range Province (Fig.1). Since the late 1970's, more than 100 wells have been drilled in the field, defining

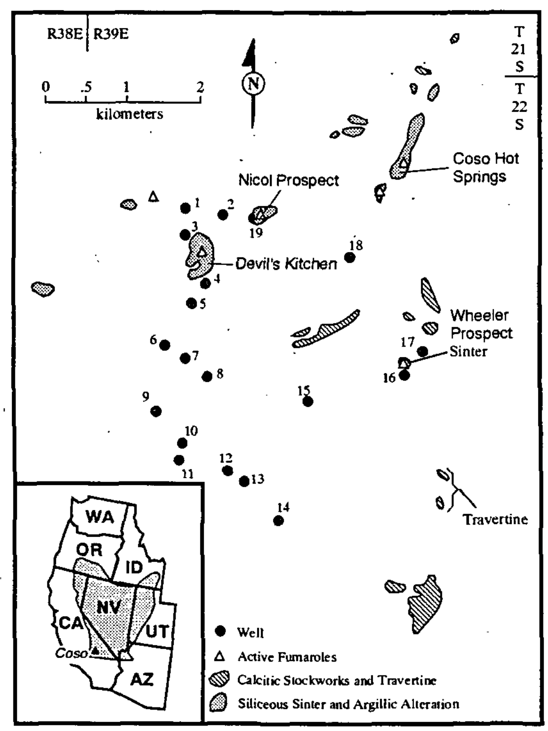

Fig. 1 Location of wells and surface features in the Coso geothermal system, California. Inset shows the location of Coso along the southwestern edge of the Basin and Range Province.

a reservoir that is approximately 30 sq. km in area. These wells currently produce 240 MW of electricity from fractures in crystalline host rocks. Despite its size, the surface expression of the geothermal system is limited to a few widely spaced fumaroles and fossil hot spring deposits located in the northern and eastern parts of the field (Fig. 1). In contrast, there is no evidence of surface activity over the upwelling center in the southern part of the field where temperatures up to 342°C have been measured at depths of less than 2.5 km.

In this paper, we describe some of the geologic and mineralogic features that have influenced fluid movement within the reservoir rocks. This work expands substantially on previous studies by Fiore (1981), Echols and others (1986), Bishop and Bird (1987), Hall and Cohen (1990), and Nielson and others (1990), because it includes observations on samples from the deep, central portions of the reservoir. These observations are used to characterize the hydrothermal alteration associated with the thermal system, and the processes that produced these mineralogic changes.

GEOLOGIC SETTING

The Coso Range, which hosts the geothermal system, is located on the eastern flank of the Sierra Nevada Range about 60 km from Death Valley, California. The geothermal reservoir is developed in fractured Mesozoic granitic and metamorphic basement rocks that were intruded by rhyolite and basalt of the Pliocene to Recent Coso Volcanic Field (Stinson, 1977; Hulen, 1978; Duffield and others, 1980). Heat for the geothermal system, and the source of the volcanic rocks, is believed to be a partially molten silicic magma body located at a depth of 5 to 20 km beneath the field (Duffield and others, 1980; Reasenberg and others, 1980).

The basement complex appears to consist of several distinct plutonic units, some of which are foliated and interpreted as older plutons with some metamorphic characteristics, and some of which appear undeformed and relatively fresh. The older granitic plutons contain small blocks of metamorphosed strata that are gneissic to schistose, as well as highly sheared mafic dikes that contain epidote-rich gouge zones. Because of their foliated character, these biotite- and hornblende-bearing granitoids and quartz diorites are generally referred to as metamorphic rocks. At the surface, these metamorphic rocks strike northwest to west-northwest and dip steeply northward (Hulen, 1978).

The undeformed granitic rocks consist predominantly of sills, dikes, and stocks of biotite quartz monzonite that may be correlative with similar intrusives in the Sierra Nevada Range to the west. In the Coso field, several textural varieties of compositionally similar intrusives are present. These include: fine-grained, quartz-rich felsite or quartz latite that is a sparsely porphyritic, medium to coarsely crystalline quartz monzonite, and fine to coarsely crystalline granodiorite to granite. The first two textural varieties contain graphic intergrowths of feldspar and quartz, abundant microcline, rare biotite, and rare to common epidote. The granodiorite is similar to the quartz monzonite except that it lacks graphic intergrowths, the potassium feldspar occurs as discrete phenocrysts, and biotite is more common.

The distribution of intrusive and metamorphic rocks along a north-south section through the field is shown in Figure 2. Although the small size of the well cuttings complicates correlation of individual units and subsurface mapping at productive depths, several important observations can be made. The proportion of intrusive rocks to metamorphic rocks appears to be greater at shallow to intermediate depths in the northern and central portions of the field than in the southern part. The intrusive rocks are shallowest in the north at the Devil's Kitchen area. The southern part of the field contains mostly metamorphic rocks at shallow to intermediate depths. Comparison of Figures 2 and 3 shows that the upwelling center of the system is developed in a granite or granodiorite. The presence of faults in the upwelling center is indicated by an abundance of veins and gouge material at the granite-metamorphic contact, and the offset of the granite between wells 10 and 11.

Although the reservoir rocks are pervasively fractured, the results of production drilling demonstrate that permeability is concentrated within a north-trending region that passes through the Devil's Kitchen (Fig. 1). A second area of northerly-trending faults, which has served to localize much of the hot spring activity, occurs on the eastern side of the field. These two regions are separated by an area of low permeabilities where the shallow temperatures are depressed. Both the productive structures and those controlling the surficial activity may be part of a broad, regional fault system that parallels the Sierra Nevada range to the west (Walter and Weaver, 1980).

THERMAL AND CHEMICAL STRUCTURE

Fluid inclusions were studied in quartz, calcite and anhydrite to characterize the chemical and thermal structure of the system (Moore and others, 1989;

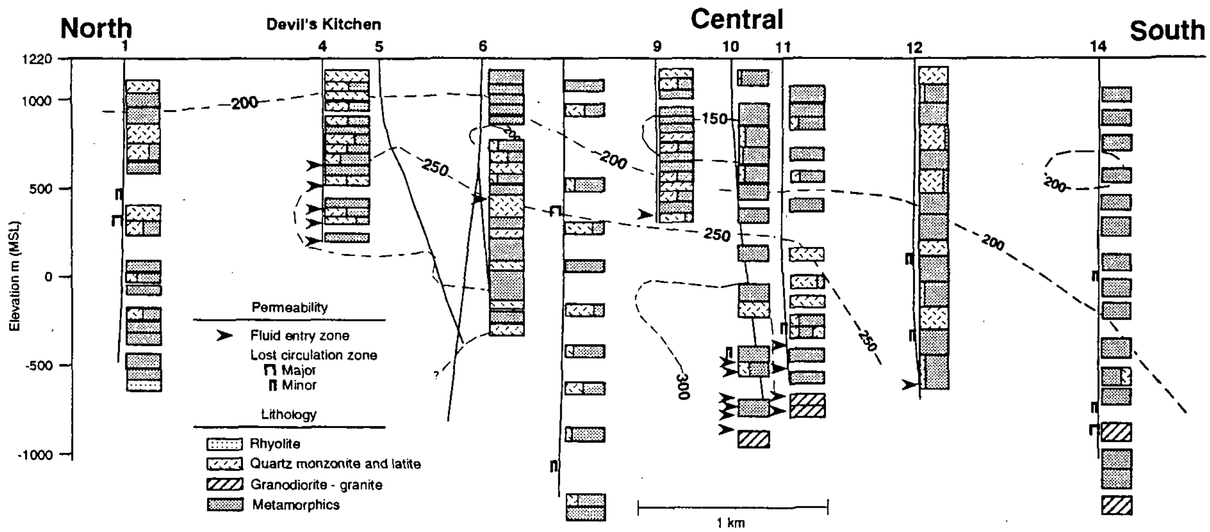

Fig. 2. North-south cross section showing the distribution of metamorphic and intrusive rocks, fluid entries and lost circulation zones. The isotherms represent maximum temperatures in degrees Celsius determined from fluid inclusion analyses (refer to Fig. 3). The elevations are in meters with respect to mean sea level (MSL).

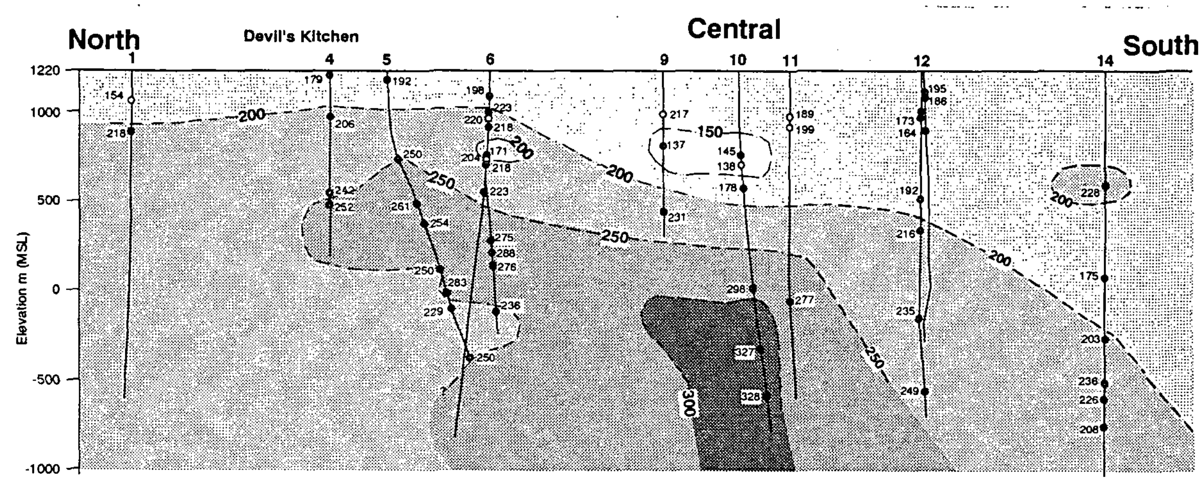

Fig. 3. North-south cross section showing maximum fluid inclusion homogenization temperatures and general thermal structure of the Coso geothermal system. Filled circles represent low-salinity fluid inclusions interpreted to be geothermal in origin. Hollow circles are presumed to be geothermal, although no salinities were obtained.

1990). Figure 3 is a north-south section displaying the maximum fluid inclusion homogenization temperatures. These data document the presence of a thermal plume that originates at depth in the southern part of the field, where fluid inclusion temperatures up to 328°C have been recorded. Movement of the fluids is away from the upwelling center and dominantly northward.

The apparent salinities of fluid inclusions related to geothermal activity range from 0.0 to 2.7 weight percent NaCl equivalent. In contrast, the salinities of the present fluids range from 0.5 to 1.5 weight percent. Comparison of fluid inclusion apparent salinities and production fluid salinities in the upwelling plume indicates that the older fluids may have been slightly more saline. However, the values of the fluid inclusion salinities may be elevated by the presence of CO_2 and other gases (Moore and others, 1989; 1990). The data suggest that within the interior of the system, CO_2 contents may have been as high as 2.4 weight percent.

The fluid inclusion data demonstrate that a shallow ground water with salinities near 0.0 weight percent NaCl equivalent was present at the top of the system

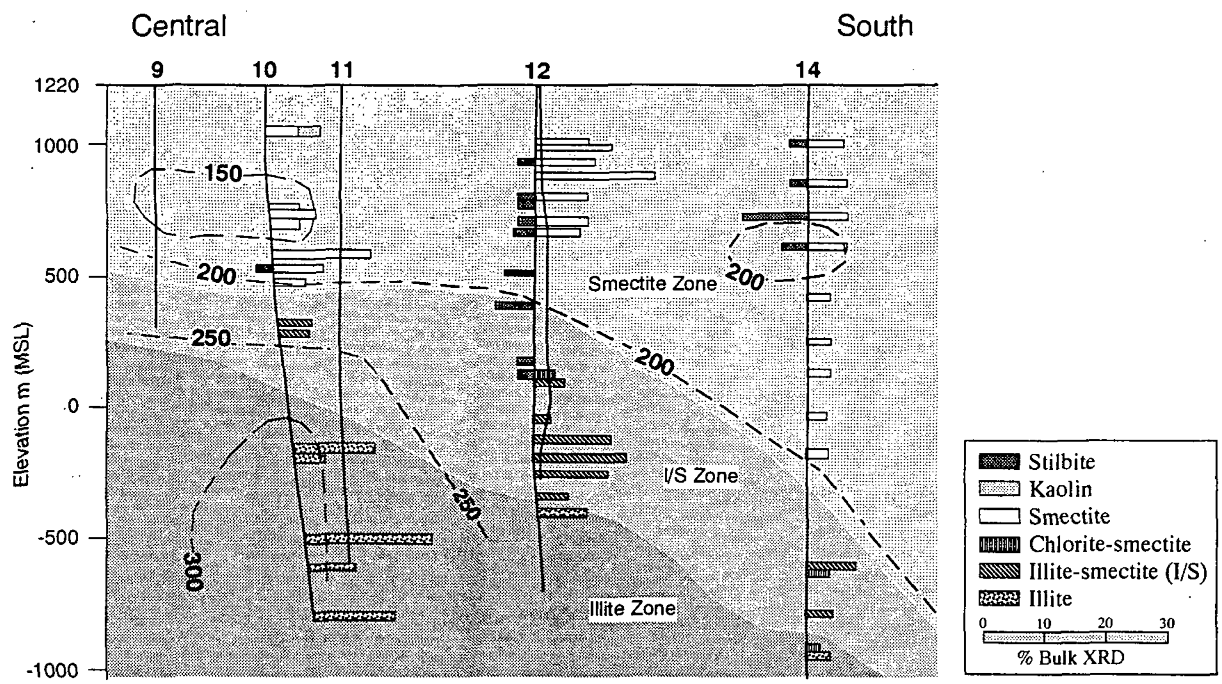

Fig. 4. Distribution of clay and zeolite minerals that define the alteration zones in the central and southern portions of the Coso field. For reference, fluid inclusion isotherms in degrees Celsius are also shown. Semi-quantitative data based on bulk X-ray diffraction (XRD) analyses.

in the past (Moore, 1993). Despite extensive drilling and testing in the field, no evidence for the persistence of this ground water has been found. Nevertheless, the salinity variations of the inclusion waters indicate that the thermal fluids did mix with a paleo ground water.

HYDROTHERMAL ALTERATION

The secondary minerals found in the reservoir rocks at Coso can be related to the effects of regional metamorphism or tectonism, intrusion of granitic stocks, and the present geothermal system. Secondary assemblages related to the present geothermal system are generally similar to those produced by earlier thermal events, with some notable exceptions. In general, paragenetically young vein assemblages lack abundant epidote, host fluid inclusions that contain only low-salinity waters, and are dominated by calcite and quartz. Calcite and quartz veins are common throughout the region at all depths, having formed during both the present and past thermal events. In general, euhedral to subhedral calcite crystals that display evidence of deposition as open space fillings yield fluid inclusion data that can be related to the present geothermal system, while anhedral crystals in tightly sealed veins do not.

Other mineral phases that appear to be related to the present geothermal system include a variety of clays, zeolites, aragonite, iron and magnesium carbonates, chlorite, sericite, epidote, wairakite, potassium feldspar, hematite, pyrrhotite, and pyrite. Thermodynamic modeling by Bishop and Bird (1987) has demonstrated that the present reservoir fluids are in equilibrium with quartz, calcite, fine-grained sericite and relict microcline at temperatures exceeding 150°C.

CLAY MINERAL ZONING

Clay separations and X-ray diffraction analyses were performed on approximately 150 samples in ten wells to determine the composition and distribution of the fine-grained hydrothermal clays. These clays include illite and mixed-layer illite-smectite (both classified petrographically as sericite), smectite, kaolin, chlorite, and mixed-layer chlorite-smectite. Figure 4 illustrates the abundance and distribution of the clay and zeolite minerals. Three alteration zones, based on the clay mineralogy, can be defined; a smectite zone characterized by kaolin and smectite, an illite-smectite zone with mixed-layer illite-smectite and chlorite-smectite, and an illite zone with illite and chlorite.

SMECTITE ZONE

In the northern and central portions of the field, smectite is abundant at shallow depths and comprises up to 30 percent of the bulk samples near the base of the zone in wells 1 and 10. Minor amounts of kaolin are present in this zone, down to a maximum depth of about 325 m. In the south, the smectite zone extends down to a depth of 1500 m. Consequently, the smectite cap is much thicker in the southern portion of the field. Comparison with the fluid inclusion data indicates that the base of the smectite zone generally follows the 200°C isotherm (Fig. 4).

The smectite zone is the most intensely veined of the three zones. Carbonate veins with chlorite-smectite selvages are common where they cut clay-altered wallrock, indicating that the carbonate minerals are younger than the smectite clay alteration. These carbonates include calcite, ferroan dolomite, aragonite, and siderite.

At shallow depths, the veins exhibit repeated dilational fracturing and complex zoning between iron- and magnesium-bearing carbonates (Hall and Cohen, 1990). In general, dolomite and calcite veins appear to be filled with later aragonite. Much of the vein-filling calcite forms rhombohedral to dogtooth shaped crystals suggesting that deposition resulted from conductive heating of calcium-rich ground waters (R. Fournier, personal communication).

Deeper in the smectite zone and especially along the southern and eastern margins of the system, veins of zeolite and calcite are common. X-ray diffraction patterns show that the zeolite has strong reflections at 9.04 and 4.07 angstroms, identifying the mineral as stilbite, a zeolite within the heulandite group. To the south in well 14, stilbite forms up to 7 weight percent of the bulk samples down to depths of 660 m (Fig. 4).

MIXED-LAYER ILLITE-SMECTITE ZONE

The illite-smectite zone is the thinnest alteration zone in the northern and central portions of the field. It is shallow in the north and deepens to the south, so that the bottom of the southern well 14 is almost entirely within this zone. The base of the illite-smectite zone ranges from a depth of 440 m in well 1 in the north, to 933 m in well 10 over the upwelling center, to 2330 m in well 14 (Fig. 4).

In northern and central parts of the field, there is a rapid change in the clay mineralogy with depth from smectite, to an illite-smectite with about 10 to 20 percent smectite interlayers (Fig. 5). In some places, pyrite is associated with the mixed-layer clay in the wallrock. Veins are relatively rare in the illite-smectite zone and consist of calcite, hematite, and minor quartz.

In the eastern part of the field, the clay zones overlap so that at some depths, smectite, illite-smectite and illite are all present (Fig. 6). In well 16, the presence of illite-smectite characterizes a thick sequence of altered rock from the depths of 100 m to 2360 m. Although there is a decrease from 30-40 percent smectite interlayers in the illite-smectite at shallow depths to less than 10 percent smectite interlayers at 2360 m, in detail, the extent of interlayering is not systematic with depth.

ILLITE ZONE

The presence of illite without detectable (less than 10 percent) smectite interlayers characterizes the illite zone. In the central part of the geothermal system, illite makes up to 25 percent of the bulk samples. In well 10, from 1150 m to the top of the granite at 2030 m, illite development is strong in both metamorphic and intrusive rocks where it replaces potassium feldspar and plagioclase. Pyrite occurs in the sericitized (illite-rich) rocks and also in quartz+calcite+pyrite veins.

In the illite zone, calcite veins commonly have a chlorite selvage and contain minor amounts of quartz, hematite, and pyrite. As in the other clay zones, these carbonate veins cut clay-altered rocks. From 1400 m to 1750 m depth in well 10, fibrous calcite+hematite veins crosscut illite+pyrite altered rocks. At 1600 m depth, the calcite forms thin, tabular crystals or "fish scales". This fish scale morphology is thought to be typical of boiling conditions (Tulloch, 1982). At this depth, the present thermal profile and fluid inclusion data lie close to the boiling-point curve (Fig. 5). While these data suggest that calcite deposition occurred in response to boiling, no direct evidence of boiling in the form of vapor-rich inclusions is observed.

The highest temperature part of the illite zone is developed in a coarsely crystalline granite. At 2033 m depth in well 10, veins of wairakite+quartz+epidote+/-chlorite+/-adularia+/-pyrite are present in the altered and brecciated rocks at the contact between the granite and metamorphic rocks. In contrast to the blocky, iron-rich(?) epidote in the wallrock at this depth, the epidote in these veins occurs as sprays of thin needles incorporated within the wairakite crystals. At greater depths and in other wells, the granite is only weakly altered.

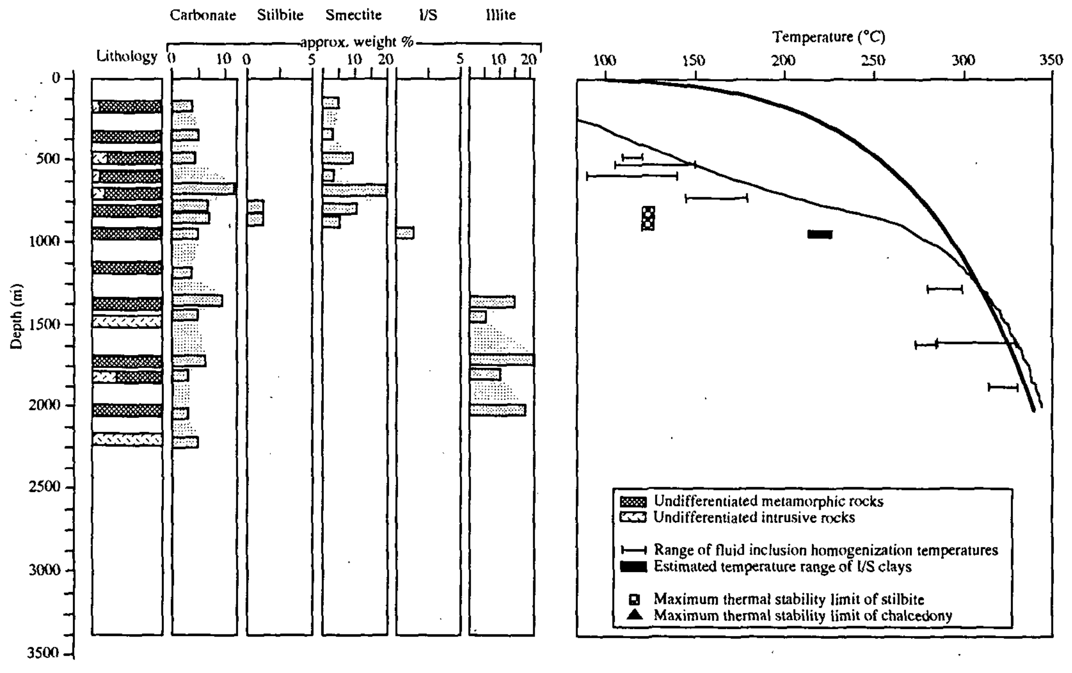

Fig. 5. Mineralogic and temperature relationships in well 10. The generalized distribution of rock types is shown in the lithology column. Interlayered illite-smectite is designated by I/S. The heavy solid line on the temperature-depth plot shows the boiling point curve for a 0.0 weight percent NaCl solution. The thinner solid line shows the present measured temperatures.

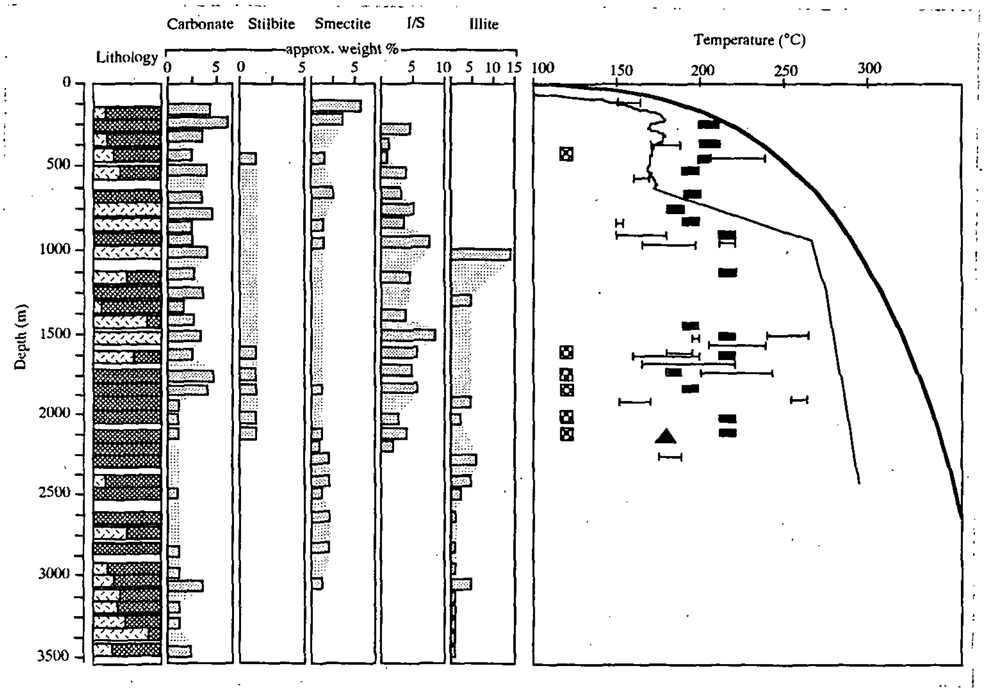

Fig. 6. Mineralogic and temperature relationships in well 16. The thin and heavy solid lines represent measured temperature and boiling point curves, respectively (refer to the key in Fig. 5).

DISCUSSION

The chemical and thermal measurements obtained on the fluid inclusions and alteration minerals can be used to augment the geochemical model of the Coso reservoir, and to assess the thermal and chemical changes that have occurred as the geothermal system evolved. In this section, we compare estimated temperatures based on the thermal stabilities of the secondary minerals with fluid inclusion and present measured temperatures.

The relationships between fluid inclusion and clay mineral-based temperatures are illustrated on plots of temperature versus depths for wells from the central and eastern portions of the field (Figs. 5 and 6). In these wells, the approximate formation temperatures for smectite, illite-smectite and illite generally overlap the range of fluid inclusion homogenization temperatures for samples from similar depths. Using X-ray diffraction analyses, the position of the basal reflection of a mixed-layer illite-smectite is used to determine the amount of interlayered smectite (Moore and Reynolds, 1989) and the approximate temperature of its formation (Browne, 1978; 1993). For example, a basal reflection between 11.8 to 10.8 angstroms correlates with about 50 to 20 percent smectite interlayers and a formation temperature of between 180° and 200°C, whereas a basal reflection between 10.8 and 10.3 angstroms correlates with 20 to less than 10 percent smectite interlayers and a formation temperature of 200° to 220°C. Above temperatures of 220°C, illite is essentially devoid of smectite interlayers. Below 150°C, smectite is the clay that is formed.

Figure 5 illustrates thermal relationships in the central portion of the field (well 10). Here, the clay mineralogy and the fluid inclusion temperatures generally parallel the measured temperature profile in the well but, significantly, are not as hot as the present measured temperatures. Both the clay data and the fluid inclusion relationships lead to the conclusion that temperatures in the core of the geothermal system are still increasing.

Stilbite forms at temperatures of less than about 125°C (Browne, 1978) and most commonly, in the 90° to 110°C range (Browne, 1993). Its presence in wells to the south and east in rocks with present temperatures above 200°C indicates that it is a relict phase probably related to the initial heating of the thermal system (Hall and Cohen, 1990). In well 16 along the eastern portion of the field, the mineral paragenesis in samples between 2000 and 2250 m depth records a history of heating. Figure 6 documents the successive formation of stilbite below 125°C, chalcedony below 180°C (e.g., Fournier, 1985), illite-smectite between 180° and 220°C, and illite above 220°C. Fluid inclusions in a calcite+hematite vein record temperatures up to 250°C. This portion of the geothermal system is still undergoing heating with measured temperatures ranging from 275° to 285°C. In contrast, comparison of the fluid inclusion homogenization temperatures and measured temperatures indicates that cooling is occurring along the marginal portions of the field (see Fig. 6 above 700 m depth).

The present-day fluid movement in the shallow parts of the system is clearly related to the clay mineralogy. Conductive gradients are associated with the presence of smectite, stilbite and dolomite in well 10 (Fig. 5) and well 14. These observations suggest that clay and subsequent vein deposition have been effective in reducing the shallow permeabilities within the upper parts of the field. Comparison of the clay mineral distributions with the fluid inclusion data suggests that the clay deposition may have resulted from the mixing of thermal and ground waters.

CONCLUSIONS

Geothermal alteration at Coso has produced a succession of mineral assemblages that vary systematically with depth and temperature. Within the interior of the system, where fluid inclusions record temperatures above 300°C, secondary minerals include calcite, quartz, illite, pyrite, chlorite, epidote, wairakite, hematite and pyrrhotite. At lower temperatures, between about 200° and 250°C, the mineral assemblages are characterized by calcite, hematite, pyrite, quartz, and interlayered illite-smectite, and chlorite-smectite. In the outermost zone, where maximum fluid-inclusion temperatures are less than about 200° C, the common minerals include smectite, stilbite, kaolin, calcite, aragonite and dolomite.

Three mineral zones are recognized; the illite zone in the upwelling center of the system, the intermediate illite-smectite zone, and the smectite zone that forms the cap to the system. Although the rocks at the surface appear to be pervasively fractured, conductive thermal gradients within the smectite-altered caprock demonstrate that this is a zone of low permeabilities. Fluid inclusion data suggest that this cap may have formed in response to mixing between the thermal waters and a low salinity ground water that is no longer present.

Fluid inclusion homogenization temperatures and inferred formation temperatures of the alteration minerals indicate that the central parts of the system are still heating up. In one well, progressive heating is reflected in the presence of stilbite and chalcedony, which are stable to 125° and 180° C, respectively, and by fluid inclusions temperatures up to 250° C. These fluid inclusion temperatures are several tens of degrees lower than the present measured temperature.

Acknowledgements. The authors wish to extend their gratitude to the management of California Energy Company, Inc. for providing data and samples for this study. Funding for SJL and JNM was provided by the Department of Energy under DOE Contract No. DE-AC07-95ID13274. Louise Spann prepared the X-ray diffraction samples for analysis and Bob Turner prepared the figures and text for publication. We thank them both.

REFERENCES

Bishop, B.P. and Bird, D.K., 1987, Variation in sericite compositions from fracture zones within the Coso Hot Springs geothermal system: Geochimica et Cosmochimica Acta, v. 51, p. 1245-1256.

Browne, P.R.L., 1978, Hydrothermal alteration in active geothermal fields: Annual Reviews of Earth and Planetary Science, v. 6, p. 229-250.

Browne, P.R.L., 1993, Application of mineralogic methods to assess the thermal stabilities of geothermal reservoirs: Eighteenth Annual Workshop on Geothermal Reservoir Engineering, Stanford University, California, p. 73-78.

Duffield, W.A, Bacon, C.R., and Dalrymple, G.B., 1980, Late Cenozoic volcanism, geochronology, and structure of the Coso Range, Inyo County, California: Journal of Geophysical Research, v. 85, n. B5, p. 2381-2404, May 10, 1980.

Echols, T.J., Hulen, J.B., and Moore, J.N., 1986, Surficial alteration and spring deposits of the Wheeler mercury prospect, with initial results from Wheeler Corehole 64-16, Coso Geothermal Area, California: Geothermal Resources Council, Transactions, v. 10, September 1986, p. 175-180.

Fiore, J.H., 1981, Hydrothermal alteration along subsurface fractures at Coso Hot Springs KGRA, Inyo County, California: M.S. Thesis, University of Nevada.

Fournier, R.O., 1985, The behavior of silica in hydrothermal systems: in B.R. Berger and P.M. Bethke, eds., Geology and Geochemistry of Epithermal Systems, Reviews in Economic Geology: Society of Economic Geologists, v. 2, p. 45-61.

Hall, D.L. and Cohen, L.H., 1990, Hydrothermal mineral deposition in a shallow portion of the Coso geothermal field: A unique mineral assemblage (abstract): PACROFI III, Third Biennial Pan-American Conference on Research on Fluid Inclusions, May 20-22, 1990, p. 40.

Hulen, J.B., 1978, Geology and alteration of the Coso Geothermal Area, Inyo County, Utah: University of Utah Research Institute Report DOE/ID/28392-4, 28p.

Moore, D.M. and Reynolds, R.C., Jr., 1989, X-ray diffraction and the identification and analysis of clay minerals: Oxford University Press, New York, 326 p.

Moore, J.N., Adams, M.C., Bishop, B.P., and Hirtz, P. 1989, A fluid flow model of the Coso geothermal system, California: Data from fluid chemistry and fluid inclusions: Fourteenth Workshop on Geothermal Reservoir Engineering, Stanford University, p. 139-144.

Moore, J.N., M.C. Adams, B. Bishop-Gollan, J.F. Copp and P. Hirtz, 1990, Geochemical structure of the Coso geothermal system, California: in J.L. Moore and M. Eskine, eds., Coso Field Trip, American Association of Petroleum Geologists Guidebook, Energy Minerals Division, p. 25-39.

Moore, J.N., 1993, Development of conceptual exploration models of geothermal systems: Proceedings, Department of Energy Program Review XI, Proceedings, p. 91-96.

Nielson, D.L., Hulen, J.B., and Copp, J., 1990, Structural and alteration controls on thermal fluid flow at the Coso geothermal field, California (abstract): American Association of Petroleum Geologists Bulletin, v. 74, p. 730.

Reasenberg. P., Ellsworth, W., and Walter, A., 1980, Teleseismic evidence for a low-velocity body under the Coso geothermal system: Journal of Geophysical Research, v. 85, p. 2471-2483.

Stinson, M.C., 1977, Geology of the Haiwee Reservoir 15" quadrangle, Inyo County, California: California Division of Mines and Geology, Map Sheet 37.

Tulloch, A.J., 1982, Mineral observations on carbonate scaling in geothermal wells at Kawerau and Broadlands: Proceedings of the Pacific Geothermal Conference, Part 1, p. 131-134.

Walter, A.W. and Weaver, C.S., 1980, Seismic studies in the Coso geothermal area, Inyo County, California: Journal of Geophysical Research, v. 85, p. 2441-2458.