PROCEEDINGS, Fourteenth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 24-26, 1989
SGP-TR-122

A FLUID FLOW MODEL OF THE COSO GEOTHERMAL SYSTEM: DATA FROM PRODUCTION FLUIDS AND FLUID INCLUSIONS

by

J. N. Moore[1], M. C. Adams, B. P. Bishop[2], and P. Hirtz[3]
1. University of Utah Research Institute
2. California Energy Company, Inc.
3. Thermochem, Inc.

ABSTRACT

Coso is one of several high-temperature geothermal systems associated with recent volcanic activity in the Basin and Range province. Within this fracture-dominated system, temperatures as high as 340°C have been measured at depths of less than 2.5 km. Chemical analyses of the production fluids show that steep gradients in the salinities, gas concentrations, and temperatures occur within the reservoir. Salinities and CO_2 contents range from 1.05 wt.% TDS and 0.95 wt.% CO_2 in the southern part of the field to 0.37 wt.% TDS and 0.06 wt.% CO_2 in the north and east.

Fluid inclusion data have been used to characterize the compositions and temperatures of the reservoir outside the production zones. Homogenization temperatures of the fluid inclusions ranged from 328° to less than 100°C. Ice- and clathrate-melting temperatures indicate that the fluids have salinities up to 1.4 equivalent wt.% NaCl and variable but significant CO_2 contents.

The chemical and fluid inclusion data define a plume of thermal fluid that rises from depth in the south, and travels outward toward the north and east.

INTRODUCTION

Detailed hydrogeochemical models of geothermal reservoirs are needed to locate production and injection wells and to numerically predict the effects of long-term production. In order for these models to be useful, they must describe the temperature, salinity, and gas distributions within the reservoir, the interactions between reservoir fluids, the extent of boiling and mixing, and the velocity and direction of fluid movement through the geothermal system. Because of the drilling and completion techniques currently in use, fluid samples collected from production wells can only provide a partial view of the reservoir. In this paper, we illustrate how production and fluid inclusion data can be combined to develop a detailed hydrogeochemical model of the fracture-dominated geothermal system at Coso. This investigation is part of an ongoing study being performed through an agreement between California Energy Company and the Earth Science Laboratory Division/University of Utah Research Institute.

The Coso geothermal field is located at the western edge of the Basin and Range province on the China Lake Naval Weapons Center in Inyo County, CA (Fig. 1). The thermal area is associated with a series of Pliocene to Pleistocene rhyolite domes which trend north-south through the Coso Range. The geothermal system is localized along discrete zones of fracture permeability in the underlying crystalline metamorphic basement. Surface manifestations of the system include fumaroles and acid-sulfate springs in the northern and eastern portions of the field at Devil's Kitchen and Coso Hot Springs.

To date, California Energy Company, as operator for the Coso Geothermal Project, has completed 66 wells ranging in depth from 400 to 2500 m and 10 core holes ranging from 600 to 1300 m in depth. Measured temperatures in the production wells range from 230°C in the shallow portion of the system in the north to 340°C at depths of 2500 m in the south. The first 30 MW power plant at Coso began operation in July of 1987. By early 1989, four additional units will be in operation, increasing the generating capacity to 123 MW.

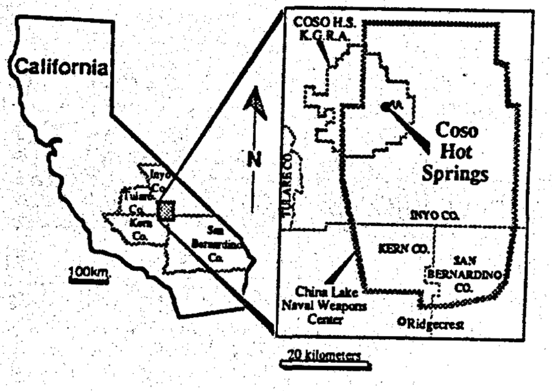

Figure 1. Location map of the Coso geothermal system.

CHEMISTRY OF THE PRODUCTION FLUIDS

Collection of gas and liquid samples from the production wells has been an important component of the development program at Coso. The data base discussed in this paper includes chemical analyses from 27 wells drilled throughout the field. Samples from these wells were collected using a mini-cyclone separator.

Many of the production wells display a greater measured enthalpy than that predicted by the chemical geothermometers. These differences in enthalpy appear to be caused by a combination of boiling around the wellbore (excess enthalpy) and the addition of steam from the reservoir (excess steam). However, because the discharge enthalpies were not measured for every well at the time of sampling, quartz adiabatic-boiling geothermometer temperatures have been used for consistency to estimate the composition of the reservoir from the fluid samples. More detailed reconstructions of the reservoir chemistries are in progress. Table 1 presents representative compositions of the reservoir fluids calculated by this method.

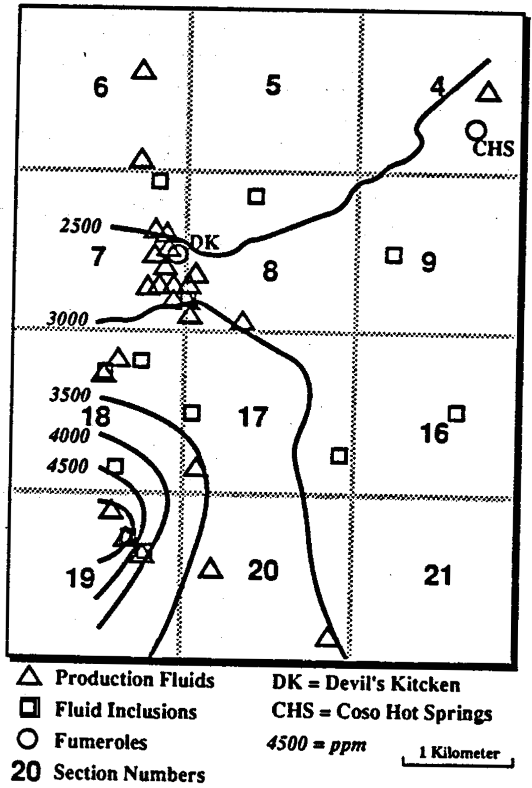

Figure 2. Plan map of the Coso geothermal field showing well locations and calculated Cl concentrations of reservoir fluids.

The fluid compositions define steep gradients in salinities, gas concentrations, and temperatures across the reservoir. Figure 2 is a plan map of the field contoured with respect to the calculated Cl contents of the reservoir fluids. Wells that define the high-chlorinity region in the southern part of the field all produce from depths greater than 1525 m. In contrast, wells drilled outside the 3500 ppm contour produce from shallower depths. The corresponding salinities range from 1.05 wt.% TDS in the south to 0.37 wt.% TDS in the north.

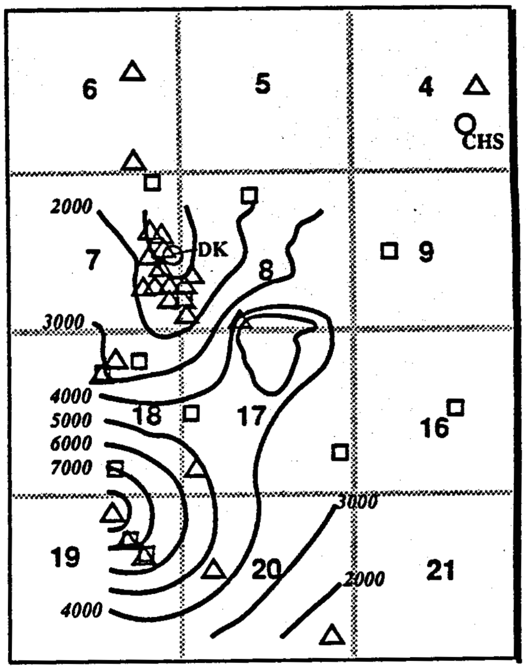

Figure 3. CO_2 concentrations in production fluids. See Fig. 2 for explanation.

Variations in CO_2, shown in Figure 3, mimic the Cl variations with the exception of the CO_2 depression in the north. Gas depletion in the north may be caused by boiling, as indicated by the occurrence of fumaroles in this area.

The relationship between the Na/K geothermometer temperatures (Truesdell, 1976) and the Cl contents of the recalculated fluids is shown in Figure 4. Because the Na/K geothermometer is a logarithmic function of the concentrations of these elements, mixtures of different temperature endmembers that have not chemically reequilibrated will define a curve that is concave downward

Table 1. Representitive analyses of production fluids from the Coso geothermal system. Concentrations are are in ppm and are restored to pre-flash conditions based on the silica geothermometer temperatures. Quartz = quartz geothermometer temperatures (Fournier and Potter, 1982) in deg C , Na/K = Na/K geothermometer temperatures (Truesdell, 1975).

Well	52-7	77-7	24-20	33-19	72-19	73-19
Date	2/88	1/87	1/88	6/88	9/86	5/87
Na	1480	1731	1949	2801	2850	1934
K	206	324	390	700	927	552
Ca	11.4	25.3	9.0	36.8	75.0	36.6
Mg	< 0.18	< 0.16	0.21	< 0.10	< 0.35	< 0.15
SiO_2	423	463	549	700	711	661
B	63	67	64	113	119	61
Li	10.9	15.1	18.4	36.3	45.3	29.9
Sr	2.43	2.58	1.42	0.77	2.79	2.08
Cl	2329	3041	3301	5121	5729	3763
F	3.20	N.A.	N.A.	2.25	1.91	1.49
HCO_3	95.5	40.4	98.6	30.2	23.3	31.4
SO_4	49.9	37.2	41.4	11.6	5.0	5.5
TDS	4615	5709	6355	9573	10468	7048
Quartz	240	249	268	307	310	296
NA/K	226	267	277	313	363	337
Total Gas	2477	1428	4678	9842	7967	9389
CO2	2449	1412	4644	9545	7786	9224
H2S	14.3	15.0	20.9	188.8	159.8	141.7
NH3	0.472	0.473	0.530	0.694	3.776	0.547
Ar	0.181	0.012	0.038	1.569	0.059	0.103
N2	9.65	1.14	9.02	94.02	9.19	18.85
CH4	0.444	0.093	0.737	4.004	1.118	1.989
H2	0.038	0.043	0.040	1.859	1.077	0.568

on a Cl-enthalpy plot. The degree of curvature increases as the salinity of the diluting fluid decreases. Equilibration to the mixture temperature results in a straight-line relationship between the geothermometer values and the Cl concentrations. The linear trend shown in Figure 4 indicates that the fluids at Coso are related by mixing, and that they have reequilibrated after mixing. The high-temperature end-members are produced from wells in section 19, and have Na/K geothermometer temperatures of 362°C and Cl contents of approximately 6000 ppm. Although it is not possible to determine uniquely the temperature of the diluting fluid from the Cl- enthalpy relationships, the data suggest that it is not much lower than about 140°C.

Comparison of chemical analyses from individual wells sampled at different times indicates that part of the scatter in Figure 4 results from local mixing of the reservoir fluids. The repeat analyses indicate that SO_4 contents of the fluids can vary as much as 100% and that increasing SO_4 correlates with decreasing geothermometer temperatures and increasing calcite scaling and total S content. In contrast, the Cl content shows no systematic correlation with SO_4 concentration. Thus, the observed compositional variations may be the result of mixing between reservoir fluids of different temperature but similar Cl concentrations, with the cooler fluids enriched in Ca, HCO_3, and SO_4 due to equilibration with calcite and anhydrite.

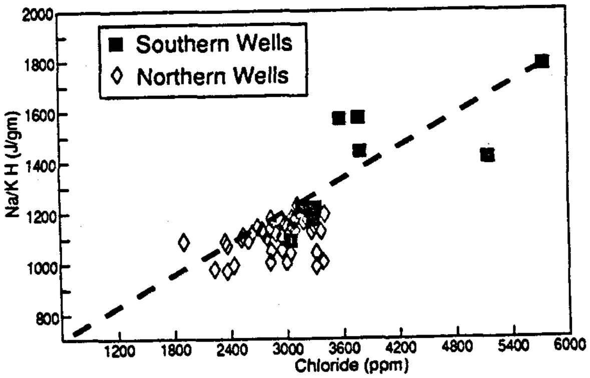

Figure 4. Enthalpy-Cl relationships of the production fluids.

FLUID INCLUSIONS

Fluid inclusions from 12 thermal gradient and production wells were studied to better characterize the composition of the reservoir fluids. Microthermometric measurements were made on approximately 1200 two-phase, liquid-rich inclusions in quartz, calcite, and anhydrite. The majority of the inclusions studied were secondary or pseudosecondary in origin and 3 to 10 microns in size. Although the temperature and salinity relationships discussed below indicate that most of these inclusions are related to the present geothermal system, a few inclusions found in quartz and anhydrite recorded salinities in excess of 6 equivalent wt.% NaCl. Such high salinity fluids are unlikely to be related to the present thermal system, and therefore these data were not included in Figures 5a-c.

Vapor-rich inclusions are found throughout the field but are most common in the upper several hundred meters of the northern and eastern wells. The presence of vapor-rich inclusions is significant because they provide evidence of boiling within the reservoir. Unfortunately, it was not possible to make reliable microthermometric measurements on them because of their small size (less than 10 microns).

Homogenization temperatures (Th) of the fluid inclusions ranged from 328° to less than 100°C. The data are grouped in Figures 5a-c according to the locations of the wells. Wells drilled in the southern part of the field are located in sections 17 through 20. The northern wells are in sections 7 and 8, while eastern wells are located in sections 9 and 16. Figure 5a shows that fluid inclusions in the upper 1200 m of the southern wells define conductive gradients but plot close to the boiling point curve at greater depths. In contrast, the thermal profiles in the shallow portions of the northern and eastern wells follow boiling point curves (Figs. 5b and c).

Ice-melting temperatures (Tm-ice) of the inclusions range from 0.0° to -2.8°C. These data are summarized in Figure 6. The plot shows that, in general, the apparent salinity of the inclusion fluids increases with increasing Th. Many individual samples, however, display large variations in Tm-ice but relatively little variation in Th. For example, Tm-ice of secondary fluid inclusions in quartz from 372 m in well 41-8 ranged from -2.2° to -0.4°C whereas the corresponding homogenization temperatures varied by only 7°C (236° to 243°C). Hedenquist and Henley (1985) described similar relationships from the Broadlands geothermal system and suggested that variations in Tm-ice of individual samples could be due to differences in the gas contents of the inclusions.

If the assumption is made that the gas is primarily composed of CO_2, as is the case at Coso, then the gas contents of the inclusions can be estimated from the range in their freezing-point depressions. For the example given above, the CO_2 content would be 4.5 wt.%. This value is obviously too high, because clathrate begins to form at 3.7 wt.%, and the freezing temperature would be positive. Thus, the artificially high concentration calculated by this method is at least in part due to natural variations in the salinities of the fluids (see Fig. 2).

A few of the inclusions from the eastern and northern wells have positive melting temperatures, which ranged from +0.3° to +1.9°C. Even though it was not possible to identify optically the last solid phase to melt in these inclusions because its refractive index is similar to that of the liquid, the observations described above suggest that the positive temperatures represent the melting of CO_2 clathrate. A minimum estimate of the CO_2 contents of these inclusions can be obtained by combining the decomposition curve of clathrate in pure water (Bozzo et al., 1975) with Henry's Law relationships and the Th values of the inclusions. These calculations yield CO_2 contents up to 4.5 wt.%.

For comparison with the fluid inclusion data, the freezing point depressions of the production fluids were calculated using a procedure similar to that of Hedenquist and Henley (1985). The data are shown in Figure 6 along with the fluid inclusion measurements. It can be seen from this figure that the salinities and temperatures of the production fluids are a subset of the fluid inclusion values. The geographic trends found in the production data are also evident from the fluid inclusion data. Fluids from the southern wells are the most saline, while those in the east and north have the lowest salinities. The vertical spike defined by the northern wells in Figure 6 reflects the high gas contents of the fluids trapped at shallow depths. These wells lie along the same zone as the gas-depleted production fluids, implying that the higher gas contents of the inclusion fluids reflects condensation of steam and gas released from the deeper fluids during boiling.

The least diluted fluid is contained in fluid inclusions sampled at a depth of 1859 m in Well 72-19, which is located in the southern part of the field. Fluid inclusions from this depth have an average Th of 322°C. The Tm-ice of these inclusions ranged from -0.6° to -1.6°C with the majority being -0.8°C. We infer from these data that the inclusion fluid has an apparent salinity of 1.4 equivalent wt.% NaCl, and a maximum CO_2 content of 2.4 wt.%. These values are slightly higher than the production fluids from this well, which have a salinity of 1.05 wt.% TDS and a CO_2 content of 0.95 wt.%. Although the higher apparent salinities of the fluid inclusions from well 72-19 may represent a more saline parent fluid than is found in the production zones, the higher gas contents of the inclusions are probably the result of gas transfer and enrichment due to boiling. Gas enrichment is likely since the majority of the highest-temperature inclusions have the lowest gas contents.

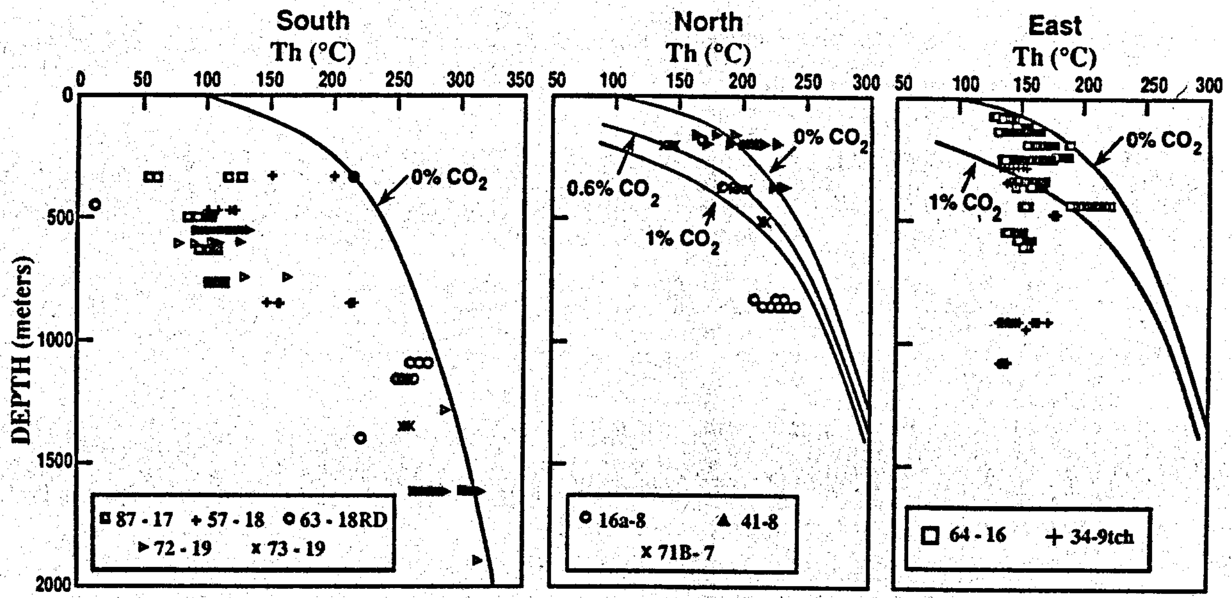

Figure 5a-c. Th-depth relationships for each of the three areas studied. Boiling point curves for a 0.3 wt% NaCl fluid with variable CO_2 contents are shown for reference.

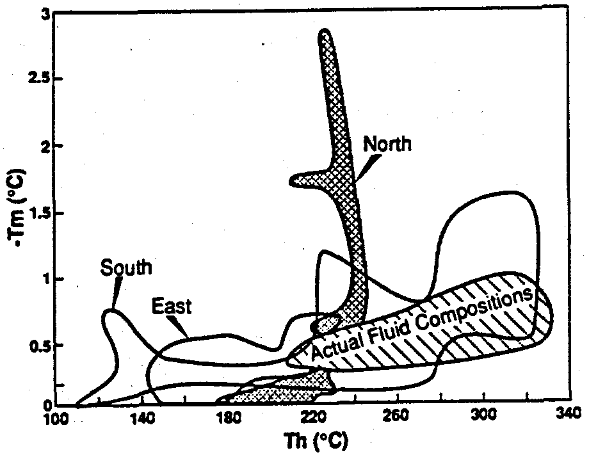

Figure 6. Th-Tm diagram summarizing the fluid inclusion and production fluid data.

CONCLUSIONS

Exploration and production drilling within the Coso geothermal system has provided an unusually complete suite of fluid and rock samples for chemical and petrologic studies. In this paper, we have combined chemical analyses of the production fluids with the results of fluid inclusion measurements to develop a detailed hydrogeochemical model of this dynamic geothermal system. This model defines a plume of hot water that originates deep in the southern part of the field and then migrates to the north and east through the fractured crystalline basement rocks.

As the deep reservoir fluid moves laterally and vertically away from the center of upwelling, it is progressively diluted by low-salinity water. Both the fluid inclusion and enthalpy-Cl data indicate that the diluting fluid has a temperature between 120° and 140°C. Estimates of the high-temperature endmember range from 322° to 360°C.

The pattern of fluid movement appears to be controlled by decreasing depth to permeable rocks north and east of section 19. Variations in permeability with depth are reflected in the abundance of veins and the widespread evidence of boiling at shallow depths in the north compared to the south.

Evidence for boiling includes CO_2 depletions of the fluids, vapor-rich inclusions, and fumarolic activity. In addition, CO_2 enrichments in fluid inclusions indicate that steam and gas have been added to some of the geothermal fluids.

The close correspondence of production fluid chemistry and fluid inclusion data demonstrates that these methods, used in conjunction, can provide detailed models of geothermal systems. In contrast, neither the chemical nor the fluid inclusion studies independently yields a hydrogeochemical model that adequately describes this reservoir.

ACKNOWLEDGEMENTS

We would like to thank J. Moore of the California Energy Company and C. Austin of the Naval Weapons Center for making this study possible. Samples and data made available by California Energy Company for this work are greatly appreciated. Funding for this work was provided by the Department of Energy, under contract no. DE-AC07-85ID-12489.

REFERENCES

Bozzo, A. T., Chen, H-S., Kass, J. R., and Barduhn, A. J., 1975, The properties of the hydrates of chlorine and carbon dioxide: Desalination, v. 16, p. 303-320.

Fournier, R. O., and Potter, R. W., II, 1982, A revised and expanded silica (quartz) geothermometer: Geothermal Resources Council Bulletin, Vol. 11, No. 10, 1982, p. 3-12.

Hedenquist, J. W., and Henley, R. W., 1985, The importance of CO_2 on the freezing point depression of fluid inclusions: evidence from active geothermal systems and implications for epithermal ore deposition: Economic Geology, v. 80, p. 1379-1406.

Truesdell, A. H., 1976, Summary of section III-geochemical techniques in exploration: Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, v. 1, p. liii-lxiii.