

## TRACING FLUID SOURCES IN THE COSO GEOTHERMAL SYSTEM USING FLUID-INCLUSION GAS CHEMISTRY

Susan Juch Lutz<sup>1</sup>, Joseph N. Moore<sup>1</sup>, Michael C. Adams<sup>1</sup>, and David I. Norman<sup>2</sup>

1. Energy and Geoscience Institute, University of Utah, Salt Lake City, UT 84108
2. Dept. of Earth and Environmental Sciences, New Mexico Tech, Socorro NM 87801

### ABSTRACT

Vein and alteration assemblages from eight Coso wells have been collected and their fluid-inclusion gases analyzed by quadrupole mass spectrometry. Four major types of alteration were sampled: 1) young calcite-hematite-pyrite veins; 2) wairakite or epidote veins and alteration that are spatially associated with deep reservoirs in the main field and eastern wells; 3) older sericite and pyrite wallrock alteration; and 4) stilbite-calcite veins that are common in cooler or marginal portions of the geothermal area.

The gas compositions of the fluid inclusions display systematic differences among the secondary assemblages. The highest  $N_2/Ar$  ratios are found in some calcite vein samples ( $N_2/Ar$  up to 5173) and in epidote assemblages ( $N_2/Ar$  ratios of 1000 to 1427). These high  $N_2/Ar$  ratios suggest the presence of a magmatic component in the fluids that produced these assemblages. Sericite-pyrite altered samples, and stilbite and calcite-hematite veins have fluid-inclusion gas compositions with  $N_2/Ar$  ratios less than 100, indicating that these assemblages formed from meteoric fluids. High  $CO_2$  and low  $H_2O$  contents (less than 98 mol %) of inclusions in wairakite and sericite-bearing assemblages suggest deposition from boiling fluids. Low  $CO_2/CH_4$  ratios of inclusions in stilbite veins indicate formation from crustal fluids.

The gas chemistry reflects mixing between two end-member fluids; one enriched in magmatic volatiles, and a second represented by meteoric fluids. With the exception of the epidote assemblage, the fluid-inclusion gases plot in the basaltic field on a He- $N_2$ -Ar diagram. This signature is similar to the present-day gas analyses from steam samples taken from both the Devil's Kitchen fumarole area and from Coso production wells.

### INTRODUCTION

Coso is one of several high-temperature geothermal systems on the margins of the Basin and Range province associated with recent volcanic activity. The Coso geothermal system is hosted in fractured Jurassic metamorphic lithologies and Cretaceous plutonic rocks that were intruded by rhyolite and basalt of the Pliocene to Recent Coso Volcanic Field (Duffield et al., 1980). Rhyolite domes surround the productive portion of the field and the heat source for the present geothermal system is thought to be related to partially molten magma bodies at a depth of 5 to 20 km. Like all modern geothermal systems, Coso production fluids are primarily meteoric water; however, the association with young volcanism allows the possibility of a magmatic component to the fluids. In this paper, we begin to examine the early evolution of the system as recorded by the fluid-inclusion gas compositions.

Sixteen vein and alteration samples from eight Coso wells were analyzed. The samples were picked from core and cuttings from wells in the "Main Field" and "East Flank" portions of the geothermal area (Fig. 1). The fluid inclusions, veins, and minerals in the samples represent a variety of depth intervals and types of alteration (Table 1). The objectives of this study were to determine possible sources of the altering fluids and the importance and distribution of magmatic, crustal or meteoric derived volatiles during the evolution of the geothermal system.

### METHODS

Major and minor gases, including  $H_2O$ ,  $CO_2$ ,  $CH_4$ ,  $H_2S$ ,  $H_2$ ,  $N_2$ , Ar, and  $C_{2-7}$  organic species contained in inclusions from Coso alteration minerals were analyzed with a Balzers QMS 420 quadrupole mass spectrometer after being released from the inclusions by crushing (crush-fast-scan (CFS) method). Norman et al. (1996) have presented the details of this analytical technique.

**TABLE 1. Alteration Samples**

Sample	Well	Depth (ft)	Mineral
1	20	9650	epidote
2	21	8846	epidote
3	22	6220	stilbite+cc
4	10	5280	py+sericite
5	18	4600	wairakite
6	23	7850	wair+qtz+cc,py
7	20	4870	pyrite
8	20	4870	cc+hem,py,qtz
9	18	4600	calcite
10	3	1810	cc+qtz
11	10	5270	qtz+cc
12	21	4940	cc+chl
13	16	5270	calcite
14	16	531+638	calcite

The CFS method involves opening inclusions with a swift crush in a vacuum chamber housing the mass spectrometer. The volatiles are removed by the vacuum pumping system in 1 or 2 seconds and recorded by operating the quadrupole in a fast scan mode with measurements taken every 150 to 225 milliseconds. Opening a 10 to 20 micron inclusion or group of smaller inclusions of equivalent volume provides the ideal amount of volatiles for the analysis. A 40 micron inclusion will overload the vacuum system. Because the volume of gas that can be analyzed is limited, data from inclusions that trapped gas-rich steam will typically be underrepresented (Moore et al., 1998). Five to 20 crushes can be made on a 0.2 g sample with the expectation that some of the analyses will be failures.

The precision of the CFS analyses is 10-20%. Ammonia is rarely detected because of the interferences of secondary water peaks at  $m/e = 17$  and 16, and He at concentrations below 30 ppm is interfered with by the tail on the  $H_2$  peak. Although air contamination can be removed by prolonged heating, the samples were not baked in order to minimize any diffusion of  $H_2$  and He.

### **HYDROTHERMAL ALTERATION**

Although the Coso reservoir is large (about 30 sq. km in area) and productive (264 MW), there are few surface expressions of the thermal system. These features include widely spaced fumaroles and fossil hot spring deposits in the northern Main Field and East Flank areas (Fig. 1; Hulen, 1978). No evidence of

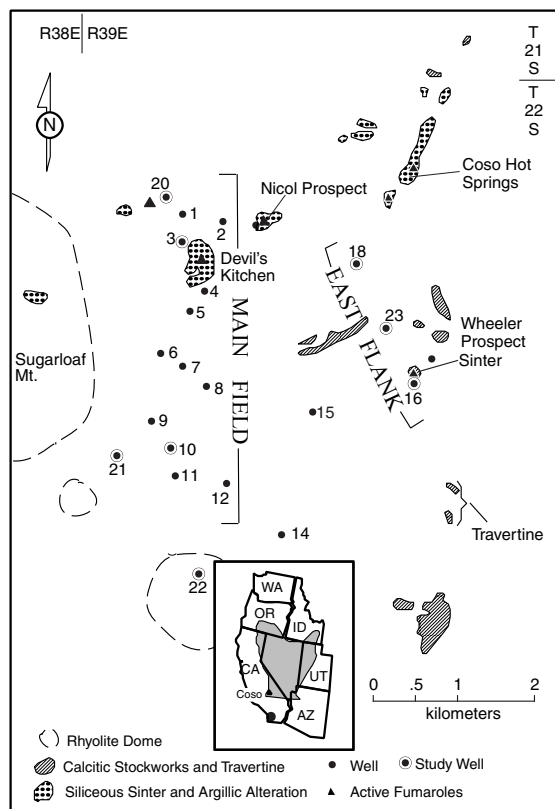


Fig. 1. Location of wells and surface features in the Coso geothermal system, California. Inset shows the location of Coso along the southwestern edge of the Basin and Range Province (shaded).

surface activity has been found in the southern part of the Main Field where temperatures of 342°C have been measured at depths of 2.5 km. In the subsurface, most of the veining associated with the present geothermal system is localized within discrete intervals that can be interpreted as fractures or faults in the reservoir rock. The alteration that best mimics the present thermal structure of the system is defined by the distribution and zoning of the clay minerals.

Based on the clay mineralogy, three alteration zones can be recognized: the smectite zone, the illite-smectite zone, and the illite zone (Lutz et al., 1996). In the Main Field, the smectite zone forms a cap over the geothermal reservoir that thickens from north to south and is characterized by smectite, kaolin, stilbite and a variety of carbonate minerals. The illite-smectite zone is thin in the north, and thickens and deepens to the south. The illite zone contains illite, chlorite, pyrite, epidote, prehnite, and wairakite in high-temperature portions of the field. Along the East Flank, the clay zones are not as clearly delineated and the illite-smectite and illite zones overlap.

Calcite and quartz veins are common throughout the Coso area at all depths, although the smectite zone is the most intensely veined. Carbonate veins with chlorite selvages are common where they cut smectite-altered wallrock, indicating that the carbonate mineralization is younger than the clay alteration. Fluid-inclusion data suggest that the smectite-altered caprock and its associated carbonate veins formed in response to mixing between thermal waters and ground waters that were present at the top of the system in the past (Moore et al., 1989; Lutz et al., 1996). Deeper in the smectite zone and especially along the margins of the system, veins of stilbite+calcite are common. In this study, stilbite veins were sampled from well 22 located along the southern margin of the Main Field (Fig. 1).

In the Main Field, calcite veins with quartz, hematite and pyrite clearly cut sericite-pyrite altered wallrock in the illite zone. In our sample set, this older sericite alteration is represented by Sample 4 from 5280 ft in well 10 (Table 1). Wairakite-quartz-calcite veins also occur within sericitized rocks deeper in the illite zone. These veins are found within brecciated rocks at the contacts between metamorphic and granitic rocks and

are spatially correlated with fluid entries in the wells. Fluid-inclusion data from well 10 (Moore et al., 1990) suggest that the wairakite may represent an older alteration assemblage because associated inclusion fluids appear to have been slightly more saline (up to 2.7 wt % NaCl equivalent) or may have contained more carbon dioxide (up to 2.4 wt percent CO<sub>2</sub>) than the present production fluids (0.5 to 1.5% salinity). Wairakite veins have a very limited distribution in the field and been observed in East Flank wells 18 and 23 at 9710 ft and 7850 ft, respectively, and in Main Field wells 10 and 20 at 6100 ft and 4870 ft, respectively. The veins sampled for this study include the two samples from the East Flank wells where the wairakite is intergrown with prismatic quartz and calcite. These veins also contain minor amounts of sphene, pyrite, and epidote.

Epidote-chlorite alteration occurs in a variety of locations and depths in the Coso area. The presence of strong epidote alteration in the wells outside of the productive portions of the field or at shallow depths (where temperatures are cooler than 240°C) in productive wells suggests that the epidote mineralization may not be related to the present geothermal system.

mineral	sample #	pregeothermal	geothermal assemblages				
			early ←				→ late
			1	2	3	4	5
epidote	1	cross-hatched					
	2	cross-hatched					
stilbite	3		cross-hatched				
sericite	4			cross-hatched			
wairakite	5				cross-hatched		
	6				cross-hatched		
pyrite	4			diagonal lines			
	6			diagonal lines			
	7					cross-hatched	
	9					diagonal lines	
quartz	6				diagonal lines		
	8					diagonal lines	
	10						cross-hatched
	11						cross-hatched
hematite	8					cross-hatched	
calcite	3		diagonal lines				
	6				diagonal lines		
	8					cross-hatched	
	9					cross-hatched	
	10						cross-hatched
	11						diagonal lines
	12						cross-hatched
13, 14						cross-hatched	

Fig. 2. Paragenetic scheme for alteration minerals associated with the Coso geothermal system. See Table 1 for description of Samples 1-14.

However, in some places (at 9650 ft in well 20 and at 8846 ft in well 21; Samples 1 and 2), epidote veining and mineralization occurs along productive fractures or fault zones in the wells. In well 20, the epidote is present as veins with calcite, chlorite, adularia, quartz and pyrite that occur within sericitized wallrock.

Along the East Flank, the geothermometry of alteration minerals and fluid inclusions suggest recent heating (Lutz et al., 1996). Most of the alteration minerals in well 16 record deposition from much lower temperatures than the present well temperatures which exceed 260°C. The presence of stilbite (stable below 125°C), chalcedony (stable below 180°C), mixed-layer illite-smectite (stable between 180° and 220°C), and fluid inclusions from calcite veins (with homogenization temperatures of 150° to 250°C) all reflect progressive heating through time.

Figure 2 presents our observations on the paragenesis of the alteration samples selected for analysis in this study. The general alteration history at Coso can be summarized as follows: 1) pregeothermal epidote mineralization; 2) initial heating to produce stilbite veins; 3) formation of clays (smectite at shallow depths, and sericite in upwelling areas) and carbonate veins as a result of mixing between thermal water and groundwater; 4) deposition of wairakite-bearing veins from fluids that were slightly more saline or carbon dioxide-rich than present production fluids; and 5) deposition of calcite veins with minor quartz, chlorite, pyrite and hematite.

## RESULTS

One hundred and twenty CFS gas analyses were performed on fluid inclusions in vein and alteration minerals from the eight wells. The minerals analyzed include quartz, calcite, pyrite, illite, wairakite and epidote. The principal component of the inclusions was water, which accounted for 44.5 to 99.9 mole percent of the analyses. Figure 3 displays the average gas composition for 14 selected samples. The samples are arranged with respect to their generalized paragenetic sequence from older (epidote assemblages) to younger (calcite assemblages). The data display important and systematic differences between inclusions trapped in the different alteration minerals.

The histograms show that alteration minerals with the highest  $N_2/Ar$  ratios are found in some of the calcite vein samples (Sample 14,  $N_2/Ar$  ratios up to 5173) and in epidote-bearing assemblages (Samples 1 and 2,  $N_2/Ar$  ratios of 1000 to 1427). Only the sericite

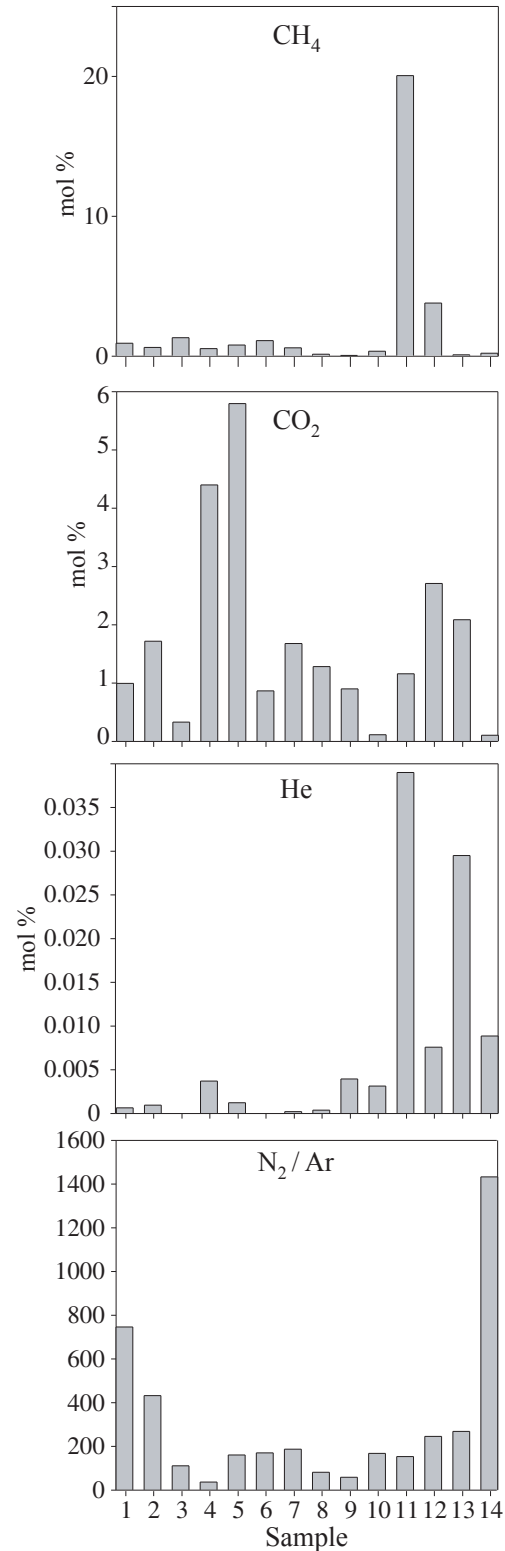


Fig. 3. Average fluid-inclusion gas compositions of alteration samples 1-14, listed in general paragenetic sequence from older (epidote samples 1 and 2) to younger (calcite samples 9-14).

(Sample 4) and a few calcite-hematite veins (Samples 8 and 9) have fluid-inclusion gas compositions with  $N_2/Ar$  ratios near the range of meteoric water (<100).  $CO_2$  contents were highest in the wairakite vein assemblage (Samples 5 and 6; 4.0 to 7.3 mol %), and next highest in the sericite-pyrite assemblage (Sample 4, 3.0 to 5.5 mol %).

Although most samples contain less than a mole percent  $CH_4$ , some wairakite and stilbite vein analyses returned higher values (2 to 4 mol %). The highest  $CH_4$  contents (up to 46 to 73 mol %) and highest He contents were found in analyses of quartz and calcite veins from intermediate depths in the Main Field (Sample 11, well 10 at 5270 ft), that also returned with low  $H_2O$  contents. Other samples with high He contents include calcite veins from shallow and intermediate depths in wells along the East Flank (Samples 13 and 14 from well 16). In the following sections we relate the differences in gas compositions to the effects of boiling and mixing between fluids of different origins.

## **DISCUSSION**

### *Determination of fluid sources*

Norman et al. (1996) demonstrated that the ratios of  $CH_4$ ,  $N_2$ , and Ar are useful indicators for tracing the sources of gases trapped in fluid inclusions. They argued that hydrothermal fluids derived from meteoric waters will have  $N_2/Ar$  ratios between those of air (84) and air-saturated water (36) although boiling will expand this range slightly because of differences in the solubilities of the two gases. Meteoric fluids that have boiled can have  $N_2/Ar$  ratios that range from about 100 to 15, depending on whether the inclusions trapped the gas-depleted liquid or the steam (Norman et al., 1997). Fluids from active Basin and Range geothermal systems have  $N_2/Ar$  ratios up to about 100 or 150 (Welhan et al., 1988). Crustal fluids (those which are not involved in the meteorological cycle) are typically enriched in  $CH_4$  and other hydrocarbons.  $N_2/Ar$  ratios up to about 350 have been found in crustal fluids at the Geysers (Hiyagon and Kennedy, 1992; Moore et al., 1998). Hydrothermal fluids may accumulate  $CH_4$  through thermal degradation of organic material, and/or oxidation-reduction reactions involving iron-bearing minerals and  $CO_2$  (Giggenbach, 1992). Magmatic gases are distinguished by low  $CH_4$  contents, high  $^3He/^4He$  isotopic ratios, and  $N_2/Ar$  ratios exceeding 100 (Giggenbach, 1986; Norman and Musgrave, 1995; Norman et al., 1996).

### *Helium composition*

Helium compositions of many geothermal and volcanic systems have been studied by Giggenbach (1992, 1995). In these studies, the end-member compositions of various types of volcanic gases were deduced from the geologic settings of the gas sample, such as andesitic or basaltic volcanoes and their associated geothermal systems. Many of the basaltic systems are from rift (New Zealand, Iceland) and hot spot (Hawaii) tectonic settings. The andesitic systems are from a variety of continental and oceanic convergent plate environments associated with subduction complexes. Giggenbach attributes the broad range in andesite gas compositions and high  $N_2$  contents to assimilation of marine sedimentary crust during ascent of the magma. In both andesitic and basaltic systems, geothermal fluids (both liquid and gases) mix with air-saturated groundwaters. We use Giggenbach's andesite-basalt divide to interpret the results of the Coso fluid-inclusion gas data (see Fig. 4).

In a study by Welhan et al. (1988), the gas compositions of a variety of Basin and Range geothermal systems and some volcanoes from western North America were analyzed. The volcanoes range from basaltic to contaminated andesitic in gas composition. The study revealed that the gases from Basin and Range hot-spring systems follow the basalt or continental line that connects fluids of a predominantly meteoric origin with more evolved fluids that have high He contents. Because He can be produced both as primary emissions from the mantle and radiogenically in the crust, it is necessary to know the  $^3He/^4He$  isotopic ratios to distinguish between a mantle or crustal origin. Ratios normalized to atmospheric abundances that are greater than 5  $R_a$  are generally considered to have a significant amount of mantle He. The Welhan study includes an analysis of steam collected from the Devil's Kitchen area at Coso. The value of the Devil's Kitchen ratio, relative to the atmospheric ratio was 7.08  $R_a$ . This value is comparable to the Mt. Hood summit fumarole (7.21  $R_a$ ) and many of the geo-thermal systems along the western edge of the Basin and Range Province. In contrast, He isotopic ratios of geothermal systems within the central Basin and Range vary from 0.1 to 2.5  $R_a$  and reflect the generally non-magmatic nature of these geothermal systems.

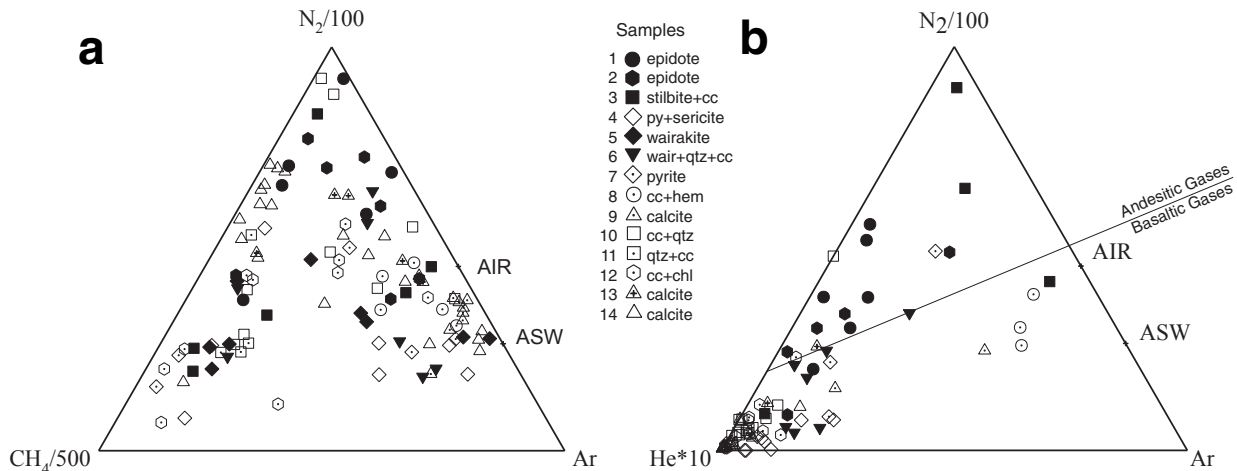


Fig. 4. Coso fluid-inclusion gas data for alteration Samples 1-14 plotted on  $\text{CH}_4/500\text{-N}_2/100\text{-Ar}$  (a) and  $\text{He}^*10\text{-N}_2/100\text{-Ar}$  (b) ternary diagrams.

#### Effects of boiling

The compositions and gas contents of the Coso inclusion analyses indicate that they consist of mixtures of both vapor- and liquid-rich inclusions. The presence of vapor-rich inclusions can be recognized by gas contents that are too high to be representative of a hydrothermal fluid consisting of only a liquid phase. At shallow depths, analyses with gas contents of more than 1 to 2 mole percent require a contribution from vapor-rich inclusions. Because most of the analyses indicate water contents of less than 98 mol %, the data indicate that a significant proportion of the analyses, irrespective of the host mineral, must contain volatiles from vapor-rich inclusions. In our sample set from Coso, the gas analyses with the highest  $\text{CO}_2$  contents are from the wairakite and sericite assemblages, indicating that these alteration minerals trapped steam and gas from a boiling fluid during or subsequent to their deposition. High  $\text{CH}_4$  and low  $\text{H}_2\text{O}$  contents of gases from intergrown quartz-calcite veins are consistent with deposition from boiling fluids.

#### Coso gas compositions

Figure 4a displays all the fluid-inclusion gas data for the Coso alteration samples in terms of their  $\text{CH}_4/500\text{-N}_2/100\text{-Ar}$  ratios. The epidote analyses (Samples 1 and 2) and the calcite analyses from well 16 (Samples 13 and 14) plot in the high  $\text{N}_2$  (magmatic) portion of the diagram. Some analyses from wairakite, stilbite, sericite and pyrite-bearing samples have high  $\text{CH}_4$  contents, while others have meteoric ratios. Gases from the calcite, hematite, and pyrite

samples (Samples 8, 9 and 14) in wells 20, 21 and 16 have the strongest meteoric signature. Analyses from calcite veins in well 16 (Sample 14) appear to represent both magmatic and meteoric gas compositions. Overall, the data suggest mineral deposition from meteoric or crustal fluids containing variable proportions of a  $\text{N}_2$ -rich gas that was probably magmatic in origin.

The Coso fluid-inclusion gas data are also plotted on a  $\text{He}^*10\text{-N}_2/100\text{-Ar}$  diagram in Figure 4b. Most of the Coso samples clearly fall in the high He basaltic or crustal corner of the diagram that is also represented by the Devil's Kitchen analysis reported by Welhan et al. (1988). Notable exceptions to this trend are the analyses from the epidote, wairakite, and calcite+hematite assemblages. The gases from the epidote samples plot in the andesitic field. The wairakite gas analyses generally plot on the divide between the andesitic and basaltic fields. The wairakite analyses that plot in the basaltic field appear to contain less He than most of the calcite vein analyses. Gas compositions of the calcite+hematite assemblage display a distinctive meteoric signature.

Two trends are evident on the  $\text{He-N}_2\text{-Ar}$  diagram. The calcite, quartz and pyrite veins link atmospheric compositions with the basaltic apex, and overlie the actual geothermal compositions. The epidote trend may be a mixture of andesitic or subduction-generated gases, and basaltic or continental gases. The epidote assemblages that plot with andesitic gases appear to be older because the current composition is in the basaltic field.

## **SUMMARY**

The results of this fluid-inclusion gas study indicate that fluids of different origins were involved in the formation of a variety of alteration minerals during the evolution of the Coso geothermal system. Figures 2 and 3 record the changes in mineralogy and in gas chemistry through time.

The epidote assemblage (Samples 1 and 2) is characterized by fluid-inclusion gases with high  $N_2/Ar$  ratios and low He and  $CH_4$  contents. The epidote-chlorite-calcite assemblage appears to represent regional propylitic alteration that occurred before the formation of the present geothermal system. These gases may be associated with an andesitic magmatic system related to an older subduction event.

Initiation of the present geothermal system is recorded by the formation of stilbite-calcite veins (Assemblage 1 in Figure 2, and Sample 3 in Figure 3). At Coso, we interpret the occurrence of stilbite to represent the presence of cool, dilute fluids either on the margin of the present geothermal system or during the initial heating of the system. Stilbite gas analyses have low  $CO_2/CH_4$  ratios because of their high  $CH_4$  contents. This composition is characteristic of gases in crustal fluids.

The high  $CO_2$  and low  $H_2O$  contents of the sericite, pyrite, and wairakite assemblages (Assemblages 2 and 3 in Figure 2, and Samples 4-7 in Figure 3) suggest boiling. Wairakite veins are commonly observed to cut moderately-sericitized wallrock but generally these two assemblages appear to be spatially linked. The presence of quartz and calcite, and traces of adularia, pyrite and sphene in the wairakite veins is consistent with deposition resulting from boiling. From our conventional fluid-inclusion analyses, we also know that the wairakite veins contain fluid inclusions that are slightly more saline or more  $CO_2$ -rich than modern-day fluids. Overall, the gas chemistry is consistent with our interpretation of the early formation of sericite from steam-heated groundwaters, and subsequent boiling to produce wairakite veins.

Calcite veining dominated the alteration mineralogy during later stages in the evolution of the Coso geothermal system (Assemblages 4 and 5 in Figure 2, and Samples 8-14 in Figure 3). These veins also contain some quartz, pyrite, hematite and chlorite. Calcite-hematite veins (Sample 8) have fluid-inclusion gas compositions with meteoric  $N_2/Ar$  ratios and low He contents. The presence of hematite in the calcite

veins is consistent with deposition from oxygenated groundwaters that must have been present in the past (based on our previous fluid-inclusion studies).  $CH_4/500-N_2/100-Ar$  ratios of Sample 9 from 4600 ft in well 18 exhibit the strongest meteoric signature of any of the study group and its gas composition may represent an endmember for the mixtures of gases in the other assemblages.

The gas compositions of calcite vein Samples 13 and 14 from East Flank well 16 plot in the magmatic region on the  $CH_4/500-N_2/100-Ar$  diagram. The highest  $N_2/Ar$  ratios of any of the study samples were found in shallow samples collected from the upper cored portion of the well. It is intriguing that these samples are from the East Flank where we have previously documented recent heating based on the succession of alteration minerals (Lutz et al., 1996). Together, these two lines of evidence suggest that the eastern portion of the field may be undergoing heating as the result of recent magmatic activity. The high He contents of the calcite samples are consistent with a significant magmatic component. This signature is similar to the present-day gas analyses from steam samples taken from both the Devil's Kitchen fumarole area and from Coso production wells.

### **Acknowledgements.**

This study would not have been possible without the cooperation of CalEnergy Co. Inc., Caithness and the U.S. Navy Geothermal Program Office. Special thanks are due to Mark Walters and CalEnergy for supplying the alteration samples. Funding for SJL, MCA, and JNM was provided by the U.S. Department of Energy, under contract no. DE-AC07-95ID13274.

## **REFERENCES**

- 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.
- Hulen, J.B., 1978, Geology and alteration of the Coso geothermal area, Inyo County, California: University of Utah Research Institute Report DOE/ID/28392-4, 28p.
- Giggenbach, W.F., 1986, The use of gas chemistry in delineating the origin of fluid discharges over the Taupo Volcanic Zone: a review: *International Volcanological Congress, Hamilton, New Zealand, Proceedings Symposium*, v. 5, p. 47-50.

Giggenbach, W.F., 1992, The composition of gases in geothermal and volcanic systems as a function of tectonic setting: in Kharaka and Maest, eds., Proceedings of the International Symposium of Water-rock Interaction, Balkema, Rotterdam, v. 7, p. 873-878.

Giggenbach, W.F., 1995, Magmatic components in hydrothermal fluids, in J.F.H. Thompson, ed., Magmas, Fluids and Ore Deposits: Mineralogical Association of Canada Short Course Volume 23, p. 247-261.

Hiyagon, H., and Kennedy, B.M., 1992, Noble gases in CH<sub>4</sub>-rich gas fields, Alberta, Canada: *Geochimica et Cosmochimica Acta*, v. 56, p. 1569-1589.

Lutz, S.J., Moore, J.N., and Copp, J.F., 1996, Integrated mineralogical and fluid-inclusion study of the Coso geothermal system, California: Proceedings, Twenty-first Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford California, January 22-24, 1996, p. 187-194.

Moore, J.N., Adams, M.C., Bishop, B.P., and Hirtz, P., 1989, A fluid flow model of the Coso geothermal system: Data from production fluids and fluid inclusions: Proceedings, Fourteenth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford California, January 24-26, 1989, p. 139-144.

Moore, J.N., Adams, M.C., Bishop-Gollan, B.P., Copp, J.F., and Hirtz, P., 1990, Geochemical structure of the Coso geothermal system, California: American Association of Petroleum Geologists Guidebook, Coso Field Trip AAPG-EMD #1, Moore, J.L. and Erskin, M., eds., p. 25-39.

Moore, J.N., Norman, D.I., and Kennedy, B.M., 1998, Fluid-inclusion gas compositions from an active magmatic-hydrothermal system: A case study of The Geysers, California geothermal field, in press.

Norman, D.I., and Musgrave, J., 1995, N<sub>2</sub>, Ar, and He in fluid inclusions: tracers of hydrothermal fluids: *Geochimica et Cosmochimica Acta*, v. 58, p. 119-131.

Norman, D.I., Moore, J.N., Yonaka, B., and Musgrave, J., 1996, Gaseous species in fluid inclusions: A tracer of fluids and indicator of fluid processes: Proceedings, Twenty-first Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford California, January 22-24, 1996, p. 233-240.

Norman, D.I., Moore, J.N., and Musgrave, J., 1997, More on the use of fluid-inclusion gaseous species as tracers in geothermal systems: Proceedings, Twenty-second Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 27-29, 1997, p. 419-426.

Welhan, J.A., Poreda, R.J., Rison, W., and Craig, H., 1988, Helium isotopes in geothermal and volcanic gases of the western United States, 1. Regional variability and magmatic origin: *Journal of Volcanology and Geothermal Research*, v. 34, p. 185-199.