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PRELIMINARY RESULTS OF GEOCHEMICAL MONITORING AND TRACER TESTS AT THE COVE FORT-SULPHURDALE GEOTHERMAL SYSTEM, UTAH

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ABSTRACT

The Cove Fort-Sulphurdale geothermal system produces both dry steam from a shallow parasitic vapor cap and liquid from the underlying liquid-dominated resource. Samples of the steam and liquid indicate that their compositions have remained stable since production began in 1985 but that the field experienced a transient pulse of increased gas shortly after injection was initiated in mid 1996. Liquid and vapor-phase tracers were injected into the reservoir in January, 1999. Steam containing R-134a, which was used to trace the movement of the vapor phase, was observed in the production wells after 2 weeks. However, as of December, 1999, tracer concentrations were still increasing. The shape of the tracer return curves suggests that the steam cap taps a small fraction of the injectate plume near the injection well, and that the majority of the tracer is still traveling slowly in the liquid phase. Fluorescein was used to trace the liquid that was injected. To date, no fluorescein has been observed in samples from the well that discharges liquid water.

INTRODUCTION

The Cove Fort-Sulphurdale geothermal system is located approximately 300 km south of Salt Lake City, within one of the largest thermal anomalies in the western U.S. (Fig. 1). The existence of this geothermal resource, which covers more than 47 km^2 (Ross and Moore, 1985), was well known to the pioneers in the 1800's because of the presence of numerous fumaroles and altered alluvium containing native sulfur. Electricity is currently being produced from a shallow steam cap and the underlying liquid reservoir adjacent to a largest of the sulfur deposits (Fig. 1). The field and power plant, which are jointly owned by the Utah Municipal Power Agency (UMPA) and Provo City, generates 6-7 MWe from a combination of condensing and binary units. The plant came on line in 1985. This paper presents information on the compositions of the reservoir fluids, the chemical changes that have occurred as a consequence of production, and preliminary results of a tracer test conducted in January, 1999.

GEOLOGIC SETTING

The geothermal reservoir is located in the structurally complex transition zone between the Basin and Range Province to the west and the Colorado Plateau to the east (Fig. 1). The reservoir rocks consist mainly of Paleozoic to Mesozoic limestones and sandstones that are covered by Tertiary ash-flow tuffs and lava flows in the eastern part of the field and Cenozoic basalt flows related to the Cove Fort Volcano in the western part. The Tertiary volcanics and older rocks were intruded by quartz monzonite and related latite dikes between 22 and 27 Ma (Steven and Morris, 1981). These intrusive rocks were encountered in two of the drill holes (wells 42-7 and P-91-4; Fig. 1) and geophysical data suggest that they are part of a larger intrusion centered under the productive portion of the field at Sulphurdale (Ross and Moore, 1985). The limestones surrounding the intrusive rocks have been thermally metamorphosed.

Permeabilities within the geothermal reservoir are related to several generations of faulting and tectonic activity (Steven and Morris, 1981; Ross and Moore, 1985). The oldest structures are thrust faults related to the Mesozoic Sevier Orogeny. These faults may be important conduits for fluids within the reservoir rocks. Basin and Range tectonism has produced large-scale gravitational glide blocks bounded by low-angle faults and steeply dipping northerly- and easterly-trending normal faults (Fig. 1). The glide blocks form a low permeability cap over the eastern part of the system that has had a profound effect on the distribution of surficial alteration, shallow temperatures, and thermal gradients. Within the glide blocks, thermal gradients are low and surficial alteration is limited to a single large zone of acid alteration on the southern edge of the producing portion of the field (Fig. 1). These relationships demonstrate that vertical permeabilities within the glide blocks are

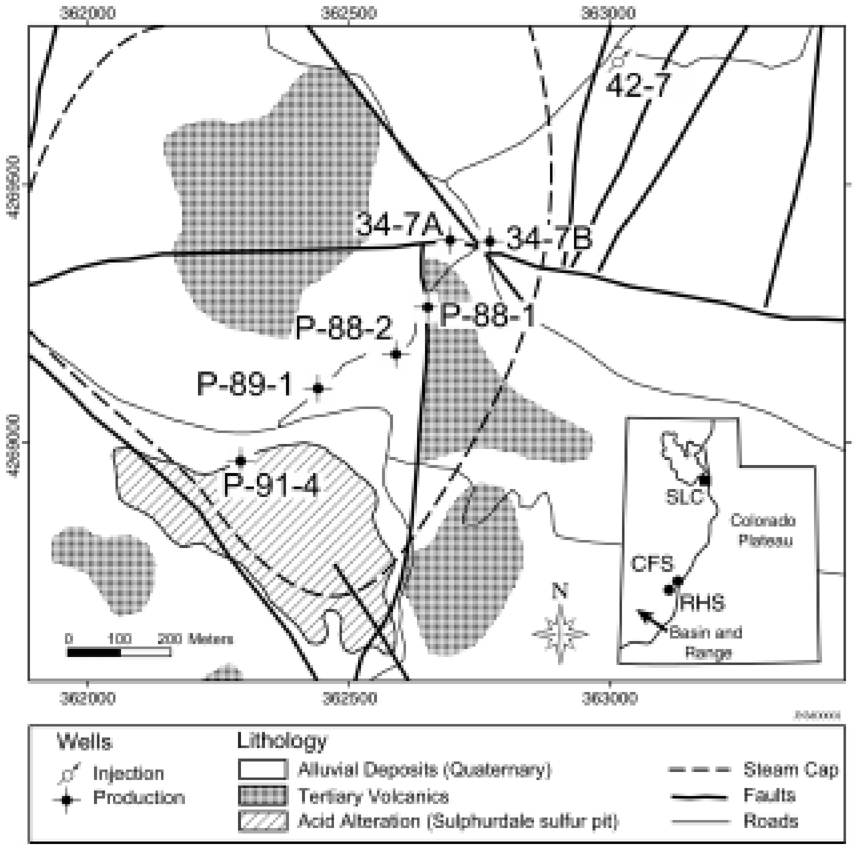

Figure 1. Map showing the major geologic features of the Sulphurdale area and the locations of the production and injection wells. Well names and numbers are used interchangeably in the text. P-88-1 = Clara; 34-7B = Linda; P-88-2 = Loretta; P-89-1 = Mary; 34-7A = Olga; P-91-4 = water well. The dashed line shows the possible extent of the steam cap. Abbreviations: CFS = Cove-Fort Sulphurdale; RHS = Roosevelt Hot Springs.

generally low, despite evidence that they have been intensely fractured. Despite the large size of the thermal anomaly and the abundance of active and extinct fumaroles, no evidence of hot spring deposits that would indicate the thermal waters ever reached the surface have been found. Deep drilling has shown that the thermal water table occurs at a depth of 300-400 m throughout this area. No overlying aquifers were encountered during the drilling of the geothermal wells even though cold springs discharge to the east and perched aquifers are found to the west of the field.

GEOTHERMAL FIELD DESCRIPTION

Figure 1 shows the locations of the production and injection wells. There are currently six production wells. Five of the wells discharge dry steam from fractured Mesozoic(?) sandstone that lies immediately below the Tertiary ash-flow tuffs. The depth to the top of the sandstone and the top of the steam cap decreases systematically from north to south. The deepest dry steam wells (Lady Olga, 34-7A; Lady Linda, 34-7B) produce steam from depths of 339-351 m. These wells had initial temperatures of 147°-151°C. P-89-1 (Lady Mary), located at the southern end of the field produces steam from 256-265 m. The sandstone appears to have a thickness of about 60 m.

P-91-4 produces water from the underlying liquid resource. This well was drilled to a depth of 745 m. P-94-1 is reported to have encountered steam at 258 m, the water table at 314 m, and a maximum temperature of 163EC. The water table appears to be located near the top of the limestones immediately below the sandstone. The limestones contain large open fractures or dissolution cavities. These were encountered at 542 m in P-94-1 and at 427 m in an adjacent deep slim hole. Below 600 m, P-94-1 encountered quartz monzonite. Liquid water is presently produced at a temperature of 152°C. After flashing through high and low pressure separators, the remaining water is injected into well 42-7 where it enters the reservoir at the base of the volcanic section between depths of 588 and 716 m. This water presently represents the sole source of injectate. Injection began in the middle of 1996. Well 42-7 was originally drilled to a depth of 2358 m and recorded a maximum temperature of 178°C near its base. To date, this is the highest temperature recorded in the field.

The full lateral and vertical extent of the vapor-dominated cap has not yet been defined by drilling. Self potential anomalies, low electrical resistivities, (Ross et al., 1997) and the distribution of steam entries in the production wells suggest that it could underlie much of the western half of the area shown in Figure 1.

GEOCHEMISTRY

Only two of the wells that have been drilled, P-91-4 and 42-7, have yielded samples of the reservoir liquid. The initial chemistry of waters discharged from these wells is listed in Table 1. Both wells produced a dilute sodium chloride liquid. The compositions of the early steam from the five steam producers are listed in Table 2. Geothermometer temperatures calculated from the water analyses are also listed in Table 1. Although the NaK temperatures (Giggenbach, 1988) are similar, the NaKCa (Fournier and Truesdell, 1973) and K-Mg (Giggenbach, 1988) temperatures differ by 10^o and 28^oC, respectively. Therefore it appears possible that the two waters originated in the same high-temperature reservoir and have subsequently re-equilibrated after leaving that reservoir.

Table 1. Chemical compositions of the water wells. Temperatures are in degrees Celsius.

	P-91-4 1/17/96	**42-7 1982**
Na	1143	1241
K	220	254
Ca	96	51
Mg	9	5
SiO_2	165	237
B	10	10
Li	5	5
Sr	4	2
HCO_3	201	100
Cl	1691	1639
F	6	6
SO_4	393	332
pH	6.0	
Na-K-Ca^1	244	258
Quartz^2	167	192
K-Na^3	291	297
K-Mg^3	158	175
Chalcedony^4	144	173
T measured	163	178

(1) Fournier and Truesdell (1973)
(2) Fournier and Potter (1982)
(3) Giggenbach (1988)
(4) Fournier (1981)

Table 2. Gas composition of the water well (P-91-4) and early production compositions of the five steam wells. Concentrations are in parts per million by weight. G/S is the gas to steam ratio in ppm and Air is the STP mls of air contained in the sample. See Figure 1 for complete well designations.

	P-91-4	Clara	Linda	Loretta	Mary	Olga
Date	1/99	10/90	5/86	10/90	10/90	05/86
G/S	934	14000	107145	30000	30900	65250
Air	0.27	20	3	2	2	3
H_20	999000	986000	893000	970000	969000	935000
CO_2	901	13900	106000	29800	30400	64600
H_2S	24.3	102	1170	185	337	453
NH_3	3.02	0	5.47	8.91	6.79	7.8
Ar	0.125	0	4.26	0.51	5.06	5.09
N_2	5.7	1.86	147	19.3	169	189
CH_4	<1.28	0.75	14.8	<0.67	1.6	2.56
H_2	<1.47	0.33	2.35	0.45	0.57	1.19

The gas composition of the reservoir water from P-91-4 is within the normal range of a low-to moderate-temperature geothermal field when compared to compilations such as those of Arnorsson and Gunnlaugsson (1985). Furthermore, the composition of the gas and the pH of the water indicate that water from P-91-4 has not boiled to produce the steam that formed the steam cap. Recent samples of P-91-4 water indicate that the pH and composition of the fluids has not changed significantly, despite several years of production.

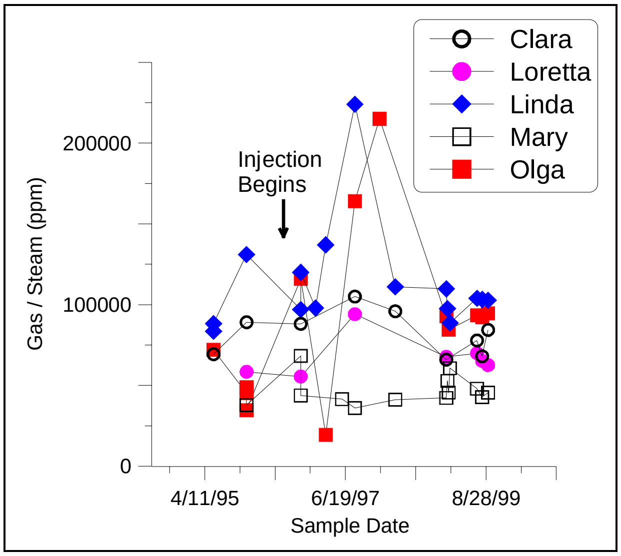

Fig. 2. Gas/steam ratios of the steam wells in ppm.

The composition of the steam, like that of the liquid, has remained relatively stable although there are systematic differences in the gas/steam ratios across the field. Figure 2 shows that the gas/steam ratio decreases from Linda and Olga to Mary as the sulfur pit is approached and the depth to the top of the steam cap decreases. Figure 2 also shows that there have been transient changes in the gas/steam ratios of the produced steam and that these ratios increased shortly after injection began in mid 1996. This is most apparent in the data from Linda and Olga. The cause of this change is uncertain; however, recent sampling indicates that the gas/steam ratios have declined and stabilized to pre-injection levels.

The steam and water discharged from the wells appear to be primarily meteoric in origin. The molar N_2/Ar ratios of the steam and water range from 35 to 85 and average 52, similar to air-saturated water. The stable isotope compositions of water from P-91-4 and two of the steam wells bracket the composition expected from the global meteoric water line, with less than one per mil oxygen shift (Table 3). A meteoric origin is consistent with the helium isotopic compositions listed in Table 4. These values, which range from 0.62 to 0.77 Ra, are similar to those found in other geothermal systems from the center of the Basin and Range that show no evidence of an association with recent magmatic activity (e.g., the Beowawe geothermal system; Welhan et al., 1988).

Table 3. Stable isotope compositions of selected waters from Cove Fort. The waters were sampled and analyzed in early 1997.

Well	Delta 18-O	Delta D
Linda (condensate)	-19.6	-135
Olga (condensate)	-19.7	-137
P-91-4 (total flow)	-15.1	-123

Although the water is clearly of meteoric origin, the tritium concentration of the steam, 0.16 TU, is very low, demonstrating that the water was exposed to the atmosphere more than 50 years ago (i.e., pre-bomb). Similar values have been found at the Coso geothermal system (Adams et al., 2000).

Table 4. ^{3}He/^{4}He isotopic ratios from four of the steam wells. Data from Tonani et al. (1998).

Well	^{3}He/^{4}He (Ra)
Clara	0.62
Linda	0.62
Loretta	0.66
Mary	0.77

TRACER TEST DESCRIPTION

Two hundred kilograms each of the liquid tracer fluorescein and the vapor-phase tracer R-134a were simultaneously injected into well 42-7 on January 14, 1999. Fluorescein was injected over a period of approximately 20 minutes. This was followed immediately by injection of R-134a over a four hour period.

Analysis of R-134a was performed by gas chromatography (GC) following a gas enrichment procedure. A megabore porous polymer capillary column was used to separate the tracers from each other and potentially interfering compounds and a modified Halogen-Specific Detector (HSD) was used for detection. Fluorescein was analyzed using a spectrofluorometer after adjusting the pH of the samples to >8.

The wells were sampled on the day of injection, then once per week for four months, and at least monthly thereafter**.** The vapor-phase tracer was detected in the third round of sampling, two weeks after injection (Fig. 3). Within a month, all five wells were producing concentrations of R-134a well above the detection limit of approximately 10 ppt. The concentrations of R-134a have continued to rise, reaching values as high as 7 ppb 10 months after injection. As of November, 1999, the concentrations of R-134a had not yet begun to decline. Water from P-91-4 has been analyzed for fluorescein at least bimonthly since injection, but to date none has been found. The half-life of fluorescein and R-134a at these temperatures are 50 (Adams and Davis, 1991) and 355 years (Adams and Kilbourn, 2000), respectively. Because of the large amount of fluorescein that was injected and the low detection limits (5 ppt), it will be detected even if it takes several years for the injected liquid to arrive at P-91-4.

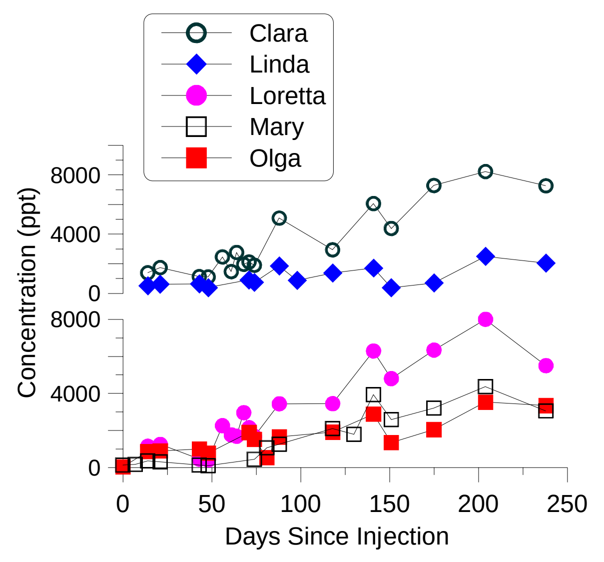

Figure 3. Steam well recovery curves for R-134a. For clarity, the data for Clara and Linda are shown on the upper graph.

DISCUSSION

The Cove Fort-Sulphurdale geothermal field is unique because production comes from both a naturally developed parasitic vapor cap and the underlying liquid-dominated reservoir. Other geothermal systems are either liquid or vapor-dominated and produce solely from the predominant phase. The return curves from the tracer test reflect this uniqueness. They have been rising for nearly a year and have not yet reached their peak (Fig. 3).

At The Geysers, the shape of the tracer return profiles can be related to the degree of depressurization, or depletion, of the reservoir (Beall et al., 1994). Regions that are extensively depleted have shown rapid tracer returns. In contrast, tracer return curves from areas that are less depleted display broader peaks, reflecting dispersion of the tracer in the longer flow paths of the liquid injectate prior to boiling. Like some tests conducted at The Geysers, tracer was detected shortly after injection, within two weeks. However, the return curves at Cove Fort-Sulphurdale are already four times as long as any from The Geysers and they have not yet peaked.

The contrast between the early first arrival of the gas tracer and the extremely long period of increasing tracer concentrations may be related to the northern boundary of the steam cap (Fig. 1). The geophysical data suggest that the steam cap intersects a fault very close to the injection well. If that fault carries only a small part of the total flow from a slowly-moving liquid injection plume, it would explain the slow tracer returns. This path is apparently most directly connected to Clara and Loretta, as tracer concentrations have remained consistently higher in these wells even though they are not the deepest or the closest to the injector. This explanation is bolstered by the low fraction of injected tracer that has been recovered to date, approximately one kilogram out of the 200 kg injected. A mechanism of this sort suggests that the majority of the flow has not yet encountered the steam cap, and that the bulk of the tracer may arrive at a later date by a different route.

CONCLUSIONS

Investigations of the Cove Fort-Sulphurdale geothermal system are providing a unique opportunity to analyze reservoir and tracer behavior in a moderate-temperature field producing dry steam from a parasitic vapor cap and liquid water from the underlying liquid reservoir. Analyses of the steam and liquid indicate that their compositions have remained relatively stable since production began in 1985. A tracer test was conducted in January, 1999, to evaluate the movement of steam and liquid and the effects of injection. Liquid (fluorescein) and vapor-phase (R-134a) tracers were injected at a depth below the producing horizons. R-134a was detected in all of the steam wells two weeks after injection. However, in contrast to tracer profiles from the vapor-dominated system at The Geysers, which typically show short duration spikes in tracer returns, concentrations of R-134a at Cove Fort-Sulphurdale have progressively increased during the last 10 months. Less than 1% of the R-134a and no fluorescein has been recovered to date. These results suggest that the early tracer returns have come from a location where the reservoir taps a small fraction of the slowly-moving liquid injection flow close to the injection well, and that the rest of the tracer may arrive later, and by a different route.

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REFERENCES

Adams M. C. and Davis J. (1991) Kinetics of fluorescein decay and its application as a geothermal tracer. *Geothermics* **20**, 53-66.

Adams M. C. and Kilbourn P. M. (2000) Thermal stability of the vapor-phase tracer R-134a. *Twenty-Fifth Workshop on Geothermal Reservoir Engineering*, in press.

Adams M. C., Moore J. N., Bjornstad S., and Norman D. I. (2000) Geologic history of the Coso geothermal system. *World Geothermal Congress*, in press.

Arnorsson S. and Gunnlaugsson E. (1985) New gas geothermometers for geothermal exploration - calibration and application. *Geochimica et Cosmochimica Acta* **49**, 1307-1325.

Beall J. J., Adams M. C., and Hirtz P. N. (1994) R-13 tracing of injection in The Geysers. *Transactions, Geothermal Resources Council* **18**, 151-159.

Fournier R. O. (1981) Application of water geochemistry to geothermal exploration and reservoir engineering. In *Geothermal Systems: Principles and Case Histories* (ed. L. Rybach, and Muffler, L. J. P.), pp. 109-143. John Wiley & Sons.

Fournier R. O. and Potter R. W., II. (1982) A revised and expanded silica [quartz] geothermometer. *Geothermal Resources Council Bulletin* **11**(10), 3-12.

Fournier R. O. and Truesdell A. H. (1973) An empirical Na-K-Ca geothermometer for natural waters. *Geochimica et Cosmochimica Acta* **37**, 1255-1275.

Giggenbach W. F. (1988) Geothermal solute equilibria, derivation of Na-K-Mg-Ca geoindicators. *Geochimica et Cosmochimica Acta* **52**, 2749-2765.

Ross H. P., Blackett R. E., and Sperry T. L. (1997) Self-potential and electrical resistivity studies of the Cove Fort-Sulphurdale geothermal system, Utah. *Geothermal Resources Council Transactions* **21**, 225-261.

Ross H. R. and Moore J. Njoe. (1985) Geophysical investigations of the Cove Fort-Sulphurdale geothermal system, Utah. *Geophysics* **50**, 1732-1745.

Steven T. A. and Morris H. T. (1981) Geologic map of the Cove Fort quadrangle, west-central Utah. U. S. Geologic Survey, Open-file Report 79-535.

Tonani F., Nagao K., Moore J., Natale G., and Sperry T. (1998) Water and gas geochemistry of the Cove Fort-Sulphurdale geothermal system. *Twenty-Third Workshop on Geothermal Reservoir Engineering*, 180-187.

Welhan J. A., Poreda R. J., Rison W., and Craig H. (1988) Helium isotopes in geothermal and volcanic gases of the western United States, I. Regional variability and magmatic origin. *J. Volcanology and Geothermal Research* **34**, 185-189.