

Update on Production Chemistry of the Roosevelt Hot Springs Reservoir

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ABSTRACT

Analyses of production fluids from the Roosevelt Hot Springs reservoir were acquired from well sampling campaigns in 2015 and 2016. The resulting data have been recalculated to reservoir conditions by correcting for effects of steam loss, and the values are compared to legacy data from earlier reports to quantify changes with time in response to fluid production. The reservoir composition is similar to that at the start of reservoir exploitation, having near neutral pH, total dissolved solids of 7000-10,000 mg/kg, and ionic ratios of Cl/HCO₃ ~50-100, Cl/SO₄ ~50-100, and Na/K ~4-5. Cation, gas and silica geothermometers indicate a range of equilibration temperatures between 240 and 300 °C, but quartz-silica values are most closely consistent with measured reservoir temperatures and well enthalpies.

The largest change in fluid composition is observed in well 54-3. The fluid has evolved from being fed by a single phase liquid to a two-phase mixture of steam and liquid due to pressure draw down. The fluid also shows a 25% increase in reservoir chloride and a ~20° C decrement of cooling related to mixing with injected brine. The other production wells also show increase in chloride and decrease in temperature, but these changes diminish in magnitude with distance from injection well 14-2.

Stable isotope compositions indicate that the reservoir water is largely meteoric in origin, having been modified by hydrothermal water-rock interaction. The water has also become progressively enriched in isotopic values in response to steam loss and mixing of injectate. N₂-Ar-He and helium isotope ratios indicate a deep magmatic source region that probably supplies the heat for the hydrothermal system, consistent with recent Quaternary volcanism in the Mineral Mountains.

1. INTRODUCTION

Roosevelt Hot Springs is a high temperature geothermal resource located on the western flank of the Mineral Mountains, approximately 20 kilometers northeast of Milford, in southwestern Utah (Fig. 1). The elongate production field covers an area <2 km², and it is situated east of and subparallel to the Opal Mound fault. The resource is the largest of the three relatively closely spaced geothermal fields in southwestern Utah (Fig. 1), and it is one of the few geothermal systems in the western USA entirely hosted by fractured crystalline rock. The reservoir rocks consist of Miocene age granitic rocks that make up the core of the Mineral Mountains and that intruded Precambrian gneiss and schist (e.g. Capuano and Cole, 1982; Nielson et al., 1986; Coleman and Walker, 1992; Coleman et al., 1997; Simmons et al., 2016). Modern hydrothermal activity appears to be associated with recent magmatism that produced rhyolitic flow dome complexes (0.8 to 0.5 Ma), which includes the Bailey's ridge located only 2-3 km east of the steamfield (Lipman et al., 1978; Moore and Nielson, 1994). Exploration drilling (1975-1984) proved a maximum reservoir temperature of ~265° C at >600 m depth (Faulder, 1991, 1994; Allis and Larsen, 2012), and production commenced in 1984, with the commissioning of the Blundell flash plant (23MWe net single-stage). Additional generation was installed in 2006 by commissioning of a bottom cycle binary plant (10 MWe net).

Capuano and Cole (1982) provided the first description and interpretation of reservoir fluid chemistry and fluid-mineral equilibria based on data collected before full scale field production commenced. In the intervening years, information regarding production-induced effects have been limited to physical parameters, including temperature and pressure (Faulder, 1991; 1994; Yearsley, 1994; Allis and Larsen, 2012). This report summarizes new water and gas data obtained from production wells in 2015 and 2016 in support of several DOE sponsored projects, including most notably work on strategic and critical metals in produced fluids and the nearby Utah FORGE site. The main purpose is to characterize the modern reservoir fluid composition and to describe their evolution in response to production.

2. SAMPLES & ANALYSES

Fluid samples were collected from all four production wells. Steam and brine were collected from the two-phase pipeline on wells 28-3 and 45-3, using a mini-separator attached to a horizontal port. Wells 54-3 and 13-10 lacked suitable sampling ports on the two-phase lines, and instead samples of brine were obtained from stainless steel capillary tubing; these capillary tubes tap into the brine line downstream of the separator and provide continuous streams of conductively cooled reservoir brine. Aliquots of brine were filtered and acidified in the field and stored in high-density polyethylene bottles, whereas untreated brines were stored in glass bottles for alkalinity, pH, and stable isotope analyses. Steam samples were collected separately in evacuated glass bottles partially filled with sodium hydroxide (NaOH).

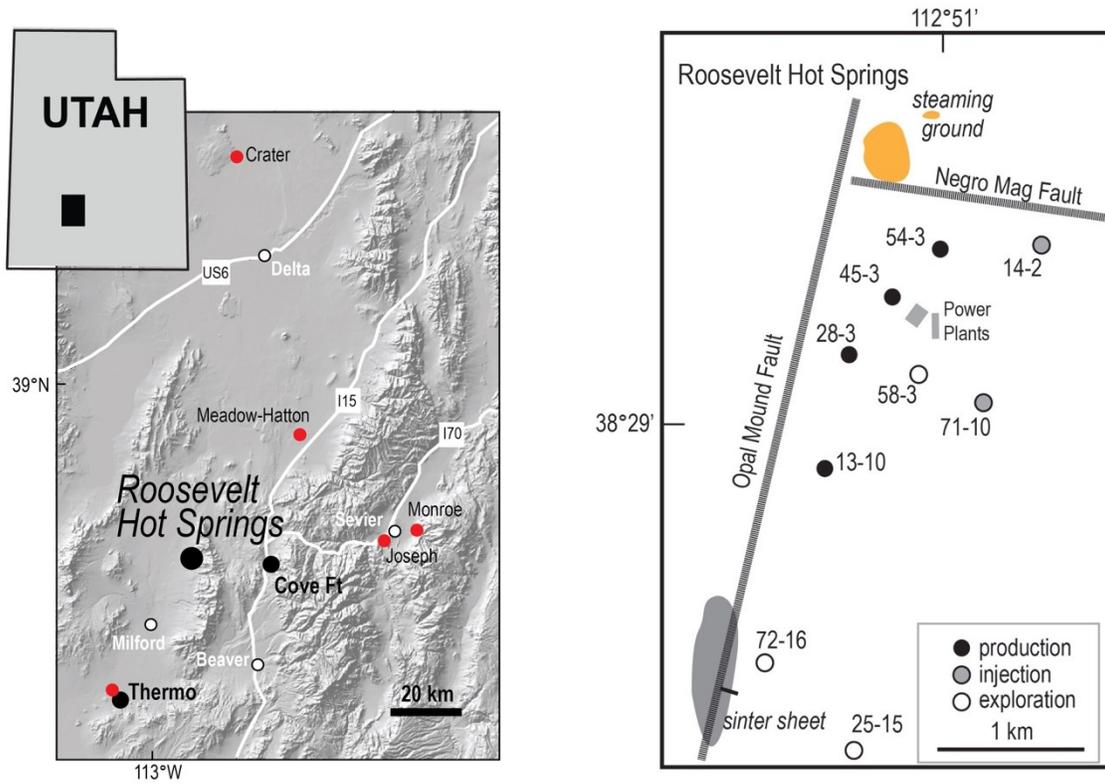


Figure 1. Regional setting of Roosevelt Hot Springs (map left), nearby geothermal production fields (Cove Fort, 25 MWe; Thermo, 10 MWe) and hot springs (red-filled circles). The production field at Roosevelt Hot Springs (map right) shows production, injection and exploration wells, and the locations of the major fault structures. The steaming ground represents modern surface activity; the sinter sheet at the south end of the Opal Mound fault represents paleo-surface activity about 1900 years ago (Lynne et al., 2005).

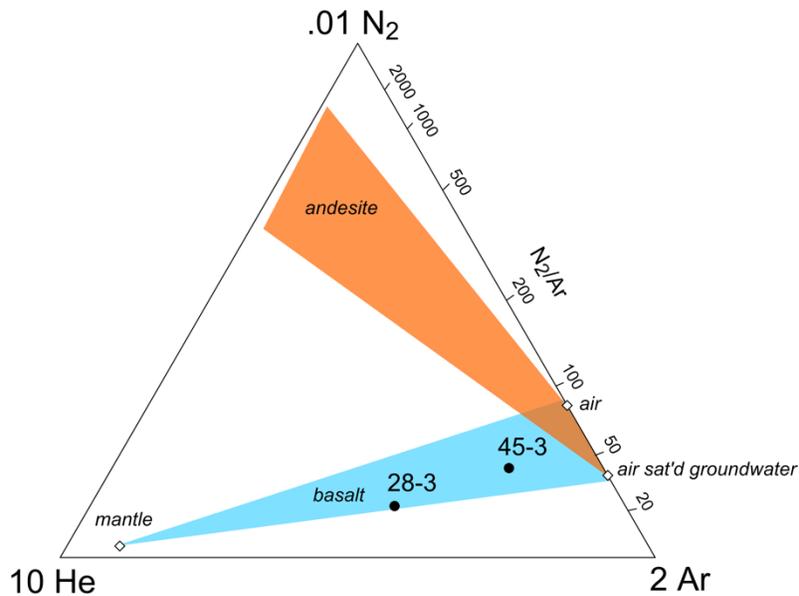


Figure 2. Trilinear plot showing the N₂-Ar-He compositions of gas samples collected in 2016 from wells 28-3 and 45-3. The basalt and andesite fields are based on Giggenbach (1997).

Aqueous samples were analyzed for major, minor and trace aqueous species at the Winchell School of Earth Sciences, University of Minnesota. Gas samples collected in 2015 were analyzed by Thermochem, whereas gas samples collected in 2016 were analyzed at the Department of Earth and Planetary Sciences, University of New Mexico. Untreated aqueous samples were analyzed for pH and alkalinity at the Utah Department of Health lab and for oxygen and hydrogen isotopes at the SIRFER lab, University of Utah. Helium isotopes were analyzed on samples of brine collected in copper tubes in the noble gas laboratory, Department of Geology and Geophysics, University of Utah. The separation pressures and mass flows of the wells were used to calculate well enthalpies. A summary of the results is presented in Table 1 and in Figures 2, 3 and 4.

3. RESERVOIR COMPOSITIONS

To make the analytical results useful for understanding reservoir conditions, the values reported in Table 1 are recalculated to reservoir conditions assuming fluid entered the well at a deep level and as a single phase liquid. Reservoir compositions are determined from the heat and mass balance expressions based on well enthalpy and sampling pressure (e.g. Henley et al., 1984). To check the validity of this approach, the enthalpies determined from quartz-silica temperature ($H_{T\text{-qtz}}$ kJ/kg) are presented in Table 1. Although there is some variation, generally with $H_{T\text{-qtz}}$ kJ/kg > H kJ/kg, the results are reasonably close and differ by less than 10%. The main exception arises in the 2015 and 2016 data for 54-3, which is discussed in further detail below.

In general, the production fluid compositions are similar to those at the start of reservoir exploitation, having near neutral pH, total dissolved solids of 7000-10,000 mg/kg, and ionic ratios of $\text{Cl}/\text{HCO}_3^- \sim 50\text{-}100$, $\text{Cl}/\text{SO}_4 \sim 50\text{-}100$, and $\text{Na}/\text{K} \sim 4\text{-}5$. The quartz-silica equilibrium temperatures (Fournier, 1991) range 240-260 °C, having values that are consistent with measured reservoir temperatures. The Na-K equilibration temperatures (Giggenbach, 1988) range from 270 to 310°C, which conceivably reflects thermal conditions in the deep part (>3 km?) of the upflow zone. The availability of gas analytical data permits application of the H_2/Ar and CO_2/Ar geothermometers (Giggenbach, 1991), which, for 2015, give equilibration temperatures of ~250 and 310°C and, for 2016, equilibration temperatures of ~190-200°C and 250-270°C, respectively. Analytical results for $\text{N}_2\text{-Ar-He}$ (2016 only) imply derivation from a deep mafic magmatic source region (Fig. 2), which is compatible with regional occurrence of mafic volcanic centers and R/Ra helium isotope values of 2.1-2.2 (Table 1); note, Kennedy and van Soest (2007) also reported R/Ra~2.2, based on a sample from surface thermal activity, presumably from the steaming ground north of the production field (Fig. 1).

Table 1. Well enthalpies (H kJ/kg), fluid compositions calculated to reservoir conditions (mg/kg), and equilibration temperatures for produced fluids from Roosevelt Hot Springs (Bowman and Rohrs, 1981; Capuano and Cole, 1982; unpublished data Intermountain Geothermal Company, this study).

Well no	pH (lab)	H kJ/kg	SiO ₂	Cl	CO ₂	δ ¹⁸ O ‰	δ D ‰	R/Ra	T Na/K	T qtz-SiO ₂	H T-qtz kJ/kg
<i>1977-1979</i>											
14-2	5.90	1160	670	2990		-14.1	-116.9		285	281	1242
54-3	?	1160	500	3435					294	253	1100
72-16	7.83	1047	480	2890					300	249	1080
<i>1991-1992</i>											
54-3	7.9	1097	518	3879	942				273	256	1115
45-3	7.7	1076	504	3626	1898				306	253	1100
28-3	8.4	1067	519	3503	886				309	256	1115
13-10	7.7	1071	501	3243	2396				312	253	1100
<i>2015</i>											
54-3	7.07	1305	453*	4311*		-11.5	-108.5		288	244	1057
45-3	7.66	1043	531	4184	913	-12.0	-111.6	2.19	294	258	1125
28-3	8.18	994	530	3677	304	-12.5	-113.2	2.09	298	258	1125
13-10	7.98	1080	486	3144		-12.9	-114.2		301	250	1086
<i>2016</i>											
54-3	7.33	1212	459*	4362*		-11.4	-107.5		304	245	1062
45-3	7.82	1042	490	4280	681	-12.0	-110.3		307	251	1091
28-3	8.34	996	500	3800	414	-12.4	-111.1		309	252	1095
13-10	7.92	1015	467	3330		-12.6	-111.4		312	246	1066

*corrected for excess steam

3.1 Well 54-3

The change in well enthalpy from an initial value of 1160 to 1305 kJ/kg by 2015, implies a change in the reservoir fluid feeding the well from a single-phase liquid to a two-phase mixture of liquid and steam. These changes are consistent with production-induced reservoir pressure drop and expansion of a shallow steam zone over the last 30 years (Yearsley, 1994; Allis and Larsen, 2012). To correct for the excess steam in calculating a reservoir composition, we assume that quartz controls silica concentration as a function of temperature in the reservoir liquid. Heat and mass balance expressions are then solved simultaneously to determine the mass fraction of excess steam in the reservoir. The calculations are simplified by the fact that the enthalpy of steam in the temperature range 200-300° C is between 2750 and 2800 kJ/kg. Calculations for both the 2015 and 2016 data yield reservoir silica concentrations that correspond with a quartz-silica equilibrium temperature close to 245° C (Table 1). Accepting this to represent the brine reservoir temperature feeding the well, the 2015 reservoir fluid comprised 86% brine and 14% steam, whereas in 2016 the fluid comprised 91% brine and 9% steam. For comparison, a 2010 temperature-pressure survey gave a maximum temperature of 254° C (Allis and Larsen, 2012).

3.2 Oxygen and Hydrogen Isotopes

The reservoir compositions of stable isotopes were calculated using heat and mass balance expressions and equilibrium fractionation factors between steam and liquid (Giggenbach and Stewart, 1982; Henley et al., 1984). The results are plotted in Figure 3. Also shown is the composition of spring waters in the Mineral Mountains, which plot close to the meteoric water line.

The preproduction reservoir composition is constrained by the value for well 14-2 on a sample collected in 1978. Extending to the right and upward from this value is a grey line that shows the trajectory of the liquid water composition due to single-step adiabatic steam loss for decrements of cooling in the range of 260 to 100° C (Giggenbach and Stewart, 1982). The 2015 and 2016 datasets mimic this curve. The progressive enrichment in isotopic composition in the values for 13-10, 28-3, 45-3, and 54-10 signifies increasing proportion of steam loss, with 13-10 being the least affected and 54-3 being the most affected. The data also reflect varying amounts of mixing with flashed injectate, and this explains why the reservoir compositions have shifted to more enriched isotopic values over time.

The thermal water produced from the Roosevelt Hot Springs reservoir has heavier $\delta^{18}\text{O}$, but lighter δD values compared to the modern cold spring waters in the Mineral Mountains. Thus the reservoir thermal water likely reflects deeply circulated meteoric water that has been made heavier in $\delta^{18}\text{O}$ in response to long-term water-rock interaction (e.g. Craig, 1963). Given the helium data indicating the presence of deep magma, it is possible that a small component of magmatic derived water is present in the Roosevelt Hot Springs reservoir fluid. If true, then the δD composition of meteoric water supplying the system must have been lighter in value than the composition represented by 14-2 (see Giggenbach, 1992). The main conclusion is that modern day ground waters are measurably different from the meteoric water feeding the system during much earlier phases of hydrothermal activity.

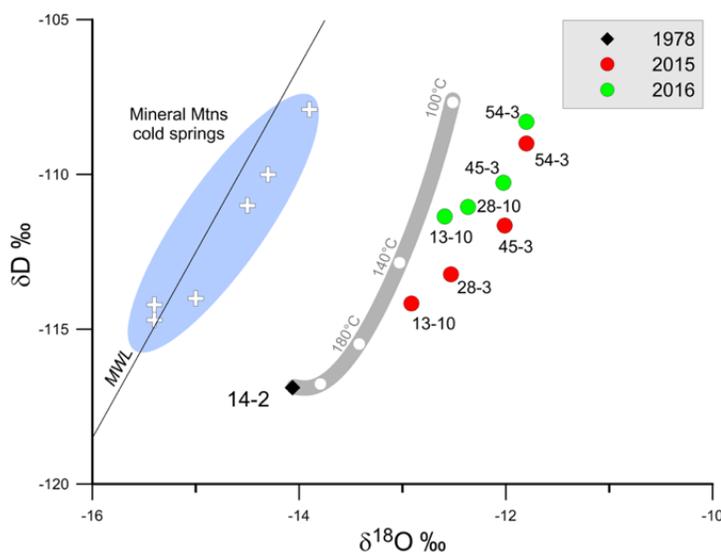


Figure 3. The stable isotope compositions of produced waters, corrected for steam-loss, from Roosevelt Hot Springs. The values for 14-2 most closely represent the preproduction composition of the deep reservoir liquid. The compositions of Mineral Mountains cold springs (Bowman and Rohrs, 1981; this study) plot close to the global meteoric water line (MWL). The grey curved line represents the evolution of the isotopic composition of water in response to single step, adiabatic flashing from 260 to 100 °C (Giggenbach and Stewart, 1982).

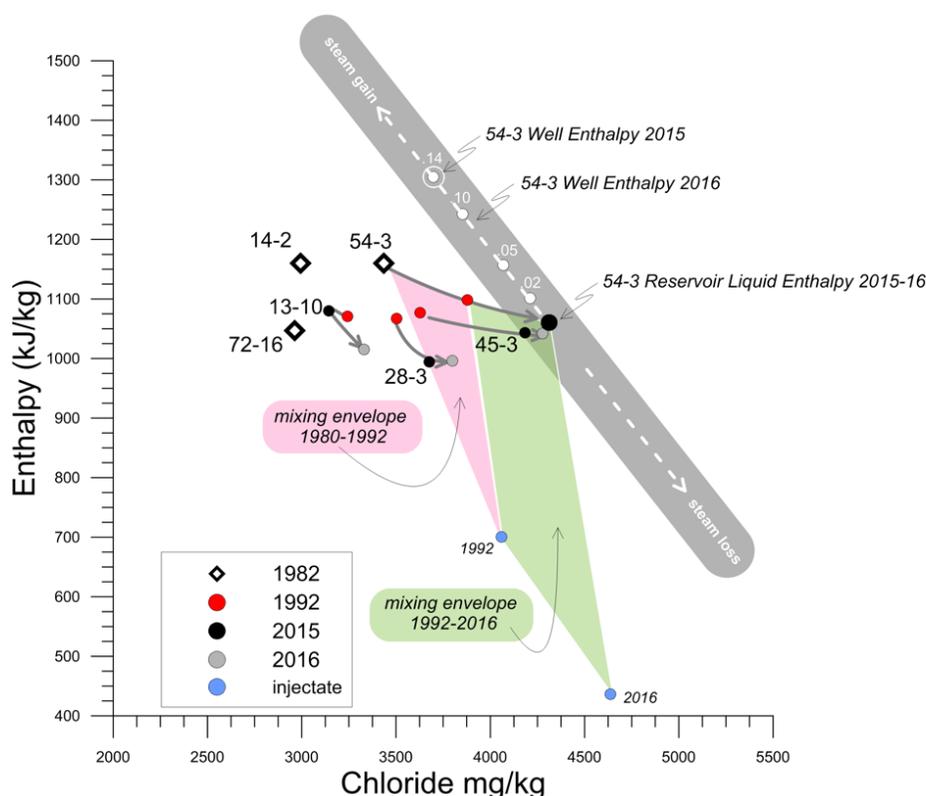


Figure 4. Chloride-enthalpy plot showing the evolution of production fluids in response to injection, mixing, and boiling. The 1992 production and injectate fluid compositions come from an unpublished report by Intermountain Geothermal Company. Grey bold line represents the trend for steam-loss and steam gain. Note the positions of 54-3 well enthalpies for 2015 and 2016 are higher than those interpreted for deep fluids entering the well; see text for discussion.

4. CHLORIDE-ENTHALPY TRENDS

The heat and mass transfer effects induced by production can be interpreted from trends in chloride and enthalpy (Fig. 4). Before production began, the reservoir fluid had a chloride composition of 3000-3500 mg/kg and an enthalpy of 1050 to 1160 kJ/kg. By their proximity to one another, 14-2 and 54-3 represent the hottest and least diluted liquid in the reservoir, corresponding to the central upflow zone of the system, whereas 72-16, having cooler enthalpy, is closer to the periphery of the upflow zone (Capuano and Cole, 1982).

By 1992, the reservoir fluid composition is modified, mostly by inmixing of injectate from 14-2, which has a low enthalpy and a high chloride concentration compared to the original deep upflow water. This effect is observed in the change in 54-3 to higher chloride and lower enthalpy. Data for 13-10, 28-3, and 45-3 first appear in this time period.

The 2015-2016 datasets reflect continuous inmixing of injectate, probably mostly from 14-2 with possibly some coming from 71-10. The least modified fluid is represented by 13-10, with measurable increase in chloride and decrease in enthalpy detected between 2015 and 2016. Going northward, wells 28-3, 45-3 and 54-3 show progressively increasing concentrations of chloride due to increasing inmixing of injectate, which by now had much lower enthalpy due to energy production from the binary plant. The wellhead enthalpies of 54-3 show too that the fluid feeding this well comprised a mixture of steam and liquid. This represents a change from a single-phase liquid feed condition that is consistent with the field-wide pressure drop and expansion of the shallow steam zone, which initiated early in the history of production (Yearsley, 1994; Allis and Larsen, 2012). The decrease in 54-3 enthalpy, from 2015 to 2016, implies that the proportion steam in the reservoir diminished.

5. CONCLUDING REMARKS

The results of this work show that the modern compositions of well fluids can be related to spatial and temporal changes induced by production. These effects include increase in chloride due to inmixing of injectate, modest reservoir cooling from an initial temperature of 265 to 235-245° C, and localized development of two-phase conditions in the reservoir. While pressure drawdown was observed across the field (Allis and Larsen, 2012), the systematic variation in Cl is consistent with differences in distance from the main injection well 14-2. Restricted lateral flow imposed by sub-vertical fracture permeability might explain localized two-phase conditions in the vicinity of 54-3, and baffled flow may have protected 13-10 from change in fluid character until recently. The most significant flow barrier is represented by the Opal Mound fault, which forms the western boundary to the Roosevelt Hot Springs reservoir and prevents deep lateral flow of hot water, the only leakage being near the surface and north of intersection between the Opal Mound and Negro Mag faults (Vuataz and Goff, 1987; Allis et al. 2016; Simmons et al., 2016).

6. ACKNOWLEDGMENTS

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