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NEW EVIDENCE FOR A MAGMATIC ORIGIN OF SOME GASES IN THE GEYSERS GEOTHERMAL RESERVOIR

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ABSTRACT

The Geysers vapor-dominated geothermal reservoir is known to have a wide range of gas concentrations in steam (<100 to >75,000 ppmw), but the variations in gas compositions and the origin of the gases have been little studied. Low gas concentrations and steam isotopes similar to meteoric waters are found in the SE Geysers, but steam high in gas and HCl from a high temperature reservoir (HTR) in the NW Geysers has been thought to be related to metamorphic or magmatic brine. New analyses of noble gas isotopes show that the highest gas steam from the HTR has high $^3He/^4He$ (8.3 Ra), and very low ^{36}Ar and radiogenic $^{40}Ar/^4He$, indicating a strong magmatic component and essentially no atmospheric or crustal noble gases. Other samples from the HTR show various amounts of atmospheric dilution of the magmatic gas and lower HCl and total gas contents. The occurrence of steam in the NW Geysers highly enriched in heavy isotopes of oxygen and hydrogen supports the indications of remnant magmatic fluid. The existence of this fluid strongly suggests that the HTR was formed by rapid heating and catastrophic boiling resulting from injection of magma.

INTRODUCTION

Geothermal reservoir gases have been less studied than geothermal reservoir waters because there are fewer well-characterized "geothermometric" reactions among gas constituents. Recently there has been increased interest in gases because it has been discovered that isotopes of stable noble gases (He, Ne, Ar, Kr and Xe) provide long lasting tracers of the source of deep fluids originating in the mantle as well as shallower fluids of crustal and atmospheric origin (Lupton, 1983; Kennedy et al., 1985). In vapor-dominated systems such as The Geysers and Larderello, wells produce only steam without liquid so the isotopes of water and the chemical and isotopic composition of the accompanying gases provide the only geochemical indications of reservoir processes and fluid origins. At The Geysers water isotopes have been widely used to trace return of injected condensate and gas equilibrium calculations have been used to indicate reservoir temperatures and to provide indications of original liquid saturation.

The extraordinary high-temperature reservoir in the NW Geysers, containing steam with high $\delta^{18}O$, high gas and high HCl (Walters et al., 1988), has been considered to originate from rapid pressure decrease causing boil down of a hot water reservoir containing connate marine brines (Shook, this meeting) or to rapid temperature increase from injection of magma (Truesdell et al., 1993). The high gas and HCl in the high-temperature reservoir have made exploitation difficult and it is a matter of some importance to discover whether the HTR extends under the normal reservoir further south in The Geysers and will contribute steam high in HCl and gas to production as pressures are depleted.. For this reason a joint study has been undertaken by the Lawrence Berkeley Laboratory and the Geothermal Technology Organization. In this study noble gas isotopes and carbon isotopes in methane and carbon dioxide will be measured throughout The Geysers. The first results of noble gas isotope analyses of steam from the NW Geysers (Figure 1) are reported here and the implications of these results to the genetic model of The Geysers are discussed.

NOBLE GAS ISOTOPES AS TRACERS IN GEOTHERMAL SYSTEMS

Noble gases are conservative tracers constraining the sources, evolution, and migration of fluids in the crustal regime. Terrestrial noble gases are of two genetic types: those indigenous to the Earth, inherited from meteoritic material through accretion, and those produced since Earth formation by natural processes such as radioactive decay or nuclear interactions. In simple Earth models, these two genetic types are contained in three sources. The first is the mantle which, because it is believed to be partially or non-degassed, is enriched in the indigenous or primordial noble gas component. The second is the crust which, due to outgassing during crust formation, tends to be enriched in radiogenic and nucleogenic components. The third is the atmosphere/hydrosphere produced through the natural degassing of the solid earth and therefore containing integrated mixture of the other two sources. Each of these sources is characterized by a distinct and different elemental and isotopic composition. For instance, volatiles from mantle magmas are enriched in ^3He with $^3He/^4He$ ratios attaining values as high as 9 Ra (Ra is the $^3He/^4He$ ratio in air, 1.4×10^{-6}) at mid-

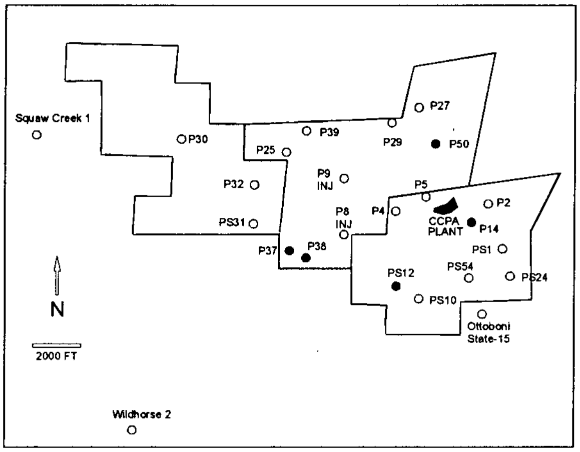

Figure 1. Locations of Coldwater Creek wells with noble gas compositions reported in Table 2 (filled circles).

ocean ridge (MOR) spreading centers, and 30 Ra associated with hotspot volcanism (e.g.- Hawaii, Yellowstone, Iceland), whereas volatiles derived from crustal sources far removed from any recent tectono-magmatic activity are enriched in radiogenic ^4He with $^3He/^4He$ ratios of 0.02 to 0.10 Ra. Origin of fluid contributions to a reservoir can, therefore, be readily identified through the occurrence of specific isotopic signatures.

Meteoric water is the primary source of atmospheric noble gases in crustal fluids, particularly in active geothermal systems. The solubility of noble gases in fresh water is known as a function of temperature up to and beyond the critical point and in brines at lower temperatures. Noble gas solubilities increase from He to Xe in a smooth, systematic fashion, facilitating multi-dimensional modeling of gas abundances. Henry's law (solubility) constants (partial pressure divided by the mole fraction in solution) are $>10^4$ bar. Their low solubility and conservative nature (low chemical reactivity) in geochemical systems make the noble gases especially adept detectors of processes such as phase separation and in favorable cases can be used to model the extent, path, and temperature of phase separation. Little is known of the inventory of atmospheric noble gases at The Geysers. It can be expected, however, that abundance variations can be used to model phase separation and fluid evolution and test fluid circulation models proposed on the basis of systematic variations of other geochemical and isotopic constituents. Furthermore assuming a uniform flux of magmatic ^3He from the underlying volcanic system, fieldwide variations in ratios of ^3He to atmospheric noble gases will provide a quantitative assessment of the influence of meteoric water.

In a preliminary survey of The Geysers geothermal field, Torgersen and Jenkins (1982) measured $^3He/^4He$ ratios of ~6-9.6 Ra, indicative of direct magmatic input from volcanic sources (Table 1 and Figure 2). Furthermore, the highest $^3He/^4He$ ratio (9.6 Ra) is on the high side of MOR values and implies an active magma beneath The Geysers. At the time of this survey the high-temperature reservoir had not yet been discovered, but one of their sampled wells (Ottoboni State 15) is in the NW Geysers.

VARIATION OF NOBLE GAS ISOTOPES IN THE NW GEYSERS

Samples for noble gas studies, were collected from selected wells of the Coldwater Creek Steamfield (Figure 1) owned and operated by the Central California Power Agency No.1 (CCPA). Dry gases for noble gas analyses were collected in copper tubes sealed by cold welds. The gases were prepared and analyzed in the RARGA (Roving Automated Rare Gas Analysis) laboratory of LBL. The results are presented in Table 2. Because of the method of analysis the isotope ratios relative to a standard are more exactly known than the absolute abundances. For this reason the "F notation" is used in which ratios to ^{36}Ar are normalized to air. In diagrams based on this notation, air plots at 1,1 and mixing between two components is linear. Table 2 also presents results in the delta notation as differences in parts per thousand from air. Finally the ratio, $^{40*}Ar/^4He$, in which $^{40*}Ar$ is radiogenic ^{40}Ar, is presented to show the degree of crustal influence.

Figure 3 shows the R/Ra values plotted against the ratio of $^{40*}Ar/^4He$. In this plot the linear relationship implies two component mixing. The end members are magmatic fluid (R/Ra ≥ 8.3 and $^{40*}Ar/^4He \leq 0.05$, consistent with a mid ocean ridge mantle source) and a second fluid enriched in crustal gas (R/Ra ≤ 6.5 and $^{40*}Ar/^4He > 0.25$). The highest R/Ra value is for steam from well Prati 37. This steam also has the lowest value of ^{36}Ar showing that there is almost no atmospheric influence. Note that steam samples from Prati 37 have had the highest total NC gas and highest HCl of the field (data from CCPA). On the basis of these analyses, the steam from this well has almost exclusively magmatic noble gases and possibly other magmatic gases as well, although these must have been modified by reaction with rock minerals. Nearby Prati 38 has lower R/Ra similar to other wells and much higher $^{40*}Ar/^4He$. This well has had maximum NCG about one fifth and HCl about one tenth of the maximum values for Prati 37, suggesting that the gradient of the magmatic gas was very sharp although the differences may recently have increased due to injectate return in Prati 38. All analyzed samples from wells to the west of Prati 37 are high in ^{36}Ar (Figure 4), indicating a large atmospheric component.

IMPLICATIONS FOR THE ORIGIN OF THE GEYSERS

The sharp boundary between strongly magmatic steam from Prati 37 and more ordinary steam to the west and

Table 1. Noble gas compositions of steam from The Geysers (Torgerson and Jenkins, 1982)

Well	Type	^{3}He/^{4}He E-6 cc/cc	He/Ne	R/Ra	R/Ra Ne corr.
McKinley-5	g	7.36	0.3	5.3	
CA956-2	g	9.95	>500	7.2	7.2
	c	9.50	2.3	6.9	7.7
unknown	g	13.11	28	9.5	9.6
	c	12.23	29	8.8	8.9
Ottoboni State-15	g	11.16	>500	8.1	8.1
	c	9.22	498	6.7	6.7
DX state-30	g	9.48		7.11	
	c	1.86	>4	1.34	1.37
Lakoma Fame-15	g	10.89	1.9	7.9	9.1
	c	11.88	>500	8.6	8.6
PDC-1	g	12.23	>500	8.8	8.8
	c	12.40	>500	9.0	9.0

Note: Sample type g, gas; c, condensate.

Table 2. Noble gas isotope compositions of steam from the NW Geysers (this study).

Sample	[36Ar] E-7 cc/cc*	[4He] E-7 cc/cc*	F(4He)	+/-	F(22Ne)	+/-	F(84Kr)	+/-	F(132Xe)	+/-
P14	0.7710	65.800	511.02	4.81	0.6178	0.0060	1.7069	0.0127	2.954	0.145
P37	0.3070	214.000	4168.07	107.61	0.8651	0.0411	1.5256	0.0874	2.895	0.638
P38	1.6000	110.800	414.30	3.90	0.6066	0.0059	1.5880	0.0113	2.588	0.124
P50	2.2650	57.960	153.24	1.44	0.4507	0.0036	1.6816	0.0115	2.630	0.129
PS12	0.8063	71.700	532.70	5.02	0.6021	0.0068	1.6676	0.0137	2.874	0.138
10°C ASW	13.3700$^{\#}$	0.484#	0.22		0.2722		1.9412		3.677	
80°C ASW	6.1600$^{\#}$	0.532#	0.52		0.4962		1.5227		2.274	
Air	316.070^{+}	52.784^{+}	1.00		1.000		1.000		1.000	

Notation: F(i) = [(i/36Ar)sample/(i/36Ar)air].
Notes: * ccSTP/ccNCgas, $^{\#}$ ccSTP/ccWater, $^{+}$ ccSTP/cc

Sample	R/Ra	+/-	Delta-20	+/-	Delta-21	+/-	Delta-38	+/-	Delta-40	+/-
P14	7.806	0.279	32.64	5.31	30.19	11.25	-4.92	5.42	52.10	7.80
P37	8.322	0.473	38.40	4.09	14.90	13.03	-10.68	6.91	159.79	11.99
P38	7.678	0.390	24.29	4.96	21.43	10.51	-0.96	5.41	31.34	8.02
P50	7.084	0.342	12.60	2.86	13.82	9.20	-3.80	5.06	21.50	5.70
PS12	7.165	0.379	18.00	3.77	30.13	11.48	-4.61	5.11	52.52	7.49

Notation: Delta i = 1000[(i)sample/(i)air-1].

Sample	40*Ar/4He	+/-
P14	0.1804	0.0271
P37	0.0678	0.0054
P38	0.1338	0.0343
P50	0.2483	0.0658
PS12	0.1745	0.0249

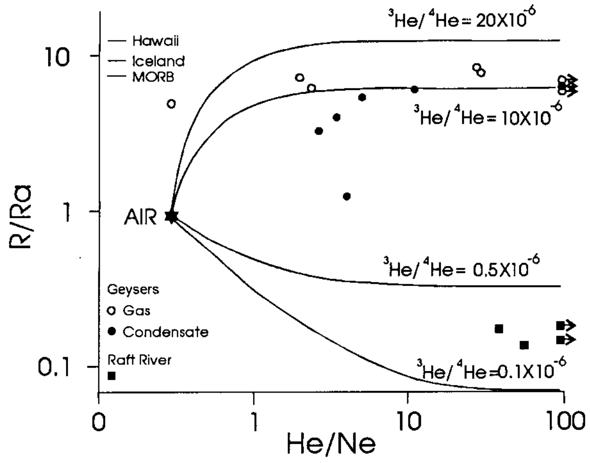

Figure 2. ^{3}He/^{4}He and Ne compositions of Geysers steam after Torgerson and Jenkins (1982). Their data for Raft River, a non-magmatic geothermal field are also shown.

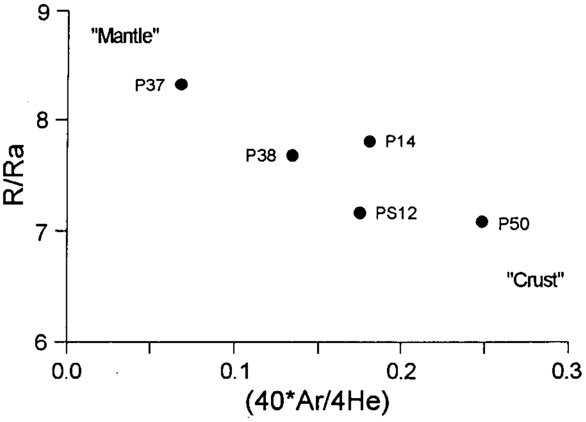

Figure 3. R/Ra plotted against 40*Ar/4He, an indicator of crustal influence

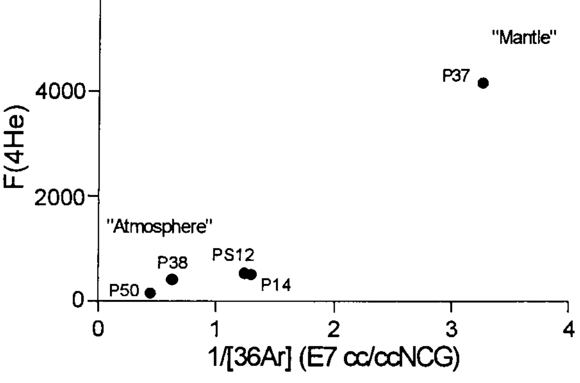

Figure 4. F(4He) plotted against 1/36Ar, an indicator of atmospheric influence.

northwest is a consequence of the lack of large scale convection in the high-temperature reservoir. This was pointed out by Truesdell et al. (1993) who hypothesized that there could be no saturated liquid layer at the bottom of the high temperature reservoir and that without such a layer, lateral steam flow within the reservoir could not occur.

In addition the existence of near-magmatic gas in the high-temperature reservoir argues against the formation of this reservoir by decompression of an earlier hot water reservoir. A hot water reservoir would most likely have been recharged by meteoric water bringing atmospheric gases into the reservoir and the strong boiling during decompression would have removed earlier formed magmatic gases. The formation of the high temperature reservoir by heating caused by massive emplacement of magma (as suggested by Truesdell, 1991) is in agreement with the persistence of magmatic gas. Heating and catastrophic boiling from this cause would have swept earlier atmospheric and crustal gases from the reservoir and replaced them with gases from the magma.

ISOTOPES OF OXYGEN AND HYDROGEN ALSO INDICATE MAGMATIC INFLUENCE

Fieldwide compilations of oxygen-18 and deuterium at The Geysers show a remarkably wide range from near meteoric values in the SE Geysers to $\delta^{18}O > 3$ permil and $\delta D > -40$ permil in the NW Geysers (Haizlip, 1985; Truesdell et al., 1987; Gunderson, 1989). These isotopically heavy steam compositions have been suggested to result from the evaporation of connate seawater or of "metamorphic" water similar to that found in coast range mineral springs. D'Amore and Bolognesi (1994) recently reinterpreted the same data and suggested that the originating water may have been subducted seawater carried in the downgoing slab. In this interpretation they have extended the idea originally proposed by Giggenbach (1992) for geothermal waters associated with andesitic volcanism. There is in fact little expected isotopic difference between seawater that has been buried for long periods at normal earth temperatures (i.e. connate) or at elevated temperatures (metamorphic) and seawater that has moved with igneous rock from a subduction zone to a near-surface magma chamber and thence into a geothermal reservoir. This idea gains credibility from the noble gas compositions and is generally consistent with magmatic influence. Figure 5 shows the data approximately as presented by D'Amore and Bolognesi (1994).

FUTURE DIRECTIONS

The analyses reported here cover a small part of The Geysers reservoir. We plan to enlarge our coverage as time and funds permit. We also plan to collect and analyze $\delta^{13}C$ in carbon dioxide and methane from much of the reservoir. The purpose of all of these analyses is to

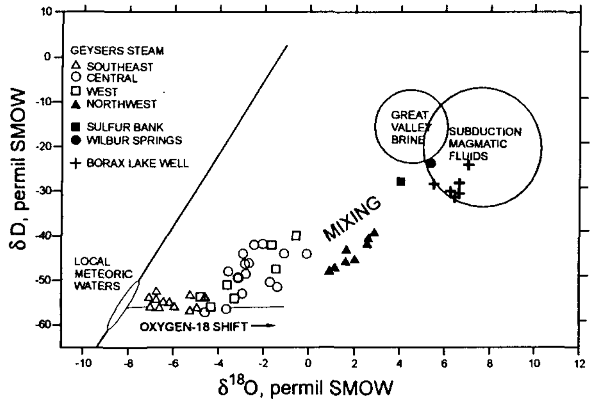

Figure 5. $\delta^{18}O$ and δD compositions of initial Geysers steam and related waters. After Truesdell et al. (1987) and D'Amore and Bolognese (1994).

map in so far as possible the influence of the high-temperature reservoir. The carbon isotope geothermometer has been shown in field and experimental studies to be very slow to reequilibrate at temperatures below 300°C. Less certainly it appears to indicate the temperature of the formation of the gases. Preliminary studies by Shigeno et al. (1987) show variations of temperature within The Geysers with some samples showing the local reservoir temperature and others showing higher temperatures. Studies at Larderello have shown CO_2-CH_4 temperatures that are higher than those measured in wells but have similar variation (Panichi et al., 1977). Deep wells at Larderello have shown that the isotopic temperatures exist below the exploited reservoir.

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