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Publication Date

1994-10-01

LBL-36262
UC-250

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

EARTH SCIENCES DIVISION

Presented at the Geothermal Resource Council, Salt Lake City, UT,
October 3–5, 1994, and to be published in the Proceedings

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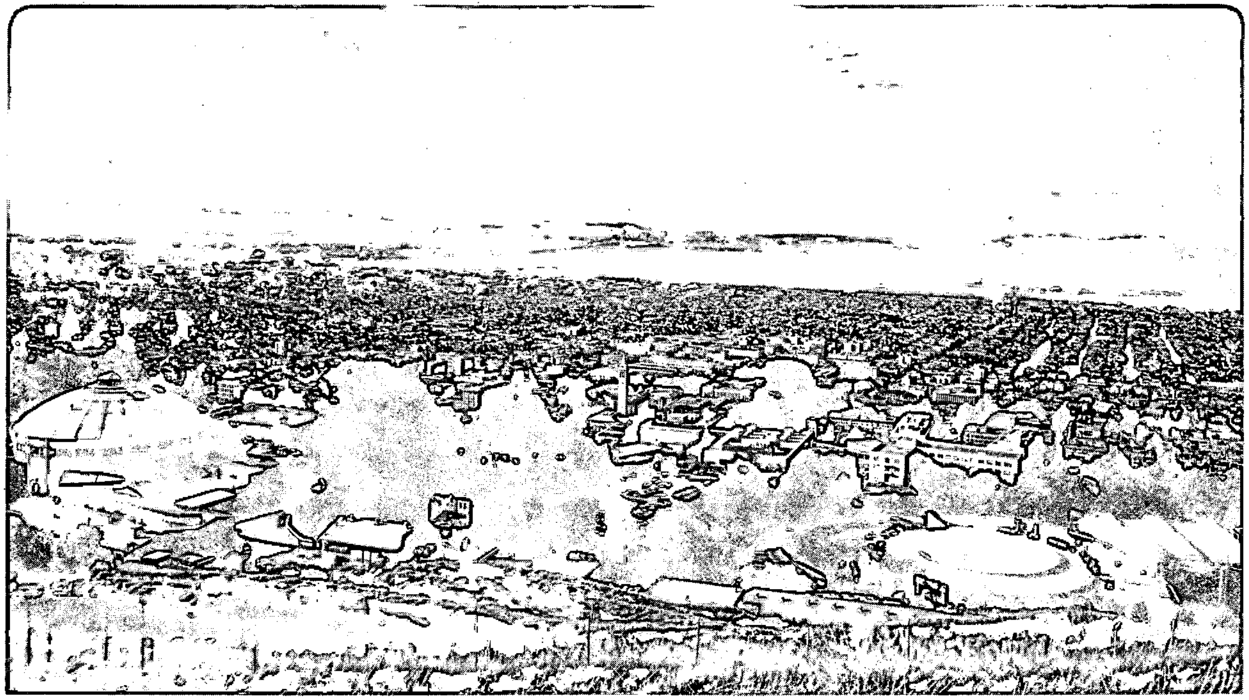

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

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This work was supported by the Geothermal Technology Organization; and by the U.S. Department of Energy, Energy Efficiency and Renewable Energy, Geothermal Division and Office of Energy Research, Office of Basic Energy Sciences, under Contract No. DE-AC03-76SF00098.

ACTIVE MAGMATIC DEGASSING IN THE NW GEYSERS HIGH-TEMPERATURE RESERVOIR

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ABSTRACT

Noble gas isotope abundances in steam from selected wells of the Coldwater Creek field of the NW Geysers, California, show mixing between a nearly pure mid-ocean ridge basalt (MORB) type magmatic gas with high $^3He/^4He$ and low radiogenic Ar ($R/Ra > 8.3$ and $^{40*}Ar/^4He < 0.07$), and a magmatic gas diluted with crustal gas ($R/Ra < 6.6$ and $^{40*}Ar/^4He > 0.25$). Gases with the highest magmatic component are from wells producing entirely (or in large part) from the high-temperature reservoir (HTR), while gases with the most crustal dilution are generally produced from the overlying normal vapor-dominated reservoir. The MORB-type magmatic gas is interpreted to show (among other things) that (1) part of the high gas of the HTR in the NW Geysers is supplied by active degassing of an underlying magma body indicated by earlier geophysical studies; (2) the HTR was formed by rapid heating and boiling of existing reservoir liquid caused by injection of magma; and (3) the large-scale convection found in the south and central Geysers does not exist in the northwest part of the field.

INTRODUCTION

A comprehensive study of noble gas isotopes and carbon isotopes in CO_2 and CH_4 in steam from The Geysers, California, is underway at the Lawrence Berkeley Laboratory with funding from the Department of Energy and the Geothermal Technology Organization. This paper reports noble gas isotope results from selected NW Geysers wells and expands on initial analyses and interpretation reported earlier (Truesdell et al., 1994). The isotopes of stable noble gases (He, Ne, Ar, Kr and Xe) partition strongly into vapor, are chemically inert and provide long-lasting tracers of fluid sources (e.g. Lupton, 1983; Kennedy et al., 1985; Hiyagon and Kennedy, 1992). These tracers include large ^3He enrichment diagnostic of deep fluids originating in the mantle, enrichment in radiogenic ^4He and $^{40*}Ar$ ($^{40*}Ar \equiv$ radiogenic ^{40}Ar), and nucleogenic components characteristic of both mantle and crustal fluids, and enrichment in ^{36}Ar which traces atmospheric input.

The presence of magma at The Geysers has been inferred from various geological and geophysical observations (reviewed in Truesdell et al., 1993), but none of these are direct except the high $^3He/^4He$ ratios found in a reconnaissance by Torgersen and Jenkins (1982) which did not include the high-temperature reservoir (HTR) of the NW Geysers. (The HTR of the NW Geysers has temperatures to 350°C and is immediately beneath a "normal" 250°C reservoir.) These indications suggest that detailed study of noble gas isotopes in steam from the entire Geysers (including the HTR) might more clearly indicate the relation of a magma chamber to The Geysers reservoir. Noble gases combined with carbon isotope temperatures may also indicate the presence in the southern Geysers of steam originating from deep high-temperature zones underlying normal reservoirs. This is important because steam with high gas (and HCl) as found in the HTR cannot be used in some powerplants without expensive modifications.

GAS COLLECTION AND ANALYSIS

Non-condensable gas 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). As the objective was to use the noble gases to characterize the NW Geysers HTR and the transition between the HTR and the overlying normal reservoir, wells were selected to insure a wide range in total gas and HCl content. Five of the sampled wells produce steam entirely or in large part from the HTR and the remainder are thought not to contain a significant HTR component (pers. comm., M. A. Walters, 1994).

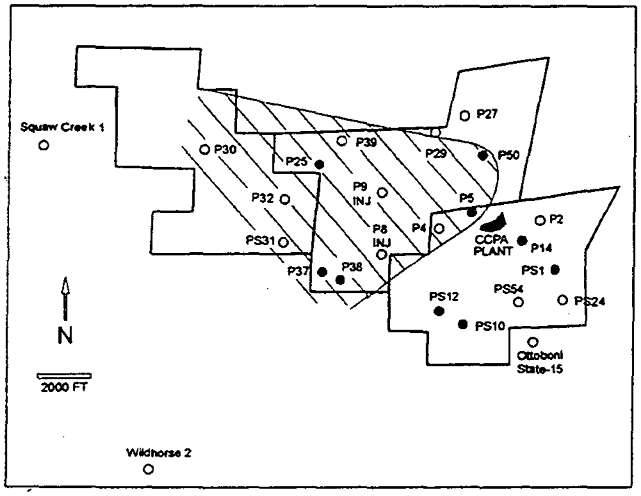

Figure 1. Coldwater Creek wells sampled (filled circles). Area with high-temperature reservoir (HTR) is cross hatched. Well Prati 4 (P4) does not penetrate the HTR.

Gases collected in copper tubes sealed by cold welds were prepared and analyzed in the LBL RARGA (Roving Automated Rare Gas Analysis) laboratory (Kennedy et al., 1985; Hiyagon and Kennedy, 1992). The results are presented in Table 1. The relative abundances of the noble gases are in F-value notation showing fractionation relative to the composition of air with ^{36}Ar as the reference isotope. The neon and argon isotopic compositions are given in conventional delta notation with air as the reference composition and the helium isotopic compositions are presented as R/Ra values where R is the measured ^{3}He/^{4}He ratio and Ra is the ratio in air (1.4×10^{-6}). Also presented in Table 1 are the calculated radiogenic ^{40*}Ar to ^{4}He ratios (^{40*}Ar/^{4}He). Radiogenic ^{40*}Ar is the ^{40}Ar in excess of atmospheric composition as defined by the measured ^{40}Ar/^{36}Ar ratio. All reported uncertainties (σ) are one standard deviation.

EVIDENCE FOR MAGMATIC GAS AND MULTI-COMPONENT MIXING

Elevated helium isotopic compositions providing evidence for a magmatic component in The Geysers steam were first reported by Torgersen and Jenkins (1982). Confirming this earlier report, all wells sampled in this study are enriched in ^{3}He with helium isotopic compositions ranging from 6.6 to 8.3 Ra. We have also found that in the NW Geysers Field, (1) the highest ^{3}He/^{4}He ratios occur in fluids produced from the HTR and (2) the helium isotopic compositions are correlated with ^{40*}Ar/^{4}He, total helium to non-condensable gas ratios, ^{36}Ar concentrations, and the ratio of total helium to the atmospheric noble gas [F(^{4}He)].

Figure 2 shows the helium isotopic compositions (R/Ra values) plotted against the ratio of ^{40*}Ar/^{4}He. Despite the scatter in this plot, a linear relationship is preserved and indicates that two-component mixing dominates the compositional variations. The end members are a fluid enriched in magmatic gas with a composition like a mid-ocean ridge basalt (MORB) mantle source ($R/Ra > 8.3$ and $^{40*}Ar/^{4}He < 0.07$) and a second fluid which dilutes the magmatic component with crustal gas ($R/Ra < 6.6$ and $^{40*}Ar/^{4}He > 0.25$). The wells most enriched in the magmatic component all have steam entries within the NW Geysers HTR (solid circles in Figures 2-5; pers. comm., M. A. Walters, 1994). These wells also have the highest total helium enrichments relative to total non-condensable gases (NCG). This is evident from Figure 3 (expanded near the origin in Figure 4) where the helium enrichment factors {F(^{4}He) values} are plotted against the inverse ^{36}Ar concentration in NCG. Once again the HTR samples (solid circles) conform to a single mixing line distinct from the apparent mixing line defined by wells not influenced by the HTR. The slopes of the mixing lines are proportional to ^{4}He/NCG in the helium-enriched end member components. The ^{4}He/NCG ratio in the HTR is 250×10^{-7} cc/cc and approximately three times greater than that in the non-HTR reservoir. The two mixing lines also require a third component enriched in ^{36}Ar ($^{36}Ar/NCG \sim 3 \times 10^{-7}$ cc/cc) that is, as suggested by near convergence of the mixing lines, probably common to both the HTR and non-HTR fluids.

Because ^{36}Ar traces the atmospheric noble gas component in the system, this ^{36}Ar-enriched gas most likely represents air-saturated water originating either from meteoric, connate, or injectate input. There is also evidence that ^{36}Ar is completely decoupled from the helium-rich fluids. Despite large variation in ^{36}Ar/NCG and F(^{4}He) values, the relative abundances of the remaining noble gases are invariant as shown in Figure 5. It is also evident from this figure that the relative abundances of the air-dominated noble gases do not match that expected for local meteoric recharge (10°C air-saturated water, ASW). The origin of this ^{36}Ar-rich component is still not well understood and a sample of the injectate has been recently collected and will be analyzed.

The highest R/Ra, lowest ^{40*}Ar/^{4}He, and highest F(^{4}He) values representing the largest magmatic enrichment is for steam from well Prati 37 (P37; Figure 1). This steam also has had the highest total NCG and highest HCl of the field (data from CCPA). On the basis of the similarity of these analyses to MORB noble gases, the steam from this well has almost exclusively magmatic noble gases and possibly other magmatic gases as well, although the latter must have been modified by reaction with rock minerals. The nearby Prati 38 well produces steam with lower R/Ra, higher ^{40*}Ar/^{4}He, lower total helium, and has had a maximum NCG about one fifth and HCl about one tenth of the maximum values observed in Prati 37. Although this well may be affected by injection from Prati 8, wells Prati 25 (in the HTR) and Prati State 12 (in the normal reservoir) are only about 1250 m from Prati 37 and show very different noble gas compositions (Table 1). These observations suggest that the lateral gradient in the flux of the magmatic component was very sharp. This could result if the flow of the magmatic component into the production reservoir was fracture-controlled or, as will be suggested later, if fluid circulation is limited to vertical flow.

It is evident from Figure 3, that the dilution of the HTR magmatic component with the second fluid enriched in crustal gas (Figure 2) cannot be accomplished simply by mixing with non-HTR fluids. Unfortunately, from the existing data the source and composition of the crustal component diluting the magmatic gas are not well defined. Its helium isotopic composition must be < 6.3 Ra and the ^{40*}Ar/^{4}He must be > 0.25 (Figure 2). Fluids associated with the non-volcanic country rocks (i.e. the Franciscan greywackes and serpentines and the Great Valley sequences) could conceivably be enriched in crustal noble gases. For instance, Sulfur Creek Spring emerging from Great Valley rocks on the northeast side of the Collayomi Fault has a ^{3}He/^{4}He ratio of 0.8 Ra (Goff et al., 1993), but the relative abundances of the noble gases in this surface spring have been extensively fractionated by phase separation so the ^{40*}Ar/^{4}He ratio is unknown. However, nearby Jones Hot Spring, also associated with Great Valley rocks, has a ^{3}He/^{4}He of 1.7 Ra and a ^{40*}Ar/^{4}He ratio of 1.4 consistent with the Figure 2 mixing line, and the relative abundances of the atmospheric noble gases are similar to that in the NW Geysers (Figure 5). Comparing Figures 2 and 3, there is a general trend of decreasing R/Ra with decreasing F(^{4}He) and increasing ^{36}Ar/NCG, suggesting that the fluid carrier of the atmospheric component may also be the carrier of the crustal component.

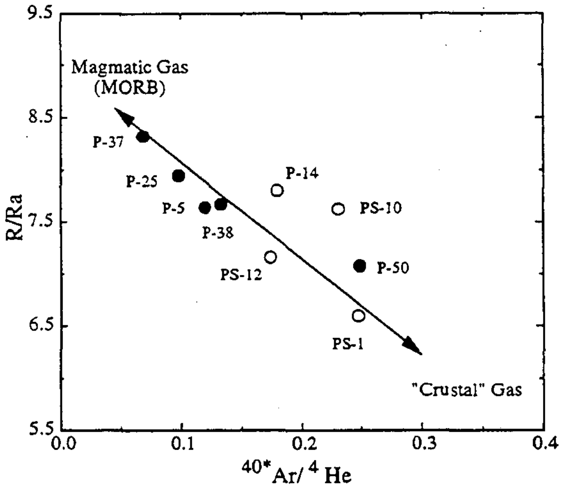

Figure 2. R/Ra plotted against $^{40*}Ar/^{4}He$, an indicator of crustal influence. Wells not in the HTR are shown as open circles.

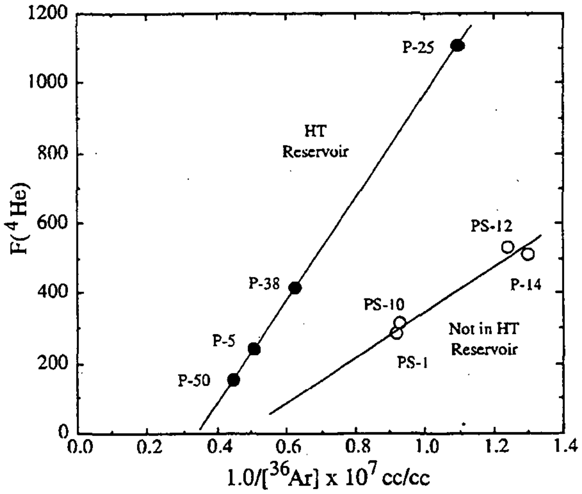

Figure 4. Detail of Figure 3 near the origin. Symbols as in Figure 2.

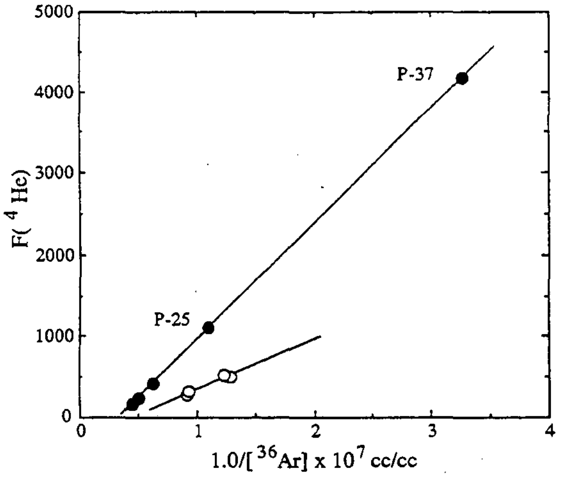

Figure 3. F(^{4}He) plotted against 1/[^{36}Ar], an indicator of atmospheric influence. Symbols as Figure 2.

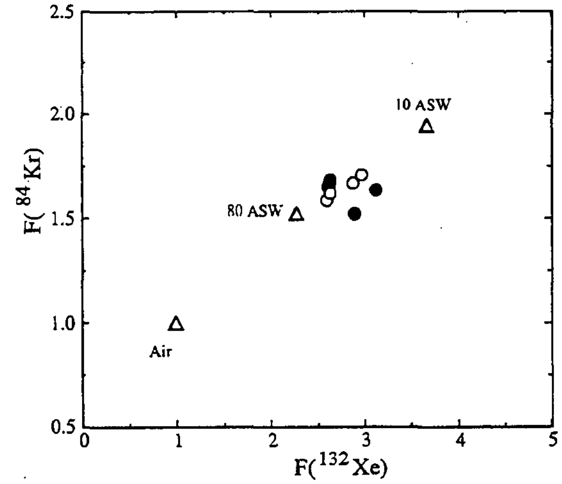

Figure 5. F(^{84}Kr) plotted against F(^{132}Xe). Air and water saturated with air at 10 and 80 °C are shown as triangles. Other symbols as in Figure 2.

IMPLICATIONS FOR MODELS OF GEYSERS RESERVOIRS

The discovery of magmatic noble gas in the NW Geysers provides new constraints on genetic models of the system. The presence of magma at The Geysers has been inferred from various observations including 1) heat flow exceeding 12 HFU or 0.5 Wm^{-2} (Walters and Combs, 1989); 2) close association with very young (≥0.03 Ma) Clear Lake volcanic rocks (Donnelly-Nolan et al., 1981); 3) a gravity low and teleseismic P-wave delays >1 sec. (Isherwood, 1981; Iyer et al., 1981); and 4) the presence of the 350°C high-temperature reservoir (HTR) with steam enriched in total gas to >9%, HCl to >200 ppm and $\delta^{18}O$ to +3‰ (Walters et al., 1988). An earlier study by Torgersen and Jenkins (1982) found high $^3He/^4He$ ratios (5.3 to 9.5 times that of air) in limited samples throughout The Geysers, but did not sample the HTR. The large magmatic noble gas enrichments reported here along with the high total gas, high $\delta^{18}O$ and high HCl are all consistent with a relatively recent intrusion and suggests active degassing of magma in this part of The Geysers system. This degassing may constitute an increasingly important source of gas in the normal reservoir at The Geysers.

Sustaining the nearly pure magmatic noble gas in the HTR probably requires continuous resupply from actively degassing magma and short reservoir residence times. The R/Ra value of the Prati 37 sample is 8.3 (Table 1). This is in the upper range of R/Ra values of MORB gases extracted from chilled glassy margins of recent basalts formed at subsea spreading centers (Figure 2 in Lupton, 1983). These glassy basalt samples retain high R/Ra values because they are very young (sometimes collected within days of their formation), the glass provides a seal against contamination, and basalt contains low U, Th and K so little *in situ* contamination with ^4He occurs. Typically geothermal systems associated with spreading centers (such as Salton Sea, Cerro Prieto, or Larderello) are usually two or more units lower in R/Ra (Figure 4 in Lupton, 1983), probably due to significant residence times in crustal rocks. Intrusive activity can have a dramatic effect on helium isotopes. Recent anomalous seismic activity related to the onset of intrusive activity beneath Mammoth Mountain in Long Valley caldera, California was accompanied by an increase in fumarolic R/Ra (3.6 to 6.7 Ra), an increase in the flux of total He relative to air gases, and an increase in the rate of total gas discharge (Sorey et al., 1993).

This indication of active magma degassing is further supported by the strong gradient in NCG concentration between the HTR and the overlying normal reservoir. The NCG concentration of the HTR is not well known because most (all?) wells have some contribution from the overlying normal reservoir, but wellhead gas collected during drilling indicates that part of the HTR has total gas >11%, compared with about 1.5% in the overlying normal reservoir, only 100 to 200 m distant as defined by measured temperatures (Walters et al., 1988). No barrier to gas diffusion exists between the adjacent reservoirs so the assumption of resupply from below appears necessary to maintain this gradient. Further support for flow of gas from a deep, possibly magmatic, source is from Joseph Beall (pers. commun., 1993), who has calculated that in some parts of the southern Geysers the flow of gas is increasing while the flow of steam is decreasing.

Several conceptual and numerical models of the vapor-dominated reservoirs at The Geysers and Larderello, Italy, have been proposed. The first generally accepted model was that of White et al. (1971) in which steam from a deep boiling brine flows upward in large fractures to the top of the reservoir where it condenses to liquid which drains downward through the rock matrix and small fractures. Direct evidence of boiling brine has not been found at The Geysers, but its presence in central areas of the field was inferred from patterns of gas and isotope compositions (D'Amore and Truesdell, 1979). The vapor-dominated reservoir was assumed to have formed from boildown of a hot-water reservoir caused by increasing heat input or decreasing fluid recharge. This model has been simulated numerically by Pruess (1975) and Ingebritsen and Sorey (1988).

The discovery of the HTR beneath the normal reservoir in the NW Geysers (Walters et al., 1988) requires modification of the White et al. model. Although a high-temperature reservoir could form by boildown of brine (e.g. Shook, 1994) the vapor remaining would be low in gas and the temperature gradient between the normal and high-temperature reservoirs could not be as steep as that observed (Walters et al., 1988). This gradient led Truesdell (1991) to suggest that the HTR and overlying normal reservoir were formed by heating due to igneous intrusion which caused rapid vaporization and venting of existing fluid leaving only superheated vapor, followed by downward migration of a two-phase normal reservoir as liquid was introduced from above. The coexistence of a two-phase fluid above superheated vapor and the downward extension of two-phase conditions as total liquid increased have been simulated numerically (Lai et al., 1994). Recently it was suggested that the entire Geysers evolved from a high-temperature reservoir with slow liquid recharge over a long time period through volcanic rocks related to Cobb Mountain resulting in much deeper vapor-dominated conditions in the south than in the NW Geysers (Truesdell et al., 1993). The sharp gradients in noble gas composition between strongly magmatic steam from Prati 37 and more ordinary steam immediately to the east and northeast supports the idea presented in this model that the NW Geysers did not have the large scale convection found in the southern Geysers because there was no liquid saturated layer at the bottom of the reservoir. Without such a layer, lateral steam flow within the reservoir cannot occur.

The origin of the HTR is clarified by the discovery of magmatic noble gases. Although superheated steam enriched in HCl and ^{18}O could result from venting and open system boiling, this process could not produce high total gas or (obviously) magmatic noble gases. Heating and catastrophic boiling from magma intrusions would sweep earlier atmospheric and crustal gases from the reservoir and replace them with gases from the magma (possibly resupplied by continued degassing) and the subsequent entry of liquid from above could have introduced only small amounts of atmospheric gases. The isotopic composition of the steam in the HTR has been suggested to originate from connate or metamorphic waters (Haizlip, 1985) or from magmatic waters (D'Amore and Bolognesi, 1994). The noble gas evidence supports the latter.

SUMMARY

Steam from the NW Geysers contain noble gases indicating a mixture of a fluid enriched in magmatic gas with a composition like a mid ocean ridge mantle source and a second fluid which dilutes the magmatic component with crustal gas. The wells most enriched in the magmatic component produce mainly from the NW Geysers high-temperature reservoir. These samples also have the highest total helium enrichments relative to total non-condensable gases. Other geochemical, geological and geophysical data also point to the existence of a magma body beneath The Geysers but the noble gas data are the most direct evidences and suggest that degassing of this magma is a continuing process.

ACKNOWLEDGMENTS

We wish to thank John Stackleberg of CCPA for assistance in sample collection, and Marcelo Lippmann and Emilio Antunez (LBL) and Mark Walters (Russian River Energy Company) for encouragement and helpful discussions. This work was supported by the Geothermal Technology Organization and the U.S. Department of Energy's Geothermal Division and Office of Basic Energy Sciences.

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Table 1. Noble gas isotope compositions of steam from selected wells of the Coldwater Creek field, NW Geysers.

Well	$[^{36}Ar]$ 10^{-7}cc/cc*	$[^{4}He]$ 10^{-7}cc/cc*	$F(^{4}He)$	σ	$F(^{22}Ne)$		$F(^{84}Kr)$	σ	$F(^{132}Xe)$	σ
P-5	1.989	80.40	242.1	2.30	0.6377	0.0072	1.676	0.0114	2.624	0.134
P-14	0.7710	65.80	511.0	4.81	0.6178	0.0060	1.707	0.0127	2.954	0.145
P-25	0.9098	168.4	1108	10.45	0.4934	0.0077	1.636	0.0143	3.117	0.174
P-37	0.3070	214.0	4168	107.6	0.8651	0.0411	1.526	0.0874	2.895	0.638
P-38	1.600	110.8	414.3	3.90	0.6066	0.0059	1.588	0.0113	2.588	0.124
P-50	2.265	57.96	153.2	1.44	0.4507	0.0036	1.682	0.0115	2.630	0.129
PS-1	1.093	52.10	285.4	2.72	0.6043	0.0128	1.657	0.0146	2.621	0.194
PS-10	1.077	56.73	315.4	3.00	0.6312	0.0087	1.623	0.0124	2.637	0.160
PS-12	0.8063	71.70	532.7	5.02	0.6021	0.0068	1.668	0.0137	2.874	0.138
10°C ASW	13.37#	0.484#	0.22		0.2722		1.941		3.677	
80°C ASW	6.160#	0.532#	0.52		0.4962		1.523		2.274	
Air	316.1+	52.78+	1.00		1.0000		1.000		1.000	
Avg Crust					???		???		???	
Avg MORB					5.800		2.200		7.000	

Notes: Wells: P = Prati; PS = Prati State. * = ccSTP/ccNCgas, # = ccSTP/ccWater, + = ccSTP/cc
Notation: $F(i) = [(i/^{36}Ar)sample/(i/^{36}Ar)air]$. σ = 1 std. dev.

Well	R/Ra	σ	$\delta^{20}Ne$	σ	$\delta^{21}Ne$	σ	$\delta^{38}Ar$	σ	$\delta^{40}Ar$	σ
P-5	7.649	0.268	33.65	4.70	30.89	9.59	-6.36	5.08	16.49	6.08
P-14	7.807	0.279	32.64	5.31	30.19	11.25	-4.92	5.42	52.10	7.80
P-25	7.955	0.381	17.79	3.84	22.53	10.52	-12.39	6.33	60.67	11.31
P-37	8.322	0.473	38.40	4.09	14.90	13.03	-10.68	6.91	159.79	11.99
P-38	7.678	0.390	24.29	4.96	21.43	10.51	-0.96	5.41	31.34	8.02
P-50	7.084	0.342	12.60	2.86	13.82	9.20	-3.80	5.06	21.50	5.70
PS-1	6.604	0.299	27.99	5.81	26.33	10.76	-3.66	5.32	39.78	8.10
PS-10	7.632	0.378	28.71	4.14	20.79	11.88	-1.92	5.49	40.91	11.57
PS-12	7.165	0.379	18.00	3.77	30.13	11.48	-4.61	5.11	52.52	7.49
10°C ASW	1.000									
80°C ASW	1.000									
Air	1.000									
Ave Crust	0.020		-1000.00		15200		???		???	
Ave MORB	8.570		224.49		1068.97		0.00		100500	

Notation: $R/Ra = (^{3}He/^{4}He)samp/(^{3}He/^{4}He)air$. $\delta\ i = 1000[(i)sample/(i)air-1]$.

Sample	$^{40*}Ar/^{4}He$	σ
P5	0.1205	0.0445
P14	0.1804	0.0271
P25	0.0969	0.0181
P37	0.0678	0.0054
P38	0.1338	0.0343
P50	0.2483	0.0658
PS1	0.2466	0.0503
PS10	0.2295	0.0649
PS12	0.1745	0.0249
Ave Crust	0.2000	
Ave MORB	0.0100	

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