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Evidence for Active Magmatic Degassing and Implications
for the Origin of The Geysers Geothermal Field

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The Northwest Geysers High-Temperature Reservoir: Evidence for Active Magmatic Degassing and Implications for the Origin of The Geysers Geothermal Field

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Abstract
Noble gas isotope abundances in steam from the Coldwater Creek field of the Northwest Geysers, California, show mixing between a nearly pure mid-ocean ridge (MOR) type magmatic gas with high $^3\text{He}/^4\text{He}$ and low radiogenic $^{40}\text{Ar}/^{40}\text{Ar}$ ($R^{40}\text{Ar}/^{40}\text{Ar} > 8.3$ and $R^{40}\text{Ar}/^{3}\text{He} < 0.07$), and a magmatic gas diluted with crustal gas ($R^{40}\text{Ar}/^{40}\text{Ar} < 6.6$ and $R^{40}\text{Ar}/^{3}\text{He} > 0.25$). The $^3\text{He}$ enriched component is correlated with $R^{40}\text{Ar}/^{3}\text{He}$ ratios, total helium to non-condensable gas ratios, and the ratios of total helium to atmospheric noble gases; and is accompanied by mantle-like $^{40}\text{Ar}/^{3}\text{He}/^{3}\text{He}/^{4}\text{He}$ and $^{4}\text{He}/^{36}\text{Ar}$ ratios. The steam most enriched in this high $^3\text{He}$ component is produced from a high-temperature reservoir (HTR) and is also the most enriched in total gas and HCl. The present data set does not allow a definitive correlation between HCl and magmatic $^3\text{He}$.

These results support the hypothesis of active magma degassing beneath the NW Geysers, suggest that a significant fraction of the non-condensable gases produced with steam from the HTR is magmatic, and add new constraints to genetic models of the system and its evolution. The intensity of the magmatic signal is inconsistent with deep boiling of connate or metamorphic waters and suggests active magma degassing. A correlation between magmatic helium and non-condensable gases implies that the HTR high gas component is also magmatic and it is likely the HTR was formed and is sustained by this active flux of magmatic volatiles. Magmatic input is unlikely to decline on the time scale of production, but injection of water into the HTR would have multiple benefits: (1) pressure and steam flow would increase; (2) gas concentrations would decrease by dilution with low-gas steam from vaporized liquid; and (3) HCl in steam would be removed once a liquid phase is established. High $^{40}\text{Ar}/^{3}\text{He}$ ratios in steam produced from the reservoirs in the southern parts of The Geysers suggests the presence of a similar HTR underlying these portions of the field. Monitoring $^{3}\text{He}$ content may provide early warning of potential pressure drawdown and entry of caustic, high-gas HTR steam.
Introduction

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, T > 350 °C) in the NW Geysers has been thought to be related to metamorphic (Haizlip, 1985) or magmatic (D’Amore and Bolognesi, 1994) brine. The high gas and HCl, and the uncertainties as to origin and persistence of the high gas component in the HTR have made its exploitation more difficult.

In vapor-dominated systems such as The Geysers, 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. The stable noble gases (He, Ne, Ar, Kr and Xe) and their isotopes are excellent natural tracers for fluid source and migration in the Earth's crust. Due to their inert chemical character, they can provide long lasting tracers which see through complex chemical processes affecting the compositions of reactive species. Therefore, fluids originating in the mantle (characterized by large $^{3}He$ enrichments) as well as shallower fluids of crustal (enriched in radiogenic $^{4}He$, $^{40}Ar$ and nucleogenic components) and atmospheric (characteristic $^{22}Ne$, $^{84}Kr$, and $^{132}Xe$/$^{36}Ar$ ratios) origin can be readily identified (e.g. Kennedy et al., 1985; Hiyagon and Kennedy, 1992).

Volatile degassed from the mantle through magmatic processes are enriched, relative to atmospheric or crustal fluids, in total helium ($^{4}He$/$^{36}Ar$ ~7400; Javoy and Pinneau, 1991) and $^{3}He$ ($^{3}He$/$^{4}He$ = 1.12-1.26 x 10^{-5}$) and have coherent $^{3}He$/$CO_2$ (~5 x 10^{10}; Marty and Jambon, 1987) and $^{40}Ar$/$^{4}He$ ratios (~0.27), the latter reflecting in-growth of radiogenic gases in accordance with the average mantle $K/(U+Th)$ ratio (Jochum et al., 1983). Geothermal fluids hosted in continental crust but in regions influenced by recent volcanic activity will be enriched in magmatic volatiles. The degree of enrichment, as measured by the above characteristic parameters, will depend strongly on the intensity of magmatism, the time since magma intrusion or eruption, and the present rate of magma chamber recharge by fresh mantle material (cf DePaolo et al., 1992). For example, recent events of anomalous seismic activity attributed to dike injection beneath Mammoth Mountain, Long Valley Caldera, California were accompanied by changes in fumarolic emissions, including a factor of two increase in the $^{3}He$/$^{4}He$ ratio (3.8 to 6.7 times Ra, the ratio in air, 1.4 x 10^{-6}) and a sevenfold increase in total helium relative to air gases (Sorey et al., 1993). Similar changes in the mantle enrichment of geothermal volatiles due to increased magmatic activity have been observed in hydrothermal plumes over the Juan de Fuca Ridge (Lupton et al., 1989) and in steam produced from Icelandic geothermal systems (Poreda and Arnorsson, 1992).

Fluids circulating through evolved upper crust, far removed from magmatic influence, are enriched in crustal volatiles acquired as a result of rock/water interaction, diffusive loss of light isotopes, and/or tectonic processes. Such fluids may also be enriched in total helium relative to air gases but the helium will be radiogenic in origin and therefore enriched in $^{3}He$ ($^{3}He$/$^{4}He$ < 10^{-7}) and other radiogenic and nucleogenic noble gases (e.g. nucleogenic $^{21}Ne$, and radiogenic $^{4}He$ and $^{40}Ar$). The relative proportions of these components reflect dominance either by local or average crustal chemistry (e.g. Kennedy et al., 1990, Hiyagon and Kennedy, 1992) and/or relative
extraction efficiencies from respective source sites (e.g. O'Nions and Ballentine, 1993; Tolstikhin et al., 1995).

Air in contact with meteoric and connate waters imparts an atmospheric signature to the elemental and isotopic compositions of noble gases. Elemental concentrations will be governed by temperature dependent gas solubilities, however solubility differences among isotopes are not great enough to cause significant isotopic shifts. Therefore, the isotopic compositions of meteoric and connate waters will be indistinguishable from that of air.

The Geysers:
The general characteristics of The Geysers reservoir and its origin have been discussed by Truesdell et al. (1993a). The Geysers geothermal reservoir is hosted in fractured graywacke of the Franciscan Assemblage, Northern California Coast Range. In the Geysers region, this assemblage is a sequence of tabular, stratigraphically continuous slabs bounded by thrust faults (McLaughlin, 1981; Thompson, 1989) and locally intruded by shallow silicic magmas during the Pleistocene forming a composite batholith-sized intrusion collectively known as "felsite" (Schriener and Suemnicht, 1980). However, the 1.3-1.4 Ma age of the drilled felsite batholith (Dalrymple, 1992) is probably too great for this to be the heat source for the present day geothermal system which would seem to require much younger intrusive bodies and perhaps recent magma injection. The presence of magma at The Geysers has been inferred from various geological and geophysical observations: (1) there is a high heat flow maximum of >12 HFU over The Geysers compared with regional Coast Range heat flow near 2 HFU (Walters and Combs, 1989); (2) there is a close spatial association with the Clear Lake volcanic field in which eruptive rocks are as young as 0.03 Ma (Donnelly-Nolan et al., 1981); (3) regional teleseismic P-wave delays exceed 1 second suggesting the presence of a partially crystallized magma chamber (Chapman, 1975; Isherwood, 1981; and Iyer et al., 1981); and (4) there is a similarity in isotopic composition of steam produced from the Northwest Geysers high-temperature reservoir with the composition of "andesitic" or magmatic water proposed by Giggenbach (1991). However, none of these examples provide evidence for magma that is as direct as that provided by high $^3$He/$^4$He ratios found in a reconnaissance of steam compositions from The Geysers normal temperature reservoir (NTR; Torgersen and Jenkins, 1982). Our work extends that early reconnaissance to include gases from the Northwest Geysers high temperature reservoir, where a detailed study of noble gas isotopes in steam more clearly indicates the potential presence of a magma chamber.

Sample 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). The sampled wells were selected to insure representation from a wide range in total gas and HCl content so as to characterize the NW Geysers HTR and the transition between the HTR and the overlying normal temperature reservoir (NTR). As seen in Figure 1, five of the sampled wells are thought to 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).
Wellhead steam was passed through an ice-bath condenser and the non-condensable gases were collected in copper tubes sealed by cold welds. Noble gas preparation and analysis were made in the RARGA (Roving Automated Rare Gas Analysis) laboratory at LBL. Detailed descriptions of the sample preparation and analysis techniques employed in the RARGA laboratory can be found in Kennedy et al. (1985) and Hiyagon and Kennedy (1992). Noble gas relative and absolute abundances are given in Table I. The relative abundances are given in F-value notation in which measured relative abundances are normalized to the air abundance with ^{36}\text{Ar} as the reference isotope [e.g. $F(i) = (i/^{36}\text{Ar})_{\text{sample}}/(i/^{36}\text{Ar})_{\text{air}}$]. As defined, F-values are fractionation/enrichment/depletion factors relative to atmospheric composition. The helium R/Ra values, where R is the measured sample $^{3}\text{He}^{4}\text{He}$ ratio and Ra is the ratio in air (1.4 x 10^-6), and argon isotopic compositions are summarized in Table 2. Also presented in Table 2 are calculated radiogenic $^{40}\text{Ar}$ to total $^{4}\text{He}$ ratios ($^{40}\text{Ar}/^{4}\text{He}$). Radiogenic $^{40}\text{Ar}$ is the $^{40}\text{Ar}$ in excess of the atmospheric composition as defined by the measured $^{40}\text{Ar}/^{36}\text{Ar}$ ratio. All reported uncertainties are one standard deviation and include the uncertainty in the measurements and subsequent data corrections.

Evidence for Magmatic Gas and Multi-Component Mixing

*Mantle Helium*

Elevated helium isotopic compositions providing evidence for a mantle 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 $^{3}\text{He}$ with helium isotopic compositions ranging from 6.6 to 8.3 Ra (Table 1). The highest $^{3}\text{He}^{4}\text{He}$ ratio (8.3 Ra) is similar to that in glassy rims of mid-ocean ridge (MOR) basalts (e.g. Lupton, 1983) and is the highest ratio reported for active volcanic centers associated with the California segment of the North American-Pacific Plate boundary (Craig et al., 1978; Welhan et al., 1988; Sorey et al., 1993). Such a high value is remarkable because any magma chamber feeding The Geysers/Clear Lake system is likely to be hosted by evolved (Mesozoic) crustal rocks enriched in radiogenic $^{4}\text{He}$. Magma chamber aging, roof foundering, and an associated elevated geothermal gradient would be expected to contribute a significant radiogenic component diluting the mantle helium signal (e.g. Hart and Zindler, 1989). Further, crustal influence on the composition of the Clear Lake-Geysers eruptive volcanics is consistent with coupled co-variations between major oxide abundances, Sr isotopic compositions, and the abundances of light rare earth elements (Hearn et al., 1981; Donnelly-Nolan et al., 1981). Apparently, the crustal contamination implied by these other chemical and isotopic signatures in prior erupted volcanics has little or no effect on the present day helium isotopic composition. As modeled by DePaolo et al. (1992), magma hosted by older and enriched crust, but experiencing a high rate of magma recharge from the mantle source, will acquire a chemical and isotopic signature similar to the source mantle. Magmatic volatiles exsolved from such a magma would also be expected to carry a signature like the mantle source. Zindler and Hart (1986) argued that magma chamber degassing will leave a residual magma strongly enriched in U relative to He and, because of in-growth of radiogenic $^{4}\text{He}$, high $^{3}\text{He}^{4}\text{He}$ ratios characteristic of the magma source could not be supported in such an environment for periods in excess of $10^4$ - $10^5$ years without significant recharge from the magma source. The high $^{3}\text{He}^{4}\text{He}$ ratios in The Geysers steam, therefore, are consistent with degassing from an active magma chamber that is probably undergoing strong recharge from the underlying mantle. The Mesozoic and
younger geothermal reservoir rocks and minerals are potential sources of crustal radiogenic helium which can reduce original $^3$He/$^4$He ratios. Therefore, sustaining the nearly pure magmatic helium composition in the HTR probably requires a continuous re-supply from an actively degassing magma coupled with short reservoir residence times.

As we discuss below, the $^3$He enriched component is: (1) correlated with $^{40}$Ar/$^4$He ratios, total helium to non-condensable gas (NCG) ratios, and the ratios of total helium to the atmospheric noble gases as measured by $F$(He) values; (2) accompanied by mantle-like $^3$He/CO$_2$ and $^4$He/$^6$Ar ratios; and (3) are, in the Northwest Geysers, most enriched in fluids produced from the HTR. These results support the hypothesis of active magma degassing beneath the NW Geysers reservoir and suggests that a significant fraction of the non-condensable gases produced with steam from the HTR is magmatic.

**He-Ar Correlations: Evidence for Two Components**

Figure 2 shows the helium isotopic compositions (R/Ra) plotted against $^{40}$Ar/$^4$He ratios. Despite some scatter, a linear correlation is apparent, requiring mixing between a minimum of two components. One end member component is a fluid enriched in mantle $^3$He with R/Ra $\geq 8.3$ and $^{40}$Ar/$^4$He $\leq 0.07$. The wells most enriched in this component (solid circles) all are thought to produce steam predominately from the HTR (pers. comm., Mark Walters, 1994). As discussed above, the helium isotopic composition of this fluid approaches that measured in the glassy rims of MOR basalts and suggests evolution from an actively degassing magma chamber. However, the inferred $^{40}$Ar/$^4$He ratio for the mantle enriched component is significantly less than the present day mantle production ratio (~0.27) calculated from measured K/(U+Th) ratios in normal MOR basalts (Jochum et al., 1983).

Although the measured helium isotopic compositions of MOR mantle are uniform (8-9 Ra), this is not true of $^{40}$Ar/$^4$He ratios measured in glassy rims of MOR basalts which range from ~0.05 to 1.0 (e.g. Dymond and Hogan, 1973; Fisher, 1975). Figure 2 shows the calculated present day mantle production ratio of $^{40}$Ar/$^4$He is 0.27 ± 0.02 (one sigma deviation about the mean), and the range in $^{40}$Ar/$^4$He values calculated from anomalous P-Type and differentiated oceanic basalts (data from Jochum et al., 1983). The latter are more consistent with the inferred values for The Geysers $^3$He-enriched end member. However, a normal MOR type source coupled with He-Ar fractionation is also plausible. Significant He-Ar fractionation during magma genesis by partial melting is not expected because their respective crystal/liquid distribution coefficients for basalts are similar and significantly less than one (Hiyagon and Ozima, 1986; Broadhurst et al., 1990, 1992) implying that these noble gases will readily partition into the melt with little or no fractionation. However, solubility differences among noble gases in tholeitic basalts (e.g. Lux, 1987) are large enough to easily fractionate He (Henry's Law constant ~ $29 \times 10^{-6}$ moles/gm-kbar) from Ar (~ $4 \times 10^{-6}$ moles/gm-kbar). Assuming an initial magma $^{40}$Ar/$^4$He ratio of 0.27 and a Rayleigh type distillation process, an exsolved gas phase with $^{40}$Ar/$^4$He of ~0.07 corresponds to a loss of ~60% of the original He content of the magma. Therefore, it is not unreasonable that volatiles derived from an active degassing magma beneath the Northwest Geysers would have an helium-argon composition like that measured in steam produced from the most $^3$He-enriched well.
The second end member fluid, characterized by $R/R_a \leq 6.6$ and $^{40}\text{Ar}/^{4}\text{He} \geq 0.25$, is enriched in the mantle component to a lesser degree, presumably reflecting dilution with a radiogenic crustal component. Measured $K/(U+\text{Th})$ ratios in local examples of Mesozoic Franciscan and Great Valley rocks (Wollenberg et al., 1967) indicate an average present day $^{40}\text{Ar}/^{4}\text{He}$ production ratio of $\sim 0.13$ with a range of 0.11 to 0.16, intermediate to the measured ratios and less than the radiogenic end member inferred from the mixing line. In the high temperature environment of The Geysers ($T > 350 \, ^\circ\text{C}$) it is unlikely that this discrepancy reflects extensive fractionation resulting in enhanced radiogenic $^{40}\text{Ar}$ relative to $^{4}\text{He}$ due to different extraction and migration efficiencies from production sites in reservoir minerals. The discrepancy is more easily explained if (1) K-rich minerals are selectively altered relative to those rich in U and Th; or (2) the radiogenic component is not derived from the local crustal component; or (3) the second end member component is a mixture of magmatic and local radiogenic noble gases, an example of which is shown as the dashed mixing line in Figure 2.

**Helium, Non-condensable Gases and Magmatic CO$_2$**

The well producing steam most enriched in the magmatic component and total helium (Prati-37, Table 1) also produces steam with the highest maximum non-condensable gas (NCG) and HCl contents of the Coldwater Creek field, suggesting a coherence between these constituents and the magmatic He. Convincing evidence for this coherence is provided by a correlation between excess helium, as measured by the $F(4\text{He})$ values, and the NCG/$^{36}\text{Ar}$ ratios which is shown in Figure 3. The two mixing lines, requiring a minimum of three components, readily distinguish steam produced from the high and normal temperature reservoirs. HTR steam, which is enriched in the magmatic component as defined above, is also enriched in total He relative to $^{36}\text{Ar}$ [$F(4\text{He}) > 4168$], and, as defined by the mixing line slope, characterized by a constant $^4\text{He}/\text{NCG}$ ratio of $2.40 \times 10^{-5}$ cc/cc which is $\sim 2.4-3.8$ times greater than that in the NTR. The value depends on which of the two NTR mixing lines is used to define the He/NCG ratio. The dashed line (Figure 3b) includes all samples presumed to be associated with the NTR, whereas the solid line omits sample PS-24, which appears to have a composition more like HTR steam. Although the NTR steam is characterized by a lower $^4\text{He}/\text{NCG}$ ratio, it is still high in total He and $^3\text{He}$ indicating that steam in the NTR is also enriched in the magmatic component. These two reservoir components, defined by their respective $^4\text{He}/\text{NCG}$ ratios, are mixed with a third component enriched in $^{36}\text{Ar}$ and presumably of atmospheric origin. As suggested by the near convergence of the two mixing lines, this third component is common to both the HTR and NTR reservoirs and is characterized by an $^{36}\text{Ar}/\text{NCG}$ ratio of $\sim 3 \times 10^{-7}$ cc/cc.

The NCG component consists primarily of CO$_2$ with minor amounts of H$_2$, H$_2$S, NH$_3$, and CH$_4$. The non-condensable gas in steam produced from Prati-37 is $\sim 70\%$ CO$_2$ (pers. comm., R. Kunzman, 1994) which, combined with the helium isotopic composition and the slope of the Figure 3 mixing line, corresponds to a $^3\text{He}/\text{CO}_2$ ratio of $4.0 \times 10^{-10}$. This is indistinguishable from the best estimate for the MOR upper mantle source ($\sim 5 \times 10^{-10}$, Marty and Jambon; 1987, Trull et al., 1993) and arc related volcanics ($\sim 1 \times 10^{-10}$, Allard, 1992) and implies that most of the HTR CO$_2$ is magmatic. Although Figure 2 implies that magma degassing may have fractionated He from Ar, it is unlikely this would have a significant effect on the He/CO$_2$ ratio. This follows from comparable basalt solubilities for He and CO$_2$ (Pineau and Javoy, 1983 and Lux, 1987) and the
observation that measured He/CO$_2$ in MOR basalts are independent of basalt vesicularity (Marty and Jambon, 1987) and carbon content (Trull et al., 1993).

A positive correlation between non-condensable gases and HCl concentrations from two areas of The Geysers (Unit 15 and Coldwater Creek) which produce corrosive HCl bearing steam has been observed by Haizlip and Truesdell (1992). The origin of HCl in The Geysers steam is unknown and remains a source of debate. Possibilities include generation from hot brines at high temperature (Haizlip and Truesdell, 1988; Truesdell et al., 1989) or from reaction of solid NaCl with silicates (Fournier, 1983; D’Amore et al., 1990). It is also possible that the HCl could be exsolved directly from magma. HCl-rich steam, where partially condensed, is highly corrosive requiring mitigation procedures to protect production wells. Unfortunately, the mitigation prevents an evaluation of the data presented here for HCl-He correlations.

Atmospheric Noble Gases

Well Prati-37 $F$(He) is equivalent to an $^{4}$He/$^{36}$Ar ratio of 696, ~11 times less than the best estimates for the MOR basalt source (Javoy and Pineau, 1991). This suggests that the third component, thought to be of atmospheric origin, dominates the $^{36}$Ar inventory. Figure 4 shows $F$(Kr) plotted against $F$(Xe) summarizing the relative abundances of the atmospheric gases. Although the compositions of these gases do not match exactly that expected for natural meteoric recharge, i.e. water in equilibrium with air at recharge temperatures of ~10°C, the similarity in composition strongly suggests a meteoric influence. Surprisingly, despite a wide variation in $F$(He) and NCG/$^{40}$Ar values (Figure 3) reflecting variable proportions of the atmospheric component in the produced steam and isotopic compositions (Figure 2), the relative abundances of the atmospheric gases are remarkably constant. As such, it is apparent that the HTR He and CO$_2$-rich NCG component is completely decoupled from meteoric waters and further implying that the bulk of the NCG component is magmatic. If not, then He-rich magmatic volatiles and CO$_2$ must form a coherent component prior to dilution with atmospheric gases as encountered in the production reservoir, which is highly unlikely.

Implications for the Origin and Evolution of The Geysers Geothermal Reservoir

The evidence provided by the noble gases for a magmatic gas component in the NW Geysers adds new constraints to genetic models of the system and its evolution. The helium isotopic composition confirms a magmatic influence upon The Geysers geothermal system. The intensity of the magmatic signal, as measured by high $^3$He/$^4$He ratios in produced steam, suggests active degassing from a source magma chamber that is in a high state of recharge from an underlying MOR type mantle. Moreover, the correlation between magmatic helium and non-condensable gases (predominately CO$_2$) implies that the high gas component characterizing the NW Geysers HTR also has a magmatic origin and, therefore, is being actively supplied to the HTR.

Petrologic and isotopic studies of vein minerals (Lambert, 1976; Sternfeld, 1981) indicate a complex thermal history for The Geysers, consisting of three separate hydrothermal episodes differing in temperature, fluid origin and type of steam. The first two phases were liquid-dominated systems. The earliest of these existed in late Jurassic to early Cretaceous time and
appears to have been related to the deposition of the Franciscan and driven by deeply circulating connate seawater heated along a normal or slightly elevated geothermal gradient. The second phase developed much later in response to Pliocene to recent igneous activity associated with the Sonoma (2.9-5.3 Ma) and Clear Lake (0.03-2.1 Ma) volcanics. In the immediate Geysers vicinity, this phase was related to the intrusion of the felsite batholith which underlies the present Geysers geothermal field and consisted of mostly meteoric water heated to -220-300 °C and slightly $^{18}$O shifted (-2.5 to -0.5 per mil) due to water-rock interaction. The present day Geysers vapor-dominated system represents the third phase.

Prior to the recent discovery of the high-temperature reservoir in the NW Geysers (Walters et al., 1988), conceptual models for the pre-exploitation state of the Geysers were based primarily on the characteristics of the "typical" Geysers reservoir found in the Southern Geysers (e.g. White et al., 1971; Truesdell, 1991). The model of White et al. (1971) is applicable to vapor-dominated systems in general and presents many (but not all) of the features observed in the Southern Geysers. The model consists of three parts: (1) a vapor-dominated main reservoir containing steam in large, through-going fractures and liquid water in the rock matrix and small fractures; (2) an underlying zone of boiling saturated liquid, assumed to be brine; and (3) a zone of condensation in effect defining the top of the vapor-dominated reservoir.

Vapor dominated reservoirs have been generally thought to form from boil down of a hot water reservoir due to an increase in heat or decrease in recharge. Steam from deep boiling liquid (brine) flows upward in large fractures to the reservoir top where it condenses and drains downward through small fractures and the rock matrix. At The Geysers, although direct evidence of deep boiling brine has not been found, its presence in the Central and SE areas of the field was inferred from patterns of gas/steam ratios and the isotopic composition of steam (Truesdell et al., 1987; Gunderson, 1989). In this part of the field, gas/steam ratios increase and $\delta^{18}$O values of steam decrease towards the margins, forming "bull's eye" patterns (Figure 5) consistent with lateral movement of a condensing plume of steam and large scale fluid convection driven by centralized boiling of an underlying liquid reservoir (D'Amore and Truesdell, 1989).

However, in the NW Geysers, gas/steam ratios increase dramatically toward the center of the field. The high gas/steam fluid is produced from the underlying high-temperature reservoir (HTR) which, as described in Walters et al. (1988), is characterized by very high total gas, oxygen-18, and HCl. Throughout the NW Geysers, the elevation of the top of the HTR is nearly constant (~ -2000 m msl) and the HTR is overlain by a thin normal-temperature reservoir (NTR). The boundary between the HTR and overlying NTR is sharp and can be located to within about ~100 m from downhole temperature measurements taken during drilling (Walters et al., 1988). There is no identified lithologic or mineralogic change at the boundary nor is there a marked pressure or permeability difference. This led Walters et al., (1988) to suggest that the boundary was a transient thermodynamic feature formed from the recent deep venting of a liquid dominated system. Deep high-temperature boiling of metamorphic or connate water cannot produce high-gas steam, but could explain high HCl and enriched $^{18}$O/$^{16}$O ratios (Figure 6) which approach the isotopic compositions of local metamorphic waters (Sulphur Bank and Wilbur Springs) and connate Great Valley brines (White et al., 1973; Haizlip, 1985). However, the high total NCG and the high proportion of magmatic gas in HTR steam required by the very high $^3$He/$^4$He ratios
reported here, are inconsistent with deep boiling of a connate or metamorphic water, which would be expected to provide low gas steam with a high proportion of accumulated radiogenic gas characterized by low $^3\text{He}/^4\text{He}$ ratios. The strong magmatic component, instead suggests that the HTR and the sharp HTR/NTR boundary were formed and are sustained by an active flux of magmatic volatiles.

Active magma degassing sustaining the HTR, and the HTR/NTR boundary is further supported by a strong gradient in NCG concentration and composition between the HTR and overlying normal reservoir. The NCG concentration of the HTR is not well known because all wells producing from this reservoir are thought to also have some contribution from the overlying NTR (M. Walters, pers. comm., 1994). Wellhead gas collected during drilling indicates that part of the HTR has total gas $>11\%$, compared with $1.5\%$ in the overlying normal reservoir measured in wells 100-200 m distant (Walters et al., 1988). Well Prati 37 which produces steam with the highest proportion of magmatic gas has also produced steam with the highest gas/steam ratio and HCl content. Well Prati 38, 200 m distant, produces steam with lower R/Ra, higher $^{40}\text{Ar}/^4\text{He}$, 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 NTR), about 600 m from Prati 37, show very different noble gas compositions (Table 1, Figures 1-3). No barrier to gas diffusion is known to exist between the adjacent reservoirs so the suggestion of resupply from below seems necessary to maintain this gradient. Such steep lateral gradients in composition also suggest that fluid circulation in the NW Geysers is limited to nearly vertical flows without the large scale fluid convection found in the Central and SE Geysers.

Model for the Origin of The Geysers

The discovery of magmatic noble gases reported here agrees with the model for the origin of The Geysers reservoir described by Truesdell et al. (1993a). As indicated in that paper, we believe that The Geysers reservoir is "mining" heat from buried, still hot, 0.1 Ma (or younger) igneous rock and possibly magma, and moving it to the near surface. This process occurs when the reservoir extends downward into hot rocks, enhancing upwards heat transfer by convection. This was suggested to have occurred recently in the Northwest Geysers by Truesdell (1991), and is even more likely to have occurred earlier in the South Geysers where recharge water is thought to be more available. The high gas/steam and HCl in steam produced in the NW Geysers reflects a lack of available recharge water as well as a lack of venting. The downward extension of a two-phase, vapor-dominated reservoir into hot rock rapidly cools the rock to normal reservoir temperature and, through the heat pipe mechanism, moves the heat to the top of the reservoir where it is conducted to the surface. This process is similar to that suggested by Lister (1976) for a penetrating convective system, but more effective because the high-temperature rock is already fractured and the vapor-dominated heat pipe removes heat more rapidly than does convecting liquid.

The Northern and Southern Reservoirs

An important difference between the northern and southern reservoirs is the initial content of liquid and the availability of recharge water. The mass of steam produced from the Central
and Southern Geysers over more than 30 years requires large initial amounts of liquid water in the reservoir. In the Northern Geysers, however, the NTR reservoir is thin and conditions of temperature and pressure in the HTR suggest that fractures (and probably rock matrix) hold only vapor. The isotopic compositions of steam and local meteoric water isotopes are nearly identical in the South, while steam from the North is most similar to metamorphic or magmatic water (Figure 6; Truesdell et al., 1987), consistent with the high proportion of magmatic gas in the North.

Lower recharge to the northern reservoir is probably due to either its greater depth and/or the character of the adjacent rocks. Studies by Johnson and Treleaven (1990) show that “non-reservoir” Franciscan rocks are “essentially non-water bearing” with low intrinsic porosity (about 1%) and permeability ($10^{-18} \text{ m}^2$) and mostly sealed fractures. Most rain falling on Franciscan rocks runs off and little infiltrates. In contrast the dacite and rhyodacite of Cobb Mountain are highly permeable and maintain open fractures. As a result little runoff is observed from Cobb Mountain and most (95%; Johnson and Treleaven, 1990) of the 200 cm average annual precipitation infiltrates. Part of this water forms springs which emerge at the contact of the volcanic and Franciscan rocks, but probably some flows down the fractured neck of the volcano into the southern reservoir directly or through the underlying felsite. The oxygen isotope data show that the composition of nearby steam is similar to that of meteoric water suggesting direct recharge (Figure 6), but gas concentration patterns indicate movement from the upflow zones toward Cobb Mountain. This suggests that recharge from Cobb (if it occurs) enters the deep liquid rather than the two-phase steam reservoir. Recharge through volcanic edifices such as Cobb Mountain was earlier suggested by Goff et al. (1977).

We believe that the greater reservoir thickness and greater initial liquid saturation in the Southern Geysers reservoir is due to a greater access to recharge water rather than to differences between the north and south in availability of heat or rock character. It seems reasonable to assume further that the source of recharge in the south is Cobb Mountain which has the required high infiltration. Possible sources of recharge in the north include, as discussed above, limited infiltration through pores and fractures in the overlying Franciscan rock and fluid transferred from the southern reservoir. The latter possibility is shown in a schematic diagram of The Geysers reservoir in its pre-exploitation state (Figure 7).

This diagram (without scale and with certain geographic rearrangements) shows from right to left (or southeast to northwest) that rain falling on Cobb Mountain recharges a liquid-saturated aquifer in fractured Franciscan and igneous (volcanics and felsite) rocks. At the top the groundwater is cold, but as it moves downward it is heated conductively and feeds the boiling liquid beneath the upflow zones of the southern reservoir. The top of the liquid-saturated reservoir is not planar, but tilted up towards the sides where it receives condensate trickling from above. The boiling liquid, steam flow upwards and laterally, condensation near the top, and condensate percolating downward to rejoin the liquid constitute a closed convection cell. This convection is analogous to the hydrologic cycle on the earth's surface.

The southern reservoir represents a mature vapor-dominated reservoir in which the edges of the reservoir are close to the limits of the zone of fracturing created during the emplacement of
the felsite (Sternfeld, 1989). In particular, if the bottom of the reservoir coincides with the maximum downward extent of fractures (at the brittle-ductile transition of the latest 0.1 Ma or younger intrusion), then the heat transfer mechanism should change from rapid removal by heat pipes through existing permeability to slower transfer through cracks formed by thermal stress cracking (Lister, 1976) or even to conduction. At an earlier stage, the southern reservoir may have been more like the northern reservoir as represented in Figure 7. The liquid-saturated zone would not be present and fluid circulation would be limited to vertical transport of steam and condensate. The lateral recharge of liquid would add to the total fluid and allow the reservoir to grow rapidly downward into the fractured hot rock. During this period of intense downward expansion the heat and fluid flow out of the reservoir may have been greater, with widespread steam venting and hydrothermal alteration. Downward extension of the heat pipe would slow greatly at the limit of preexisting fractures. With this decrease in extension rate, additional water recharge would pool at the bottom and allow the formation of the large convection cells now observed.

When major convection cells were established in the southern reservoir (and perhaps earlier), some steam could migrate into the northern reservoir to add to the limited recharge from above and initiate local convection. There is evidence that convection and cooling in the Northern Geysers started much later than in the south. Temperature studies of the caprock above the high temperature reservoir have found that heat flow near the top of the caprock is higher than at the bottom indicating cooling in the lower portion of the caprock within the last 5000 to 10,000 years (Williams et al., 1993). Studies of the Central Geysers show no recent heat flow changes in the caprock (Urban et al., 1976). The recent cooling and relatively thin normal reservoir in the north may reflect recent recharge and initiation of convection. In the northern reservoir heat mining would be limited by slow heat loss through a thick caprock as well as by limited recharge of liquid.

High $^3\text{He}/^4\text{He}$ ratios in steam produced from the southern reservoirs (Torgersen and Jenkins, 1982) reflect a magmatic influence and suggest the presence of an existing underlying high temperature reservoir similar to that found in the northwest Geysers. Some transitional areas in the north-central part of The Geysers initially produced low-gas, chloride-free steam from a normal reservoir and later steam high in gas and chloride suggesting a high temperature reservoir source (Haizlip and Truesdell, 1992). Whether more of the southern reservoir will produce this type of high-gas, high-chloride steam probably depends on whether the inferred deeper high temperature reservoir in that part of the field is fractured and can therefore readily communicate with the overlying normal reservoir. High $^3\text{He}/^4\text{He}$ ratios in this area would suggest some degree of communication. As pressures in the producing overlying exploited reservoir drop, steam from both marginal zones and underlying hot zones (where these zones exist along with suitable conduits) will be drawn in, carrying high-gas and potentially high-chloride steam to the wells. Monitoring the content of $^3\text{He}$ and other magmatic components may distinguish marginal from deep steam and provide an early warning system for inflow of steam from underlying high temperature zones.

In the southern reservoir the initial presence of liquid water in matrix pores and small fractures combined with recharge from the south provided a plentiful supply of low-gas steam to
dilute the gas contained in the original vapor. The loss of this liquid in the late 1980’s caused rapid declines in reservoir pressures and steam flow along with increases in gas concentrations (Truesdell et al., 1993b). The northern reservoir, which at present produces from both a normal, vapor-dominated reservoir and a high temperature reservoir, may not undergo these unfavorable changes to the same extent. Although the magmatic input is unlikely to decrease on the time scale of commercial production, gas concentrations in the produced steam are high, but they may be near the maximum in the area and continued production from the high temperature reservoir may cause a pressure decrease, with lower gas steam pulled into the exploited zone. Injection of water into the high-temperature reservoir would have multiple benefits. Steam pressures and flow would increase, gas concentrations would decrease due to dilution by vaporized liquid, and HCl would be scrubbed as soon as a liquid phase is established. With water injection, the high-temperature reservoir could be the largest un-exploited resource at The Geysers.

Acknowledgments

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References


Figure Captions

Figure 1: Coldwater Creek field of the NW Geysers. Well locations shown are mean steam entries; those sampled are indicated by solid circles. Area with high-temperature reservoir (HTR) is cross hatched. Well Prati 4 (P4) does not penetrate the HTR.

Figure 2: R/Ra plotted against $^{40}\text{Ar}^{4}\text{He}$, an indicator of crustal influence. Wells producing only from the NTR are shown as open circles. Solid line, observed mixing; dashed line, mixing between MORB and local crust, see text.

Figure 3: $F(\text{He})$ plotted against the non-condensable gas (NCG) to $^{36}\text{Ar}$ ratio. Figure 3b is a detail of Figure 3a near the origin. Symbols as in Figure 2.

Figure 4: $F(\text{Kr})$ plotted against $F(\text{Xe})$. Air and 10 and 80 °C air saturated water (ASW) are shown as triangles. Other symbols as in Figure 2.

Figure 5: Contour maps showing variations in the gas/steam ratios (Figure 5a) and the oxygen isotopic composition (Figure 5b) in initial produced steam of The Geysers geothermal field.

Figure 6: The isotopic composition of pre-exploitation Geysers steam. For comparison, the compositions of local meteoric waters, connate waters (Great Valley brines), metamorphic waters (Sulfur Bank and Wilbur Springs), and the inferred composition of subduction magmatic fluids are shown. After Truesdell et al. (1987) and D'Amore and Bolognesi (1994).

Figure 7: Schematic NW-SE cross section of The Geysers geothermal system.
Table 1. Noble gas abundances in steam from the NW Geysers.

<table>
<thead>
<tr>
<th>Sample</th>
<th>[36Ar] E-7 cc/cc*</th>
<th>[4He] E-7 cc/cc*</th>
<th>F(4He) +/-</th>
<th>F(22Ne) +/-</th>
<th>F(84Kr) +/-</th>
<th>F(132Xe) +/-</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2</td>
<td>1.2750</td>
<td>54.879</td>
<td>257.74</td>
<td>2.46</td>
<td>0.6012</td>
<td>0.0139</td>
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<tr>
<td>P5</td>
<td>1.9890</td>
<td>80.401</td>
<td>242.05</td>
<td>2.30</td>
<td>0.6377</td>
<td>0.0072</td>
</tr>
<tr>
<td>P14</td>
<td>0.7710</td>
<td>65.800</td>
<td>511.02</td>
<td>4.81</td>
<td>0.6178</td>
<td>0.0060</td>
</tr>
<tr>
<td>P25</td>
<td>0.9098</td>
<td>168.366</td>
<td>1108.13</td>
<td>10.45</td>
<td>0.4934</td>
<td>0.0077</td>
</tr>
<tr>
<td>P37</td>
<td>0.3070</td>
<td>214.000</td>
<td>4168.07</td>
<td>107.61</td>
<td>0.8651</td>
<td>0.0411</td>
</tr>
<tr>
<td>P38</td>
<td>1.6000</td>
<td>110.800</td>
<td>414.31</td>
<td>3.90</td>
<td>0.6066</td>
<td>0.0059</td>
</tr>
<tr>
<td>P50</td>
<td>2.2650</td>
<td>57.960</td>
<td>153.24</td>
<td>1.44</td>
<td>0.4507</td>
<td>0.0036</td>
</tr>
<tr>
<td>PS1</td>
<td>1.0930</td>
<td>52.097</td>
<td>285.42</td>
<td>2.72</td>
<td>0.6043</td>
<td>0.0128</td>
</tr>
<tr>
<td>PS10</td>
<td>1.0770</td>
<td>56.731</td>
<td>315.42</td>
<td>3.00</td>
<td>0.6312</td>
<td>0.0087</td>
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<tr>
<td>PS12</td>
<td>0.8063</td>
<td>71.700</td>
<td>532.70</td>
<td>5.02</td>
<td>0.6021</td>
<td>0.0068</td>
</tr>
<tr>
<td>PS24</td>
<td>2.4960</td>
<td>71.045</td>
<td>170.44</td>
<td>1.60</td>
<td>0.6737</td>
<td>0.0056</td>
</tr>
</tbody>
</table>

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 | 1.0000 | 1.0000 | 1.000 |

Notation: F(i) = [(i/36Ar)sample/(i/36Ar)air].
Notes: * ccSTP/ccNCgas, # ccSTP/ccWater, + ccSTP/cc
Table 2: Noble gas isotope compositions of steam from the NW Geysers.

<table>
<thead>
<tr>
<th>Sample</th>
<th>R/Ra</th>
<th>+/-</th>
<th>Delta-38</th>
<th>+/-</th>
<th>Delta-40</th>
<th>+/-</th>
<th>40*Ar/4He</th>
<th>+/-</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2</td>
<td>6.295</td>
<td>0.337</td>
<td>-6.24</td>
<td>5.28</td>
<td>17.18</td>
<td>9.25</td>
<td>0.1180</td>
<td>0.0635</td>
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<td>P5</td>
<td>7.649</td>
<td>0.268</td>
<td>-6.36</td>
<td>5.08</td>
<td>16.49</td>
<td>6.08</td>
<td>0.1205</td>
<td>0.0445</td>
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<tr>
<td>P14</td>
<td>7.806</td>
<td>0.279</td>
<td>-4.92</td>
<td>5.42</td>
<td>52.10</td>
<td>7.80</td>
<td>0.1804</td>
<td>0.0271</td>
</tr>
<tr>
<td>P25</td>
<td>7.955</td>
<td>0.381</td>
<td>-12.39</td>
<td>6.33</td>
<td>60.67</td>
<td>11.31</td>
<td>0.0969</td>
<td>0.0181</td>
</tr>
<tr>
<td>P37</td>
<td>8.322</td>
<td>0.473</td>
<td>-10.68</td>
<td>6.91</td>
<td>159.79</td>
<td>11.99</td>
<td>0.0678</td>
<td>0.0054</td>
</tr>
<tr>
<td>P38</td>
<td>7.678</td>
<td>0.390</td>
<td>-0.96</td>
<td>5.41</td>
<td>31.34</td>
<td>8.02</td>
<td>0.1338</td>
<td>0.0343</td>
</tr>
<tr>
<td>P50</td>
<td>7.084</td>
<td>0.342</td>
<td>-3.80</td>
<td>5.06</td>
<td>21.50</td>
<td>5.70</td>
<td>0.2483</td>
<td>0.0658</td>
</tr>
<tr>
<td>PS1</td>
<td>6.604</td>
<td>0.299</td>
<td>-3.66</td>
<td>5.32</td>
<td>39.78</td>
<td>8.10</td>
<td>0.2466</td>
<td>0.0503</td>
</tr>
<tr>
<td>PS10</td>
<td>7.632</td>
<td>0.378</td>
<td>-1.92</td>
<td>5.49</td>
<td>40.91</td>
<td>11.57</td>
<td>0.2295</td>
<td>0.0649</td>
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<tr>
<td>PS12</td>
<td>7.165</td>
<td>0.379</td>
<td>-4.61</td>
<td>5.11</td>
<td>52.52</td>
<td>7.49</td>
<td>0.1745</td>
<td>0.0249</td>
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<tr>
<td>PS24</td>
<td>7.869</td>
<td>0.443</td>
<td>-0.40</td>
<td>5.27</td>
<td>17.21</td>
<td>6.19</td>
<td>0.1790</td>
<td>0.0640</td>
</tr>
</tbody>
</table>

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