Geothermal Resources Council, Monograph on The Geysers Geothermal Field, Special Report No. 17, 1991

A GEOCHEMICAL OVERVIEW OF THE GEYSERS GEOTHERMAL RESERVOIR

A.H. Truesdell
U.S. Geological Survey, Menlo Park, California

W.T. Box, Jr.
Geysers Geothermal Company, Santa Rosa, California

J.R. Haizlip
GEO Operator Company, Santa Rosa, California

F. D'Amore
Istituto Internazionale per le Ricerche Geotermiche, Pisa, ITALY

AUTHORS NOTE: This paper is reprinted from the Transactions of the 4th Circum-Pacific Energy and Mineral Resources Conference held in Singapore, August 17-22, 1986. The state of knowledge of the geology and geochemistry of The Geysers has progressed significantly in the 5 years since this conference, and undoubtedly some of the interpretations in this paper now deserve modification. In particular, new geochemical data have become available on the high-temperature reservoir in the northern part of The Geysers (Walters and others, 1988). The role of this reservoir in the origin of The Geysers field is, however, incompletely understood, and accordingly we have not attempted to update the interpretations in this paper.

ABSTRACT

Examination of fieldwide data for The Geysers geothermal reservoir shows relatively small variations in geology, geophysics, and steam temperature and pressure. Steam composition, however, shows large gradients of gas content (from 100 to >65,000 ppm gas by weight) and $\delta^{18}O$ (from -7 to +3 per mil SMOW) from the southeast to the northwest of the field. The areal extent (about 3 to 7 km wide by 18 km long) and the depth and thickness (from 0.5 km to 2-6 km deep) are defined by steam productivity, induced microseismicity, and (less definitely) geologic boundaries. Fluid circulation at The Geysers is dominated by vertical upward flow of steam and downward flow of condensate (the "heat pipe" mechanism) over short distances, by lateral ("Rayleigh") steam flow and condensation over intermediate distances, and by flushing of connate brines with meteoric water over most of the field. This flushing produced the major gas and isotope gradients.

INTRODUCTION

The Geysers, in northern California (Figure 1), is one of two known great vapor-dominated geothermal systems. (The other is Larderello in Tuscany, Italy; smaller vapor-dominated fields occur in Japan, Indonesia, and elsewhere). Unlike the more common hot-water systems, these systems produce steam with little or no liquid water, although most of this steam results from vaporization of liquid in the reservoir. Fieldwide studies have been made of the geophysics and surface and subsurface geology of The Geysers, but very little has been published on the chemical and isotopic compositions of fluids and reservoir rocks. Large-scale variations in isotopic and chemical compositions of steam from Larderello (Celati and others, 1973; D'Amore and others, 1977) have led to models for fluid circulation and steam origin (D'Amore and Truesdell, 1979; Calore and others, 1982) that have been useful in guiding exploration and estimating reserves. Although variations in steam composition at The Geysers have been known informally and were suggested by study of chemical variations in altered reservoir rocks (Lambert, 1976; Sternfeld, 1981), only the fieldwide variation of steam isotope compositions has been published (Haizlip, 1985). It is our purpose to present a general description of The Geysers reservoir, to show (with new data) that large fieldwide gradients in isotope and gas compositions exist in Geysers steam, and to discuss the origin of these gradients.

The Nature of The Geysers Reservoir Fluid

Wells at The Geysers generally produce nearly saturated steam. This steam may be slightly wet (contain entrained droplets of liquid), especially during very early

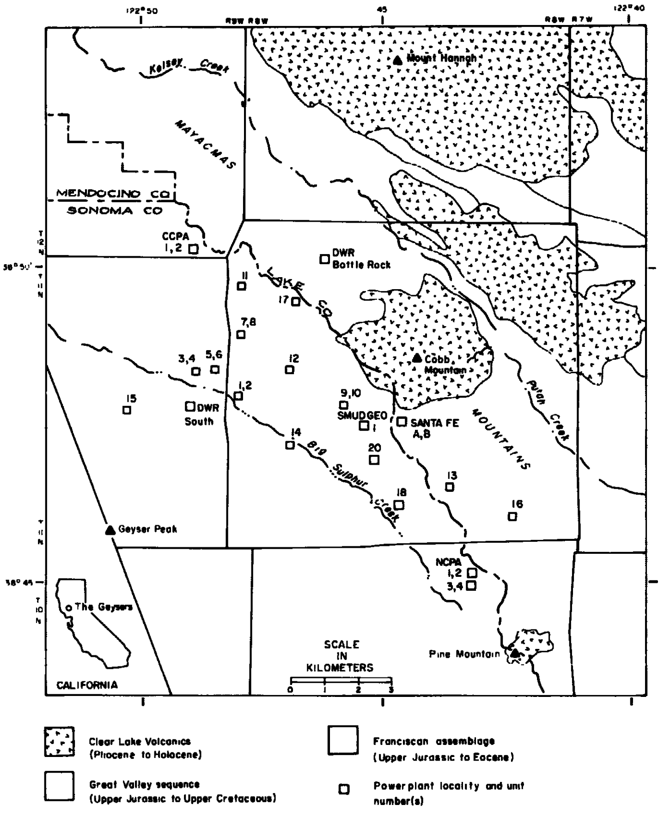

Figure 1. Location of The Geysers field and power plants with generalized regional geology. (Modified from Brook, 1981.)

production, or it may be slightly superheated. The widely accepted model of "vapor-dominated" systems presented by White, Muffler and Truesdell (1971) and Truesdell and White (1973) suggests that the reservoir contains highly mobile steam in large fractures and essentially immobilized liquid water adsorbed on surfaces and held in small fractures (akin to a "cracked sponge"; Weres, Tsao and Wood, 1977). In zones affected by exploitation, pressure decreases, assisted by heat transferred from the rock, cause most of this water to boil. As exploitation proceeds, pressures continue to drop and boiling extends further from the well. Boiling of liquid continues until the rock is dry or until the only liquid remaining is sealed from connection with the fracture network (as for example in fluid inclusions), is held in very small cracks by capillarity, or has a high salt content. Water in very small cracks or containing large concentrations of salt has a lower vapor pressure than dilute "bulk" water in larger cracks and may remain after bulk water is boiled off. In a continuous, permeable reservoir, pressure drops are transmitted long distances from wells and the immobilized water in a large volume of rock boils, possibly without producing a totally dry zone near the well. Thus steam remains close to saturation. This is probably the situation for most of The Geysers. In much of Larderello there is less water in the reservoir and lower permeability, so for most wells the near-well volume is dried out completely. Steam originating further away undergoes nearly isothermal decompression near the well to produce mainly superheated steam.

In areas of The Geysers unaffected by previous exploitation (except the northwest), most wells produce a water and steam mixture for days or months after the start of production and then produce saturated or slightly superheated steam. This behavior could be the result of initial production from a liquid-rich condensate zone near the top of the reservoir or of production from a two-phase liquid-steam reservoir with some mobile liquid and an initial pressure drop insufficient to cause total vaporization.

Natural fluid circulation in vapor-dominated reservoirs has been described (White, Muffler and Truesdell, 1971) and simulated experimentally (Sondergeld and Turcotte, 1977) and mathematically (Preuss, 1985) as resembling that in a "heat pipe." In a heat pipe, heat is rapidly transmitted by a fluid that vaporizes at one end and condenses at the other, with counter flows of vapor and liquid along the pipe. The heat pipe effect produces high heat flow (to 9×10^{-6} cal cm^{-2} sec^{-1}) observed over The Geysers; Urban, Diment and Jamieson, 1976) without a net upward mass flux. A similar mechanism (essentially a horizontal heat pipe) produces the lateral steam flow and condensation responsible for the areal variations in steam composition observed at Larderello and parts of The Geysers (D'Amore and Truesdell, 1979). The heat pipe effect is important for the fluid reserves of The Geysers because most steam produced originates in the reservoir from boiling of liquid that is either fixed (adsorbed on mineral surfaces, or held in small pores and fractures closed downward) or draining downward from zones of condensation.

Geology of The Geysers Reservoir

The surface geology of The Geysers was mapped by McLaughlin (1978) and the subsurface geology was discussed by McLaughlin (1981) and Thomas (1981). The Geysers reservoir is generally developed within a thick, areally extensive body of greywacke of the Jurassic Franciscan assemblage that is overlain by a tectonic "thrust assemblage" (also Franciscan) and intruded and underlain to an unknown depth by a Pliocene or younger siliceous igneous rock locally known as "felsite." The overlying thrust assemblage consists of bodies of metagreywacke, melange, greenstone, chert, blueschist, and serpentine. The felsite locally contains steam (as do parts of the thrust assemblage) but to a lesser extent than the main greywacke. Massive felsite is encountered in wells in the southeast and south-central Geysers and probably exists at greater depths further north. Felsite dikes have been encountered in wells throughout The Geysers field.

The main greywacke is intensely faulted and fractured, and productivity of the reservoir is related to the number, size, and continuity of these fracture networks. This is because the intrinsic porosity and permeability of this greywacke are very small (<3 percent and <1 md, respectively) and fluids must be contained and move in fractures rather than in the rock matrix. Jurassic to Tertiary thrust faulting has imparted a horizontal or subhorizontal fracture permeability to The Geysers reservoir and overlying rocks. Later San Andreas style wrench faulting (Tertiary to present) has produced locally intense, vertical fracture zones (i.e., along Big Sulphur Creek and Squaw Creek), which are often used as drilling targets in highly deviated wells. Stress solutions of current seismic activity indicate that the directions of maximum and minimum stress in The Geysers are consistent with those along the San Andreas fault to the west (Oppenheimer, 1986). Fracture density in the main greywacke appears to decrease at the reservoir margin, and the remaining fractures are often sealed with alteration minerals in this area. Temperatures in some wells drilled outside The Geysers reservoir, but near the margin of the field, are higher than the reservoir temperature, indicating conductive heat flow in this area consistent with the model presented by White, Muffler and Truesdell (1971).

The petrologic and isotopic studies of Lambert (1976) and Sternfeld (1981) document a complex thermal history for the field, with three separate hydrothermal systems differing in temperature, fluid origin, and type of system. The earliest hydrothermal system was developed in the Jurassic and Cretaceous soon after deposition of the Franciscan. Temperatures were 170° to 200°C and the fluid was isotope- shifted connate sea water ($\delta^{18}O = +3$ to $+7$) heated by deep burial in a normal geothermal gradient. Much later, Pliocene to recent igneous activity related to the Sonoma (2.9 to 5.3 Ma) and Clear Lake (0.01 to 2.1 Ma) volcanics again heated The Geysers to form a liquid-dominated geothermal system with temperatures of 220° to 320°C and fluids of mainly meteoric origin with d18O values of -2.5 to -0.5 affected by oxygen isotope shift. The fluid appears to have been isotopically lighter in the south-central Lakoma Fame area (Lambert's data) than in the north-central Sulphur Bank area (Sternfeld's data). This difference is interesting in light of present variations in steam compositions discussed later. Alteration and vein minerals now found in The Geysers reservoir were mainly formed by these earlier liquid-dominated systems.

The last documented hydrothermal system corresponds to the modern Geysers vapor-dominated reservoir. Fluids changed little in $\delta^{18}O$ but temperatures (~250°C) generally decreased. Although few hydrothermal minerals are deposited by steam and condensate, these fluids can dissolve and alter existing minerals. Calcite, common in upper zones, is rare within the vapor reservoir because CO_2-saturated condensate is acid and dissolves carbonate as HCO_3, which is carried down to boiling zones where calcite is precipitated and CO_2 regenerated. Similar leaching processes probably affect quartz and other silicates where freshly formed CO_2-charged condensate aggressively dissolves rock in zones of condensation. Since these zones are near the top and sides of the reservoir at the distal ends of steam-flow paths, mineral solution may be an important means of enlarging the reservoir. This process would also cause deposition of dissolved minerals in the deep boiling zones, which would rapidly decrease porosity and fluid flow if fluid conduits were not kept open by continuing tectonic movement.

Extent of The Geysers Reservoir

Successful wells at The Geysers are contained in an irregular southeast-northwest-trending area about 18 km long and 3 to 7 km wide (Figure 2). The depth to steam varies from less than 200 m to more than 3,000 m. The depth to the first occurrence of steam is in the public record and has been used by Thomas (1981) to divide the field into "anomalies" (or highs) that appear to coincide in part with "pressure sinks" reported by Lipman, Strobel and Gulati (1977). The productive steam field was suggested by McLaughlin (1981) to be limited to the "main greywacke" and bounded by the Mercuryville fault on the southwest and the Collayami fault on the northeast. In Figure 2 we indicate locations of unproductive wells (either low permeability or flooded with liquid water) along with depth to first steam (generalized from Thomas, 1981) and the Mercuryville and Collayami faults. The boundary of The Geysers reservoir is not yet determined to the northwest and other boundaries are not everywhere well located.

The close correspondence of productive (15 tons/hour) wells and first steam entries at depths less than -1,500 m asl (Figure 2) suggests that reservoir productivity decreases rapidly across near-vertical boundaries. This is also shown by the number of dry or subcommercial wells drilled just outside these boundaries to depths exceeding 3,000 m (or greater than 2,000 m below sea level) and by induced microearthquakes in the west-central production areas that extend below 3 km depth and have a sharp cutoff to the southwest (Eberhart-Phillips and Oppenheimer, 1984).

The thickness of the producing reservoir is much less well known. The upper limit of the reservoir is known from the elevations of first steam entries as compiled by Thomas (1981), who also compiled the elevation of the top of the "main greywacke" reservoir rock (see discussion of geology). The lower limit is not known from drilling. No well has definitely penetrated below the reservoir and no deep water table has been detected. Most models of vapor-dominated systems suggest a boiling water-saturated

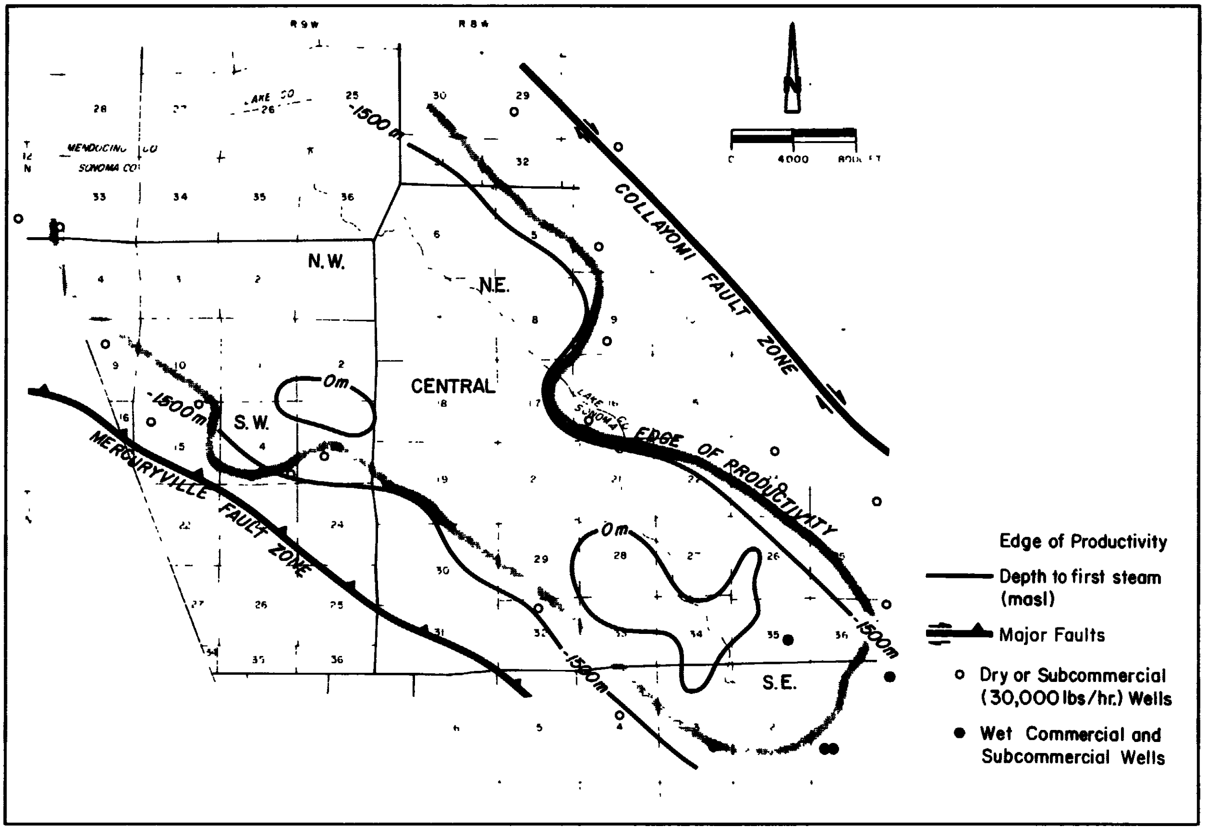

Figure 2. The areal extent of The Geysers reservoir as indicated by the maximum extent of productive (15 tons/hr) wells and the -1500 m asl depth to first steam. Also shown are nonproductive wells and major faults located close to the field boundaries.

zone (water table) under the vapor- dominated reservoir; such a zone has been detected chemically and by drilling at Larderello. There is no direct evidence of a boiling water table at The Geysers, but we know indirectly that boiling liquid zones must exist from the high heat flow produced by condensing steam and the low mass flow out of the system—the "heat pipe" effect. The best direct evidence of the nature of the deeper parts of The Geysers reservoir (below drilled depths) comes from induced microseismicity.

Induced seismicity is characteristic of the central and northeast Geysers (Bufe and others, 1981; Eberhart-Phillips and Oppenheimer, 1984; Oppenheimer, 1986). Detailed seismic study of The Geysers started in 1975 and the latest published data is for 1982; most of the following discussion is based on Eberhart-Phillips and Oppenheimer (1984).

In the central Geysers area (Figure 1), frequent (greater than 10 a day) microearthquakes occur in the reservoir at depths of 0 to 6 km (Figure 3). Microseismic activity also occurs in the southern part of The Geysers but with much lower frequency. The microearthquakes occur both continuously and in swarms and are related to production and not to injection of condensate. The area with the most microearthquakes was developed earliest (Units 1-8 in the central Geysers) and includes the area of major natural thermal activity. In the central and southwestern Geysers the opening of new power plants was followed within a year by microseismicity that increased rapidly in frequency.

Although the clearly induced nature of the microseismicity is not encouraging for its use as an exploration tool, it is very useful as an indication of the dimensions of the reservoir. Whatever the mechanism, the production of steam triggers the microseismicity so that the locations of the earthquakes indicate the locations of steam production. Using this as a guide, we see that steam is produced rather evenly from depths of 1 to 3 km beneath areas feeding Units 9, 10, 14, and 15 and from depths of 0.2 to 6 km beneath the area feeding Units 1-8 (Figure 3). Between and outside these zones of greatest seismicity are relatively aseismic zones that may correspond with areas of less production, as between Units 1-8 and Units 9 and 10, or may be less seismic for unknown reasons, as at Unit 13. (Both very low and very high permeability may be associated with reduced microseismicity.) Although most seismicity is connected to exploited areas, increasing seismicity was observed after 1978 in previously aseismic zones to the north of exploited areas, suggesting lateral

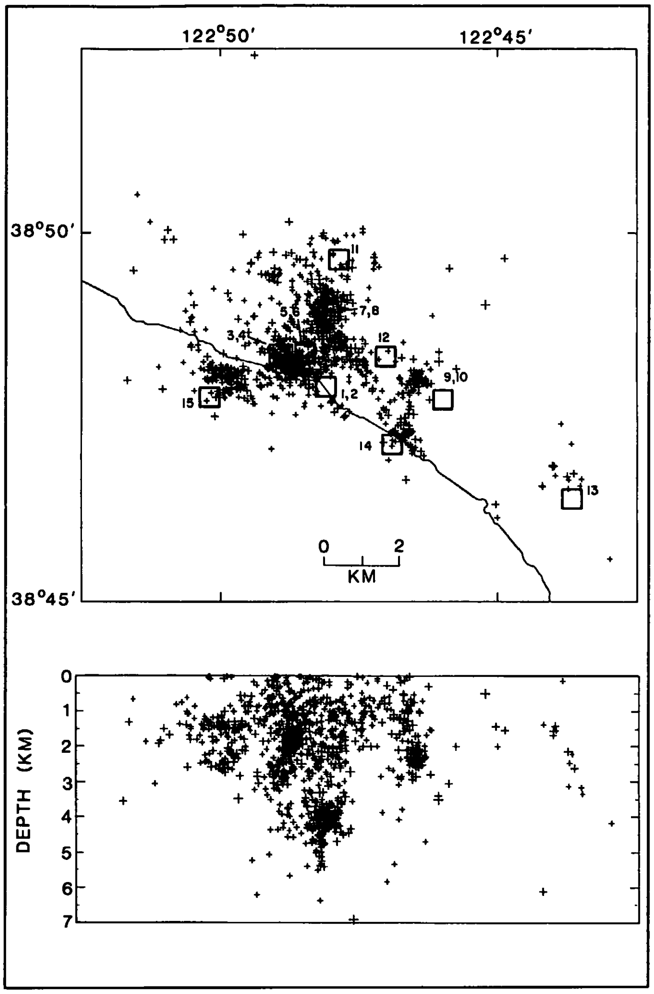

Figure 3. Locations of epicenters of microseisms measured from January through April 1981 in plan view and projected on an east-west section. Power plants operating in 1982 are also shown. (Modified from Eberhart-Phillips and Oppenheimer, 1984).

flow of steam from a distance. Pressure drops observed in areas drilled but not yet produced also indicate lateral drainage of steam to producing areas (sometimes a matter of economic concern at The Geysers).

The seismic zones are more extensive vertically than horizontally and generally show no concordant lower boundary or concentration at a particular depth that might indicate boiling from a deep water table or a condensate layer. Except in the Units 1-8 area, the depth of the seismicity is comparable to the depth of the wells, with the shallowest seismicity corresponding to the depth of the first steam entries. In the Units 1-8 area (the "Big" Geysers) seismicity is much deeper than drilled depths, which may be the result of much greater total production over a longer time period. The existence of a shallow reservoir in this area (Lipman, Strobel and Gulati, 1977) is also reflected in the microseismicity. The depth of seismicity appears to increase with time and production, although this is not well documented. Recent shallow microseismicity in the southwest Geysers may indicate production of steam from an overlying water-saturated condensate zone.

The Collayami and Mercuryville fault zones were suggested by McLaughlin (1981) to bound the reservoir on the northeast and southwest. This does not seem to be exactly true, although the reservoir boundaries are parallel to these faults (Figure 2) and may be controlled in part by associated structures. Near Unit 15 the limit of productivity and the southwest edge of microseismicity coincide with the Mercuryville fault zone, but in other areas this fault zone is not a reservoir boundary. To the northeast of The Geysers field the induced seismicity appears to end southwest of the Collayami fault zone (Figures 2 and 3). This is consistent with the known limits of commercial production in this area and indicates that the Collayami fault is not the reservoir boundary although other parallel faults may be.

Gases in Geysers Steam

A small number of gas analyses have been reported for steam from The Geysers. Allen and Day (1927) reported that steam from six of the shallow steam wells drilled from 1921 to 1925 contained notably less CO_2 and more H_2 and CH_4 than steam samples from Lassen Park. The difference was probably due to the presence of far more organic matter in The Geysers sedimentary reservoir rock than in the volcanic Lassen system. Other than providing this observation, the gas analyses were not very useful to Allen and Day. This situation continued until the early 1980s with small numbers of analyses reported by Barnes and others (1973), Weres, Tsao and Wood (1977), Nehring (1981), and Truesdell, Nathesson and Frye (1981) without well locations and without significant interpretation.

The use of gas chemistry in geothermometry had been successfully applied to hot-water systems (e.g., Hulston and McCabe, 1962), but gases from vapor-dominated systems did not appear to be in equilibrium. Some progress (more at Larderello than at The Geysers) was made by D'Amore and Truesdell (1980) in applying semi-empirical gas geothermometers, but understanding of The Geysers gas chemistry awaited recognition that wellhead steam was a mixture of reservoir vapor and vaporized reservoir liquid.

Gases at equilibrium in reservoir liquid and vapor will have quite different concentrations (according to solubilities) in each phase. Mixtures of vapor and vaporized liquid collected at the wellhead will, therefore, have gas concentrations that cannot be related to equilibrium in either phase unless the reservoir temperature or the fraction of reservoir vapor (or liquid) is known. Using a method that Giggenbach (1980) developed for hot-water systems, D'Amore, Celati and Calore (1982) and D'Amore and Celati (1983) showed that by combining two gas equilibria with gas solubilities, both the reservoir temperature and the vapor fraction or effective reservoir steam saturation (called "y") could be calculated. D'Amore and Truesdell (1985) used this method to show that areas of The Geysers differed greatly in y but relatively little in temperature (Figure 4). Southeast Geysers samples showed y values from 0.005 to 0.1, indicating that produced steam originated almost entirely from vaporized liquid, but samples from the central and southwest Geysers showed y values of 0.1 to 1.0, indicating a much larger contribution of reservoir vapor to produced steam.

The variation in y is directly related to the variation in gas/steam ratio. Representative gas analyses are given in Table 1 for low, medium, and high total gas/steam ratios from three areas of The Geysers.

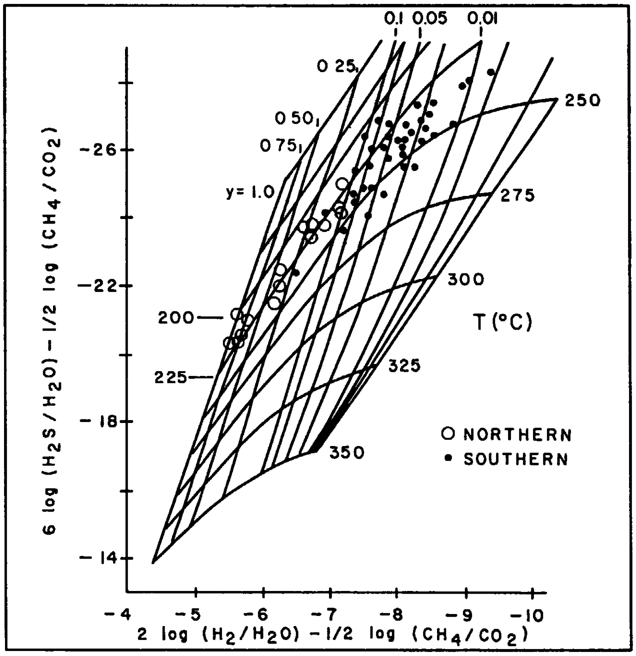

Figure 4. Reservoir temperatures and steam saturation for two areas of The Geysers calculated from gas geothermometers. (Adapted from D'Amore and Truesdell, 1985).

Fieldwide Patterns in Gases and Isotopes

Studies of the fieldwide gas and isotope chemistry of Larderello steam (Celati and others, 1973; D'Amore and others, 1977) show that, in general, gas concentrations (gas/steam, NH_3) increase from the center of the field toward the edge while concentrations of substances more soluble in liquid (^{18}O, H_3BO_3, Cl) decrease in this direction. These patterns were interpreted by D'Amore and Truesdell (1979) to result from lateral steam movement and condensation that could be modeled as a Rayleigh condensation process. In this process the concentration of each constituent (C) is related to its original concentration Co and the fraction of remaining steam M/Mo by the equation

$$(C/Co) = (M/Mo)^{(1/B-1)}$$

in which B is the distribution coefficient of the constituent between vapor and liquid (C_v/C_l). Limited data from The Geysers were presented that supported this process. This model of convective circulation of steam and condensate was used to explain observed gradients in the depth to the liquid saturated zone at the margins of the Larderello field (Calore and others, 1982) and to indicate an extension of the field to the east (R. Celati, oral commun., 1981).

From the isotope data of Haizlip (1985), fragmentary published gas data, and many unpublished analyses, it is known that large concentration gradients of gas and isotope constituents exist at The Geysers. Understanding the natural processes that caused these gradients will advance our knowledge of the field and possibly assist exploitation as it did at Larderello.

With the cooperation of some of the major steam producers (GEO Operator Co., Geysers Geothermal Co., Unocal, and Sante Fe Geothermal), maps have been drawn of gas/steam ratios (in ppm gas by weight) and $\delta^{18}O$ in steam from the entire drilled Geysers field (Figures 5 and 6). These maps are highly generalized and represent different densities of data in various parts of the field. Early production data representative of original conditions were sought. Steam compositions indicating influence of injected water have been rejected as have analyses from unusually shallow (gas rich) and subcommercial (low flow rate) wells. The maps show variations only in gas/steam ratios and $\delta^{18}O$; other variations in isotopes are shown in Figure 7 and in gases in Table 1.

Nonrayleigh Gradients

Geysers steam shows ranges in gas and isotope compositions much larger than those observed at Larderello. The range in gas/steam is from about 150 parts per million by weight (ppmw) to more than 65,000 ppmw (Table 1); the published range at Larderello is from 10 to 120 liters STP/kg (approximately 17,000 to 200,000 ppmw). The range in $\delta^{18}O$ is also larger at The Geysers, -7 to +3 permil compared with -6 to 0 at Larderello. The magnitude and direction of these composition gradients at The Geysers require a different interpretation.

The Rayleigh condensation model is consistent with composition gradients in the central and Serrazzano zones at Larderello (about two-thirds of the entire field). At The Geysers this model appears to apply to the southern half of the field. Data are most complete for the southernmost end, where steam flow appears to be from west to east, as indicated by gradients in gases and isotopes. These gradients show increases to the east in total gas and NH_3 and decreases in $\delta^{18}O$ and B (Figure 8). Data supplied by Unocal for part of the south-central Geysers show the expected change in CO_2, although this could not be compared with changes in other constituents (D'Amore and Truesdell, 1979). This model does not work, however, for the central and northwest Geysers. The general increase

Table 1. Representative gas analyses.

	High		Medium		Low	
	ppm (weight)	mole % w/o H_2O	ppm (weight)	mole % w/o H_2O	ppm (weight)	mole % w/o H_2O
Northwest Geysers						
Total gas	65,223		29,422		8,410	
CO_2	55,500	74.3	26,600	71.8	7,450	69.8
H_2S	1,710	2.96	958	3.34	356	4.31
NH_3	576	1.99	414	2.89	251	6.08
Ar	--	--	.86	.0026	.11	.0012
N_2	560	1.18	270	1.15	48.8	.717
CH_4	2,580	9.49	1,020	7.56	161	4.13
H_2	347	10.1	225	13.3	73.1	14.9
S/G (mole)		30.7		66.1		227
Central and Southwest Geysers						
Total gas	13,524		5,422		2,616	
CO_2	11,500	62.5	4,460	58.5	2,080	53.6
H_2S	662	4.65	310	5.26	184	6.12
NH_3	223	3.13	101	3.41	151	10.0
Ar	<2	<0.01	2.0	0.03	.7	.02
N_2	153	1.3	78.3	1.61	35.5	1.44
CH_4	851	12.7	412	14.8	131	9.24
H_2	133	15.8	57.3	16.4	34.8	19.5
S/G (mole)		133		185		608
Southeast Geysers						
Total gas	982		443		143	
CO_2	734	51.9	322	51.1	94.7	43.2
H_2S	116	10.6	75	15.3	36.4	21.4
NH_3	30	5.46	34	13.9	.3	.37
Ar	1.0	.08	.03	.006	.01	.0062
N_2	46	5.17	3.3	.82	2.5	1.79
CH_4	43	8.33	3.4	1.54	6.4	8.06
H_2	12	18.4	5.3	18.3	2.4	23.8
S/G (mole)		1,724		3,870		11,100

of *both* gas and oxygen-18 in steam from the south-central Geysers toward the northwest is inconsistent with the condensation model, which requires changes in oxygen-18 and gas concentrations to be opposite. In addition, the magnitude of the observed changes, if caused by condensation, would require more than 99.8 percent condensation (based on gas/steam) in the northern part of the reservoir, which seems highly unlikely. Isotope and gas gradients are less definite for the south-central Geysers, and data toward the field boundaries are missing or fragmentary. Faced with explaining the oxygen-18 data, Haizlip (1985) rejected processes involving the fluid alone (boiling, condensation, etc.) and concluded that only a south-to-north increase in the amount of remanant connate water or in the rock/water ratio could explain the isotope gradient.

The isotopic similarity of steam from the northwest Geysers with connate or metamorphic waters from the

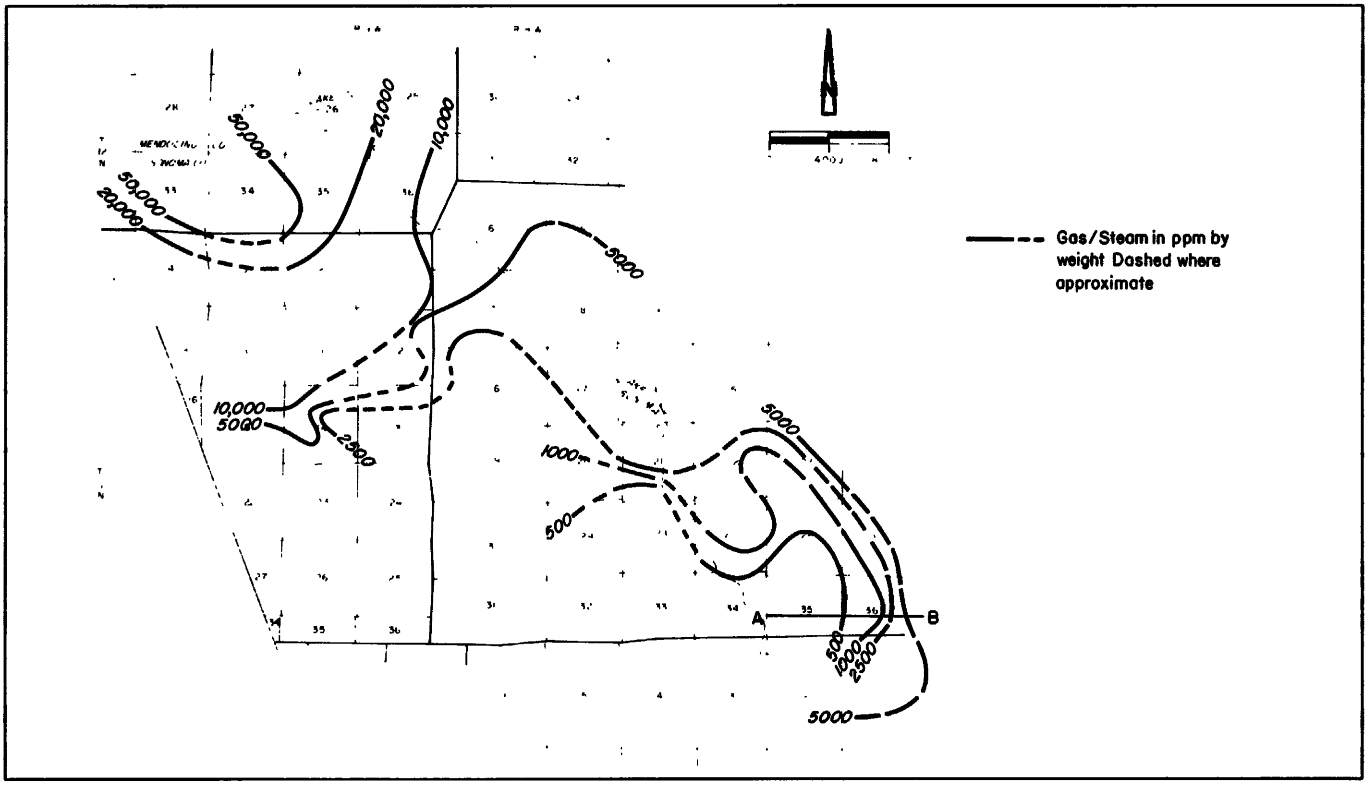

Figure 5. Gas/steam ratios for early production from wells at The Geysers, expressed as parts per million by weight. Data from the U.S. Geological Survey and steam-producing companies including GEO Operator, Geysers Geothermal, Unocal Geothermal, and Sante Fe Geothermal.

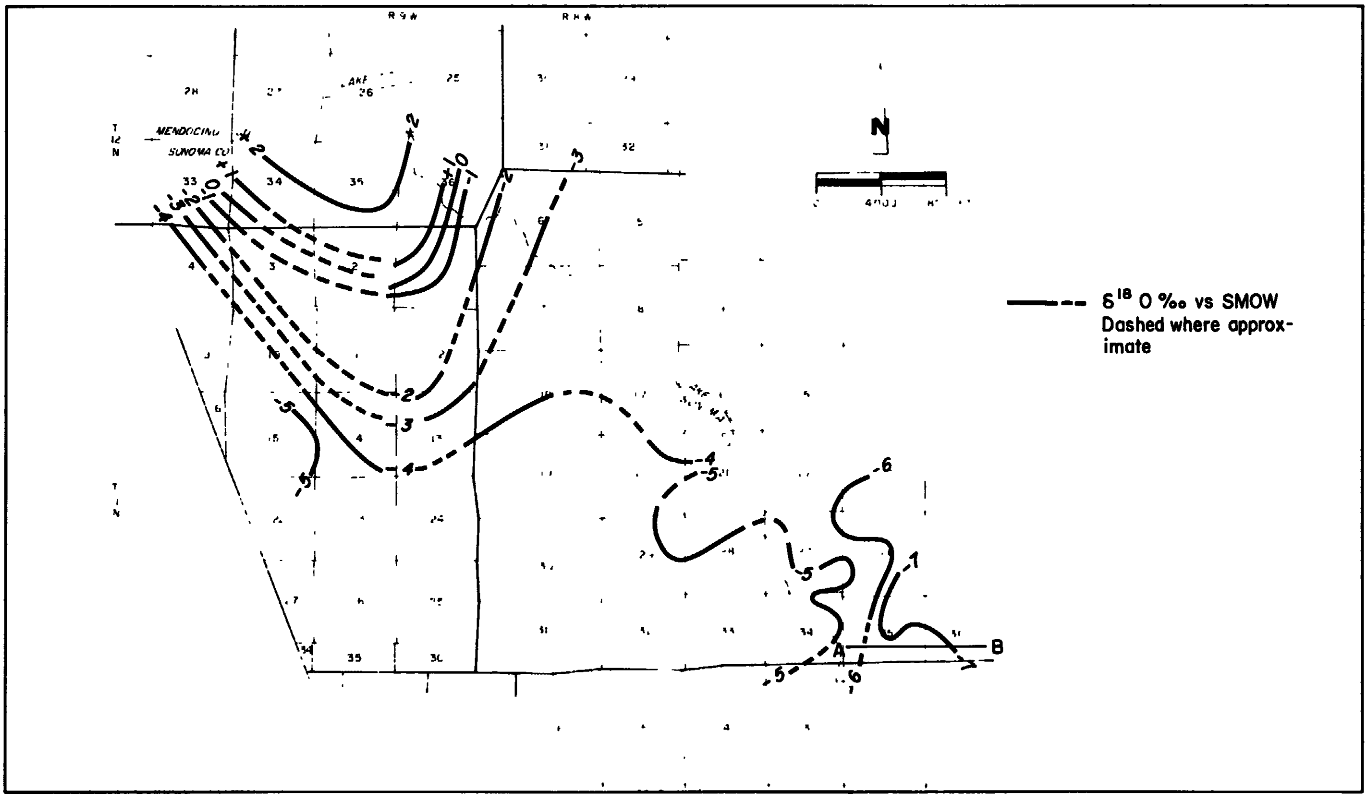

Figure 6. Oxygen-18 compositions of early production steam from The Geysers. Data sources as in Figure 5.

Sulphur Bank mine and Wilbur Spring, 25 and 40 km northwest of The Geysers, was noted by Haizlip (1985). These mineralized thermal waters were described by White, Barnes and O'Neil (1973) as originating from the metamorphism of connate sea water (original $\delta^{18}O$ and $\delta D = 0$) contained in Jurassic marine sediments, with $\delta^{18}O$ values increased to +4 to +5 by exchange with silicates and carbonates and dD reduced to -20 to -30 by exchange with low-deuterium marine clays. The Sulphur Bank and Wilbur Spring waters are similar in $\delta^{18}O$ to the connate(?) fluids described by Lambert (1976) and Sternfeld (1981) as once present in the central Geysers, and fall approximately along the $\delta^{18}O$-δD trend of northwest Geysers steam Figure 7).

Gas compositions are less distinctive. No analyses of Wilbur Spring gases are available, but Sulphur Bank mine gas is mainly CO_2, CH_4, N_2, and trace H_2S (Nehring, 1981). This gas, collected at the surface, may have lost H_2S and H_2, but the high CH_4 contents and light $\delta^{13}C$ in CO_2 are similar to Geysers samples (-14 for Sulphur Bank; about -11 to -16 for The Geysers; Huebner, 1981, and unpublished data).

Flushing by Meteoric Recharge

The major gradients in gas and isotope composition of steam are almost certainly due to meteoric recharge entering the reservoir from the southeast. Wells drilled at the southeast and east edges of The Geysers field are known to produce steam-water mixtures or water alone from the same depth as the steam reservoir a few hundred meters away. The similarity between isotopic compositions of local meteoric water and steam from the southeast Geysers (Figure 7) together with the low gas contents of steam in this area suggest that this part of the field was the site of massive recharge to the system. Recharge adjacent to outcrops of the reservoir rock has been observed at Larderello, with increases in tritium and decreases in gas and $\delta^{18}O$ in steam observed over periods of a few years (Calore and others, 1982; D'Amore and others, 1983). The lack of tritium in the steam at the southeast Geysers suggests that recharge is not a rapid process related to present exploitation (as at Larderello) but has occurred over a longer period or from older waters (>60 years).

Low gas content, δ18O and y values, and high steam flows in the southern Geysers all suggest that a large proportion of the reservoir fluid consists of liquid water. This liquid water must be held in small fractures and pores of the reservoir rock coexisting with vapor in larger openings because neither drilling nor seismic observations favor the existence of a large, well-defined water-saturated zone within the productive volume of the reservoir. In the northern Geysers there is also no evidence of a well-defined water-saturated zone even to the 5-6 km maximum depths of induced seismicity in the oldest producing zone. In this part of The Geysers, high gas, $\delta^{18}O$ and y, and lower productivity suggest much lower liquid water contents in the productive reservoir.

Boiloff, Then Flushing

The apparent lack of a deep water-saturated zone in any part of The Geysers suggests that the system has undergone a near-complete boiloff of its original liquid. This is in agreement with geologic, petrologic, and simulation studies, which all suggest that The Geysers started as a hot-water saturated reservoir and became vapor-dominated through a deficit of fluid recharge to discharge (see for example, White, Muffler, and Truesdell, 1971; Lambert, 1976; Preuss, 1985). This process does not necessarily tend to a stable steady state; the vapor- dominated zone can extend downward as long as there is liquid to displace. It is possible that a seismic event or other disturbance could allow liquid to enter the underpressured vapor-dominated reservoir from the side where adequate permeability exists. If liquid water entered a nearly dry vapor-dominated reservoir, its effect would depend on its quantity and the depth of entry. Moderate quantities and shallow entry would favor recharge of liquid suspended in the reservoir, while large quantities and deep entry

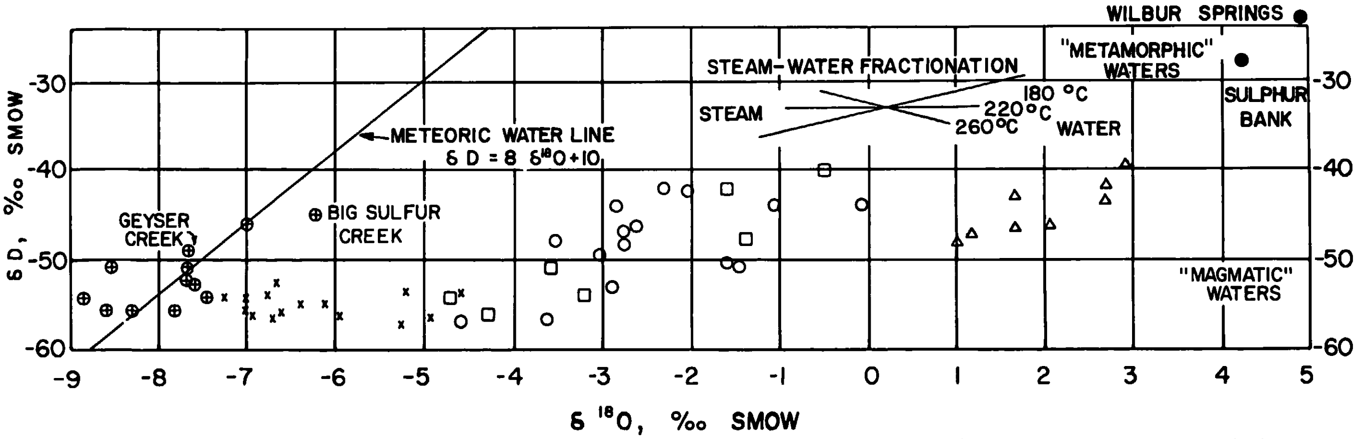

Figure 7. Oxygen-18 and deuterium compositions of early production steam from The Geysers (Data sources as in Figure 5). Symbols: x southeast; □ central; ⊕ west; △ northwest; ○ meteoric waters; ● connate or metamorphic waters.

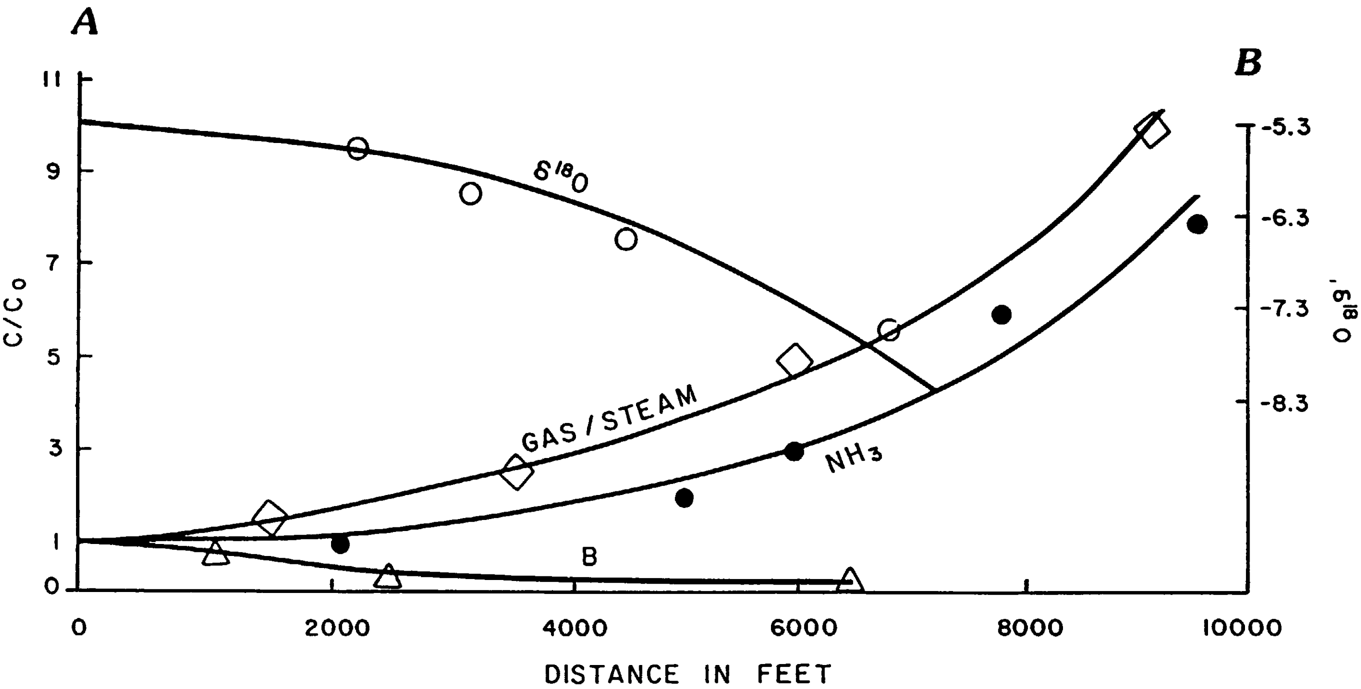

Figure 8. Gradients in steam composition across part of the southern Geysers. Location of cross section line A-B shown in Figures 5 and 6.

could produce a liquid saturated zone that might be large enough to reverse the process of vapor domination. In either case, with time the liquid would move throughout the reservoir. The movement of suspended liquid would depend on vaporization and condensation and would be relatively slow unless hastened by removal (production) of steam as observed with recent recharge at Larderello. Venting of steam and resulting lateral pressure gradients must be important in causing lateral movement of liquid away from areas of recharge. The relative locations of recharge areas and vents have apparently influenced the flow of recharge at The Geysers.

Gradients Related to Vents

Although surface alteration is found throughout The Geysers, the greatest concentration is in the area of the Big Geysers (Units 1-8) along with the largest natural vents. The distribution of vent areas may explain the smaller gradients in ^{18}O and gas between the southeast and central Geysers and the steepening gradients to the northwest. Driven by meteoric recharge from the southeast, gases and high $\delta^{18}O$ steam would have gradually migrated to these vents and left the system. Strong venting in the central Geysers (the Big and Little Geysers areas) would have allowed extensive flushing and homogenization of fluid compositions between this area and the southeast Geysers, while less venting to the northwest would have allowed less flushing and homogenization.

If recharge waters entered the system from the southeast, reservoir rocks in this area would have undergone the greatest alteration of their oxygen isotopes to reach equilibrium with fresh (unaltered) meteoric water. Reservoir rocks further to the northwest would have been progressively less altered as oxygen-18 in recharge waters increased through exchange with rock or mixture with connate formation waters. The influx of meteoric recharge would also be expected to leach minerals with which it was not in equilibrium. Sulfide minerals and organic matter would be oxidized by air-saturated meteoric recharge; calcite would be dissolved through the refluxing action of steam condensation and downward flow of steam condensate. The existence of Rayleigh condensation gradients at the southern margin of The Geysers (Figures 5, 6 and 8) that are counter to gradients resulting from flushing suggests that flushing occurred and was complete before the Rayleigh gradients were established. Exploration of this chronology may be possible through petrologic studies.

With continued exploitation of The Geysers, reservoir pressure differentials between the reservoir and surrounding ground water will increase and, as at Larderello, renewed recharge may occur and tritium may appear. For this reason the use of tritium as an artificial tracer should be avoided.

CONCLUSION

The Geysers geothermal field is large and geologically and geochemically complex with a history that is only starting to be understood. Natural circulation at The Geysers is locally dominated by the "heat pipe" mechanism in which upward-flowing steam condenses and produces downward-flowing condensate driven by volcanic heat supplied to yet undiscovered boiling zones. Larger scale circulation patterns based on lateral steam flow away from boiling zones (and condensate back-flow) indicated by "Rayleigh" composition patterns appear to dominate at Larderello and in parts of The Geysers. Large-scale circulation at The Geysers appears to have been dominated by flushing with meteoric water probably initiated by catastrophic breakthrough of liquid at the southeastern margin of the system. In this process recharge has progressively removed oxygen-18 and gases (including gas-forming minerals) from the reservoir, with effects diminishing from the southeast, where steam is almost gas free and similar in $\delta^{18}O$ to local meteoric water, to the northwest, where steam is gas and oxygen-18 rich. The exact roles of residual connate waters and high rock/water ratios in the original fluid compositions flushed by meteoric recharge are not yet known. The association of high permeability with highly flushed fluids suggests that the flushing has had physical as well as chemical effects on the reservoir or that flushing was facilitated by existing high permeability.

ACKNOWLEDGEMENTS

We wish to thank the GEO Operator Co., Geysers Geothermal Co., Unocal Geothermal Co., and Sante Fe Geothermal Co. for the use of data on steam compositions. We wish to thank our colleagues, especially Don White, and Dave Oppenheimer for stimulating discussions, and Cathy Janik and Bob Fournier for careful reviews. Steve Mason, Barbara Bernegger, and Mary Ann Mikus were indispensable to the production of this paper.

REFERENCES

Allen, E.T. and Day, A.L., 1927. Steam wells and other thermal activity at The Geysers, California: Carnegie Institution of Washington Publication 378, p. 106.

Barnes, Ivan, Hinkle, M.E., Rapp, J.B., Heropoulos, Chris and Vaughn, W.W., 1973. Chemical composition of naturally occurring fluids in relation to mercury deposits in part of north-central California: U.S. Geological Survey Bulletin 1382-A, 19 p.

Brook, C.A, 1981. Variability and sources of hydrogen sulfide and other gases in steam at The Geysers, *in* McLaughlin, R.J. and Donnelly-Nolan, J.M., eds., Research in the Geysers-Clear Lake geothermal area, northern California: U.S. Geological Survey Professional Paper 1141, p. 193-203.

Bufe, C.G., Marks, S.M., Lester, F.W., Ludwin, R.S. and Stickney, M.C., 1981. Seismicity of The Geysers-Clear Lake region, *in* McLaughlin, R.J. and Donnelly-Nolan, J.M., eds., Research in the Geysers-Clear Lake geothermal area, northern California: U.S. Geological Survey Professional Paper 1141, p. 129-137.

Calore, C., Celati, R., D'Amore, F. and Noto, P., 1982. Geochemical evidence of natural recharge in the Larderello and Castelnuovo areas: Proceedings, 8th Workshop on Geothermal Reservoir Engineering, Stanford, December 1982, p. 323-328.

Celati, R., Noto, P., Panichi, C., Squarci, P. and Taffi, L., 1973. Interactions between the steam reservoir and surrounding aquifers in the Larderello geothermal field: Geothermics, v. 2, no. 3-4, p. 174-185.

D'Amore, Franco and Celati, C., 1983. Methodology for calculating steam quality in geothermal reservoirs: Geothermics, v. 12, no. 2-3, p. 129-140.

D'Amore, Franco, Celati, R. and Calore, C., 1982. Fluid geochemistry applications in reservoir engineering (vapor-dominated systems): Proceedings, 8th Workshop on Geothermal Reservoir Engineering, Stanford, December 1982, p. 295-308.

D'Amore, F., Celati, R., Calore, C. and Bertrami, R., 1983. Effects of natural recharge on gas composition in the Larderello-Castelnuovo area: Proceedings, 9th Workshop on Geothermal Reservoir Engineering, Stanford, December 1983, p. 221-227.

D'Amore, F., Celati, R., Ferrara and Panichi, C., 1977. Secondary changes in the chemical and isotopic composition of the geothermal fluids in Larderello field: Geothermics, v. 5, p. 153-163.

D'Amore, F. and Truesdell, A.H., 1979. Models for steam chemistry at Larderello and The Geysers: Proceedings, 5th Workshop on Geothermal Reservoir Engineering, Stanford, December 1979, p. 283-297.

D'Amore, F. and Truesdell, A.H., 1980. Gas thermometry for drillhole fluids from vapor-dominated and hot-water geothermal fields: Proceedings, 6th Workshop on Geothermal Reservoir Engineering, Stanford, December 1980, p. 351-360.

D'Amore, F. and Truesdell, A.H., 1985. Calculation of geothermal reservoir temperatures and steam fraction from gas compositions: 1985 International Symposium on Geothermal Energy, Geothermal Resources Council Transactions, v. 9, pt. 1, p. 305)310.

Eberhart-Phillips, D. and Oppenheimer, D.H., 1984. Induced seismicity in The Geysers geothermal area, California: Journal of Geophysical Research, v. 89, no. B-2, p. 1191-1207.

Giggenbach, W.F., 1980. Geothermal gas equilibria: Geochimica et Cosmochimica Acta, v. 44, p. 2021-2032.

Haizlip, J.R., 1985. Stable isotope composition of steam from wells in the northwest Geysers, The Geysers, Sonoma County, California: 1985 International Symposium on Geothermal Energy, Geothermal Resources Council Transactions, v. 9, pt. 1, p. 311-317.

Huebner, Mark, 1981. Carbon-13 isotope values for carbon dioxide gas and dissolved carbon species in springs and wells in The Geysers-Clear Lake region, *in* McLaughlin, R.J., and Donnelly-Nolan, J.M., eds., Research in the Geysers- Clear Lake geothermal area, northern California: U.S. Geological Survey Professional Paper 1141, p. 211-213.

Hulston, J.R. and McCabe, W.J., 1962. Mass spectrometer measurements in the thermal areas of New Zealand. Part 1. Carbon dioxide and residual gas analyses: Geochimica et Cosmochimica Acta, v. 26, p. 383-397.

Lambert, S.J., 1976. Stable isotope studies of some active geothermal systems: California Institute of Technology, Ph.D. thesis, p. 387.

Lipman, S.C., Strobel, C.J. and Gulati, M.S., 1977. Reservoir performance of The Geysers field, *in* Proceedings of the Larderello workshop on geothermal resource assessment and reservoir engineering: Geothermics, v. 7, p.209-219.

McLaughlin, R.J., 1978. Preliminary geologic map and structural sections of the central Mayacmas Mountains and The Geysers steam field, Sonoma, Lake, and Mendocino Counties, California: U.S. Geological Survey Open-File Map 78-389, scale 1:24,000.

McLaughlin, R.J., 1981, Tectonic setting of pre-Tertiary rocks and its relation to geothermal resources in The Geysers- Clear Lake area, Northern California: U.S. Geological Survey Professional Paper 1141, p. 3-23.

Nehring, N.L., 1981. Gases from springs and wells in The Geysers-Clear Lake area, *in* McLaughlin, R.J., and Donnelly- Nolan, J.M., eds., Research in the Geysers-Clear Lake geothermal area, northern California: U.S. Geological Survey Professional Paper 1141, p.205-209.

Oppenheimer, D.H., 1986. Extensional tectonics at The Geysers geothermal area, California: Journal of Geophysical Research, v. 91, p. 11463-11476.

Preuss, Karsten, 1985. A quantitative model of vapor-dominated geothermal reservoirs as heat pipes in fractured porous rock: Geothermal Resources Council Transactions, v. 9, pt. II, p. 353-359.

Sondergeld, C.H. and Turcotte, D.L., 1977. An experimental study of two-phase convection with applications to geological problems: Journal of Geophysical Research, v. 82, p.2045-2053.

Sternfeld, J.N., 1981. The hydrothermal petrology and stable isotope geochemistry of two wells in The Geysers geothermal field, Sonoma County, California: University of California, Riverside Report UCR/IGPP 81/7, M.S. thesis, 202 p.

Thomas, R.P., 1981. Subsurface Geology, *in* A reservoir assessment of The Geysers: California Department of Conservation, Division of Oil and Gas Report TR-27, p. 9-20.

Truesdell, A.H. and White, D.E., 1973. Production of superheated steam from vapor-dominated geothermal systems: Geothermics 2, v. 3-4, p. 154-173.

Truesdell, A.H., Nathenson, M. and Frye, G.A., 1981. Downhole measurements and fluid chemistry of a Castle Rock steam well, The Geysers, Lake County, California: Geothermics, v. 10, no. 2, p. 103-114.

Urban, T.C., Diment, W.H., Sass, J.H. and Jamieson, I.M., 1976. Heat flow at The Geysers, California: Proceedings, 2nd United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, 1975, v. 2, p. 1241-1245.

Walters, M.A., Sternfield, J.N., Haizlip, J.R., Drenick, A.F. and Combs, Jim, 1988. A vapor-dominated reservoir exceeding 600°F at The Geysers, Sonoma County, California: Proceedings, 13th Workshop on Geothermal Reservoir Engineering, Stanford Report. SGP-TR 113, p. 73-81.

Weres, O., Tsao, K. and Wood, B., 1977. Resource technology and environment at The Geysers: Lawrence Berkeley Laboratory Report LBL-5231.

White, D.E., Muffler, L.J.P. and Truesdell, A.H., 1971. Vapor-dominated hydrothermal systems compared with hot-water systems: Economic Geology, v. 66, no. 1, p. 75-97.

White, D.E., Barnes, Ivan and O'Neil, J.R., 1973. Thermal and mineral waters of nonmeteoric origin, California Coast Ranges: Geological Society of America Bulletin, v.84, p. 547-560.