DOWNHOLE MEASUREMENTS AND FLUID CHEMISTRY OF A CASTLE ROCK STEAM WELL, THE GEYSERS, LAKE COUNTY, CALIFORNIA

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Introduction

Certain wells within The Geysers steam field have standing water columns either when first drilled or when produced at low flow rates. These water columns have been attributed by Lipman et al. (1978) to accumulation of water condensing in the well bore. Alternative explanations are that perched water bodies exist within the reservoir or that a deep water body underlying the steam reservoir has been tapped. A well in the Castle Rock field of The Geysers drilled by Signal Oil and Gas Company (now Aminoil, U.S.A.) with such a water column was sampled in 1976 for water, gas, and isotope chemistry in hopes of distinguishing between these possible origins; the results along with the well history and downhole pressure and temperature measurements are reported here.

The well is located in Lake County, California, in the central part of the Castle Rock field, 4.8 km west-northwest of the town of Anderson Springs. Drilling was started in mid 1970 on a ridge at an elevation of 700 m above sea level. Steam entries were encountered at depths (below land surface) of 1,899, 1,902, 2,176, 2,248 2,288, and 2,295 m; the total depth drilled was 2,498 m. Large volume water entries above 685 m were cased off to 762 m.

Downhole Measurements

Static downhole pressure and temperature surveys were made each year from 1973 to 1977. During that period the well was held at a small bleed flow through a 2.5-cm orifice, except during short (usually less than 8 hour) performance tests. The results of the downhole surveys are shown in figures 1 and 2. In each of these surveys standing water was found in the well below a vapor zone. Temperatures and pressures above the water level generally decreased with time, and the level of water in the well rose. The pressure in the water zone was remarkably constant at each depth and the pressure and temperature near the bottom of the well at 2,484 m remained at 53.6 20.3 bars and 247.7 ±1.6°C from 1973 to 1976. (Measurements in 1977 were not made below 2,164 m.) The variations of pressure and temperature at this depth are well within the expected instrumental reproducibility of 22% of full range or 20.8 bars and ±2.2°C.

Above the level of standing water the measurements indicate the presence of vapor (steam + gas). Below 610 m in this vapor zone the temperatures were those expected for steam-water saturation at the measured pressures within less than ±0.7°C in 1973, 1974, and 1977, with larger differences (to 2.7°C) in 1975 and 1976 possibly due to instrumental error. Above 610 m the temperature differences increased probably due to accumulation of gas. The pressure gradients (near 0.17 bars/100 m) were also close to those calculated for columns of saturated steam except in 1976 and 1977 when the observed gradients were almost twice those calculated. These high gradients could be produced by accumulation of nearly 100% CO_2 in the well but this was not observed in the chemical samples. Pressure gradients near the surface were slightly higher due to gas accumulation.

Below the water level, pressure gradients were equal to those calculated for pure water; and temperatures, although greater than in the vapor zone, were much lower than those expected for saturation at the observed pressures indicating absence of steam.

Pressures and temperatures in the water zone were remarkably constant despite large changes in the vapor zone above. This suggests that the physical conditions within the well were controlled by the reservoir away from the well. The temperature at the well bottom is close to that at similar depths in Castle Rock wells without standing water and similar to the temperature at the bottom of the vapor zone in 1973 (at 2,270 m). Pressures at 2,286 m have remained at 3820.3 bars, close to field pressures for this depth as observed or extrapolated from other wells without standing water.

These observations suggest that steam enters the well from the deepest observed steam entries (at 2,290 ± m) and the pressure in the water column is controlled at this depth by the pressure of steam outside the well. Temperatures at this point have been below the field average for this depth after 1973 but pressure communication could be maintained even if the formation cooled off locally.

The standing water may be local to the well or could represent the top of a more extensive water body. Nearby wells did not enounter water but were not drilled to as great a depth. Redrilling of this well to 2,714 m in early 1977 did not encounter any deeper steam zones nor did it greatly affect the water level when measured in May 1977. This suggests that the rocks drilled were impermeable or that the water, if perched, extends at least to 2,714 m.

The cooling off of the well and the accumulation of gas in the upper 600 meters both suggest that a large proportion of the steam flowing up the well is condensing in the well bore and flowing down the well. This is the probable origin of the water in the well, although this water may have mixed with water of a larger water zone. The continuing decrease in temperature and pressure in the well suggest that steam entry to the well at its normally low flow rate was not sufficient to maintain reservoir pressure and temperature conditions in the well and that condensed water continued to flow away from the well. During a full flow test the accumulated water clogging the steam entries (probably near 2,290 m) was expelled and steam access was sufficient to temporarily heat the well bore. A shorter period of rest after testing may explain the inconsistently high downhole pressures and temperatures measured in 1976.

Collection and testing on March 9, 1976.

Samples of condensed steam, gas, and expelled water were collected during a flow test on March 9, 1976. The samples were taken on bleed (2.5-cm orifice) and at various intervals after the well was opened (at 12:45 p.m.) to flow through a 10-cm orifice. Liquid water was ejected from the well immediately after increasing its flow. This ejected water was sampled at the lip of the horizontal silencer before it stopped flowing at about 1:15 p.m. A second slug of water was ejected from the well at 3:30 p.m. and sampled at 4:00 p.m. Again the flow lasted only a short time. Throughout the test the steam which had been initially wet and opaque at the mouth of the silencer became gradually drier and more transparent. During ejection of the second slug of water the steam was again opaque. Samples of steam condensate and gas were taken 15 minutes before the flow was increased and 2-1/4 and 4-1/4 hours afterwards. Chemical and isotopic analyses of steam condensate and ejected water (along with earlier condensate analyses from Aminoil Laboratories) are shown in table 1 and gas analyses in table 2.

Water Analyses

The condensate analyses show that compared to bleed steam, full flow steam contained higher concentrations of chemical constituents more soluble in liquid (Cl, B, NH_4) and lower concentrations of constituents more soluble in vapor (CO_2 as HCO_3, H_2S). These observations are consistent with partial condensation during bleed and removal of liquid-soluble constituents to the water draining down the well bore and concentration of gas-soluble constituents in the bleed steam. The ejected water was much higher than either condensate in most salts because salts are only slightly soluble in steam at these pressures. The salts contained in the ejected water could all have been leached from reservoir rock and their concentrations are quite consistent with this water originating as steam condensate rather than from the deep brine body which has been hypothesized to underlie the field.

The second slug of ejected water was more concentrated in most constituents than the first slug suggesting a longer period of rock leaching. It is possible that this slug represented relatively stagnant water below the main steam entry to the well. This water may have been ejected when a deeper steam passage was cleared and steam entered the well at a lower point.

Gas Analyses

The gas/steam molal ratio of the bleed steam (1/1,720) was much lower than that of full flow steam ($\sim$1/4,500, table 2). This is consistent with partial condensation of steam in the well bore when the well is on bleed flow. If it is assumed that negligible condensation occurs on full flow and that the amount of gas dissolved in the liquid water is negligible it is possible to calculate the relative amounts of steam condensing and flowing out of the well near the bottom and of steam (and entrained water) flowing out at the wellhead when the well is on bleed. Calculations from the gas/H_2O ratios suggest that 40% of the total steam is leaving at the top of the well with 60% condensing and flowing down and out at the bottom.

Hydrogen and oxygen isotopes.

Oxygen-18 and deuterium were measured in the condensates from bleed and full flow steam and in the ejected water (table 1 and figure 3). The isotopic composition of the ejected water appears to bear little relation to the calculated composition of water condensed in the well bore and the second sample appears to have been in isotopic equilibrium with full flow steam at 95°C. It is suggested that the isotopic composition of the ejected water was rapidly altered in the silencer at temperatures near surface boiling (97°C at this altitude) by exchange with steam blowing over it. This alteration was partial when the first sample was collected and complete when the second sample was collected.

The ratio of change in oxygen-18 to the change in deuterium for bleed versus full flow steam indicates partial isothermal separation of steam and water at about 250°C (figure 3). This suggests that the temperature of separation between steam entering the well and liquid water leaving it is close to the reservoir temperature, and is consistent with the pressure control mechanism suggested earlier of a steam entry at 2,290 m from the main reservoir initially at 247°C. The precision of the deuterium measurement (±1°/₀₀) is not however sufficient to indicate the temperature of separation to better than ±25°C so this slope is consistent with separation at the temperatures observed in the well.

The isotopic changes can also be used to calculate the fraction of steam leaving the wellhead and the fraction condensing and draining down the well. Assuming that the bleed steam may actually have some entrained water, the initial flow of saturated steam divides into three streams. Part of the steam remains vapor and flows out of the well; part of the steam condenses to liquid water and is entrained in the bleed steam and leaves the well with it; and finally, part of the steam condenses to liquid water and flows down the well and out into the formation. Applying conservation of energy to this process including the effects of wellbore heat loss (Ramey, 1962), the enthalpy of the bleed steam may be determined as a function of $m/m_s(0)$ where m is the mass flow rate of bleed steam and entrained condensate out of the well and $m_s(0)$ is the mass flow rate of saturated steam into the well at the bbttom. If the enthalpy of the bleeding mixture were known, this ratio could be determined directly. The enthalpy was not measured, but this energy balance provides upper and lower bounds on the ratio $m/m_s(0)$. The enthalpy of the bleeding discharge must be between that for saturated liquid and saturated vapor at 230 to 240°C, and these bounds constrain $m/m_s(0)$ to be between 0.42 and 0.74 for the bleed steam and between 1.0 and 0.90 for the full flow steam.

Isotopic fractionation of oxygen-18 and deuterium between the steam flow and the condensing water flows may also be modeled by writing conservation of mass (steam up, water up and down), conservation of isotopes in those flows, and the equilibrium fractionation factors between water and steam (Truesdell, et al., 1977). These equations may be used to derive the isotopic composition of feed steam from the measured compositions of surface bleed steam and water as a function of the ratio of mass of bleed flow to initial mass flow of steam $m/m_s(0)$. For each isotopic ratio ($^{18}O/^{16}O$, D/H) two curves are shown on figure 4 for the compositions of feed steam derived from the measured isotopic composition of bleed steam and water, one for assumed fractionation at 230°C and one for 240°C. The curves are only plotted in the range of $m/m_s(0)$ of 0.42 to 0.74 as determined by the enthalpy calculation. Also shown are two short curves marked "full flow." Each full flow curve is for the average of the two measured contents of deuterium and of oxygen-18 isotopes given in table 1. For $m/m_s(0)$ of one, all the flow exits the well. Since the enthalpy was not measured, there is some possibility of condensation and flow down the well, so the curves have been calculated down to $m/m_s(0)$ of 0.9. For the oxygen-18 contents of the source steam to have been the same from full flow and bleed measurements, the bleeding well would have to produce about 55% of the inlet steam with 45% draining down the well at either 230 or 240°C. For deuterium, the two sets of measurements are only consistent for an assumed 240°C fractionation temperature. Deuterium measurements have, however, standard deviations of ±1°/₀₀. This large error compared to oxygen-18 measurements, means that the failure of consistency for deuterium values at 230°C is hardly significant. The ratio of 55% of the inlet mass of steam being produced by the bleeding well is in reasonable agreement with a value of 40% based on the gas analyses and with the 42% to 74% indicated by heat transfer calculations.

Summary

Standing water in a Geysers steam well has been shown from physical measurements and chemical and isotopic analyses of bleed and full flow steam to result from condensation in the well bore. Pressures and temperatures in the standing water suggest pressure communication with the steam reservoir at a point below the standing water level. Limited inflow of steam and outflow of condensed water has allowed the well bore and surrounding rock to decrease markedly in temperature and pressure over the period 1973-1977. Chemical analyses of condensate and ejected liquid water show significant differences, although ejected water also appears to originate as steam condensate.

Gas and isotopic analyses of bleed and full flow steam agree with heat transfer calculations that indicate that about half of the steam entering the well during bleed flow is condensed in the well bore. We conclude that the chemical and isotopic composition of steam collected from this well and probably also from other wells on bleed is dominated by condensation and phase separation in the well and only full flow steam can be clearly related to field conditions.

References

Lipman, S. C., Strobel, C. J. and Gulati, M. S., 1978, Reservoir performance of The Geysers field: Proceedings, Larderello Workshop on Geothermal Resource Assessment and Reservoir Engineering, September 1977. Geothermics (in press).

Ramey, H. J., Jr., 1962, Wellbore heat transmission: Transactions AIME, v. 225, p. 427-435.

Truesdell, A. H., Nathenson, Manuel, and Rye, R. O., 1977, The effects of subsurface boiling and dilution on the isotopic compositions of Yellowstone thermal waters: Journal of Geophysical Research, v. 82, p. 3694-3704.

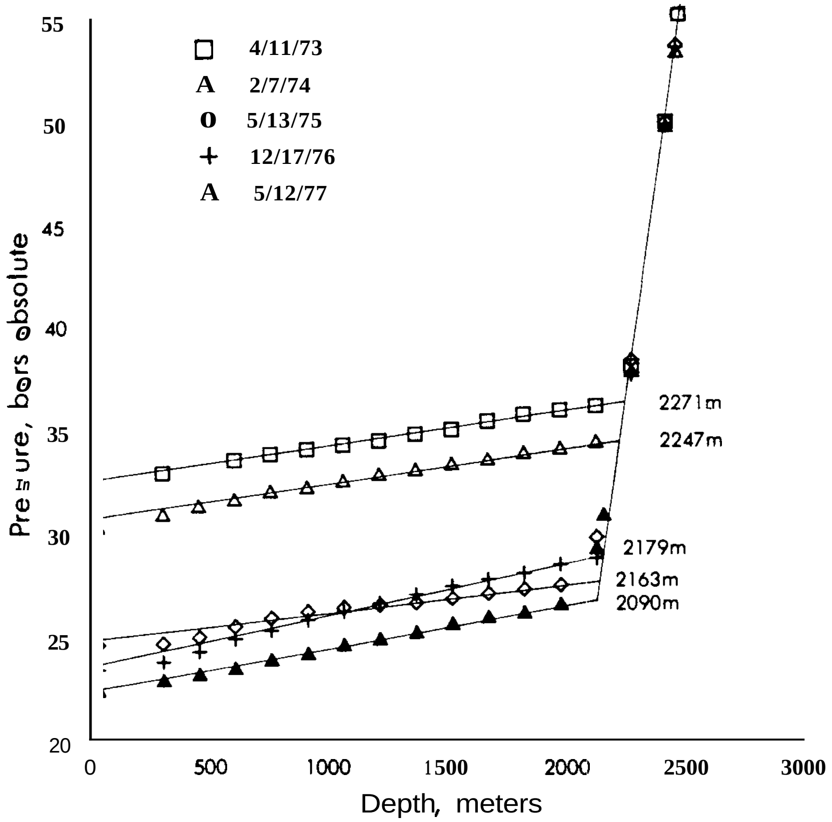

FIGURE 1 Downhole pressures measured from 1973 to 1977 in the Castle Rock steam well with position of water-steam interface indicated.

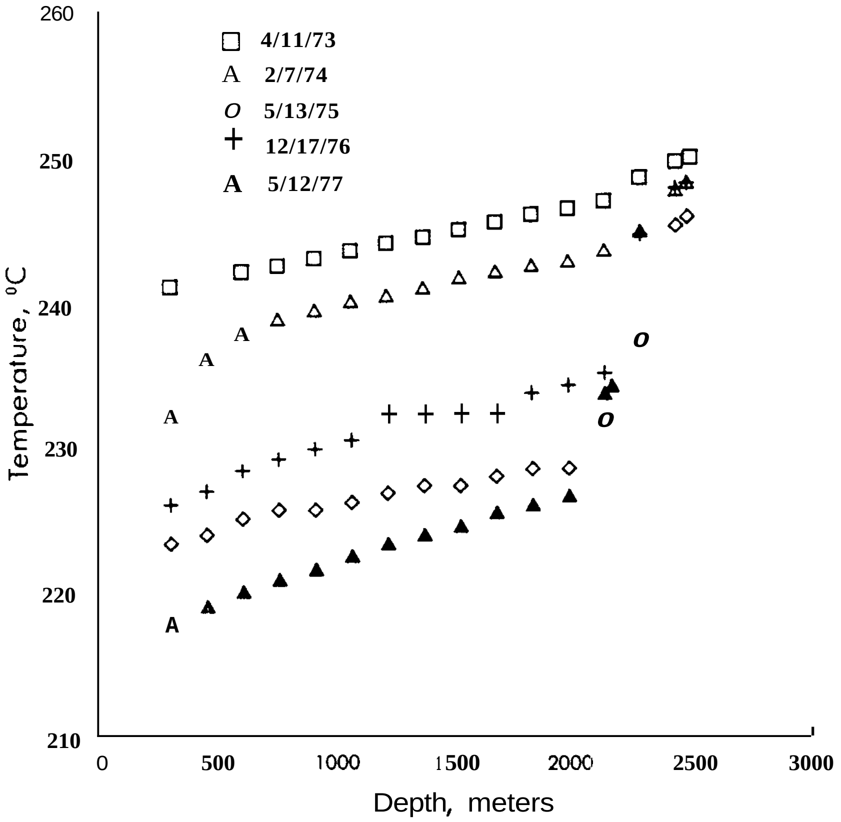

FIGURE 2 Down hole temperatures measured from 1973 to 1977 in the Castle Rock steam well.

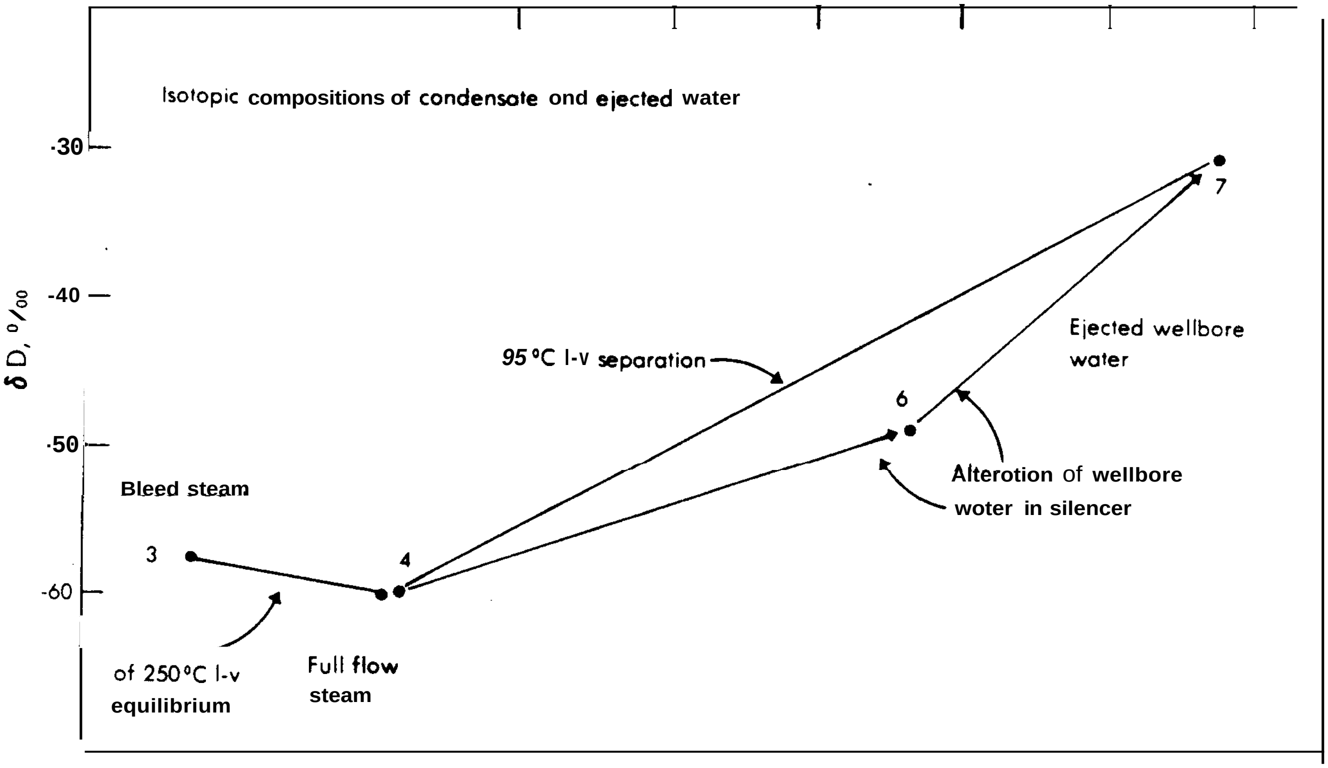

Figure 3 Oxygen-18 and deuterium compositions of bleed and full flow steam condensates and of ejected liquid water collected March 9, 1976 from the Castle Rock steam well with equilibrium slopes indicated for water-steam separation at reservoir and silencer temperatures.

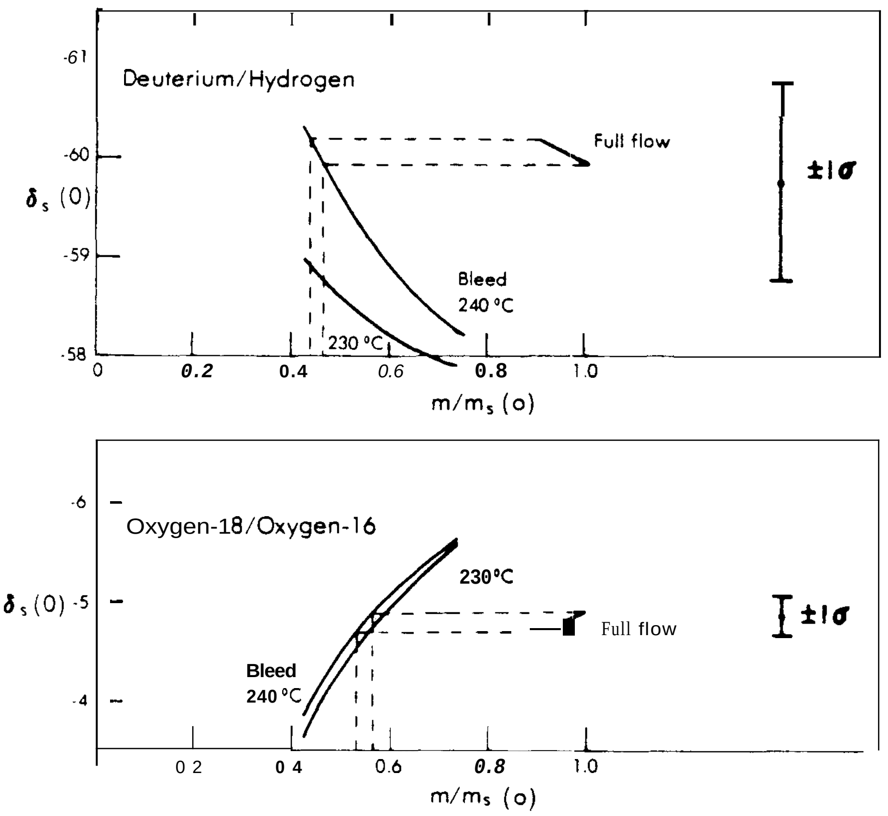

Figure *4* Isotopic compositions of source steam derived from measurements under full flow and bleeding conditions as a function of ratio of mass flow measured at the surface to input mass flow of saturated steam. Curves for bleeding flow calculated for two assumed temperatures of isotopic equilibration. Assuming the isotopic composition of feeding steam to be the same under full flow and bleed, a horizontal projection from the full flow values implies that the bleeding flow was only about 55% of the input steam flow. Standard deviations for deuterium and oxygen–18 measurements are shown on the figure.

Table 1. Chemical and isotopic analyses of steam condensate and ejected water from the Castle Rock Springs well (in mg/ℓ unless otherwise noted)

	Steam condensate			--	--	Ejected water	
Analysis	1	2	3	4	5	6	7
Data and time of collection	7/7/75	2 PM 3/9/76	3/9/76 12:30 PM	3 PM	5 PM	1 PM	4 PM
Well condition	flowing	10 cm orifice	2.4 cm orifice	10 cm orifice			
WHP bars gauge	--	--	25.6	5.2	5.2	5.2	5.2
pH	5.7	5.4	6.1	5.7	5.7	8.9	7.8
Ca	0.6	<0.1	0.1	<0.1	<0.1	1.8	2.9
Mg	0.2	<0.1	0.04	0.04	0.03	1.0	0.7
NH_4	10.6	<0.2	5	9	n.d.	n.d.	n.d.
Na	<0.5	<0.05	<0.5	<0.5	<0.5	18	71
K	<0.00	<0.05	<0.5	<0.5	<0.5	7.8	12
Li	n.d	n.d.	<0.01	<0.01	<0.01	0.12	0.6
Cl	24	52	7.1	10	10	7.1	18
F	0.01	<0.1	<0.1	<0.1	<0.1	0.5	3.7
HCO_3	28	22	95	46	38	64	162
SO_4	8.4	5	13(4)*	7.3	10(3)*	9	40
NO_3	0.4	1.7	n.d.	n.d.	n.d.	n.d.	n.d.
B	0.4	2.3	0.1	1.2	2.2	42	n.d
SiO_2	<0.3	0.4	4.3	4.3	4.3	46	80
H_2S	33	122	40	35	35	n.d.	n.d.
Hg (μg/ℓ)	n.d.	0.6	n.d.	n.d.	n.d.	n.d.	n.d.
$\delta^{18}O(H_2O)$	n.d.	n.d.	−6.26	−4.83	−4.95	−1.34	+0.75
$\delta D(H_2O)$	n.d.	n.d.	−57.5	−59.8	−60.1	−48.2	−29.8

Analysts: 1, 2 J. Muggee and D. Sarkaria, Aminoil USA, Huntington Beach, Calif.
3-7 Water chemistry; J. M. Thompson
^{18}O, D; N. L. Nehring and L.D. White } U.S. Geol. Surv., Menlo Park, Calif.

*sulfate in parentheses determined on samples with H_2S fixed in the field as CdS to prevent oxidation. H_2S analyses are also on these samples.

Table 2. Gas analyses of steam collected 3/9/76
Condensate includes dissolved gases.

Analysis #	1				2				3			
Time of coll.	12:30				3:00				5:00			
Orifice	2.5 cm				10 cm				10 cm			
gas phase/ condensate molal	1/2250				1/8580				1/8630			
gas/H_2O molal	1/1720				1/4300				1/4600			
	mole % in gas	moles/1000 moles in gas	moles/1000 moles in cond.	H_2O total	mole % in gas	moles/1000 moles in gas	moles/1000 moles in cond	x_{H_2O} total	mole % in gas	moles/1000 moles in gas	moles/1000 moles in cond.	x_{H_2O} total
CO_2	[illegible]3 4	0 [illegible]	0 11	0 53	92 2	0 11	0.093	0.20	90 [illegible]	0 11	0 078	0 19
H_2S	0 53	0 002[illegible]	0 02Z	0 024	0.[illegible]2	2 6x10^{-4}	0.020	0.0[illegible]0	0.10	1 2x10^{-4}	0 020	0.020
H_2	4 [illegible]				[illegible]				3.5			
Ar	0 001				0 003				0			
O_2	0				0				0			
N_2	0.33				0 57				0.32			
CH_4	1.9				2.8				1.9			

Analyst: N. L. Nehring, U.S. Geol. Surv., Menlo Park, Calif.