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ABSTRACT

Analyses of chemical and isotopic compositions of well and spring waters at Steamboat Springs, Nevada, are used to evaluate chemical composition and temperature of the reservoir, flow, boiling, and mixing of the reservoir water, and recharge to the system. The silica, NaK, NaKCa, and sulfate-water isotope geothermometers and the chloride versus enthalpy relationship show evidence for a 230°C reservoir temperature. Correction of surface conditions to reservoir conditions gives a chloride content of 700 mg/L and a deuterium value of -119.5 permil for the reservoir. Upflow of the thermal water occurs almost exclusively along faults and fissures. Lateral flow of thermal water is present only in uncemented alluvium. During upflow along faults and fissures, decreased pressure causes boiling of the thermal water and separation of carbon dioxide into the vapor. Supersaturation with respect to calcite results from the loss of carbon dioxide into the vapor phase, which causes an increase in pH and an increase in carbonate. Mixing with cold, meteoric water is observed in only one of the sampled springs near the eastern margin of the thermal area. Isotopic analyses of cold waters indicate that recharge probably originates in the Carson range west of Steamboat Springs at an average elevation of 1920 m (6300 ft). Minor contributions to the recharge from the Virginia range cannot be ruled out.

INTRODUCTION

The thermal activity at Steamboat Springs, Nevada, was studied in the 1950's and 1960's for two reasons: to study ore deposition from thermal water and to assess the potential for generating electricity. Fundamental research was carried out at Steamboat Springs on the relationship of hydrothermal activity to ore-metal transport and ore deposition. Both mercury and antimony currently are being deposited as sulfides, and geochemical processes studied at Steamboat Springs have been applied to understanding the formation of ore bodies, such as the Comstock Lode located 11 km to the southeast. Thermal Power Company drilled 4 wells (each about 650 m in depth) in the early 1960's in an attempt to produce steam for generating electricity. Scaling of the wells with calcite was so rapid that the project was abandoned. In 1979, Phillips Petroleum Company completed a 1000 m well in a renewed attempt to obtain steam for generating electricity. Current technology may be able to alleviate the scaling problems.

Investigations of the hydrothermal processes at Steamboat Springs have been quite limited since the early 1960's, whereas methods of analyses and interpretation of geothermal data have advanced greatly. The purpose of this study is to apply these new methods and techniques of

geothermal assessment to Steamboat Springs, Nevada, in order to obtain a better understanding of the thermal reservoir and the processes involved in the formation of the hot spring waters, and to document changes in the reservoir over the last 20 years.

REGIONAL GEOLOGY

Steamboat Springs is located in southern Washoe County, Nevada, 17 km south of Reno (fig. 1). The thermal area lies in a structural trough about 9 km wide, bounded by the Carson range, with a maximum elevation of 3050 m (10,000 ft) on the west and the Virginia range, with a maximum elevation of 2320 m (7,600 ft), on the east. The trough is cut by several transverse ridges, of which Steamboat Hills is one, forming a series of north-trending, oval basins including Steamboat Valley, Pleasant Valley, Washoe Valley, and Truckee Meadows. Although the Carson range is closely related to the Sierra Nevada, the entire area lies within the Great Basin.

The regional geology of this area was described in detail by Thompson and White (1964) and is summarized here. The basement rocks consist of regionally- and contact-metamorphosed Mesozoic volcanic and sedimentary rocks. Steeply dipping, northeast- to northwest-trending faults in the basement rocks controlled the formation of the basin and ranges and the internal structure of the basin. These same faults today control the flow of thermal water. The Mesozoic rocks were intruded by Cretaceous granodiorite related to the Sierra Nevada batholith. After deep erosion exposed the granitic rocks, sporadic Tertiary volcanism

produced thick andesitic accumulations in the Virginia range and lesser accumulations elsewhere. During and after these eruptions, alluvium began accumulating in the structural basins that were forming between the mountain ranges. In the late Pliocene or early Pleistocene, flows of basaltic andesite and pumiceous rhyolite were extruded. These flows formed Steamboat Hills, and the underlying magma chamber may be the major heat source for the thermal area. A period of Pleistocene glaciation, related to glaciation of the Sierra Nevada, eroded the valleys of the Carson range that are above 3000 m. Sedimentation of the basins which occurred during and after glaciation, continues to a small degree today.

GEOLOGY OF THE THERMAL AREA

An intensive investigation of the geology of the thermal area is described by White and others (1964). The present thermal area lies along the eastern edge of Steamboat Hills and is divided into two parts, the Main Terrace and Low Terrace (fig. 2). These are separated by a vertical displacement of about 8 m. Both terraces are covered with sinter deposited by thermal water. A series of north- and northwest-trending faults, referred to as the Steamboat Fault Zone, appears to control the vertical displacement on the terraces and the flow of thermal water at the surface. An old sinter terrace, known as the High Terrace, is no longer active. The investigation of White and others (1964) included the drilling of 8 wells (GS-1 through GS-8) of intermediate depth (40 to 235 m). Sinter deposits up to 15 m in thickness generally are underlain by alluvial deposits from 15 to 35 m in thickness. Basaltic andesite is present only in GS-6, indicating its presence under Sinter Hill but not under the present hot springs area. Tertiary volcanics, mostly dikes and tuff breccias, are present in all wells except GS-3, 4, and 8. GS-4 and 8 are only 43 and 50 m deep, respectively, and probably are too shallow to intersect the tertiary volcanics. Extensive hydrothermal alteration was evident in all of the drill holes.

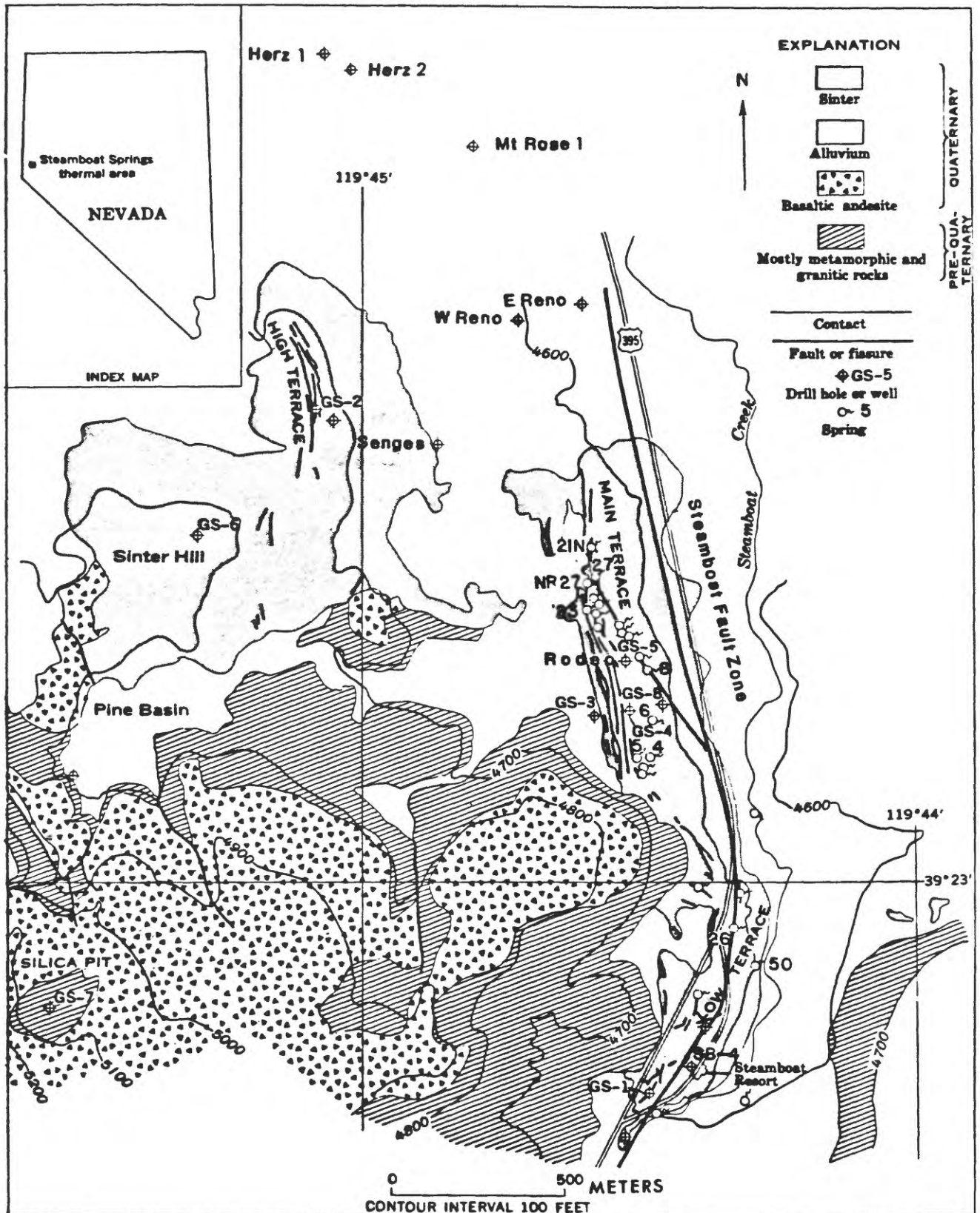


Figure 2. Generalized geologic map of the Steamboat Springs thermal area with thermal water sample locations (after Schoen and White, 1967).

ORIGIN OF THE THERMAL WATER AND ITS CHEMICAL CONSTITUENTS

Isotopic analyses suggest that the thermal water at Steamboat Springs is composed entirely of meteoric water (Craig, 1963), but the addition of up to 5 percent magmatic water would not noticeably affect the isotopic composition and has been suggested to explain the carbon dioxide, lithium, boron, and heavy-metal content (White, 1968a, p. C-15).

The general flow of water is thought to involve three main processes. Rain and snow melt from the Virginia and Carson ranges accumulate in gravels and flow into fissures that reach into the basement rock. The water probably is heated by conduction from cooling magma under Steamboat Hills and may gain additional water from the magma. Convection then causes the thermal water to rise to the surface (White, 1968a).

The moderate mineral content of the thermal waters is the result of leaching of rock, of possible magmatic contributions, and of hydrothermal alteration as the water rises along faults on its way to the surface. Two types of hypogene alteration and one type of surficial alteration occur at Steamboat Springs (Schoen and others, 1974).

Sericitization caused by hydrogen metasomatism is the more intense of the two hypogene alterations and occurs

along faults and in the deeper parts of the system. Hydrogen ions replace cations such as iron, magnesium, calcium, sodium, potassium, aluminum, and silicon. All primary and secondary minerals except quartz are replaced by illite, quartz, and pyrite.

As the hydrostatic pressure decreases near the surface, a vapor phase rich in carbon dioxide forms, causing an increase in the pH of the water and a subsequent increase in the K^+/H^+ ratio. A zone of argillization caused by potassium metasomatism forms above 100 m. Potassium ions only replace ions of similar size, such as calcium and sodium, resulting in less intense alteration. Hornblende and calcic plagioclase are altered to montmorillonite or mixed-layer illite-montmorillonite and iron-rich chlorite; biotite alters pseudomorphically to chlorite; primary K-feldspar and quartz remain unaltered.

Areas of surficial alteration occur where steam containing hydrogen sulfide enters the zone of aeration. Sulfuric acid is generated from hydrogen sulfide and oxygen in the presence of sulfur-oxidizing bacteria (Schoen and Ehrlich, 1968) or iron-oxidizing bacteria (Singer and Stumm, 1970), and the acid attacks the rocks. All minerals except quartz are altered to kaolinite, alunite, and opal. This type of alteration is most notable in the Silica Pit (fig. 2).

SAMPLE COLLECTION

Selection of Sampling Sites

The major collections for this paper were made in 1977 with minor collections in 1974 through 1976. 1977 was a very dry year in the western United States, and many of the cold springs marked on the topographic maps for the Steamboat Springs area were dry, especially in the Virginia range. Where a reasonable spatial distribution of cold springs could not be found, flowing wells were sought. Water samples also were taken from wells in the gravels of Pleasant and Washoe Valleys to test the theory that the ground water follows the northward flow of Steamboat Creek. The sample locations for the cold springs and wells are shown in figure 1. It will be noted that all of these were found in alluvial deposits, suggesting that these act as a water reservoir.

A survey of all the springs in the thermal area was made in June 1977. This included descriptions, measurement of temperature and pH, and estimation of discharge and gas flow. Because the major use of this inventory is for comparison of activity in the past and future, it is presented as Appendix 1. The numbering system for the springs is from a publication by White (1968a), which includes a detailed geologic map of the Low and Main Terraces with all fissures

and vents marked. After the survey, a representative group of flowing springs, preferably with gas discharge, was selected for sampling. The locations of the sampled thermal springs are shown in figure 2.

Collection

Several samples were taken from each spring and treated in the field to preserve the constituents of interest. Samples for chemical analyses were filtered through 0.45 μm cellulose acetate filter paper to remove particulates. The sample for anion analysis received no further treatment. The sample for cation analysis was acidified to pH 1 with hydrochloric acid to prevent precipitation of alkaline earths and heavy metals. A 1:10 dilution was made to prevent silica polymerization (Thompson, 1975). Samples for H/D, $^{16}\text{O}/^{18}\text{O}$ and tritium in water were collected directly with no treatment. The sample for $^{16}\text{O}/^{18}\text{O}$ in sulfate was treated with 10 mL/L of formaldehyde to prevent oxidation of hydrogen sulfide to sulfate (Nehring and others, 1977). For ^{14}C analysis, 200 L of water were collected. To this was added a few grams of cadmium chloride, which precipitated the hydrogen sulfide and acted as a flocculating agent, 250 mL of 50 percent sodium hydroxide, and a quantity of 1M strontium chloride sufficient to precipitate all the carbon species (Pearson

and Bodden, 1975). Gas samples were obtained by collecting the bubbles in an inverted funnel and then transferring the gas to an evacuated bottle containing sodium hydroxide (Giggenbach, 1976).

METHODS AND RESULTS OF ANALYSES

The methods of analysis for major chemical constituents and approximate error of each are given in table 1. These analyses were done by standard methods outlined in Brown and others (1970) and Environmental Protection Agency (1976). Results are in table 2.

Major and minor cation analyses were made using a Spectraspan III A DC argon plasma spectrophotometer. This

Table 1.--Methods of analysis for major chemical constituents and approximate error (mg/L unless noted).

Constituent	Method	Error
Temperature	maximum reading thermometer	$\pm 1^{\circ}\text{C}$
pH	meter-in situ	± 0.1 pH unit
TDS	gravimetric-dried at 160°C	--
NH_3	electrode-field	± 0.05
H_2S	methylene blue-field	--
SiO_2	molybdate blue	--
Cl^-	mercurometric titration	$>100 \pm 5$ $<100 \pm 1$
HCO_3^-	titration	± 10
SO_4^{-2}	gravimetric	± 2
F^-	electrode	--
B^{+3}	carmin	± 5
Na^+	electrode	$>100 \pm 5$ $<50 \pm 0.5$
K^+	atomic emission	$>50 \pm 1$ $<50 \pm 0.1$
Ca^{+2}	atomic absorption	$>50 \pm 10$ $10-50 \pm 2$ $<10 \pm 0.2$
Mg^+	atomic absorption	$>0.1 \pm 0.1$ $<0.1 \pm 0.002$
Li^+	atomic emission	$>0.2 \pm 0.2$ $<0.1 \pm 0.002$

Table 2.--Major chemical analyses of waters.

Description	Date	Temp °C	pH*	Chemical constituents reported in mg/L															
				TDS	NH ₃ *	H ₂ S*	SiO ₂	Cl	HCO ₃	SO ₄	F	B	Na	K	Ca	Mg	Li		
Dry Creek	8Jun77	15	n.d.	n.d.	n.d.	n.d.	n.d.	2.2	164	n.d.	n.d.	n.d.	n.d.	0	13.5	3.2	n.d.	n.d.	n.d.
Stock Spring	8Jun77	15	7.9	0.05	0	47	2.9	235	235	1.1	0.05	0	0.05	0	12.5	3.5	25	0.70	0
Thomas Creek Spring	8Jun77	13	7.7	0.10	0	48	1.5	193	193	0.8	0.05	0	0.05	0	13.0	3.8	20	0.77	0
Slide Mountain Spring	11Jun77	6	8.3	0.05	0	12	0	0	20	0	0.05	4	0.05	4	7.6	0.3	9	0.05	0
Davis Creek Spring	11Jun77	13	8.0	0.05	0	20	0	0	148	3.6	0.06	0	0.06	0	10.5	2.2	32	0.32	0.01
Davis Creek Well	11Jun77	15	7.5	n.d.	n.d.	24	0	0	91	n.d.	0.07	0	0.07	0	7.9	0.8	17	0.26	0.014
Pleasant Valley School	12Jun77	22	7.5	n.d.	0	45	1.5	107	107	6.3	0.18	0	0.18	0	9.0	2.3	12	0.38	0.01
Jumbo Grade Springs	9Jun77	11	7.5	0	20	20	8.0	420	420	73	0.08	0	0.08	0	35.0	1.4	100	0.83	0.01
Scorpion Springs	9Jun77	13	7.6	0.15	0	20	2.9	244	244	145	0.08	0	0.08	0	20.0	0.3	80	0.70	0
Alum Spring	9Jun77	12	3.3	0	0	104	8.7	0	0	385	0.04	0	0.04	0	89	1.8	26	2.1	0.066
Guyton Ranch Well	12Jun77	19	7.6	1506	n.d.	61	471	288	288	129	0.36	14	0.36	14	180	19	90	1.1	0.9
Hidden Valley Well	12Jun77	17	8.2	n.d.	n.d.	43	8.7	190	190	n.d.	0.22	3	0.22	3	50.0	5.8	24	0.44	0.034
50	8Jun77	53	5.9	2532	0.15	n.d.	773	412	412	117	1.9	42	1.9	42	570	62	24	0.061	6.6
50	12Jul77	50	5.7	n.d.	n.d.	n.d.	773	n.d.	n.d.	n.d.	n.d.	39	n.d.	39	n.d.	58	n.d.	n.d.	n.d.
26	8Jun77	95.5	7.3	2877	0.30	n.d.	857	412	412	112	2.5	44	2.5	44	640	71	11.2	0.018	7.3
26	12Jul77	89	7.4	n.d.	n.d.	238	n.d.	n.d.	n.d.	n.d.	n.d.	47	n.d.	47	650	74	n.d.	n.d.	n.d.
4	10Jun77	76.5	6.5	2877	0.15	n.d.	913	412	412	134	2.1	50	2.1	50	690	70	5.4	0.011	8.2
4	11Jul77	76	6.8	n.d.	n.d.	194	902	n.d.	n.d.	n.d.	n.d.	49	n.d.	49	730	50	n.d.	n.d.	n.d.
5	10Jun77	95	7.7	2996	0.20	n.d.	896	412	412	118	2.5	45	2.5	45	645	86	8.6	0.021	8.0
6	10Jun77	97	7.4	2684	0.15	n.d.	871	387	387	123	2.2	48	2.2	48	660	65	6.8	0.016	7.8
8	10Jun77	91	7.4	2723	0.15	n.d.	835	410	410	107	2.2	45	2.2	45	635	77	7.9	0.011	7.3
8	11Jul77	93	7.6	n.d.	n.d.	252	857	n.d.	n.d.	n.d.	n.d.	45	n.d.	45	605	75	n.d.	n.d.	n.d.
23	11Jun77	95.5	7.3	2831	0.20	n.d.	897	363	363	141	2.2	45	2.2	45	675	82	4.2	0.017	7.8
23	12Jul77	95	7.2	n.d.	n.d.	n.d.	898	n.d.	n.d.	n.d.	n.d.	45	n.d.	45	700	88	n.d.	n.d.	n.d.
Near 27	10Jun77	78	6.2	2826	0.15	n.d.	864	321	321	145	2.1	45	2.1	45	645	74	5.6	0.012	7.4
Near 27	12Jul77	90	6.3	n.d.	n.d.	257	859	n.d.	n.d.	n.d.	n.d.	45	n.d.	45	635	81	n.d.	n.d.	n.d.
27	11Jun77	87	6.2	n.d.	n.d.	243	878	297	297	n.d.	2.1	45	2.1	45	640	77	5.6	0.010	7.5
21N	11Jun77	70.5	7.8	3039	0.15	n.d.	917	379	379	147	2.3	45	2.3	45	725	78	3.0	0.004	7.8
21N	12Jul77	66	7.6	n.d.	n.d.	266	920	n.d.	n.d.	n.d.	n.d.	50	n.d.	50	665	95	n.d.	n.d.	n.d.

*Field analysis
n.d. not determined

is a relatively new technique similar to atomic emission but with the species measured (17 at one time) in a plasma instead of a flame. To date the method has not been published. Table 3a presents the results for cold springs and wells; table 3b presents the results for thermal springs. Comparison of the major cation concentrations (tables 2 and 3) are in good agreement except for magnesium in cold waters.

Precise descriptions for isotopic methods generally are not available in the literature. Personal communication among members of the handful of laboratories doing isotopic analyses has resulted in modification of the methods without literature documentation. H/D analyses were done by reducing water in a uranium furnace at 800°C and collecting the hydrogen on charcoal at liquid nitrogen temperatures. The samples were analysed by mass spectrometry. Original reference for this method is Friedman (1953). Papers discussing the methods for $^{16}\text{O}/^{18}\text{O}$ in water (Epstein and Mayeda, 1953) and in sulfate (Nehring and others, 1977) more closely describe current procedures. Carbon dioxide was isotopically equilibrated with water or generated from the reaction of carbon and barium sulfate at 1100°C, then analysed by mass spectrometer. Table 4 presents the stable isotope analyses. Temperature and chloride also are reported in

Table 3a.--Cation analyses of cold waters collected 8-11Jun77 using Spectraspan III A.

Element	Stock Spring	Thomas Creek Spring	Slide Mtn. Spring	Davis Creek Spring	Davis Creek Well	Pleasant Valley School	Jumbo Grade Spring	Scorpion Springs	Alum Spring	Guyton Ranch Well	Hidden Valley Well
(mg/L)											
Na	14.20	12.80	1.91	11.30	9.21	6.28	33.10	22.20	111.00	193.00	48.30
K	5.44	5.83	0.87	3.81	1.76	3.68	2.44	0.74	2.50	18.50	7.55
Si	32.30	30.50	5.61	9.84	12.60	28.60	9.94	9.35	50.30	42.00	29.00
Ca	41.30	34.20	5.38	26.90	16.00	14.60	93.80	81.40	331.00	85.20	42.60
Mg	18.40	14.50	0.48	4.18	2.88	5.98	18.70	19.20	166.00	27.30	7.12
B	<0.02	0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	13.20	0.24
Li	<0.20	<0.20	<0.20	<0.20	<0.20	0.20	<0.20	<0.20	<0.20	1.30	<0.20
Al	<0.01	<0.01	0.02	<0.01	<0.01	<0.01	0.24	0.02	204.00	<0.01	<0.01
As	<0.20	<0.20	0.57	0.51	0.34	<0.20	<0.20	0.44	6.82	<0.20	<0.20
(ug/L)											
Sr	653.00	438.00	30.60	66.10	122.00	279.00	1040.00	659.00	1060.00	1100.00	257.00
Ba	137.00	147.00	<5.00	<5.00	<5.00	36.50	116.00	11.90	7.48	146.00	62.30
Rb	<50.00	<50.00	72.90	<50.00	352.00	<50.00	<50.00	<50.00	88.10	<50.00	<50.00
Zn	107.00	18.80	<3.00	<3.00	8.21	293.00	195.00	129.00	2140.00	1900.00	112.00
Cu	<3.00	<20.00	<20.00	<20.00	<20.00	815.00	<3.00	<3.00	13.50	11.70	5.03
Fe	<20.00	<10.00	<10.00	<10.00	<10.00	<10.00	<20.00	<20.00	5290.00	<20.00	<20.00
Mn	11.50	13.60	13.20	11.30	16.60	<1.00	28.60	<10.00	5810.00	<10.00	177.00
Cd	16.00	4.00	4.00	4.00	4.00	<4.00	16.40	19.00	30.90	18.20	17.20
Ni	<4.00	<3.00	<3.00	13.00	<3.00	<3.00	<3.00	<4.00	210.00	<4.00	<4.00
Mo	<3.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<3.00	<3.00	<3.00	<3.00
Co	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	313.00	5.66	<5.00
Cr	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00	3.64	<2.00	14.60	9.18	<2.00
Se	<30.00	<30.00	<30.00	176.00	<30.00	<30.00	30.00	121.00	<30.00	133.00	76.70
Bi	23.90	<10.00	44.50	35.10	66.10	<10.00	44.50	53.00	54.60	72.60	47.60
Sb	<200.00	<200.00	<200.00	<200.00	<200.00	<200.00	<200.00	<200.00	<200.00	<200.00	<200.00
Hg	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00	8.80	10.40	<2.00
Ti	<10.00	<10.00	<10.00	<10.00	<10.00	<10.00	116.00	<10.00	<10.00	178.00	<10.00
V	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	22.50	26.50	<5.00
Tl	<4.00	<4.00	<4.00	<4.00	<4.00	<4.00	<4.00	<4.00	20.70	13.60	<4.00
Pb	<15.00	<15.00	<15.00	<15.00	<15.00	<15.00	20.60	<15.00	103.00	54.10	<15.00
Be	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00	8.69	<2.00	<2.00

Analyses by J. Ball and A. Chadwick, U.S.G.S., Menlo Park

Table 3b.---Cation analyses of thermal waters collected 8-11Jun77 using Spectraspan III A.

Element	Spring 50	Spring 26	Spring 4	Spring 5	Spring 6	Spring 8	Spring 23	Spring nr 27	Spring 27	Spring 21 N
(mg/L)										
Na	571.00	632.00	702.00	673.00	647.00	636.00	693.00	626.00	677.00	658.00
K	58.60	68.70	65.50	74.60	61.30	70.20	73.40	72.60	69.90	76.40
Si	86.00	122.00	102.00	131.00	105.00	125.00	146.00	129.00	117.00	132.00
Ca	24.10	22.30	6.43	10.30	8.68	10.30	13.40	8.31	22.90	3.88
Mg	1.64	0.58	0.26	0.53	0.38	0.29	0.31	0.31	0.36	<0.20
B	38.20	43.70	47.50	46.40	44.60	42.60	47.00	44.10	46.10	46.20
Li	8.45	9.15	10.60	10.90	9.72	9.15	9.84	9.61	9.50	9.82
Al	<0.01	<0.01	0.03	0.03	0.03	0.01	0.03	0.02	<0.01	0.05
As	2.18	2.15	3.78	3.77	3.17	3.47	2.81	2.96	4.08	3.46
(ug/L)										
Sr	1360.00	1420.00	1300.00	1620.00	1100.00	1370.00	976.00	983.00	1010.00	964.00
Ba	63.40	86.00	59.50	108.00	49.50	107.00	77.60	87.30	83.20	55.10
Rb	517.00	639.00	673.00	747.00	642.00	704.00	697.00	758.00	680.00	777.00
Zn	<5.00	206.00	1380.00	33.70	77.30	47.50	188.00	31.80	346.00	374.00
Cu	<3.00	<3.00	36.60	<3.00	<3.00	<3.00	<3.00	<3.00	<3.00	<3.00
Fe	47.90	<20.00	<20.00	<20.00	<20.00	<20.00	<20.00	<20.00	<20.00	<20.00
Mn	65.30	65.30	<10.00	<10.00	20.10	<10.00	<10.00	28.10	25.90	<10.00
Cd	11.50	6.59	7.69	<1.00	11.80	109.00	22.10	3.91	12.20	7.01
Ni	<4.00	<4.00	<4.00	<4.00	<4.00	<4.00	<4.00	<4.00	<4.00	<4.00
Mo	<3.00	<3.00	<3.00	<3.00	<3.00	<3.00	<3.00	<3.00	<3.00	<3.00
Co	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00
Cr	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00
Se	<30.00	<30.00	43.80	<30.00	<30.00	<30.00	34.60	<30.00	64.10	<30.00
Bi	<10.00	29.90	71.80	<10.00	55.30	54.80	129.00	62.40	75.10	27.30
Sb	<200.00	<200.00	210.00	<200.00	359.00	<200.00	527.00	<200.00	<200.00	697.00
Hg	23.40	<2.00	10.70	<2.00	<2.00	<2.00	<2.00	<2.00	21.40	<2.00
Ti	<10.00	<10.00	<10.00	<10.00	14.40	<10.00	<10.00	13.70	<10.00	<10.00
V	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00
Tl	<4.00	<4.00	19.90	<4.00	14.10	22.20	37.20	10.80	8.53	19.30
Pb	<15.00	<15.00	33.00	<15.00	<15.00	26.50	27.30	<15.00	<15.00	18.10
Be	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00

Analyses by J. Ball and A. Chadwick, U.S.G.S., Menlo Park

Table 4.--Stable isotope analyses.

Description	Date	Temp. °C	Cl mg/L	δD H ₂ O SMOW	$\delta^{18}O$ H ₂ O SMOW	$\delta^{18}O$ SO ₄ SMOW
COLD WATERS						
Dry Creek	8Jun77	15	2.2	-115.0	-15.10	n.d.
Stock Spring	8Jun77	15	2.9	-118.1	-15.57	n.d.
Stock Spring	6Nov77	13	1.5	-118.8	-15.49	n.d.
Thomas Creek Spring	8Jun77	13	1.5	-122.3	-15.94	n.d.
Thomas Creek Spring	6Nov77	13	1.5	-122.7	-16.29	n.d.
Slide Mountain Spring	11Jun77	6	0	-105.5	-14.94	n.d.
Slide Mountain Spring	10Jul77	9	0	-106.4	-14.91	n.d.
Slide Mountain Spring	29Aug77	n.d.	0	-109.5	-14.76	n.d.
Slide Mountain Spring	6Nov77	0	0	-109.3	-15.03	n.d.
Davies Creek Spring	11Jun77	13	0	-108.8	-14.48	-0.73
Davies Creek Spring	12Jul77	17	0	-109.5	-14.65	n.d.
Davies Creek Spring	6Nov77	7	0	-109.4	-14.59	n.d.
Davies Creek Well	11Jun77	15	0	n.d.	-14.58	n.d.
Davies Creek Well	12Jul77	23	0	-107.8	n.d.	n.d.
Pleasant Valley School	12Jun77	22	1.5	-109.0	-14.86	-2.75
Pleasant Valley School	12Jul77	25	1.5	-110.0	-14.85	n.d.
Pleasant Valley School	6Nov77	12	1.5	-111.6	-14.83	n.d.
Jumbo Grade Spring	9Jun77	11	8.0	-114.2	-14.36	-2.45
Jumbo Grade Spring	5Nov77	9	8.0	-116.0	-14.70	n.d.
Scorpion Springs	9Jun77	13	2.9	-115.8	-14.90	-3.88
Alum Spring	9Jun77	12	8.7	-115.8	-14.76	-4.98
Alum Spring	12Jul77	16	14.6	-112.7	-14.19	n.d.
Alum Spring	29Aug77	n.d.	13.8	-114.9	-14.60	n.d.
Alum Spring	6Nov77	12	13.0	-115.5	-14.49	n.d.
Guyton Ranch Well	12Jun77	19	471.0	-113.2	-13.64	-3.24
Hidden Valley Well	12Jun77	17	8.7	-116.4	-15.24	n.d.
Washoe Lake	26Mar76	n.d.	20	-57.5	-4.99	n.d.
Washoe Lake	6Nov76	n.d.	42	-16.6	+2.60	n.d.
Washoe Lake	3Apr78	n.d.	n.d.	-63.8	-6.36	n.d.
Lake Tahoe	11Jul76	n.d.	n.d.	-57.3	-5.30	n.d.
THERMAL WATERS						
50	8Jun77	53	773	-115.8	-12.22	-4.50
50	12Jul77	50	773	-114.6	-12.43	n.d.
50	6Nov77	52	767	-115.8	-12.63	n.d.
25SS	15Jul75	88	835	-116.2	-12.49	n.d.
26NW	15Jul75	95	787	-114.1	-10.36	-3.28
26	8Jun77	95.5	857	-115.8	-12.36	-5.45
26	12Jul77	89	n.d.	-115.6	-12.05	n.d.
26	6Nov77	90	856	-115.6	-12.10	n.d.
Near 1	6Nov77	72	804	-118.1	-12.41	n.d.
3	6Nov77	72	844	-116.5	-12.18	n.d.
4	19May74	58	928	-110.3	-10.45	n.d.
4	27Mar76	53	933	-107.2	-10.72	-5.06
4	18Jul76	70	983	-110.4	-10.97	n.d.
4	10Jun77	76.5	913	-111.3	-11.26	-5.50
4	11Jul77	76	902	-113.0	-11.21	n.d.
4	29Aug77	n.d.	892	-114.1	-11.26	n.d.
4	6Nov77	83	816	-114.0	-11.03	n.d.
4	10Dec77	n.d.	869	-114.4	-11.46	n.d.
5	15Jul75	81	896	-115.3	-12.12	n.d.
5	10Jun77	95	896	-114.9	-12.03	-5.38
Mine Tunnel near 5	11Jul77	70	905	-114.2	-12.05	n.d.
6	10Jun77	97	871	-115.6	-12.05	-5.23
6	11Jul77	97	876	-114.9	-11.94	n.d.
6	6Nov77	98	859	-116.1	-12.29	n.d.
6	10Dec77	n.d.	856	-116.0	-12.57	n.d.
8	19May74	n.d.	857	-115.5	-11.80	n.d.
8	15Jul75	90	847	-115.6	-12.16	n.d.
8	27Mar76	90	n.d.	n.d.	-12.30	n.d.
8	18Jul76	96	843	-116.6	-12.22	n.d.
8	10Jun77	91	835	-115.9	-12.79	-5.65
8	11Jul77	93	857	-115.9	-12.19	n.d.
8	6Nov77	87	845	-116.2	-12.10	n.d.
8	10Dec77	n.d.	839	-116.5	-12.39	n.d.
10	19May74	85	n.d.	-115.5	-10.78	n.d.
13	15Jul75	90	899	-113.0	-11.71	-5.42
13	18Jul76	91	899	-113.7	-11.27	n.d.
23	11Jun77	95	897	-114.6	-12.08	-5.96
23	12Jul77	95	898	-115.0	-12.02	n.d.
23	6Nov77	95	890	-114.2	-12.01	n.d.
24	10Dec77	n.d.	883	-115.2	-11.85	n.d.
17S	15Jul75	84	983	-112.4	-10.76	n.d.
Near 27	10Jun77	78	864	-115.6	-12.11	-5.80
Near 27	12Jul77	90	859	-115.2	-12.17	n.d.
Near 27	6Nov77	85	863	-116.9	-12.44	n.d.
Near 27	10Dec77	n.d.	869	-114.7	-12.10	n.d.
27	11Jun77	87	878	-114.8	-12.13	n.d.
21 N	11Jun77	70	917	-112.8	-11.65	-4.92
21 N	12Jul77	66	920	-112.9	-11.51	n.d.
GS-8 5/7 Unflashed	11Jul77	128	878	-117	-12.62	n.d.

* $\delta D \pm 1$ permil, $\delta^{18}O \pm 0.2$ permil

this table because they are essential to the interpretation of isotopic data. For springs that are not shown in figure 2, refer to White (1968a). Tritium analyses were made using a procedure similar to that described by Taylor and others (1963). The ^{14}C analyses were carried out by acidifying the strontium carbonate precipitate with phosphoric acid to generate carbon dioxide. The gas was scrubbed in a dichromate trap to remove hydrogen sulfide before counting (Pearson and Bodden, 1975). Table 5 presents the radio-isotope data.

Gas analyses were obtained using a method similar to that described by Giggenbach (1976). Gases not absorbed by sodium hydroxide were analysed by gas chromatography; gases dissolved in the sodium hydroxide were analysed by wet chemical methods. Table 6 presents the major gas analyses and figure 3 shows a chromatogram identifying hydrocarbons found and their relative abundances.

Some analyses of water and gas constituents from Steamboat Springs are available in the literature. Chemical analyses of the waters have been reported by Brannock and others (1948), White and Brannock (1950), White and others (1953), White and others (1956), and White (1968a). Isotopic analyses have been reported by White and others (1963), Begemann (1963), and Craig (1963). Gas analyses have been reported by Brannock and others (1948).

Table 5.--Radio-isotope analyses.

Spring	Date	Tritium tritium units	C-14 percent of modern
50	08Jun77	4.8±0.4	
26	08Jun77	0.4±0.2	0.46±.16
4	10Jun77	12.0±0.6	
5	10Jun77	0.5±0.2	1.21±.12
6	10Jun77	0.6±0.2	
8	10Jun77	0.4±.2	0.97±.13
23	11Jun77	0.3±0.2	
Nr 27	10Jun77	0.7±0.2	1.64±.16
21N	11Jun77	0.6±0.2	

Tritium analyses by T. Wyerman, U.S.G.S., Reston
C-14 preparation by N. Nehring and counting by
S. Robinson, U.S.G.S., Menlo Park

Table 6.--Analyses of major gases (mole percent).

Spring	Date	CO2	H2S	NH3	He	H2	Ar	O2	N2	CH4
26	8Jun77	95.3	0.80	0.014	0.00025	0.012	0.093	0.00	3.87	0
26 NW	15Jul75	96.7	1.98	.015	.00025	.011	n.d.2	.021	1.17	0.00039
Mine Pit	10Jun77	98.7	.48	.0022	.00042	.028	.013	.00	.78	.0015
4	19May74	93.1	n.d.1	n.d.	.0041	.11	n.d.	.87	5.76	trace
4	19May74	94.8	.051	n.d.	.0023	.089	n.d.	.57	4.60	.0088
4	10Jun77	97.9	.41	.0034	.0012	.062	.033	.00	1.50	.0043
5	10Jun77	86.5	.32	.025	.0091	.16	.24	.00	21.54	.0038
6	10Jun77	95.6	1.93	.027	.00022	.022	.095	.00	2.39	.00
8	15Jul75	95.7	.49	n.d.	.00072	.022	.075	.061	3.34	.0017
8	10Jun77	97.6	.94	.00083	.00028	.022	.032	.00	1.42	.00003
13	15Jul75	94.0	trace	n.d.	.00090	.026	.50	.92	4.63	trace
13	15Jul75	93.4	.054	n.d.	.0013	.025	n.d.2	1.12	4.95	trace
24	10Jun77	97.3	1.39	.043	.00037	.0082	.029	.00	1.17	.0016
Near 27	10Jun77	97.3	.63	.0017	.00079	.055	.048	.00	.91	.0037

1included with CO2
2included with O2

Comparison of the analyses reported here with analyses reported in the literature indicates general agreement. For simplicity, current analyses will be used exclusively except for those of well waters reported in Table 7 (White, 1968a). These wells no longer are accessible.

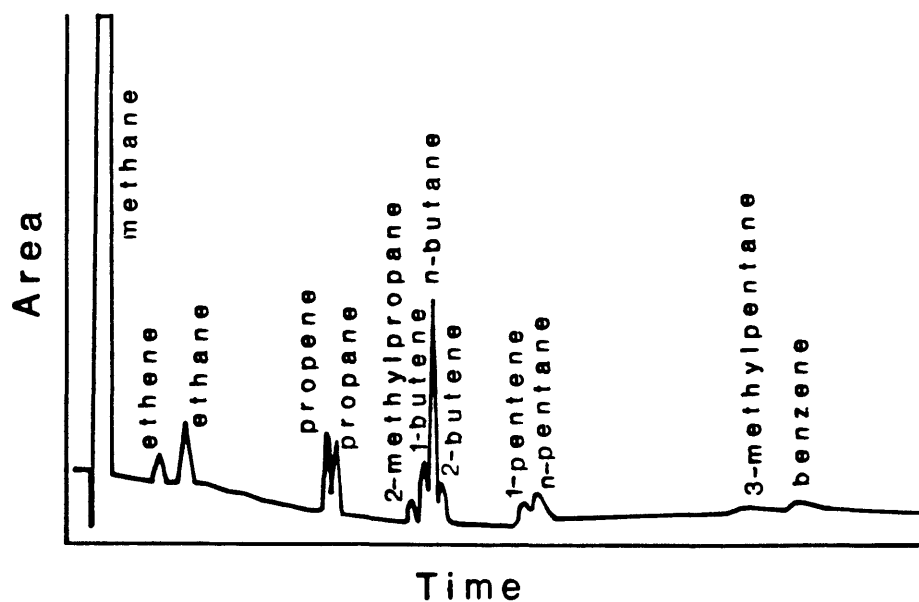


Figure 3. Chromatogram of hydrocarbon gases.

Table 7.--Well data from White (1968a).

Well	Depth m(ft)	Temp. °C	Enthalpy J/g	Non- erupted Cl ⁻	Erupted Cl ⁻	Cl ⁻ Corrected for Steam loss
GS-5	174 (575)	170	717	---	864	717
GS-4	153 (505)	171	733	---	828	687
GS-3	208 (686)	164	667	---	796	692
GS-1	121 (400)	157	662	---	860	710
GS-2	121 (398)	154	651	---	856	727
Mt Rose 1	48 (160)	133	559	844	---	---
Herz 1	47 (155)	93	390	416	---	---
Herz 2	46 (153)	90	375	400	---	---
E Reno	48 (157)	138	579	868	---	---
W Reno	56 (186)	138	579	898	---	---
Senges	54 (177)	146	613	826	---	---
Rodeo	85 (280)	169	714	---	836	694
SB-4	56 (184)	155	652	702	---	---
No. 32	13 (43)	115	480	885	---	---
SSW	35 (114) ¹	65	272	870	---	---
GS-8	39 (130)	129	546	860 ²	---	---

¹Used shallow (high temp.) aquifer

²Downhole sample

GEOTHERMOMETERS AND MIXING MODELS

Silica (Fournier and Rowe, 1966; Mahon, 1966), NaK (Fournier and Truesdell, 1973; Truesdell, 1975), NaKCa (Fournier and Truesdell, 1973; Fournier, 1979), and sulfate-water isotope (Mizutani and Rafter, 1969; McKenzie and Truesdell, 1977) geothermometers were applied to the hot spring compositions reported in tables 2 and 4. Predicted temperatures for the reservoir are given in table 8. Temperatures estimated by the silica, NaK, NaKCa, and sulfate geothermometers are 183^o, 230^o, 230^o, and 210^o (230^o after correction of raw data for interferences), respectively. The silica and sulfate temperatures are probably too low due to precipitation of silica and formation of sulfate near the surface. This results in a best estimated temperature for the reservoir of 230^oC. The boiling springs mixing model (Truesdell and Fournier, 1975) based on an enthalpy-chloride relationship indicates that of the springs sampled only spring 50 was mixed and that about 10 percent cold water was present.

Silica

The indicated silica temperatures, based on equilibrium with quartz at depth and assuming adiabatic cooling between the reservoir and surface, range from 162-192^oC with a

Table 8.--Predicted geothermometer temperatures
(all temperatures in °C).

Spring	Date	Temp	SiO ₂	NaK	NaKCa	SO ₄ ¹
50	8Jun77	53	162	224	207	216
26	8Jun77	95	181	226	218	211
26	12Jul77	89	172	228	---	---
4	10Jun77	76.5	171	218	222	224
4	11Jul77	76	167	187	---	---
5	10Jun77	95	190	243	233	215
6	10Jun77	97	175	216	217	213
8	10Jun77	91	184	234	228	206
8	11Jul77	93	---	235	---	---
23	11Jun77	95	192	234	236	224
23	12Jul77	95	---	237	---	---
Nr 27	10Jun77	78	183	229	228	216
Nr 27	12Jul77	90	184	239	---	---
27	11Jun77	87	182	233	231	---
21N	11Jun77	70	184	223	233	204
21N	12Jul77	93	---	250	---	---
best guess			183	230	230	210

¹Conductive cooling assumed for spring 50, single stage steam loss for all others.

weighted average of 183°C. This agrees with the maximum observed temperature of 186°C at 240 m (White, 1968a). The difference between 183°C and the estimated reservoir temperature of 230°C is probably due to precipitation of silica during a long residence time at depth where temperatures are cooler than 230°C. This process recently has been shown to be widespread in thermal springs (Nehring and Mariner, 1979).

Figure 4 is a plot of the measured spring temperature

versus the silica concentration in the waters and shows the saturation curves for amorphous silica and quartz (Fournier, 1977). A reservoir at 230°C in equilibrium with quartz would contain about 375 mg/L of silica (point A, fig. 4). A spring at 95°C in equilibrium with such a reservoir is represented by point B. Springs 50 and 21 N have precipitated silica and are in equilibrium with amorphous silica at the observed spring temperature. The remainder of the springs appear to be supersaturated with respect to amorphous silica but to have precipitated substantial

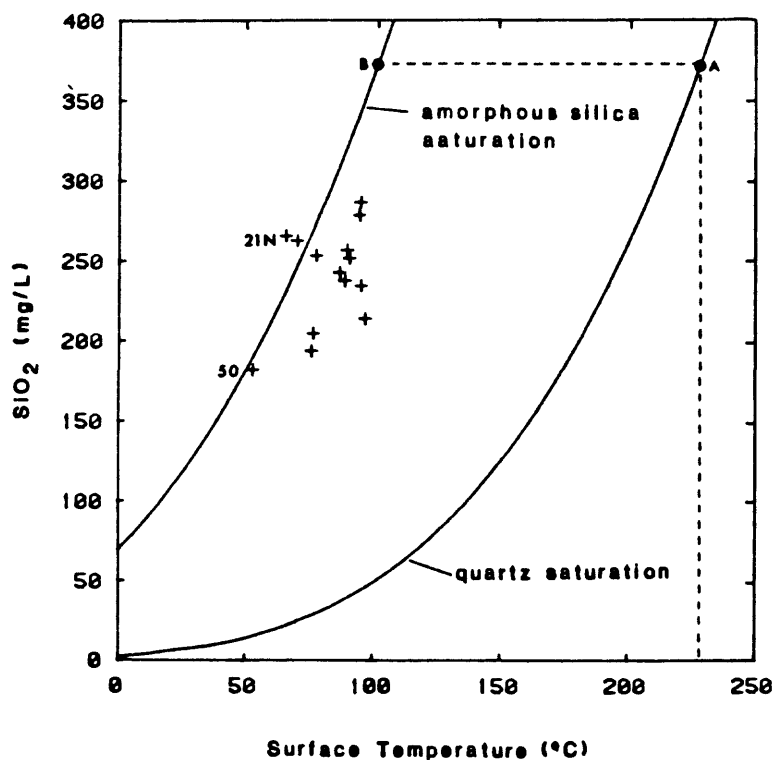


Figure 4. Surface temperature versus silica with saturation curves for amorphous silica and quartz (Fournier, 1977). Point A represents the inferred reservoir composition.

amounts of silica. The precipitation of silica is the cause for the low silica geothermometer temperatures.

NaK and NaKCa

The NaK and NaKCa temperatures are in good agreement, in spite of the fact that most of the thermal waters are in equilibrium or supersaturated with respect to calcite. A decrease in the calcium, due to precipitation of calcite, would cause the NaKCa geothermometer to predict temperatures that are too high. It is possible that the spring waters are not precipitating calcite even though supersaturated. Calcite deposits have only been found in flowing wells and veins at depth.

Sulfate

Evaluation of the sulfate geothermometer is based on the relationship of the chloride/sulfate ratio to $\delta^{18}\text{O}$ in sulfate (fig. 5). The chloride/sulfate ratio was used so that the effects of boiling on the concentration of ions in solution would be eliminated. The $\delta^{18}\text{O}$ value of sulfate produced by surface oxidation of hydrogen sulfide to sulfate, with the aid of sulfur-oxidizing bacteria, is near 0.5 permil (N. L. Nehring and L. D. White, unpublished data). The addition of surface sulfate is evident in springs 26, 5, 6, 4, and 21N.

Springs 23 and near 27 probably contain surface-oxidized

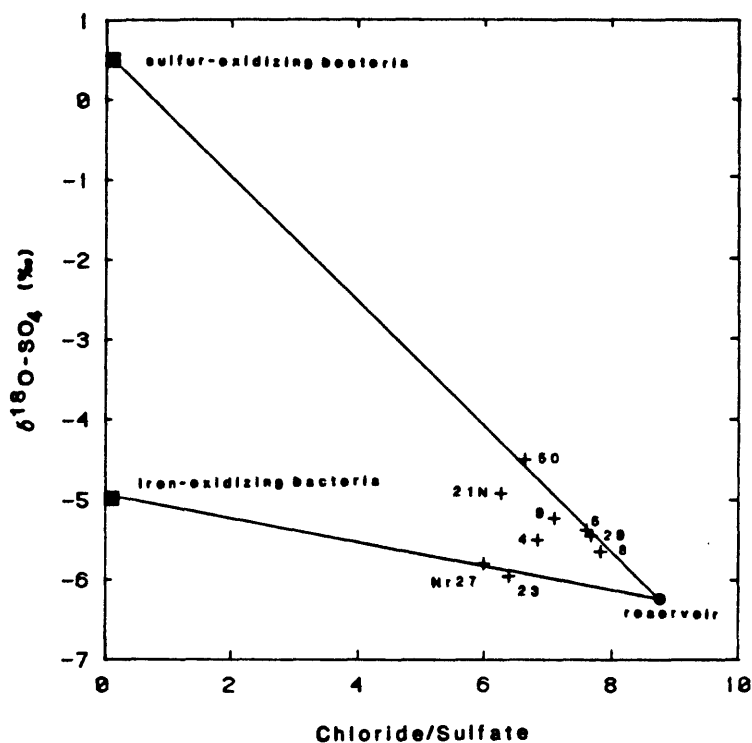


Figure 5. Chloride/sulfate versus $\delta^{18}\text{O}$ in sulfate showing possible effects of surface-produced sulfate on the oxygen isotopes.

sulfate, but this is shadowed by other processes. Variation of the $\delta^{18}\text{O}$ in sulfate in these springs, and to a lesser extent in springs 4 and 21N, appears to be due to the addition of sulfate with a more negative (lighter) $\delta^{18}\text{O}$. The origin of the sulfate is not fully understood, but may be due to the oxidation of pyrite by iron-oxidizing bacteria. This process is thought to produce the sulfate in Alum Spring. The isotopic value of oxygen in this sulfate is -4.98 permil (table 4).

Plotting of lines representing addition of sulfate

produced by sulfur-oxidizing bacteria and addition of sulfate produced by iron-oxidizing bacteria suggests that the oxygen isotopic value of sulfate in the reservoir is -6.3 permil (point A, fig. 4). If this value for oxygen in sulfate and a value of -13.7 permil is used for oxygen in water (correction of the surface value of -12.5 permil for steam loss, Truesdell and others, 1977) a temperature of 230°C is predicted. This agrees with the NaK and NaKCa geothermometers.

RESERVOIR PROCESSES

An understanding of the processes that cause changes in the reservoir fluid as it ascends is necessary so that the composition of the reservoir itself can be determined. Processes such as boiling, cooling, mixing, mineral solution, precipitation of compounds, and ion exchange all can cause the surface composition to differ from the reservoir composition.

Boiling, Cooling, and Mixing

Two relationships are particularly useful in determining boiling, cooling, and mixing. These are enthalpy-chloride and deuterium-chloride.

The chloride versus enthalpy diagram (fig. 6) uses analyses from tables 2 and 7. Chloride contents reported by White (table 7) were from samples collected at the wellhead. These surface samples were corrected to bottomhole conditions by using the following two assumptions: (1) erupted samples from wells with their main aquifer in granodiorite (well depths greater than 80 m) were assumed to have lost steam by single-stage steam loss; and (2) non-erupted samples from wells with their main aquifer in alluvium (well depths less than 70 m) were assumed to have cooled conductively. The corrected chlorides were

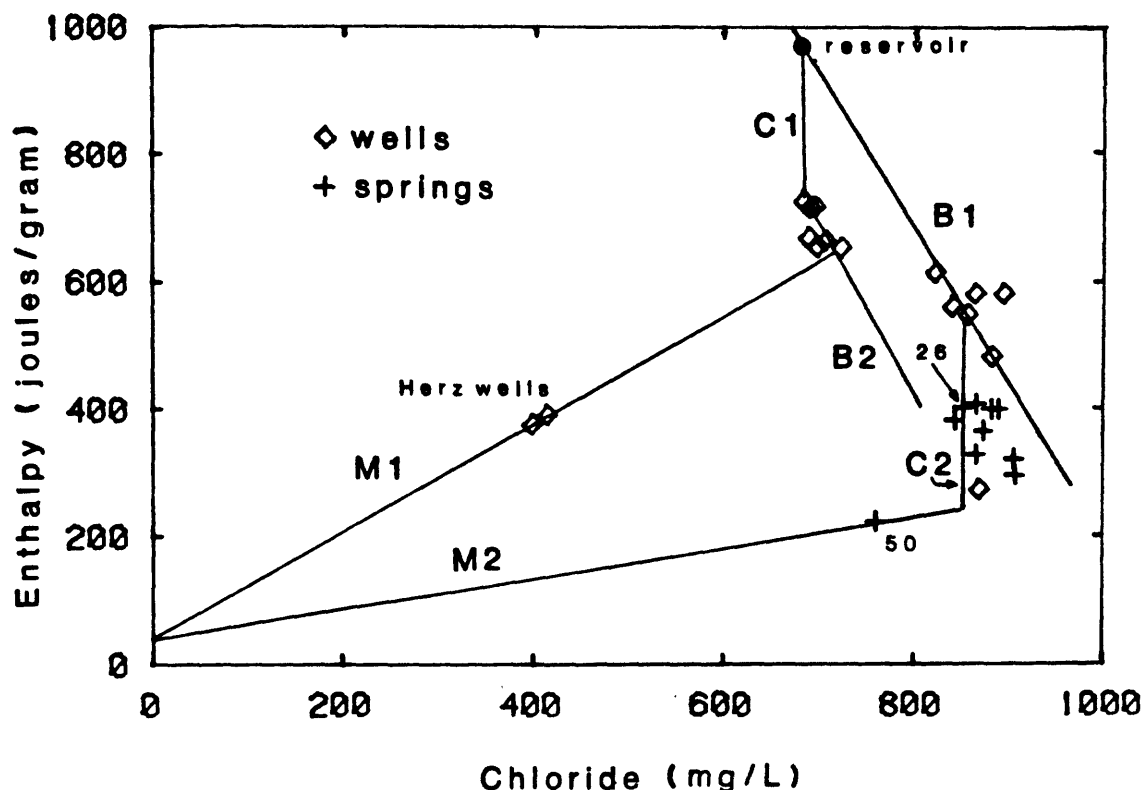


Figure 6. Chloride versus enthalpy showing reservoir conditions and boiling, conductive cooling, and mixing paths required to produce surface compositions of springs and wells. Estimated value of chloride in the reservoir is 700 mg/L.

plotted against the enthalpy of liquid water at the measured bottomhole temperature.

The well waters fall into two distinct groups that correlate with the near-surface reservoir rock type. Waters in granodiorite have approximately 700 mg/L chloride and are near 170°C (650 J/g). Waters in alluvium have approximately 850 mg/L chloride and are near 130°C (550 J/g). These well waters in alluvium have chloride contents similar to those

of the hot springs, but are at slightly higher temperatures than the springs.

Three processes are involved in producing the relationships shown on the enthalpy versus chloride diagram: boiling, conductive cooling, and mixing. The boiling lines, B1 and B2, are radial to a point determined by the enthalpy and chloride of steam (2,668 J/g and 0 mg/L chloride) and connect all points related by various amounts of boiling from a single source water. Line B1 was drawn through the right-most group of waters (well waters from alluvium); line B2 was drawn through the well waters from granodiorite. Conductive cooling lines, C1 and C2, indicate a loss of temperature without steam loss and, therefore, involve no change in chloride contents. All points along one of these conductive cooling lines could be derived from a single source water. The source water (reservoir water) has been estimated to be at 230°C (990 J/g) by the geothermometers. This coincides with the intersection of B1 and C1. An estimated 700 mg/L chloride is obtained for the reservoir chloride concentration. Line C2 was drawn through the composition of spring 26 to illustrate that the waters from springs, other than spring 50, can be derived from the same reservoir water as the well waters in alluvium by boiling then conductive cooling.

Mixing lines, M1 and M2, contain all possible mixtures

of the indicated cold water (40 J/g and 0 mg/L chloride) and thermal water. Mixing of 10 percent meteoric water with this conductively cooled spring water would give the composition of spring 50. The Herz wells contain a mixture of 50 percent meteoric water and 50 percent water from the granodiorite.

It is suggested that the waters in granodiorite are conductively cooled from the 230°C reservoir by slow passage through the granodiorite as shown by line C1. Cementation of the overlying alluvium by the thermal water and low permeability in the granodiorite apparently prevent significant upward movement and boiling of the water.

The well waters in alluvium originate from reservoir water rising along faults and fissures and flowing laterally into uncemented alluvium north of the Main Terrace, and lose heat by boiling as indicated by B1. The spring waters ascend in a manner similar to the well waters. This water loses heat by a combination of boiling (along line B1) and conductive cooling (along line C2 or parallel lines not shown). Apparently no springs or shallow wells are derived exclusively from boiling of the conductively cooled 170°C water. Such spring or shallow well compositions would plot on or to the left of B2. Alternatively, the springs could be derived from mixtures of waters along B1 and B2. This mechanism is not considered important because the shallow

wells do not appear to contain any water of compositions suggested by B2, and yet appear closely related to the springs.

Spring water compositions from table 4, single-stage steam loss, and continuous steam loss lines (Truesdell and others, 1977) are plotted in figure 7. In addition, well analyses of GS-5, Steamboat 4, West Reno (D. E. White and Harmon Craig, unpublished data), and GS-8 also are plotted. Calculation of the steam loss lines assuming 700 mg/L chloride for the reservoir (fig. 6) gives a δD value of -119.5 permil for the reservoir water. The addition of 10 percent cold water with a δD value of -116 permil to water with a composition of spring 26 would be required to produce the composition of spring 50. Spring 4 is a cooler spring that has undergone considerable surface evaporation due to its large surface area and plots above the single-stage steam loss line.

It can be seen that GS-5 and Steamboat 4 indicate boiling from about 170°C (equivalent to bottom hole temperature) to 95°C (boiling point at the surface for that elevation). This is a lower initial boiling temperature than any of the springs, which range from 175°C to 210°C. GS-8 and West Reno wells appear to have boiled from an initial temperature of 210°C to 95°C. The West Reno well is in alluvium, and GS-8 is a shallow

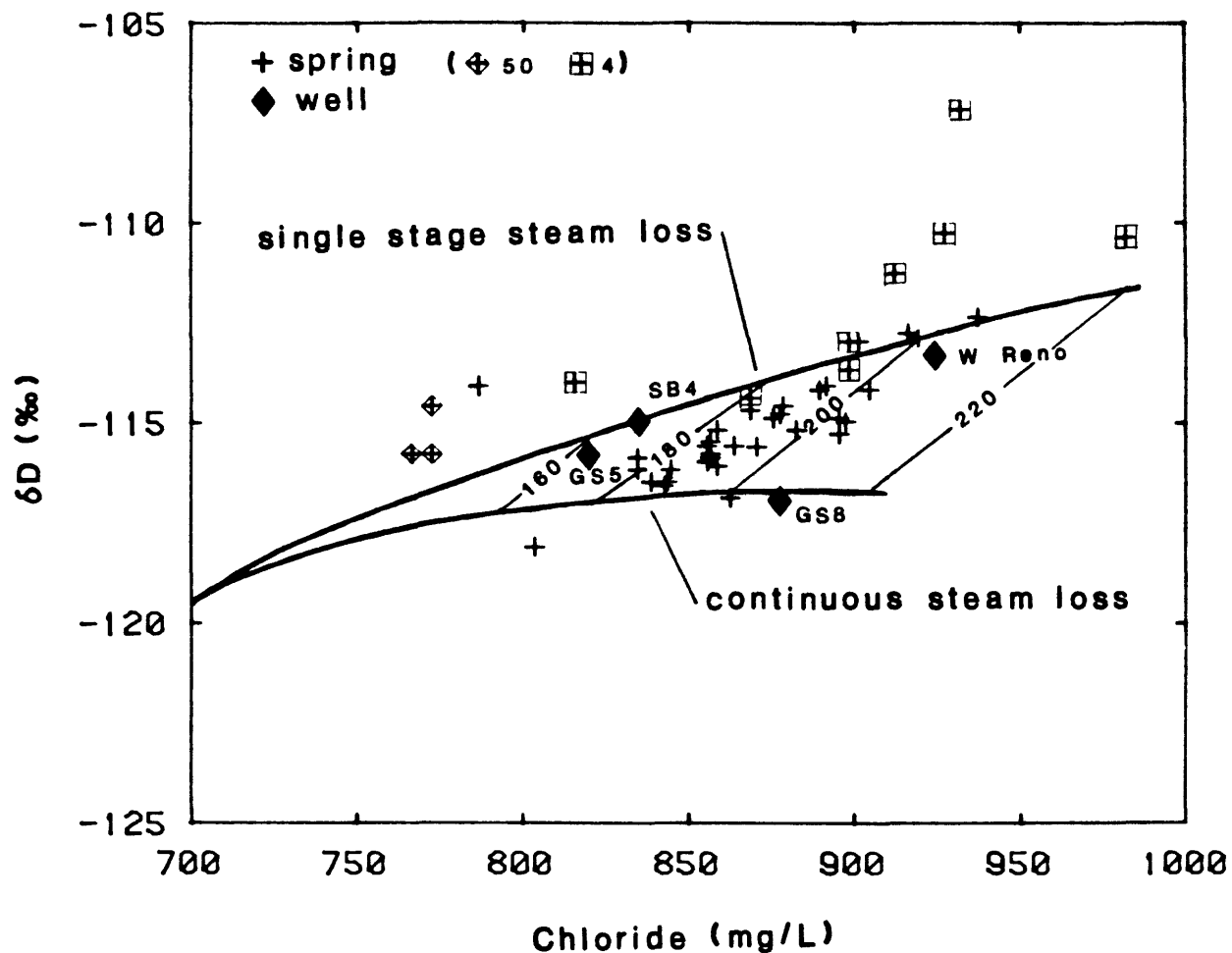


Figure 7. Chloride versus δD with single-stage steam loss and continuous steam loss lines (Truesdell and others, 1977). An estimated δD value of -119.5 permil for the reservoir is indicated.

well which may acquire its water from the major northwest segment of the Steamboat Fault Zone.

These observations further support the hypothesis that the movement of thermal water to the surface is almost entirely along faults and fissures where the springs emerge and that the area between faults and fissures is so

impermeable, and the water moves so slowly, that only conductive cooling occurs until the water enters a well bore.

Subsurface Flow

The bicarbonate/chloride ratio increases away from the area near spring 27 (table 2). Because chloride is a conservative element, Fournier and Truesdell (1970) proposed that changes could be attributed to changes in bicarbonate contents resulting from the reaction,

$$\text{CO}_2 + \text{H}_2\text{O} + (\text{Na},\text{K})\text{silicate} = \text{HCO}_3^- + (\text{Na}^+, \text{K}^+) + \text{H silicate}.$$

This reaction is favored by decreasing temperature. Since the reservoir is assumed to be at a constant temperature, the bicarbonate increase indicates the length of time at lower temperatures and, therefore, the length of time the thermal water took to reach the surface. This is supported by higher chloride contents due to more boiling, caused by a faster release of pressure on the water, in springs 27, near 27, and 21N and lower chlorides due to more conductive cooling in springs 8 and 26. Springs 4 and 21N may have enhanced chloride values due to surface evaporation. This strong upflow of the thermal water in the vicinity of spring 27 coincides with the intersection of northwest- and north-trending segments of the Steamboat Fault Zone (fig. 2) as described by White and others (1964).

Deposition of Calcite

Increase in bicarbonate results in supersaturation of the thermal water with respect to calcite. Figure 8 shows that all of the spring waters except springs 27, near 27, and 50 are saturated or supersaturated with respect to calcite. Spring 50 probably is undersaturated because of

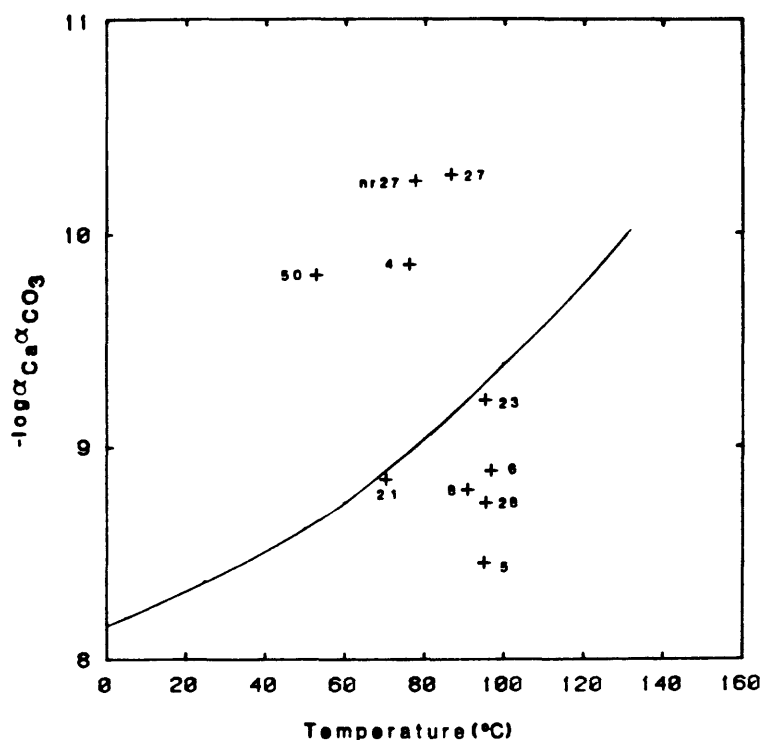


Figure 8. Temperature versus $-\log \alpha_{\text{Ca}} \alpha_{\text{CO}_3}$ with calcite equilibrium line (Helgeson, 1969).

dilution with meteoric water. Two explanations for the water in springs 27 and near 27 being undersaturated with respect to calcite are possible. All the springs may have precipitated calcite at depth, but near the surface, springs

27 and near 27 lost bicarbonate through a different process and are no longer saturated with respect to calcite. This is supported by the occurrence of calcite-filled veins at depth. Alternatively, springs 27 and near 27 always may have been undersaturated with respect to calcite. The remainder of the spring waters could have acquired additional calcium through near surface rock-water reactions during their longer residence times in the near-surface environment.

Although most of the springs are saturated or supersaturated with respect to calcite, calcite deposits generally are not evident at or near the surface. This indicates that deposition of calcite is not taking place near the surface and accounts for the agreement of the NaK and NaKCa geothermometers.

TRITIUM AND C-14

Tritium content of the thermal water can be used to determine the degree of mixing of the reservoir water with shallow meteoric water or to determine the residence time of reservoir water in a system if the residence time is less than 50 years and no mixing occurs. Springs 50 and 4 both show substantial amounts of tritium (table 5). As has been shown previously, spring 50 is a mixture of thermal and meteoric water. Spring 4, because of its large surface area, low temperature, and relatively small discharge, probably has exchanged tritium with the atmosphere at the surface. The much higher tritium in spring 4 than in spring 50 and the small amount of tritium in all the other springs may be due to rain showers on 9 Jun 77. The residence time of the thermal water is thought to be much greater than 50 years.

Carbon-14 analyses of the total carbon species dissolved in geothermal waters usually show little or no ^{14}C because old, ^{14}C -free carbonates in the aquifer rocks exchange carbon with the carbon dioxide, carbonate, and/or bicarbonate in the thermal water. It was therefore expected that no ^{14}C would be found at Steamboat Springs. Although only 4 samples were analysed because of the long times required for collection and counting, a definite trend in the amount of ^{14}C found is present. The sample from near

27, where the upflow is fastest, shows the most ^{14}C , and spring 8, where upflow is slowest, shows the least ^{14}C . This trend coincides with a decrease in chloride, increase in bicarbonate, and an increase in the amount of conductive cooling. These changes have been related to flow rate, and therefore, residence time. Flow rate and residence time also control fractionation of carbon isotopes. If the ^{14}C were fractionating when the vapor phase formed as the water ascended from the reservoir, the lighter ^{12}C and ^{13}C isotopes would be expected to go into the vapor phase with the ^{14}C remaining in the liquid phase. In addition, the heavier ^{14}C isotope would be the first to precipitate in calcite.

GASES

Analyses of the spring gases do not show any spatial trends but do give some indication of the processes forming and conditions in the reservoir. Analyses in table 6 indicate that, for samples free of atmospheric contamination, the gas contains 97 percent CO_2 , 1 percent H_2S and N_2 , and lesser amounts of H_2 , He, Ar, and CH_4 . Magmatic origins are probable for carbon dioxide, hydrogen sulfide, and helium (Craig, 1963; White, 1968b; H. J. Jenkins, unpublished data). Hydrogen is produced by high temperature reaction of water with ferrous oxides and silicates contained in the reservoir rocks (Seward, 1974). The nitrogen/argon ratio falls between that of air and of water saturated with air and indicates an atmospheric origin of the nitrogen and argon entering with the recharge water (Mazor and Wasserberg, 1965). The low concentrations of oxygen are due to reactions such as the oxidation of hydrogen sulfide to sulfate. Methane probably is generated from the reaction of carbon dioxide with hydrogen in the presence of liquid water (Hulston, 1964). The other hydrocarbons indicate that organic sediment is present in only insignificant amounts at depth (Nehring and Truesdell, 1978).

RECHARGE

Stable isotope analyses are used to trace water movement in geothermal systems. Hydrogen/deuterium is particularly useful, because nearly all the hydrogen is contained in the water, leaving the hydrogen/deuterium ratio unchanged by rock-water interactions. Oxygen isotopes are somewhat less useful because oxygen in water exchanges with oxygen in rocks. This exchange is particularly rapid above 140°C and is known as ^{18}O shift.

The chloride versus deuterium diagram (fig. 7) suggested a deuterium value of -119.5 permil for the reservoir. The ^{18}O versus deuterium diagram (fig. 9) shows that recharge water with a δD value of -119.5 permil could originate from precipitation falling on the Carson range at an average elevation of 2,100 m (fig. 9B). The recharge area is more or less limited to the area from Galena Creek to Evans Creek, an area covering about 15 km² (fig. 1). South of Galena Creek, the δD value is about -105 permil. This water flows east into Pleasant and Washoe Valleys. The δD value of ground water in a Pleasant Valley elementary school well is about -109 permil. This groundwater does not appear to be related to the thermal area. The δD values north of Evans Creek probably again become too positive to be considered part of the recharge although no samples were taken from that area.

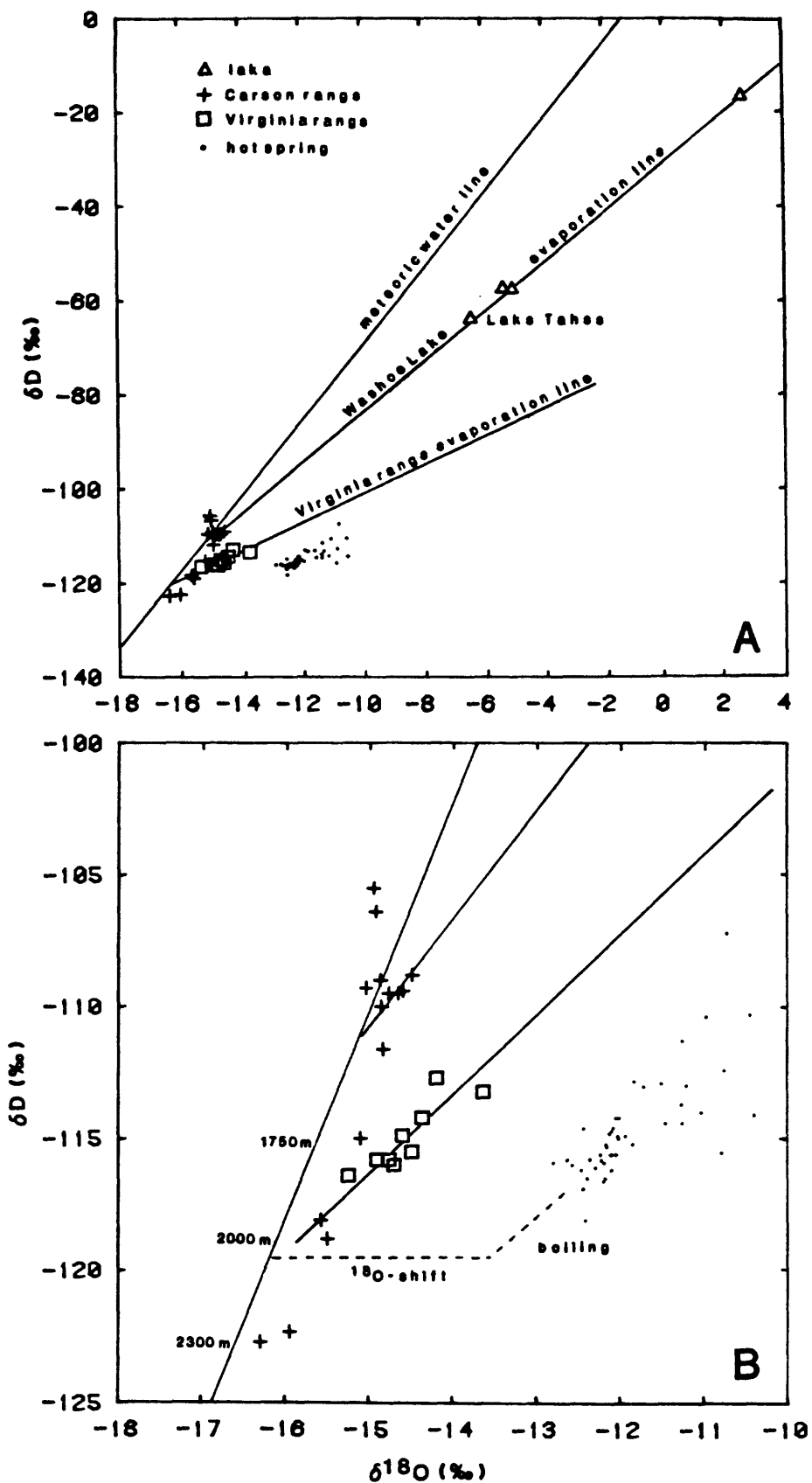


Figure 9. $\delta^{18}O$ versus δD . Figure 9A shows the meteoric water line (Craig, 1963) and regional evaporation trends. Figure 9B is an enlargement of the lower left corner of 9A; it emphasizes the change in δD with elevation in the Carson range and illustrates how oxygen isotope shift and boiling of the recharge water could account for spring compositions.

The Virginia range is nearly 1,000 m lower in elevation than the Carson range, and it is in the rain shadow of the Carson. The small amount of precipitation and large amount of evaporation in the Virginia range are shown by the low temperature evaporation line formed by the Virginia range springs (fig. 9). It is possible that a small part of the recharge water comes from the Virginia range.

The shallow, cold water found in spring 50 probably comes from the Virginia range. The isotopic value of -116 permil indicated for the cold water (page 33) fits the waters in the Virginia range better than water in Steamboat Creek, which varies from -90 permil to -110 permil within one year (D. E. White and Harmon Craig, unpublished data). The cold water in the Herz wells is considered, on the basis of well locations, to come from the Carson range, although no isotopic analyses are available.

SUMMARY

A reservoir temperature of 230°C is estimated for Steamboat Springs based on three independent geothermometers and the chloride-enthalpy relationship. Boiling and conductive cooling adequately explain the chemical and isotopic changes between the reservoir and the surface. Mixing with meteoric water is evident only near the eastern margin of the Low Terrace and in shallow wells drilled into the alluvium north of the Main Terrace. Calcite may be precipitating after the thermal water leaves the reservoir and may be responsible for changes in the ¹⁴C contents.

Flow is almost exclusively along faults and fissures with the strongest upflow at the intersection of north- and northwest-trending segments of the Steamboat Fault Zone at the crest of the Main Terrace. The thermal water apparently flows very sluggishly through the granodiorite where faults are not present. North of the Main Terrace, the ascending thermal water in the fault system can flow laterally into the uncemented alluvium.

Recharge water for the thermal area collects in alluvium in the Carson range directly to the west of Steamboat Springs at an average elevation of 3100 m. This water flows along deep faults in the basement rocks where it eventually is heated, presumably by a magma chamber under Steamboat

Hills. Recharge water does not originate in Pleasant Valley or from Steamboat Creek, which flows from south to north along the eastern edge of the Low Terrace.

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APPENDIX 1-SPRING OBSERVATIONS

The estimation of water discharge and gas discharge, measurement of pH and water temperature, and general description of the springs on the Low and Main Terraces were made on 7 June 1977. Water discharge was visually estimated. The gas discharge was divided into four categories--very high, high, moderate, and low. An attempt was made to measure the actual discharge of gas but condensation of steam made the measurements unreliable. The pH was measured in situ by first warming pH 7 buffer in the spring and calibrating the pH meter at spring temperature, then measuring the pH near the vent. Temperature was measured with a maximum reading thermometer known to agree with an NBS calibrated thermometer at 91°C. Springs generally are listed in a south to north order. The numbering system is from White (1968a), and those springs not shown on figure 2 are shown on plate 3 of White (1968a).

LOW TERRACE

Spring No.	Temp °C	pH	Discharge Lpm	Gas	Remarks
33	cold		0		Flow contained in stone and concrete cylinder 0.6 m (2 ft) high by 0.6 m (2 ft) diameter. Water level 0.5 m (1½ ft) below outlet spout.
32SE					Dry.
32E					Dry. White precipitate around vent, probably flowed recently.
31S					Dry.
31					Dry.
31N					Dry.
30S					Dry, a little steam.
30					Dry.
30N					Dry.
29					Dry.
54					Marshy seep on top of second cliff.

LOW TERRACE (continued)

Spring No.	Temp °C	pH	Discharge Lpm	Gas	Remarks
50	53	5.9	8		Issues from second 1.2 m (4 ft) cliff above creek. Pipe stuck in vent. Flow channeled into cylinder like spring 33. Black and pink bottom (algae or bacteria).
50N					Dry below first cliff.
25SS	88	6.8	1	Intermittent	Northernmost pool along fissure. Black bottom.
25S	76	7.8	2		0.9 m (3 ft) by 0.6 m (2 ft) pool with green algae except at outlet where algae are gray.
25	93	7.5	0.25	High	0.6 m (2 ft) oblong pool with black bottom. Bridged to spring 26 and water overflows into spring 25.
26	95.5	7.3	2	Moderate	Like spring 25 but slightly larger 0.9 m (3 ft).
26NW	92.5	8.1	1	High	Gray-bottomed pool 1.8 m (6 ft) by 0.3 m (1 ft). Some yellow deposits. Fissure 3 m (10 ft) long extending south. Three or four gas and water vents along fissure.

LOW TERRACE (continued)

Spring No.	Temp OC	pH	Discharge Lpm	Gas	Remarks
44					Marshy seep. Slight seep from sinter mound just north.
44E			0		Below ridge. Similar in appearance to spring 50.
44NE	45	6.3	4		Below ridge. Similar in appearance to spring 50. Several other seeps near 44E and 44NE at bottom of cliff.

MAIN TERRACE

Spring No.	Temp OC	pH	Discharge Lpm	Gas	Remarks
1-1N					Nothing in this area has any discharge except one marshy seep about 1.8 m (6 ft) south of cattle crossing into area.
No #	30				1.8 m (6 ft) south of the mine prospect between spring 1 and spring 2 marked by an X on plate 1, White and others (1964). A pot-shaped vent 0.3 m (1 ft) diameter at surface, 0.6 m (2 ft) diameter beneath. Vent is steaming gas and entirely lined with SO crystals. Could not find good vent at bottom for temperature or gas sample.
No #	95	7.7	0	High	Next mine prospect north marked by a half-colored square on plate 1, White and others (1964). Three small springs inside pit. Largest and best 0.15 m (6 in) diameter.
No #					Several small seeps below springs 2 & 3.
2					Dry.
2NW	75.5	6.1	8	Intermit-	15 cm (6 in) by 5 cm (2 in) black-bottomed pool along small fissure.

MAIN TERRACE (continued)

Spring No.	Temp OC	pH	Discharge Lpm	Gas	Remarks
3	60	6.1	2	Intermittent, low	0.3 m (1 ft) diameter black-bottomed pool with long, pale-yellow, filamentous bacteria.
No #	87		10		Discharge from wall of mine adit near spring 5. Along fault running through mine adit and spring 5.
5	95	7.7	8	Intermittent, high	All three features here have water and intermittent gas. Only southern spring has discharge. 2 cm (1 in) by 0.15 m (6 in) black-bottomed pool.
4	76.5	6.5	4	Very high	1.2 m (4 ft) diameter pool with red-black bottom. Inflow of 1 Lpm from spring 5. Red deposits on sinter near algae fan may be metastibnite.
35N					Steaming. Old pipe with valves jammed in fissure.
35					Steaming.
40					Steaming.
6	97	7.4	1	High	Superheated 0.9 m (3 ft) diameter pool with black bottom. Much of gas may be steam.

MAIN TERRACE (continued)

Spring No.	Temp °C	pH	Discharge Lpm	Gas	Remarks
No #	57		0		Slimy green pool between springs 6 and 7.
7	78	6.6	0	Low	0.6 m (2 ft) by 2 m (7 ft) along pool with tail. Black bottom.
43	63		0	Low	Double-butterfly shaped pool 1.2 m (4 ft) by 0.5 m (1.5 ft). Slightly opalescent, very deep.
41S					Steaming fissure. 3 m (10 ft) NE is steaming ground with copious SO deposits.
39-36					The fissure is open most of this length. Very little steam. Can see water and vigorous gas at about 4.5 m (15 ft) depth. Water is not flowing much, if at all.
8	91	7.4	0.25	High	0.3 m (1 ft) square pool. Yellow deposits around edge at water line.
8NW	77		0	Intermittent, low	0.6 m (2 ft) by 0.9 m (3 ft) rectangular pool. Almost dry.
9					Almost dry. Could not get good temp.

MAIN TERRACE (continued)

Spring No.	Temp °C	pH	Discharge Lpm	Gas	Remarks
No #	63	6.1	0		Pot-shaped spring 0.15 m (6 in) at surface, 0.6 m (2 ft) diameter underground along a fault. Not much water but HgS and possibly HgO depositing on sinter in bottom just above water level. Pale yellow crystals lining rim.
10	85	6.6	0	High	0.3 m (1 ft) by 0.9 m (3 ft) oval pool with tail. Lots of yellow deposits around edges. 10 cm (4 in) pool of same description 2.4 m (8 ft) south.
11	75	6.5	0.25		Small 0.15 m (6 in) spring with pale-yellow, filamentous bacteria. Gas bubble now and then.
42	72		0	Low	Spring along a fissure with very little water about 0.9 m (3 ft) down. Hard to reach.
42W					Like 42 only narrower yet.
125W					Dry.
12	95		0	High	Another narrow spring along a fissure. Water and gas at 0.9 m (3 ft) depth. May be superheated at south end.

MAIN TERRACE (continued)

Spring No.	Temp OC	pH	Discharge Lpm	Gas	Remarks
13					Almost dry.
13W-14					Dry, steaming. Yellow deposits.
14W-15SW					Dry.
16-16SE					Dry. Actually connected through underground cavern.
15					Lightly steaming.
15W					A little water at 1.2 m (4 ft) depth. Hard to reach.
No #			0	Moderate	South of spring 38. 0.5 m (1.5 ft) diameter pool.
38	84	7.4	0	Moderate	0.6 m (2 ft) diamond-shaped pool. Gray bottom.
37					Dry.
24	97	7.3	0	Very high	Superheated, along fault 0.15 m (6 in) below surface. Ground level has dropped enough that water is now at surface.
24E					Dry.
24W					Dry, steaming.

MAIN TERRACE (continued)

Spring No.	Temp OC	pH	Discharge Lpm	Gas	Remarks
23	95	7.3	20	High	Fissure with 3 good sampling points. Farthest south has good discharge, no gas. Middle one has some discharge, intermittent gas. North one has inflow, no gas. Probably same water flowing along fault as spring 24. Mostly inflow from spring 23.
23N					Mostly inflow from spring 23.
17SS					Inflow into vent from spring 23.
17	86	7.0	0.25		Small double oval pools.
22					Dry.
18	90	6.7	4		Several small seeps along fissure.
19	77	5.9	0.25		Seep.
19N-20					Marshy seeps.
No #					1.2 m (4 ft) by 1.5 m (5 ft) pool with E-W fissure in bottom. Mostly runoff from springs to west.
27	87	6.2	4	Intermittent, moderate	Small spring under rock with water from spring to west flowing past.

MAIN TERRACE (continued)

Spring No.	Temp OC	pH	Discharge Lpm	Gas	Remarks
No # (Nr 27)	78	6.8	20	High	1.2 m (4 ft) by 0.6 m (2 ft) pool along a fissure. Bottom covered with fine black sediment.
34				Intermit- tent, low	Small stagnant spring in gully.
21-21S					Dry.
34N					Dry.
21W					Dry.
21N	70.5	7.8	4	0	Further north than before--just off plate 3, White (1968a). Copious red deposits near here probably metastibnite.