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HOT SPRINGS OF THE CENTRAL SIERRA NEVADA, CALIFORNIA

By R. H. Mariner, T. S. Presser, and W. C. Evans

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ABSTRACT

Thermal springs of the central Sierra Nevada issue dilute to slightly saline sodium chloride, sodium bicarbonate, or sodium mixed-anion waters ranging in pH from 6.4 to 9.3. The solubility of chalcedony appears to control the silica concentration in most of the spring waters. Fales Hot Springs may be associated with a higher temperature aquifer, 150° Celsius or more, in which quartz is controlling the silica concentration.

Carbon dioxide is the predominant gas escaping from Fales Hot Springs, the unnamed hot spring on the south side of Mono Lake, and the two thermal springs near Bridgeport. Most of the other thermal springs issue small amounts of gas consisting principally of nitrogen. Methane is the major component of the gas escaping from the unnamed spring on Paoha Island in Mono Lake.

The δD and $\delta^{18}O$ composition of most of the thermal waters are those expected for local meteoric water which has undergone minor water-rock reaction. The only exceptions are the hot spring on Paoha Island in Mono Lake and perhaps the unnamed warm spring (south side of Mono Lake) which issue mixtures of thermal water and saline lake water.

INTRODUCTION

Most hot springs in the central Sierra Nevada issue along the eastern side of the range in the transitional area between the Sierra Nevada and Basin and Range provinces. Long Valley, which is included in this area, has potential as a source of geothermal energy but has been discussed in other reports (Werner and others, 1967; Mariner and Willey, 1976). Waring (1965) lists 18 thermal springs in this part of the Sierra Nevada; however, the thermal springs issuing on the north and south sides of Mono Lake are not included in his listing. Fourteen of these thermal springs were sampled to determine chemical, isotopic (δD and $\delta^{18}O$), and gas composition.

Concentrations of silica, sodium, potassium, and calcium in thermal waters have been shown to have a quantitative relationship to the temperature at which the water was last in equilibrium with rock in the thermal reservoir. Fournier and Rowe (1966) demonstrated the usefulness of silica concentrations in estimating reservoir temperatures. Arnórsson (1975) has shown that chalcedony usually controls the silica concentration in systems at temperatures of less than 110°C (Celsius). The proportions of sodium, potassium, and calcium were related to reservoir temperature in Fournier and Truesdell (1973).

The composition of gases escaping from thermal springs has a qualitative relationship to the temperature of the thermal aquifer (Ellis, 1970). Relationships between deuterium and oxygen-18 are useful in demonstrating mixing and determining the source water (Giggenbach, 1971). Chemical and isotope analyses of six cold waters from springs, streams, or lakes are included to establish background data.

Wildcat geothermal wells have been drilled in the vicinity of Fales Hot Springs, Travertine Hot Springs, and the unnamed hot springs north and south of Mono Lake. These wells are relatively shallow and generally have bottom-hole temperatures that are less than the temperatures of thermal springs near them. "Fales 1" near Fales Hot Springs was 126 m (meters) deep and had a bottom-hole temperature of 38°C. "Bridgeport 1" near Travertine Hot Springs was 299 m deep and had a bottom-hole temperature of 51°C. A 1,253-m well, "State PRC 4397.1" no. 1, drilled near the warm spring at the south side of Mono Lake had a reported temperature of 54°C. A 542-m well, "State PRC 4572.1" no. 23-1, near the hot spring at the north side of Mono Lake, had a reported temperature of 58°C (Axtell, 1972; Koenig, 1970).

The primary consideration in the development of a geothermal system is the temperature and type of thermal reservoir. The chemical composition of a thermal water provides the only indirect means of quantitatively estimating the temperature of the thermal reservoir and determining the type of thermal system. Except for Long Valley, which has recently been studied by the U.S. Geological Survey (Mariner and Willey, 1976), chemical data for thermal waters along the eastern side of the Sierra Nevada are generally unavailable or of questionable quality. The data and information in this report allow an initial estimate of temperatures expected in thermal aquifers associated with these hot springs.

METHODS AND PROCEDURES

Water collected in a 4-liter stainless-steel pressure vessel at points as close to the orifice of the springs or wells as possible was immediately pressure-filtered through a 0.1 μm (micrometer) membrane filter using compressed nitrogen as the pressure source. Filtered water samples were stored in plastic bottles which had been acid-washed to remove contaminants prior to use. Samples for heavy-metal analyses were immediately acidified with concentrated nitric acid to pH 2 or less to insure that the metals would remain in solution. Samples collected for Group II metals were acidified with concentrated hydrochloric acid to pH 2. Ten ml (milliliters) of filtered sample was diluted to 100 ml with distilled, deionized water to slow the polymerization of silica. Three samples of unfiltered water were collected in 125-ml glass bottles with polyseal caps for analysis of deuterium and oxygen-18. Samples of gases escaping from the springs were collected in gas-tight glass syringes which were placed in a bottle of the native water for transport to the laboratory.

Field determinations were made of water temperature, pH, alkalinity, ammonia, and sulfide. Extraction of aluminum and preservation of mercury were also performed in the field. Detailed descriptions of our sampling techniques are given by Presser and Barnes (1974). Water temperatures were determined with a thermistor probe and a maximum-reading mercury-in-glass thermometer. The pH was measured directly in the spring using the method of Barnes (1964). An alkalinity titration was performed immediately after the sample was withdrawn from the spring. Sulfide was precipitated as zinc sulfide from the hot sample and titrated by the iodometric method described by Brown, Skougstad, and Fishman (1970). Mercury was stabilized for analysis in the laboratory by addition of 2:1 H_2SO_4:HNO_3, 5-percent $KMnO_4$(W/V), and 5-percent $K_2S_2O_8$(W/V). Ammonia was determined by allowing the sample to cool to ambient temperature, adding sodium hydroxide to raise the pH to approximately 12, and measuring the dissolved ammonia with an ammonia specific-ion electrode. Water samples for aluminum determination were complexed with 8-hydroxyquinoline, buffered at pH 8.3, and extracted with methyl isobutyl ketone in the field as described by Barnes (1975).

Silica, sodium, potassium, lithium, rubidium, cesium, calcium, magnesium, cadmium, cobalt, copper, iron, nickel, lead, manganese, and zinc were determined by direct aspiration on a double beam atomic absorption spectrophotometer. Detection limits in micrograms per liter (μg/L) for the heavy metals are: cadmium (10), cobalt (10), iron (20), lead (100), manganese (20), nickel (20), copper (10), and zinc (10). Boron, depending on the concentration range, was determined by either the Dianthrimide or the Carmine method (Brown and others, 1970). Fluoride was determined by specific-ion electrode using the method of R. B. Barnes (U.S. Geological Survey, written commun., 1973). The colorimetric Ferric Thiocyanate method (ASTM, 1974) was used for samples containing less than 10 mg/L chloride. Higher chloride concentrations were titrated by the Mohr method (Brown and others, 1970). Sulfate was titrated by the Thorin method (Brown and others, 1970). Mercury was determined by a flameless atomic absorption technique (U.S. Environmental Protection Agency, 1971). The organic extract containing the aluminum complex was analyzed by atomic absorption.

The CO_2-equilibration method of Cohn and Urey (1938) and the uranium technique of Bigeleisen, Perlman, and Prosser (1952) were used in the analysis for oxygen and hydrogen isotope ratios. Isotopic ratios of $^{18}O/^{16}O$ and D/H in the water samples were measured on a modified Nier double-collecting 6-inch 60° sector mass spectrometer.

Gases were analyzed by gas chromatography as soon as possible after returning to the laboratory, always within two weeks of collection. Linde Molecular Sieve 13X[1/] was used to separate and quantify (O_2 + Ar), N_2, and CH_4, while Porapak Q was used for CH_4 and CO_2. The gas-chromatography columns were operated at room temperature with helium as the carrier gas. Gases were detected by thermal conductivity.

LOCATION OF SAMPLE SITES

The locations of the sampled thermal springs are shown on figure 1 and listed in table 1. A brief description of the spring, including an estimate of the flow rate, is included in the table. Discharge from Grovers and Keough hot springs is utilized in swimming pools. Although not commercially utilized, Mono, Reds Meadow, Fales, and Brockway Springs, and the unnamed springs on the north side of Mono Lake have also been modified to supply baths, showers, or swimming pools. During the summer and late fall of 1974 attempts were made to sample all the thermal springs in the central Sierra Nevada which issue at temperatures of more than 40°C. The unnamed warm spring at the south side of Mono Lake issues at 33°C but was sampled because of its high rate of gas discharge. Fish Creek Hot Springs, southeast of Devils Postpile National Monument, was not sampled because of the inaccessible location, low flow rate, and temperature reported in Waring (1965).

1/ The use of the brand name in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

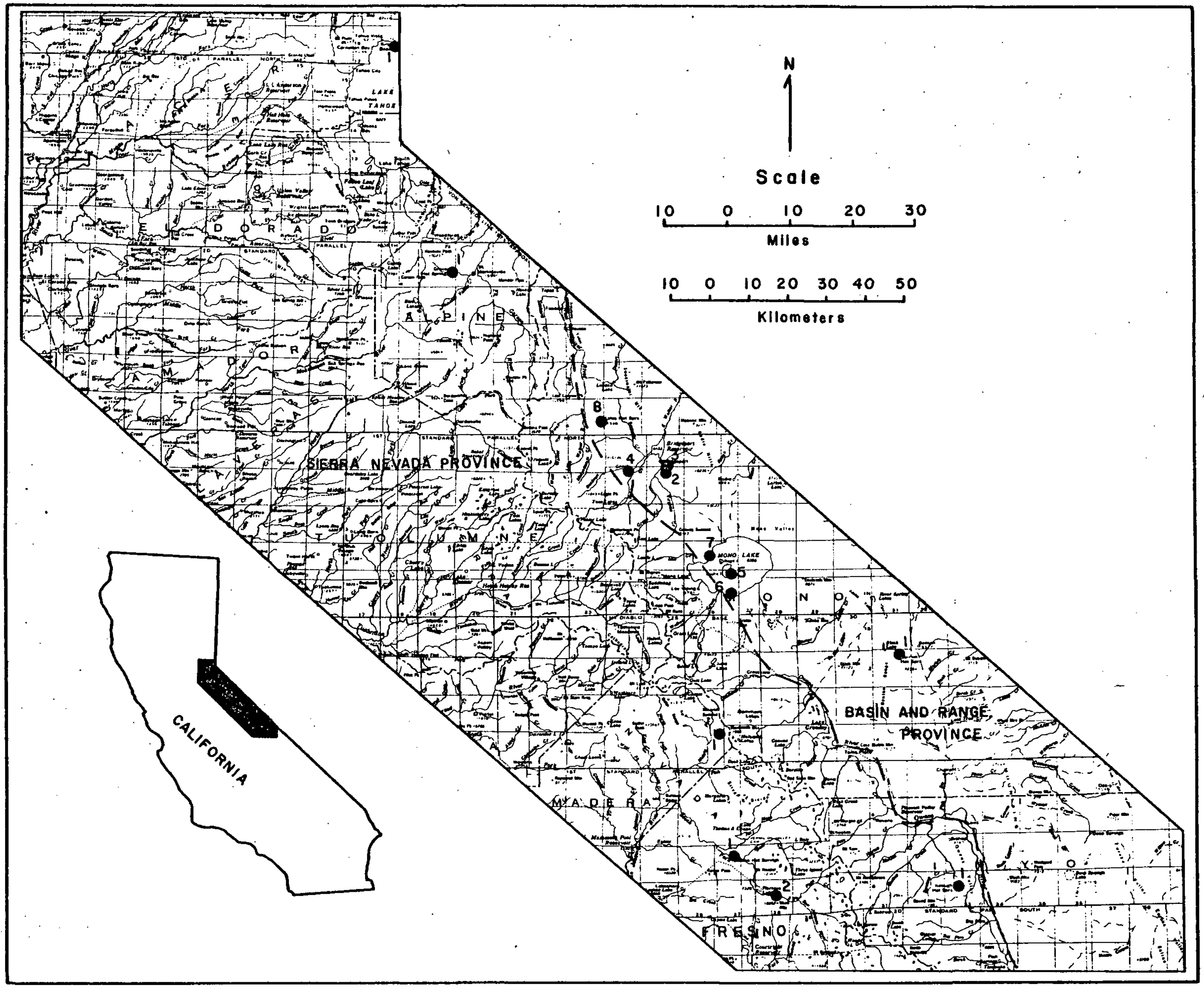

Figure 1.--Map of the central Sierra Nevada showing the location of sampled thermal springs. The numbered dots correspond to sampled springs listed by county in table 1. The dashed line is the approximate boundary between the Sierra Nevada Province and the Basin and Range Province.

Table 1.--Location and description of sampled springs

Spring	Location	Description
		Alpine County
1. Grovers Hot Springs----------------------	W½sec. 24, T. 10N., R. 19E.	Two principal springs, several seep springs; aggregate flow 400 Lpm; swimming pool.
		Fresno County
1. Mono Hot Springs-------------------------	Unsurveyed, 37°20'N by 119°1'W.	Numerous small gassy springs issue in concrete tanks; discharge estimated at 200 Lpm total.
2. Blayney Meadows Hot Springs--------------	Unsurveyed, 37°14'N by 118°52'W.	Minor gas discharge; springs issue from a fracture in granodiorite; aggregate flow 150 Lpm.
		Inyo County
1. Keough Hot Springs-----------------------	NW¼sec. 17, T. 8S., R. 33E.	Resort; high flow rate (>2,000 Lpm), no gas; springs issue in concrete-lined basins.
		Madera County
1. Reds Meadow Hot Springs------------------	Unsurveyed, 37°37'N by 119°4'W.	Spring rises in a concrete tank; flow rate 50 Lpm, no gas; campground.
		Mono County
1. Benton Hot Springs-----------------------	SW¼sec. 2, T. 2S., R. 31E.	Water used for irrigration; flow rate 800 Lpm, gassy spring.
2. The Hot Springs--------------------------	NE¼sec. 9, T. 5N., R. 25E.	Gassy springs issuing through travertine mounds; flow rate less than 100 Lpm.
3. Travertine Hot Springs-------------------	SW¼sec. 34, T. 5N., R. 25E.	Gassy springs issue along the western end of several long parallel travertine ridges; flow less than 50 Lpm.
4. Buckeye Hot Spring-----------------------	NE¼sec. 4, T. 4N., R. 24E.	Old travertine deposits; aggregate flow perhaps 400 Lpm; some carbonate precipitated around spring.
5. Unnamed hot springs (Paoha Island, Mono Lake)	NW¼sec. 32, T. 2N., R. 27E.	Springs issue along the southeastern shore line of Paoha Island; at least 15 springs; some gas; several springs issue in the lake; flow rate 250 Lpm?
6. Unnamed hot spring (S. Shore, Mono Lake)	E½sec. 18, T. 1N., R. 27E.	Very gassy spring issuing among tufa mounds on the south shore of Mono Lake; flow rate 150 Lpm.
7. Unnamed hot springs (N. Shore, Mono Lake)	E½sec. 11, T. 2N., R. 26E.	Springs are covered and inaccessible; sample from outflow pipe 150 m from source; flow rate 150 Lpm.
8. Fales Hot Springs------------------------	SE¼sec. 24, T. 6N., R. 23E.	Very gassy spring; more than 1,000 Lpm; swimming pool, bathhouse, and old travertine deposits.
		Placer County
1. Brockway Hot Springs---------------------	NE¼sec. 30, T. 16N., R. 18E.	Gassy springs issue in concrete tanks at edge of Lake Tahoe.

GEOLOGIC SETTING

The Sierra Nevada is a large, westward-tilted block of the earth's crust which has a steep faulted escarpment on the east side. Sediments of the Great Valley sequence overlap the range to the west and volcanic flows bury the northern end of the range. The central Sierra Nevada is principally Mesozoic granitic rock with capping remnants of upper Tertiary to Quaternary volcanics extruded along faults of the eastern escarpment (Bateman and Wahrhaftig, 1966). Generally, the hot springs issue along faults in or near the volcanic rocks. References to geologic mapping of the area around each hot spring are included in table 2 along with the age and bedrock type.

Mono, Blayney Meadows, and Keough hot springs issue from granitic rocks. However, young basalt flows in the vicinity of these springs may be associated with the heat source. Basaltic flows of variable thickness overlie granitic rock at Brockway, Buckeye, and Fales hot springs. Travertine Hot Springs, The Hot Springs, and the unnamed thermal springs at the north side of Mono Lake are associated with basaltic rock. The unnamed hot springs on Paoha Island in Mono Lake are associated with rhyolite and rhyodacite. Reds Meadow Hot Springs issue in an area underlain by rhyolite and basalt. Grovers Hot Springs issue from a fault separating granite and andesite. Benton Hot Springs and the unnamed hot springs on the south shore of Mono Lake issue from rhyolitic tuffs.

WATER COMPOSITION

Waters from the 14 hot springs display a large range in chemical composition (table 3). The waters range from neutral to alkaline (pH 6.4 to 9.3). Sodium is the major cation in all of the thermal waters. The spring waters include Na-Cl, Na-HCO_3, and Na-mixed anion types ranging from fresh to very saline. By the classification of Robinove, Langford, and Brookhart (1958) waters containing less than 1,000 mg/L (milligrams per liter) dissolved solids are fresh waters; slightly saline waters range from 1,000 to 3,000 mg/L; moderately saline waters range from 3,000 to 10,000 mg/L; very saline waters range from 10,000 to 35,000 mg/L; and briny waters contain more than 35,000 mg/L. As the dissolved solids of the springs increase from 319 to 2,500 mg/L, the pH decreases from 9.3 to 6.4. At higher concentrations of dissolved solids, 4,000 to 26,000 mg/L, the pH increases from 6.7 to 9.3. The unnamed spring on Paoha Island in Mono Lake, which has the highest salinity and pH, issues a mixture of thermal and lake water. Several of the more dilute, high-pH waters are unusual in that almost half of the alkalinity is noncarbonate alkalinity. Benton, Keough, and Brockway hot springs have pH values of 9.32, 8.80, and 8.73, respectively; the percentage of noncarbonate alkalinity decreases in a similar manner, 51 percent, 41 percent, and 36 percent. The major noncarbonate

Table 2.--Age and type of bedrock at each spring

Springs	Age and type of bedrock	References to geologic mapping
	Alpine County	
Grovers Hot Springs-------------------	Fault contact between Mesozoic granite and Pliocene volcanic flows (andesitic).	Koenig (1963)[1/]
	Fresno County	
Mono Hot Springs-----------------------	Cretaceous granodiorite; Pliocene trachybasalt crops out 1 km northwest of the spring.	Bateman, Lockwood, and Lydon (1971).
Blayney Meadows Hot Springs------------	Cretaceous granodiorite, near Jurassic-Triassic metavolcanic rocks.	Bateman (1965).
	Inyo County	
Keough Hot Springs---------------------	Cretaceous granite.	Strand (1967)[1/]
	Madera County	
Reds Meadow Hot Springs----------------	Pleistocene rhyolitic tuff, near Pleistocene andesite, quartz latite, and recent basalt.	Huber and Rinehart (1965).
	Mono County	
Benton Hot Springs---------------------	Pleistocene pyroclastic rocks (rhyolitic) overlying Mesozoic granite.	Strand (1967).
The Hot Springs------------------------	Pliocene volcanic rocks (principally andesite and basalt flows).	Koenig (1963).
Travertine Hot Springs-----------------	Pliocene volcanic rocks (principally andesite and basalt flows).	Koenig (1963).
Buckeye Hot Spring---------------------	Quaternary glacial deposits overlying Pliocene volcanic rocks (andesitic) and Mesozoic granite.	Koenig (1963).
Unnamed hot springs (Paoha Island, Mono Lake)	Pleistocene andesite, may be overlying Pleistocene lake deposits.	Kistler (1966).
Unnamed hot spring (S. Shore Mono Lake)	Quaternary alluvium and lake beds; may be associated with Holocene rhyolite or Pleistocene andesite flows.	Kistler (1966).
Unnamed hot springs (N. Shore Mono Lake)	Quaternary lake deposits and pyroclastics, near Pleistocene andesite flow.	Koenig (1963).
Fales Hot Springs----------------------	Pliocene andesite flows underlain by Mesozoic granite.	Koenig (1963).
	Placer County	
Brockway Hot Springs-------------------	Quaternary lake deposits; Pliocene pyroclastics rocks; Mesozoic granite, near exposure of Pleistocene basalt.	Koenig (1963).

[1/]The maps of Koenig (1963) and Strand (1967) are largely compilations of previous maps, some of which are unpublished.

Table 3.--Chemical analyses of sampled thermal springs

[Concentrations are in milligrams per liter]

Spring	Temperature (°C)	pH	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Alkalinity as bicarbonate (HCO_3)[1]	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Boron (B)	Dissolved constituents[2]
						Alpine County								
Grovers Hot Springs	64	6.79	100	31	1.9	440	13	0.82	776	160	190	4.2	3.1	1,720
						Fresno County								
Mono Hot Springs	43	6.92	60	70	3.2	300	8.8	.89	307	74	370	3.0	2.9	1,200
Blayney Meadows Hot Springs	43	8.00	51	75	.2	200	5.0	.65	28	48	400	2.1	2.0	812
						Inyo County								
Keough Hot Springs	51	8.80	44	9.4	<.1	160	2.5	.40	39	68	180	7.8	.65	512
						Madera County								
Reds Meadow Hot Springs	45½	7.29	150	61	2.5	140	6.2	.83	516	33	6.7	4.8	1.8	923
						Mono County								
Benton Hot Springs	56½	9.32	63	1.4	<.1	80	1.0	.18	96	50	22	3.8	.30	319
The Hot Springs	40	7.03	65	76	18	1,100	62	2.8	1,880	910	210	4.3	11	4,394
Travertine Hot Springs	69	6.73	100	64	18	1,100	55	2.5	1,800	920	200	4.5	9.9	4,324
Buckeye Hot Spring	60	7.33	75	22	4.2	310	10	.84	429	340	28	9.2	1.1	1,234
Unnamed hot springs (Paoha Island, Mono Lake)	83	9.31	220	.2	<.1	8,000	225	2.5	7,700	2,700	6,000	26	130	26,342
Unnamed hot spring (S. Shore Mono Lake)	33	6.38	130	120	61	410	34	2.8	1,560	28	105	.4	6.1	2,496
Unnamed hot springs (N. Shore Mono Lake)	66	7.68	76	13	2.9	430	8.8	.28	454	100	350	4.8	7.7	1,487
Fales Hot Springs	61	6.55	114	41	10	560	37	1.3	1,130	260	160	4.7	8.2	2,356
						Placer County								
Brockway Hot Springs	55	8.73	71	4.4	.2	110	3.0	.50	84	34	100	2.9	2.8	426

[1]Total alkalinity as bicarbonate. Calculated bicarbonate concentrations: Blayney Meadows Hot Springs, 24 mg/L; Keough Hot Springs, 23 mg/L; Benton Hot Springs, 47 mg/L; Unnamed hot springs (Paoha Island, Mono Lake), 7611 mg/L; Unnamed hot springs (N. Shore, Mono Lake), 447 mg/L; Brockway Hot Springs, 54 mg/L.

[2]Dissolved constituents represent the total of all analyzed constituents.

constituents contributing to the total alkalinity in these waters is the silica species, $H_3SiO_4^-$.

Trace-constituent concentrations (table 4), are noteworthy only for the high mercury concentration in water from the thermal spring on Paoha Island (0.024 mg/L). Thermodynamic calculations using the computer program SOLMNEQ (Kharaka and Barnes, 1973) indicate that most of the mercury is complexed and unavailable for reaction with sulfide. The only detectable ammonia occurs in the thermal springs issuing on Paoha Island and on the north side of Mono Lake. Concentrations of aluminum are relatively high in the most dilute thermal springs, Benton Hot Springs (0.036 mg/L) and Keough (0.014 mg/L). Cadmium, cobalt, and lead were not detected in any of the samples.

Major-constituent chemical analyses of six waters from cold springs, streams, or lakes are given in table 5 to establish background data. Chloride concentrations in Lake Tahoe, Senger Creek, Buck Creek, and an unnamed creek east of Reds Meadow Hot Springs are all very low (<2.4 mg/L). The creek near Reds Meadow Hot Springs and the cold spring on the southeast shore of Mono Lake are exceptionally high in silica, 69 and 90 mg/L, respectively. The remaining creeks and lakes have silica contents ranging from 12 to 24 mg/L. Mono Lake, a briny $Na\text{-}HCO_3\text{-}Cl\text{-}SO_4$ water, may be mixing with the thermal springs which issue in the basin. The lack of mixing between the lake water and the cold spring which issues on the southeast side of the lake (<1 part per 1,000 based on chloride concentration) may have resulted from self-sealing. Water from the high-calcium cold spring may have reacted with the high-carbonate lake water producing calcite and sealing the conduit.

Carbonate-rich springs such as Fales Hot Springs, the unnamed hot spring on the south shore of Mono Lake, The Hot Springs, Travertine Hot Springs, Buckeye Hot Spring, and Reds Meadow Hot Springs have high B/Cl ratios (table 6) which are characteristic of springs issuing from volcanic rocks. Reds Meadow Hot Springs, issuing from rhyolitic rock, has the highest F/Cl ratio (1.3/1), whereas the other five springs have the lowest F/Cl ratios and are probably associated with basaltic rocks. The high Mg/Ca ratios at Travertine Hot Springs, The Hot Springs, Buckeye Hot Spring, Fales Hot Springs, and the unnamed hot springs on the north and south sides of Mono Lake probably also indicate association with mafic rocks. The low Mg/Ca ratios for Keough, Benton, and Blayney Meadows hot springs indicate association with granitic rocks which contain almost no magnesium. Ratios of K/Na and Li/Na are very similar for these springs. However, the K/Na ratio is several times larger than the Li/Na ratio for The Hot Springs, Travertine, Fales, and the unnamed hot springs at the north side of Mono Lake. Chloride is high relative to sulfate or bicarbonate in springs issuing from granitic or rhyolitic rocks, but low in springs associated with mafic rocks. Also the lower the dissolved solids of the thermal waters, the higher the $(\sqrt{Ca})/Na$ ratios. In the

Table 4.--Trace constituent concentrations in thermal waters

[Concentrations are in milligrams per liter; dashes indicate the absence of data]

Spring name	Sulfide (as H_2S)	Aluminum (Al)	Rubidium (Rb)	Ammonia (as N)	Cesium (Cs)	Manganese (Mn)	Copper (Cu)	Nickel (Ni)	Mercury (Hg)	Zinc (Zn)	Iron (Fe)
Alpine County											
Grovers Hot Springs	<0.5	0.002	0.06	<0.1	<0.1	0.08	<0.01	<0.02	<0.0001	0.11	<0.02
Fresno County											
Mono Hot Springs	[1]<1	<.001	.06	<.1	.1	.23	.01	<.02	<.0001	.04	.08
Blayney Meadows Hot Springs	<.5	.002	.05	<.1	<.1	<.02	<.01	<.02	<.0001	.38	<.02
Inyo County											
Keough Hot Springs	<.5	.014	.02	<.1	<.1	<.02	<.01	<.02	<.0001	.04	<.02
Madera County											
Reds Meadow Hot Springs	<.5	.001	<.02	<.1	<.1	.54	<.01	<.02	.0002	.11	<.02
Mono County											
Benton Hot Springs	<.5	.036	<.02	<.1	<.1	<.02	<.01	<.02	.0005	.02	<.02
The Hot Springs	<1	.003	.42	<.1	.5	.09	.01	.02	.0001	.20	.02
Travertine Hot Springs	<.5	.004	.40	<.1	.4	<.02	.02	.02	<.0001	.18	.05
Buckeye Hot Spring	<.5	.003	.10	<.1	.1	.03	<.01	<.02	<.0001	.05	<.02
Unnamed hot springs (Paoha Island, Mono Lake)	38	.005	.95	8.6	.3	<.02	---	---	.024	---	.16
Unnamed hot spring (S. Shore Mono Lake)	<.5	.003	.04	<.1	<.1	1.7	.06	.03	<.0001	.24	1.4
Unnamed hot springs (N. Shore Mono Lake)	<.5	.003	.02	3.0	<.1	<.02	.01	<.02	<.0001	.02	<.02
Fales Hot Springs	<1	<.001	.22	<.1	.2	.18	.05	<.02	.0001	.09	.02
Placer County											
Brockway Hot Springs	<1	---	.02	<.1	<.1	<.02	<.01	<.02	---	<.01	<.02

[1] Detection limits of <0.5 mg/L are for iodometric titrations, whereas detection limits of <1 mg/L indicate that there was no detectable smell of hydrogen sulfide at the spring.

Table 5.--Chemical composition of selected nonthermal waters in the Sierra Nevada

[Chemical concentrations are in milligrams per liter]

Sample	Location	Temperature (°C)	pH	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Alkalinity as bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Boron (B)	Ammonia (as N)	Dissolved solids
Cold spring	Southeast shore of Mono Lake, E½sec. 16, T. 1N., R. 27E.	14	6.67	90	140	40	64	9.0	0.37	816	4	18	0.2	1.3	0.6	1,183
Mono Lake	SE¼sec. 17, T. 1N., R. 27E.	15	9.77	13	4	38	1/ 29,000	1,500	12	35,400	9,700	18,200	48	400	.2	94,305
Lake Tahoe	Stateline Point, NE¼sec. 30, T. 16N., R. 18E.	19	8.07	13	8.4	2.4	6.6	1.8	<.02	51	<1	2.4	<.1	<.02	<.1	86
Senger Creek	Creek near Blayney Meadows Hot Springs, E½sec. 14, T. 8S., R. 28E.	8	7.10	12	3.7	.2	3.4	.7	<.02	21	4	<1	<.1	<.02	---	45
Buck Creek	Creek near Grover Hot Springs, NW¼sec. 24, T. 10N., R. 19E.	13	7.24	24	6.3	1.5	5.1	1.2	<.02	38	<1	.4	<.1	<.02	---	140
Unnamed creek	Creek east of Reds Meadow Hot Springs, 37°37'N. by 119°4'W.	10	7.98	69	7.6	7.5	11	5.2	.03	88	6	.3	.2	.02	---	195
Unnamed creek	Creek near Mono Hot Springs 37°20'N. by 119°1'W.	9	8.19	50	68	3.2	310	8.8	.87	257	83	410	2.5	2.8	---	1,196

1/ Also contains Cs (0.4 mg/L) and Rb (2.2 mg/L).

Table 6.--Mole ratios of major and minor constituents in the thermal waters

[Dashes indicate that one of the constituents used in the ratio was less than the detection limit.]

Springs	pH	Dissolved solids (mg/L)	Cl/SO_4	Cl/HCO_3	$(F/Cl)x10^2$	$(B/Cl)x10^2$	$(\sqrt{Ca})/Na$	$(K/Na)x10^3$	$(Li/Na)x10^3$	$(Mg/Ca)x10^2$
Alpine County										
Grovers Hot Springs	6.79	1,720	3.2	0.42	4.1	5.3	1.4	17	6.2	10
Fresno County										
Mono Hot Springs	6.92	1,200	1.4	2.1	1.5	2.6	3.2	17	9.8	7.5
Blayney Meadows Hot Springs	8.00	812	22	25	.98	1.6	5.0	15	11	.44
Inyo County										
Keough Hot Springs	8.80	512	7.2	7.9	8.1	1.2	2.2	9.2	8.3	---
Madera County										
Reds Meadow Hot Springs	7.30	923	.55	.022	130	88	6.4	26	20	6.8
Mono County										
Benton Hot Springs	9.32	319	1.2	.39	32	4.4	1.7	7.4	7.5	---
The Hot Springs	7.03	4,394	.63	.19	3.8	17	.91	33	8.4	39
Travertine Hot Springs	6.73	4,323	.59	.19	4.2	16	.83	29	7.5	46
Buckeye Hot Spring	7.33	1,234	.22	.11	61	13	1.7	19	9.0	32
Unnamed hot springs (Paoha Island, Mono Lake)	9.31	26,342	5.8	1.2	.81	7.1	.006	16	1.0	---
Unnamed hot spring (S. Shore Mono Lake)	6.38	2,491	9.7	.11	.75	20	3.1	49	23	77
Unnamed hot springs (N. Shore Mono Lake)	7.68	1,487	9.5	1.3	2.6	7.2	.96	12	2.2	37
Fales Hot Springs	6.55	2,365	1.7	.24	5.5	1.7	1.3	39	7.7	40
Placer County										
Brockway Hot Springs	8.82	426	8.0	2.0	5.4	9.2	2.2	16	15	7.5

Sierra Nevada, changes in the ($\sqrt{Ca}$)/Na ratio may be a function of the dissolved solids rather than the temperature of the aquifer.

GAS COMPOSITION

The composition of gases escaping from hot springs may give a qualitative indication of the subsurface temperature. Springs associated with high-temperature systems discharge carbon dioxide (Ellis, 1970) whereas springs associated with low-temperature systems discharge nitrogen (Bodvarsson, 1961). The springs which release nitrogen generally have a slow, sporadic rate of gas discharge whereas springs which release a high proportion of carbon dioxide (80 percent or more) virtually effervesce.

Eleven of the 14 springs release sufficient gas to make sampling feasible. Mono, Blayney Meadows, Benton, Buckeye, and Brockway hot springs release principally nitrogen (table 7). Fales Hot Springs, Travertine Hot Springs, The Hot Springs, and the unnamed hot springs on the south shore of Mono Lake release principally carbon dioxide. Methane is the major component of the gas from the unnamed springs on Paoha Island; Brockway Hot Springs at the north end of Lake Tahoe release both nitrogen (90 percent) and methane (8.1 percent). Grovers Hot Springs release a mixture of nitrogen (62 percent) and carbon dioxide (36 percent).

SOLUTION-MINERAL EQUILIBRIUM

Consideration of solution-mineral equilibrium is important in determining the validity of geothermal calculations. The composition of thermal waters moving from a reservoir at depth to the surface may be changed by precipitation or solution of minerals. These compositional changes can have a pronounced effect on the estimated temperature from the cation and silica geothermometers. Waters which are theoretically in equilibrium with respect to calcite, aragonite, or amorphous silica at the temperature of the spring are particularly suspect.

Results of thermodynamic calculations using the computer program SOLMNEQ (Kharaka and Barnes, 1973) to determine the states of reaction of the aqueous solution with respect to calcite, aragonite, chalcedony, alpha-cristobalite, amorphous silica (opal), and fluorite are given in table 8. Positive values calculated for the Gibbs free energy of formation (ΔG) indicate that the water is supersaturated with respect to the mineral, and that the mineral <u>may</u> precipitate. Equilibrium between a mineral and water is theoretically possible whenever the free energy of formation is zero (arbitrarily ± 0.2 kcal/mole for this discussion). A negative free energy of formation indicates that the water is unsaturated with respect to that mineral and the mineral would dissolve in water.

Table 7.--Composition of gases issuing from the thermal springs

Spring	Percent by volume				
	O_2+Ar	N_2	CH_4	C_2H_6	CO_2
Alpine County					
Grovers Hot Springs	1.4	62	0.3	<0.1	36
Fresno County					
Mono Hot Springs[1/]					
(A)	1.7	95	.1	<.1	2.7
(B)	1.9	95	<.1	<.1	2.2
Blayney Meadows Hot Springs	1.8	97	<.1	<.1	<0.1
Mono County					
Benton Hot Springs	2.1	95	<.1	<.1	.2
The Hot Springs	1.1	3	<.1	<.1	85
Travertine Hot Springs	0.4	1.1	<.1	<.1	93
Buckeye Hot Spring	3.9	91	<.1	<.1	4.3
Unnamed hot springs (Paoha Island, Mono Lake)	1.3	25	70	2.8	.3
Unnamed hot spring (S. Shore, Mono Lake)	.5	1.3	<.1	<.1	97
Fales Hot Springs	1.1	5.8	<.1	<.1	92
Placer County					
Brockway Hot Springs	1.9	90	8.1	<.1	.2

[1/] (A) From spring on west end of complex. (B) From concrete tank near road at east side of complex.

Table 8.--States of reactions with respect to calcite, aragonite, chalcedony, alpha-cristobalite and fluorite

[Magnitude of ΔG indicates degree of departure from equilibrium in kilocalories; plus values indicate supersaturation, minus values indicate unsaturation.]

Spring	Gibbs free energy of formation, ΔG (kcal)				
	Calcite	Aragonite	Chalcedony	Alpha-cristobalite	Fluorite[1/]
Alpine County					
Grovers Hot Springs-------------------	-0.16	-0.26	+0.59	+0.29	-0.46
Fresno County					
Mono Hot Springs----------------------	-.26	-.32	+.52	+.25	-.23
Blayney Meadows Hot Springs-----------	-.17	-.24	+.39	+.12	-.43
Inyo County					
Keough Hot Springs--------------------	-.19	-.26	+.02	-.26	-.17
Madera County					
Reds Meadow Hot Springs---------------	+.62	+.55	+1.06	+.79	+.14
Mono County					
Benton Hot Springs--------------------	-.20	-.29	-.17	-.46	-1.60
The Hot Springs-----------------------	+.56	+.50	+.62	+.35	+.26
Travertine Hot Springs----------------	+.45	+.35	+.53	+.24	-.41
Buckeye Hot Spring--------------------	-.03	-.06	+.44	+.15	+.12
Unnamed hot springs (Paoha Island, Mono Lake)	-.50	-.63	+.03	-.28	-1.66
Unnamed hot spring (S. Shore, Mono Lake)	-.04	-.10	+1.12	+.86	-1.91
Unnamed hot springs (N. Shore, Mono Lake)	+.40	+.30	+.36	+.06	-.65
Fales Hot Springs---------------------	-.27	-.36	+.72	+.43	-.33
Placer County					
Brockway Hot Springs------------------	+.02	-.05	+.23	-.03	-1.32

1/ Fluorite values based on $10^{-10.57}$ at 25^{o} (Ksp) given by Smyshlyaev and Edeleva (1962).

Equilibrium with calcite or aragonite is possible at Brockway Hot Springs, the unnamed hot springs on the south shore of Mono Lake, Grovers Hot Springs, and Buckeye Hot Spring. Supersaturation with respect to calcite and aragonite occurs at Reds Meadow Hot Springs, The Hot Springs, Travertine Hot Springs, and the unnamed hot spring on the north side of Mono Lake. Loss of calcium is possible from these springs; however, only The Hot Springs and Travertine Hot Springs have travertine deposits. Buckeye, Reds Meadow, and Keough hot springs are theoretically in equilibrium or supersaturated with both calcite and fluorite.

Equilibrium between spring water and chalcedony is possible at Keough Hot Springs, Benton Hot Springs, and the unnamed spring on Paoha Island. Reds Meadow Hot Springs and the unnamed hot spring at the south shore of Mono Lake are supersaturated with respect to amorphous silica at the spring temperature. However, none of the springs issue through silica deposits similar to the travertine deposits.

ISOTOPES

The isotopic compositions of the hot spring waters are given in table 9. The data are expressed in the δ-notation,

$$\delta_x = \left[\frac{R_x - R_{std}}{R_{std}}\right] 10^3, \text{ where } R_x = (D/H)_x \text{ or } (^{18}O/^{16}O)_x \text{ of the}$$

sample and R_{std} is the corresponding ratio for Standard Mean Ocean Water (SMOW). The isotopic relationship of these waters to the meteoric water line defined by Craig (1961), $\delta D = 8\delta^{18}O + 10$, is shown on figure 2. Data for most of the thermal waters plot very close to the meteoric water line. Shifts to more positive $\delta^{18}O$ values are attributed to oxygen exchange with the isotopically heavier country rock (Craig and others, 1956).

All of the thermal springs except the unnamed hot spring on Paoha Island have deuterium compositions similar to fresh water in the same area (table 10). The spring on Paoha Island probably issues a mixture of water from Mono Lake and water similar to that issuing from the unnamed hot spring on the north side of the lake. Another possibility is that a cold water similar in composition to the cold spring at the south side of the lake mixes with lake water before it circulates through the thermal reservoir. The other thermal spring in the Mono Basin has a small shift in δD and $\delta^{18}O$ relative to the cold spring which issues near it. Its composition could result from mixing of lake and cold spring water, or less likely, a slightly different source water.

Table 9.--Deuterium and oxygen-18 composition of thermal waters[1/]

[Delta values are reported relative to SMOW]

Spring name	Parts per mil		
	δD	$\delta^{18}O$	Oxygen shift[2/]
Alpine County			
Grovers Hot Springs	-115.4	-15.62	+0.06
Fresno County			
Mono Hot Springs	-118.4	-16.05	0
Blayney Meadows Hot Springs	-121.3	-16.21	+.20
Inyo County			
Keough Hot Springs	-137.4	-17.85	+.58
Madera County			
Reds Meadow Hot Springs	-111.2	-15.18	-.03
Mono County			
Benton Hot Springs	-135.5	-17.46	+.73
The Hot Springs	-137.3	-16.29	+2.12
Travertine Hot Springs	-139.3	-16.64	+2.02
Buckeye Hot Springs	-137.9	-17.66	+.83
Unnamed hot springs (Paoha Island, Mono Lake)	-99.5	-10.44	+3.25
Unnamed hot spring (S. Shore, Mono Lake)	-126.0	-16.91	+.09
Unnamed hot springs (N. Shore, Mono Lake)	-126.9	-15.69	+1.42
Fales Hot Springs	-132.8	-17.46	+.39
Placer County			
Brockway Hot Springs	-96.3	-11.50	+1.79

1/ Analyses by L. Adami and S. Grigg, U.S. Geological Survey.

2/ Shift in $\delta^{18}O$ relative to meteoric water, based on the equation $\delta D = 8\delta^{18}O + 10$.

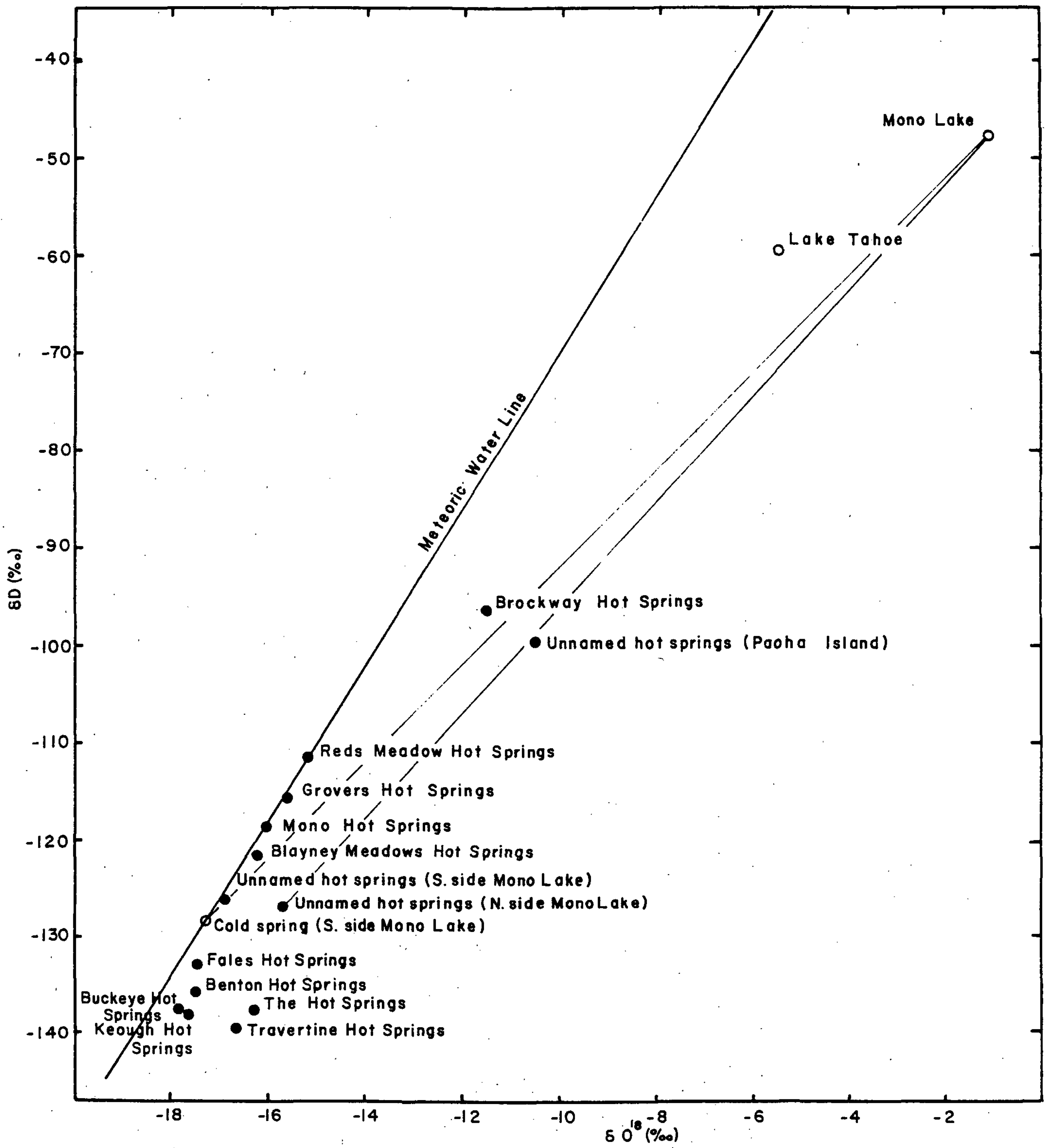

Figure 2.--Plot of δD versus $\delta^{18}O$ in thermal and selected nonthermal waters from the Sierra Nevada. The "tie lines" connecting the compositions of cold and thermal waters around Mono Lake with the composition of water from the lake indicate that the thermal springs on Paoha Island issue a mixture of water of undetermined source and saline water from Mono Lake.

Table 10.--Isotopic compositions of selected nonthermal waters in the Sierra Nevada

[Delta values are reported relative to SMOW]

Source	Location	Parts per mil	
		δD	$\delta^{18}O$
Cold spring-------	Southeast shore of Mono Lake, E½sec. 16, T. 1N., R. 27E.	-128.3	-17.34
Mono Lake---------	SE¼sec. 17, T. 1N., R. 27E.	-47.5	-1.4
Lake Tahoe--------	Stateline Point, NE¼sec. 30, T. 16N., R. 18E.	-59.3	-5.49
Buck Creek--------	Creek near Grover Hot Springs, NW¼sec. 24, T. 10N., R. 19E.	-112.8	-15.38
Unnamed creek-----	Creek east of Reds Meadow Hot Springs, 37°37'N. by 119°4'W.	-110.3	-15.07
Unnamed creek-----	Creek near Mono Hot Springs, 37°20'N. by 119°1'W.	-114.7	-15.42

The other hot spring where extensive mixing could be expected is Brockway Hot Springs which issues in the edge of Lake Tahoe. Fresh waters in the Tahoe Basin range in δD from -90 to -105 (L. D. White, U.S. Geological Survey, unpub. data, 1976). The isotopic composition of the hot spring ($\delta D = -96.3$ and $\delta^{18}O = -11.50$) and local fresh waters are approximately the same; thus large scale mixing with water from Lake Tahoe ($\delta D = -59.3$ and $\delta^{18}O = -5.49$) does not appear plausible. Other springs could also issue mixed waters but the fresh-water component must have approximately the same δD as the thermal spring water.

GEOTHERMOMETRY

Five basic assumptions must be fulfilled before the silica and Na-K-Ca geothermometers can be used to estimate quantitatively the temperature in the associated thermal aquifer (Fournier and others, 1974). These assumptions are listed below.

1. Temperature dependent reactions at depth.
2. An adequate supply of the constituents used for geothermometry.
3. Water-rock equilibrium at depth.
4. Negligible reequilibration as the water flows to the surface.
5. No dilution or mixing of hot or cold waters.

The last two assumptions are violated in some of the sampled springs. Mixing, which is possible for many of the thermal springs, leads to low aquifer-temperature estimates from the silica geothermometer. Isotope-chloride relationships indicate that several springs in Mono Basin issue mixtures of thermal and surface waters. Reequilibration of water with its environment probably affects the Na-K-Ca geothermometer more often than the silica geothermometer. Loss of calcium due to precipitation of calcium carbonate is probably the major cause of excessively high temperature estimates from the Na-K-Ca geothermometer. Another problem is encountered with the Na-K-Ca geothermometer when magnesium makes up a significant part of the cation composition. An excessively high temperature is indicated by the Na-K-Ca geothermometer because it was derived assuming that variations in magnesium concentrations do not affect the proportions of sodium, potassium, and calcium.

The cation (Na-K-Ca) and silica geothermometers indicate that Mono, Blayney Meadows, Keough, Reds Meadow, and Benton hot springs are associated with low-temperature (<90°C) thermal systems (table 11). Dilution of Mono Hot Springs water with a surface water of high silica concentration, such as the creek above Mono Hot Springs (table 5), may explain the low surface temperature but high silica content of the spring. The creek apparently derives some of its water from warm seeps

Table 11.--Measured spring temperatures and estimated thermal-aquifer temperatures based on the chemical composition of the thermal spring waters

[All temperatures are in °C]

Spring	Spring temperature	Estimated aquifer temperatures for various geothermometers[1/] Quartz	Chalcedony[2/]	Alpha-cristobalite[2/]	Amorphous silica[2/]	Na-K	Na-K-1/3Ca	Na-K-4/3Ca	Comments
Alpine County									
Grovers Hot Springs----------------------	64	137	108	87	48	75	134	118	Could be mixed water or 110°C reservoir.
Fresno County									
Mono Hot Springs-------------------------	43	110	81	62	26	75	122	80	Low flow rate; equilibrium with chalcedony at 81°C.
Blayney Meadows Hot Springs--------------	43	102	70	52	17	64	110	57	Low-temperature reservoir.
Inyo County									
Keough Hot Springs-----------------------	51	96	52	33	3	37	102	75	Low-temperature reservoir; equilibrium with chalcedony at the spring temperature.
Madera County									
Reds Meadow Hot Springs------------------	45½	161	127	105	66	105	130	64	Probable equilibrium with opal (amorphous silica).
Mono County									
Benton Hot Springs-----------------------	56½	113	45	27	<0	25	97	79	Low temperature; may be mixed with a very low silica water.
The Hot Springs--------------------------	40	114	85	66	30	125	172	177	Low flow rate; precipitation of calcium carbonate; Na-K-Ca geothermometer in doubt.
Travertine Hot Springs-------------------	69	137	107	86	48	115	167	176	Low flow rate; precipitation of calcium carbonate; Na-K-Ca geothermometer in doubt.
Buckeye Hot Spring-----------------------	60	122	92	72	35	81	138	112	Low flow rate, possibly some mixing.
Unnamed hot springs (Paoha Island, Mono Lake)	83	186	84	66	28	71	---	---	Probable equilibrium with chalcedony at spring temperature.
Unnamed hot spring (S. Shore, Mono Lake)	33	152	120	99	61	163	170	117	May be a mixed water; geothermometers in doubt.
Unnamed hot spring (N. Shore, Mono Lake)	66	122	92	73	35	52	124	125	Saturated with calcite; geothermometer in doubt.
Fales Hot Springs------------------------	61	145	113	93	55	140	174	160	Probably a mixed water; reservoir temperature probably 150°C or more.
Placer County									
Brockway Hot Springs---------------------	55	119	73	54	19	70	124	94	Low-temperature reservoir; possible equilibrium with calcite and alpha-cristobalite at the spring temperature.

[1/]Underlined numbers are those favored by the authors.

[2/]Adjusted for dissociation of H_4SiO_4 at spring temperature and pH.

which issue uphill from the main Mono Hot Springs area. The low flow rate of Reds Meadow Hot Springs makes interpretation of the geothermometers difficult. Equilibrium with amorphous silica (opal) at the spring temperature (66°C) may be the reason for the high silica content of the water. The Na-K-Ca geothermometer also has a low value (64°C). If dissociation of silica with pH is considered at Benton Hot Springs (pH 9.3) an aquifer temperature of 45°C can be calculated based on equilibrium with chalcedony. This is less than the spring temperature, and may indicate mixing of thermal water originally in equilibrium with chalcedony and a fresh water of low silica concentration. Blayney Meadows Hot Springs issue water which may be in equilibrium with alpha-cristobalite at 52°C or chalcedony at 70°C; the cation geothermometer indicates an aquifer temperature of 57°C.

Brockway Hot Springs is difficult to interpret because of the low flow rate and the possible equilibrium with alpha-cristobalite and calcite. The Na-K-Ca geothermometer indicates temperatures of less than 100°C, as does the chalcedony geothermometer. The low flow rates of Buckeye Hot Spring, Travertine Hot Springs, and The Hot Springs make the geothermometers only qualitative indicators of temperature. All three issue water which is saturated with respect to calcite; however, only Travertine Hot Springs and The Hot Springs issue from a tufa deposit. Travertine Hot Springs and The Hot Springs also contain appreciable magnesium (18 mg/L) which may interfere with the Na-K-Ca geothermometer. These springs may be associated with a reservoir which contains water at a temperature of 90-110°C. The low flow rates may have resulted in conductive cooling to moderate temperatures (40-70°C). Grovers Hot Springs may be a similar case where water of 110°C comes from a low-temperature reservoir and cools by conduction to the spring temperature.

Fales Hot Springs and the unnamed warm spring on the south shore of Mono Lake probably issue mixed waters; temperatures of 150°C or more may be reasonable for the thermal aquifer feeding Fales Hot Springs. Both springs release such large quantities of carbon dioxide that the water surfaces appear to effervesce. The Na-K-Ca geothermometer must be considered unreliable because of the large magnesium concentrations (10 and 61 mg/L, respectively). The warm spring on the south side of Mono Lake may be a mixture of calcium-rich water, similar to that issuing from nearby tufa mounds, with carbonate-rich lake waters. Mixing of these waters would result in precipitation of calcium carbonate and some heating of the water due to the spontaneous reaction. Minor variations in the cation and anion ratios relative to the mixture of lake and cold spring waters could be due to the effects of membrane filtration of the lake water prior to mixing. The unnamed hot spring on the north side of Mono Lake is saturated with respect to calcite and is relatively dilute. It does not appear to be a mixture and therefore is probably associated with a low-temperature aquifer. The unnamed hot spring on Paoha Island may be associated with a high temperature system, 186°C or more, assuming equilibrium with quartz. However, the possible equilibrium with chalcedony at the spring temperature (83°C), and the methane-rich gas escaping from the spring make a lower temperature system seem more probable. The Na-K-Ca geothermometer was not calculated for the hot spring on Paoha Island because of the large negative value for log $\sqrt{Ca}$/Na.

Pačes (1975) suggested that the Na-K-Ca geothermometer should be corrected for the pressure of carbon dioxide (P_{CO_2}) in hot spring waters which issue at temperatures of less than 75°C and have P_{CO_2} of more than 10^{-4} atm. Taking this correction into consideration, aquifer temperatures estimated for 10 of the 11 hot springs, which have a temperature and P_{CO_2} within the suggested range, are 9° to 38°C below the measured spring temperatures. Although one spring had an estimated aquifer temperature 27°C hotter than the measured water temperature, the "CO_2-corrected Na-K-Ca geothermometer" did not produce viable results with our data. A previous chemical analysis of Grovers Hot Spring was part of the data used to establish the original correction factor. The "CO_2-corrected Na-K-Ca geothermometer" calculated from our data indicated an aquifer temperature 32°C less than the measured temperature of the spring water.

SUMMARY

The 14 thermal springs sampled for chemical and isotopic analyses are located in the central Sierra Nevada between Lake Tahoe and Mt. Whitney. They issue waters ranging from near neutral to alkaline (pH 6.4 to 9.3) at temperatures from 33° to 83°C. These thermal waters are Na-Cl, Na-HCO_3, or Na-mixed anion in character and range from fresh (319 mg/L) to very saline (26,342 mg/L). Silica concentrations range from 44 to 220 mg/L. Thermal springs with high bicarbonate concentrations have the highest Mg/Ca, K/Na, and B/Cl ratios but the lowest $\sqrt{Ca}$/Na and Cl/HCO_3 ratios. They are generally saturated with respect to calcite but not fluorite. Reds Meadow, Buckeye, and Keough are the only hot springs theoretically saturated with respect to both calcite and fluorite.

Carbon dioxide is the major gas escaping from Fales Hot Springs, the unnamed hot spring on the south side of Mono Lake, Travertine Hot Springs, and The Hot Springs. Gas discharges at relatively constant high rates from Fales Hot Springs and the unnamed hot spring at the south side of Mono Lake, whereas the discharge rate at Travertine Hot Springs and The Hot Springs is low and sporadic. Grovers Hot Springs sporadically discharge a 2 to 1 mixture of nitrogen and carbon dioxide at a very low rate. The springs on Paoha Island discharge a mixture of methane (70 percent) and nitrogen (25 percent). All other springs with collectable quantities of gas sporadically discharge nitrogen at low rates.

Keough, Blayney Meadows, Mono, Benton, Reds Meadow, and Brockway hot springs are probably associated with low-temperature systems (less

than 90°C). Chalcedony is apparently controlling the silica concentration in these low-temperature systems except at Reds Meadows Hot Springs where amorphous silica (opal) may be the controlling silica phase. Grovers Hot Springs, The Hot Springs, Travertine Hot Springs, Buckeye Hot Springs, and the unnamed hot springs on the north and south sides of Mono Lake have a large disparity between the aquifer temperatures estimated from the chalcedony and Na-K-Ca geothermometers. These springs are probably associated with low-temperature aquifers (less than 110°C) in which the silica concentration is being controlled by the solubility of chalcedony. The Na-K-Ca geothermometer is of questionable value for these springs because the waters are in equilibrium or supersaturated with respect to calcium carbonate at the spring temperature. Fales Hot Springs may be a mixed water from a high-temperature aquifer (150°C or more) because it has a large rate of flow, releases a large volume of carbon dioxide, and has aquifer temperatures estimated from the Na-K-Ca and quartz geothermometers which are well above the spring temperature.

Mixing is also suggested for the unnamed hot spring on Paoha Island in Mono Lake and at the south shore of Mono Lake where lake water and thermal or "fresh" water apparently mix before the fluid comes to the surface.

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