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CHEMISTRY OF THERMAL WATER IN SELECTED GEOTHERMAL AREAS OF CALIFORNIA

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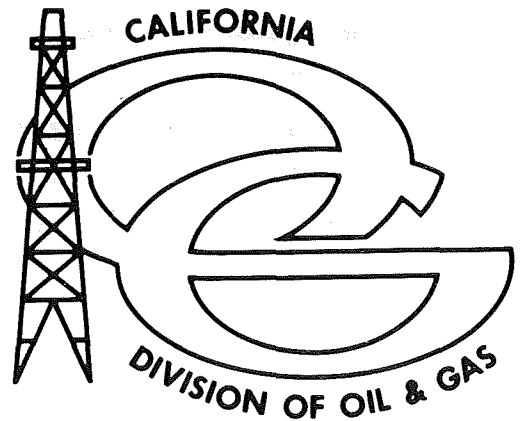
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CONTENTS

CHEMISTRY OF THERMAL WATER IN SELECTED GEOTHERMAL AREAS OF CALIFORNIA[a]

By Marshall J. Reed [b]

ABSTRACT

Careful collecting procedures and modern analytical methods were used to determine the chemical composition of thermal water in five geothermal areas of California. Water analyses from hot wells and springs are presented for the Imperial Valley, Sierra Valley, Honey Lake Valley, Surprise Valley, and Modoc Plateau areas. Subsurface temperatures have been estimated from the concentrations of silica, sodium, potassium, and calcium. In most of the areas, estimated temperatures are less than 150°C, probably a result of mixing with near-surface, cold water. At the present time 180°C is the minimum efficient temperature for a flashed steam geothermal power plant. The indicated temperatures for thermal waters in most of the areas are within the range needed for process heating or space heating.

INTRODUCTION

For a geothermal resource to be economic, it must have four attributes: a heat source; a large volume of high-temperature rock within 10 km of the earth's surface; water to act as a heat-conducting fluid to transport the heat to the surface; and rocks of high permeability to supply a large volume of hot water to wells. Geothermal exploration is an attempt to quantitatively evaluate these four essential chacrateristics.

The chemistry of thermal surface water has been used as an exploration

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tool for locating geothermal resources. Geochemical investigations have been credited as an important part of geothermal exploration in Italy, New Zealand, El Sàlvador, and Mexico. Water chemistry has been considered useful because, under ideal conditions, the temperature and composition of geothermal fluids at depths of 1,000 m or more can be inferred. In many areas, however, the usefulness of water chemistry in exploration is limited because of mixing of geothermal water with near-surface water.

Analyses of hot water from springs and wells in California have been reported in the scientific literature since the middle of the nineteenth century, but the coverage of the state remains incomplete. In the revised compilation of Waring (1965), the waters of only 70 of the 190 thermal springs in California have reference to chemical analyses. In assembled literature the chemical data does not have the reliability needed for the proper evaluation of geothermal prospects, and it is necessary to apply recent sophisticated modern methods to the collection and analysis of thermal waters.

Recent chemical analyses are presented for five geothermal areas in California (Figure 1). All samples were collected by the method of Barnes (Barnes and O'Neil, 1969), and the analyses were performed in two comparable U. S. Geological Survey laboratories. This information may be useful in the evaluation of these geothermal areas, and it will increase in general value as more deep wells are drilled and the temperature predictions are verified. Collection procedures and sample preparation were designed to obtain representative samples for analysis. Where possible, locally derived meteoric water was collected for comparison with the thermal water at each sample locality. The local geologic setting of each area is described insofar as it pertains to the thermal water.

FIELD PROCEDURES

The collection of a geothermal water sample and the analysis of the sample both require a great deal of care. Volatile chemical species will be lost during transportation to the laboratory, and other species will react in response to changes in their physical environment. Analysis of the carbonate species in the field and stabilization of the cations for transportation are necessary to accurately characterize the thermal water at its source.

The pH and alkalinity of each sample were measured in the field using the method of Barnes (1964). Other field measurements included air and water temperature, flow rate, and electrical conductivity.

Samples for laboratory analysis were collected in a stainless steel pressure vessel and immediately filtered through a 0.45 μm membrane filter using compressed nitrogen as a non-reactive pressure source. The filtered water samples were stored in acid-rinsed plastic bottles. A portion of the filtered water was immediately acidified with concentrated nitric acid to a pH of 2 in order to keep the divalent cations in solution. Dilution of 10 ml of the filtered samples to 100 ml with distilled, deionized water was done to retard the precipitation of silica. Three samples of unfiltered and untreated

Location   Map

1 IMPERIAL VALLEY
2 SIERRA VALLEY
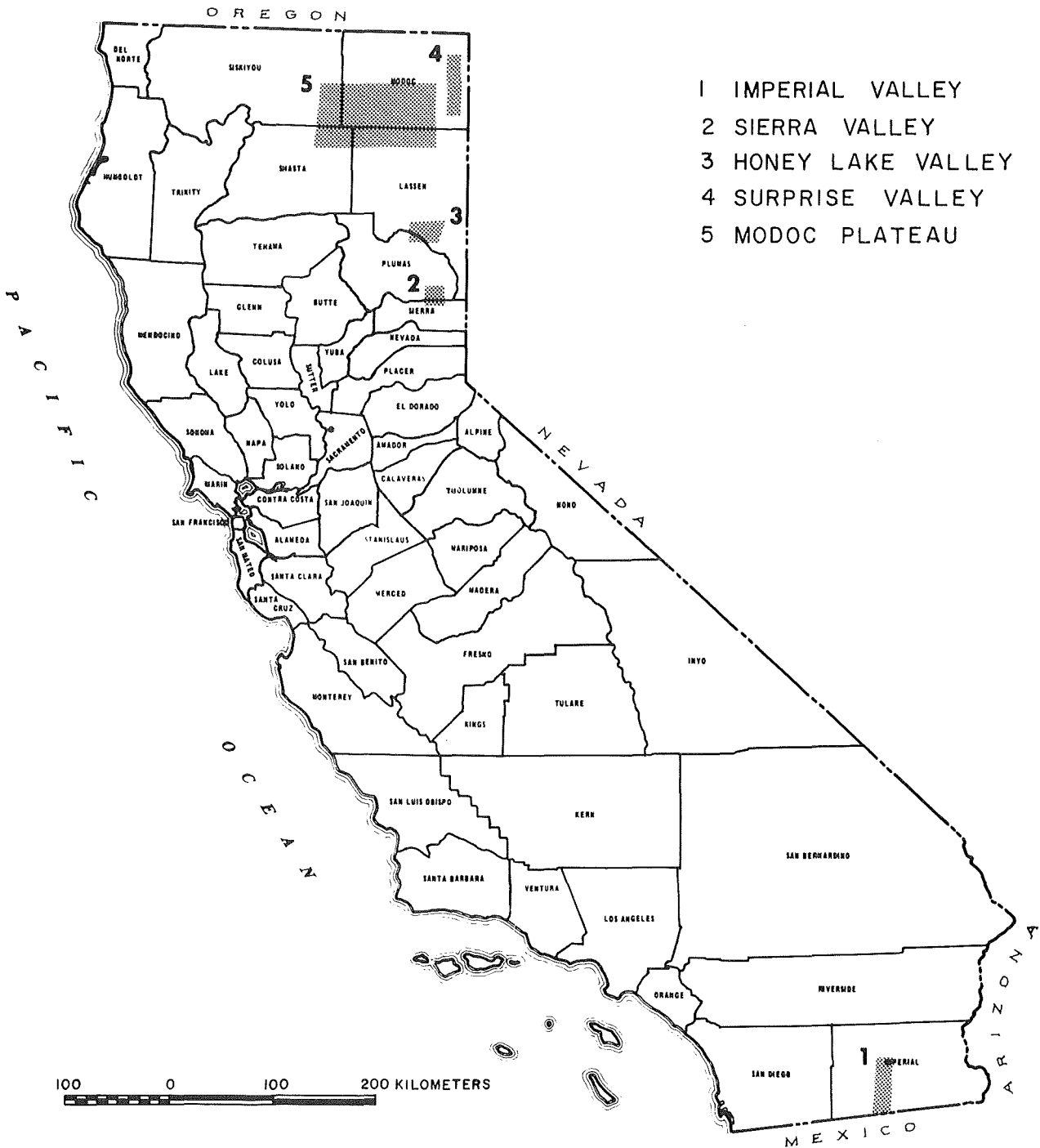3 HONEY LAKE VALLEY
4 SURPRISE VALLEY
5 MODOC PLATEAU

Figure 1.

water were collected from each site for stable isotope analysis. Isotope samples were kept in 125-ml glass bottles with air-tight, plastic, cone-sealed caps.

LABORATORY ANALYSES

Concentrations of silica and all cations were determined by using an atomic absorption spectrophotometer. Boron was analyzed by either the dianthrimide or carmine methods (Brown and others, 1970), depending on the concentration. Chloride was titrated with silver nitrate solution to an electrometric endpoint determined by a specific-ion electrode, and fluoride was measured directly using a specific-ion electrode. The Imperial Valley samples were analyzed in the Central Laboratory, U.S. Geological Survey, Salt Lake City, Utah. The composition of the various samples from northeastern California was determined in the laboratory of I. Barnes at the U.S. Geological Survey, Menlo Park, California.

Isotopic analyses were performed utilizing mass spectrometers after using the oxygen-carbon dioxide equilibration method (Epstein and Mayeda, 1953) and the hydrogen-uranium reaction method (Bigeleisen and others, 1952). Isotopic analyses of the samples from the Imperial Valley were performed in the laboratories of T. Coplen at the University of California, Riverside; of R. Clayton at the University of Chicago; and of J. O'Neil at the U.S. Geological Survey, Menlo Park. Isotopic values for the Imperial Valley samples were previously presented by Coplen (1972). Samples from the other geothermal areas were analyzed in the laboratory of J. O'Neil.

PRESENTATION OF DATA

The sample locations are given in sixteenths of a section (approximately 0.16 km²), using the standard section, township, and range, land survey system. The locations given in this study are with reference to either the San Bernardino (S.B.) or Mount Diablo (M.D.) base line and meridian. The latitude for each sample location was estimated from the U.S.G.S. topographic map series. Isotopic ratios are reported in parts per thousand (⁰/oo) difference for the heavier isotope from standard mean ocean water (SMOW) (Craig, 1961).

$$\delta H^2 (^o/_{oo}) = \left[\frac{H^2/H^1 \ sample}{H^2/H^1 \ standard} - 1 \right] \times 1000$$

$$\delta O^{18} (^o/_{oo}) = \left[\frac{O^{18}/O^{16} \ sample}{O^{18}/O^{16} \ standard} - 1 \right] \times 1000$$

The depths of producing intervals in wells were obtained from drilling records or from the present owners. The pH and conductivity are for the water at the sampling temperature, unless otherwise noted. The concentrations of bicarbonate and carbonate were calculated from the field titrations, using the method of Barnes (1964) to determine the equilibrium distribution for the sampling temperature. The concentrations of all chemical constituents are given in milligrams per liter (mg/1).

CALCULATIONS OF SUBSURFACE TEMPERATURE

The existence of high-temperature aqueous systems at depth can be inferred from the chemical constituents in the surface discharge of hot springs. In the rare case where a steam phase is present below the surface, hot-spring discharge will be abnormally low in chloride, sodium, potassium, and calcium. Only those constituents carried in the steam will appear at the surface, and the discharge will contain sulfate (from oxidation of hydrogen sulfide), bicarbonate (from solution of carbon dioxide), ammonium (from solution of ammonia), boric acid, and mercury. Surface-discharge water from the much more common system with a continuous liquid phase will usually be a sodium-chloride solution and may also contain high concentrations of other chemical species. It is possible to derive all the constituents of thermal waters by solution of the rocks through which they flow (Ellis and Mahon, 1964 and 1967).

The relationships of the chemical species in solution, when considered in the context of the local geologic setting, can be used to predict the temperature of a geothermal reservoir. In general, the concentrations of all constituents will increase with temperature as the solubility of the minerals increases. Magnesium shows a contrary relationship, with higher concentrations at low temperature from the solution of dolomite, amphiboles, or pyroxenes, and lower concentration at high temperature from the slight solubility of chlorite.

Various investigators have proposed methods for calculating temperatures from water chemistry. Fournier and Row (1966) presented temperature calculations based on the solubility of some of the silica minerals. Experience in several geothermal areas shows that regardless of the silica mineral originally present, quartz is the phase that

usually controls the concentration in solution (Mahon, 1966). Temperature calculation from the sodium/-potassium ratio (Ellis, 1970) is based on the assumption that the cations in solution are in equilibrium with albite and orthoclase at temperatures above 150°C. Fournier and Truesdell (1973) developed an empirical method for estimating temperature from the sodium, potassium, and calcium concentrations.

All the chemical indicators of temperature are based on the assumptions that the water was in equilibrium with the surrounding minerals in the reservoir and that the water moved to the surface rapidly, without reacting at lower temperature on the way to the surface (Fournier and others, 1974). Mixing of cold, shallow ground water can dilute geothermal water and will often give misleading results for the chemical geothermometers. Fournier and Truesdell (1974) developed a mathematical method for estimating the amount of mixing of hot water with cold water. In addition, a computer program is available for performing the iterative calculations (Truesdell and others, 1973).

In this study, the temperature calculations were made for each water source using the following equations of R. O. Fournier (personal communication, 1974):

1. Calculated temperatures for the solubility of silica minerals:

   Amorphous Silica and Rhyolitic Glass (SiO_2 in mg/kg)

   $$T(^oC) = \left[\frac{731}{4.52 - log \ (SiO_2)} \right] - 273.15$$

   Cristobalite (SiO_2 in moles/kg)

   $$T(^oC) = \left[\frac{-1000}{log \ (SiO_2)} \right] - 273.15$$

   Chalcedony (SiO_2 in moles/kg)

   $$T(^oC) = \left[\frac{-1032}{0.09 + log \ (SiO_2)} \right] - 273.15$$

   Quartz (SiO_2 in mg/kg)

   $$T(^oC) = \left[\frac{1309}{5.19 - log \ (SiO_2)} \right] - 273.15$$

   Quartz with steam loss from boiling (SiO_2 in mg/kg)

   $$T(^oC) = \left[\frac{1522}{5.75 - log \ (SiO_2)} \right] - 273.15$$

2. Calculated temperatures for the solubility of feldspars and empirical equations (cations in moles/kg)

Feldspars (albite and orthoclase)

$$T(^{0}C) = \left[\frac{777}{0.47 + \log (Na/K)}\right] - 273.15$$

Empirical Equation

$$T(^{0}C) = \left[\frac{1647}{2.24 + A + B}\right] - 273.15$$

A = log (Na/k)

B = βlog ($\sqrt{Ca/Na}$)

Calculate first using β = 4/3; then if T is greater than 100°C, recalculate using β = 1/3.

The temperatures calculated from amorphous silica solubility were all below the measured temperatures, and are not given in the tables. Temperatures calculated from quartz solubility with correction for steam loss are not applicable below 105° C and are not recorded for lower temperatures. Some extremely low values of temperatures calculated from feldspar solubility are not presented in the tables.

AREAS OF STUDY

Imperial Valley, Imperial County

Geologic Setting - The Imperial Valley is on the northward-sloping portion of the large, cone-shaped, Colorado River delta. The delta sediments have accumulated in a structural trough which is the landward extension of the Gulf of California rift. During deposition of the delta, the high sedimentation rate of the Colorado River kept pace with the rapid tectonic subsidence of the Salton trough. Up to 6 km of delta sediments have been deposited in the valley since Miocene time (Biehler and others, 1964). The deepest well in the valley, drilled near Brawley, penetrated over 4 km of interbedded, fine-grained sandstone and siltstone (Muffler and Doe, 1968).

The Colorado River delta sediments consist primarily of quartz and calcite, with lesser amounts of dolomite, plagioclase, potassium feldspars, mica, and clay. In addition, gypsum occurs sporadically throughout the sediments (Muffler and Doe, 1968).

View northward over the Imperial Valley toward the Chocolate Mountains. Faults of the San Andreas and San Jacinto systems bound the valley and cut the sediments within the valley. The Mesozoic granitic basement rocks exposed in the mountains are up to 6 km below the valley sediments. Artesian wells in the eastern part of the valley produce water up to 55°C. Photo by U.S. Air Force, November 1967.
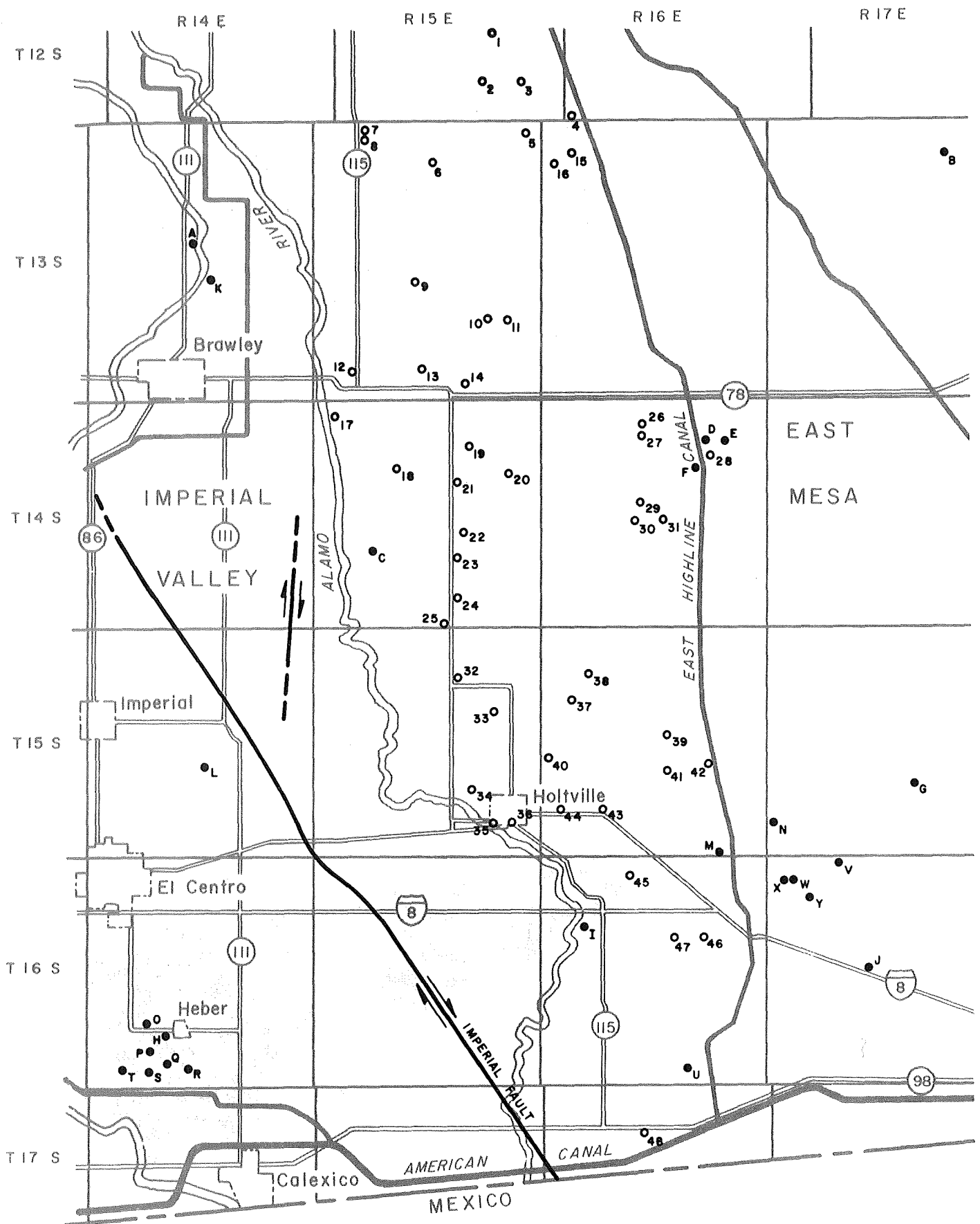
FIGURE 2. SAMPLE LOCATIONS IN IMPERIAL VALLEY, CALIFORNIA

HOLOCENE FAULTS   ● R EXPLORATORY WELLS   o 5 SAMPLE LOCATIONS

Metamorphic processes occur in the sediments, and greenschist-facies minerals are forming at temperatures of up to 300°C at depths of 900 m or more (Muffler and White, 1969).

There is little rainfall in the Imperial Valley (average 1.5 cm/yr); however, subsurface flow from the Colorado River maintains the ground-water table at or near the surface in undeveloped areas of the valley. In agriculturally developed areas, the water table has been lowered 3 to 4 m below the surface. Many artesian wells have been drilled along the eastern side of the valley for domestic or stock use, and 48 of these wells were sampled in this study (Figure 2).

Crustal thinning has occurred in the Salton trough (Biehler and others, 1964), and the geothermal activity in the Imperial Valley appears to be related to heat from the mantle moving through the thinner crust. The East Pacific Rise intersects the North American continent at the head of the Gulf of California, and the upwelling of hot mantle material may extend north-ward, under the Imperial Valley.

TABLE 1. Exploratory Oil and Geothermal Wells, Imperial Valley

Ident. Letter	Location	Operator	Well	Status	Total Depth (m)
	Exploratory Oil Wells				
A	SE/SE Sec. 9, T. 13S., R. 14E., S.B.	Amerada Hess Corp.	"Veysey" 1	Abd. 1945	2,545
B	SW/NE Sec. 2, T. 13S., R. 17E., S.B.	Ajax Oil & Development Co.	"U.S.L. Phillis" 1	Abd. 1955	1,010
C	SW/SE Sec. 20, T. 14S., R. 15E., S.B.	Standard Oil Co. of Calif.	"Wilson et al" 1	Abd. 1963	4,097
D	NE/NW Sec. 11, T. 14S., R. 16E., S.B.	104 Oil and Drilling Co.	1	Abd. 1925	582
E	NE/NE Sec. 11, T. 14S., R. 16E., S.B.	104 Oil and Drilling Co.	2	Abd. 1926	701
F	SW/SW Sec. 11, T. 14S., R. 16E., S.B.	104 Oil and Drilling Co.	3	Abd. 1927	301
G	NE/NE Sec. 27, T. 15S., R. 17E. S.B.	American Petrofina Exploration Co.	"U.S.A." 27-1	Abd. 1966	3,238
H	NW/SW Sec. 28, T. 16S., R. 14E., S.B.	Amerada Hess Corp.	"Timken" 1	Abd. 1945	2,232
I	SW/SW Sec. 8, T. 16S., R. 16E., S.B.	Texaco, Inc.	"Grupe Engebretsen" 1	Abd. 1945	3,753
J	SW/SE Sec. 16, T. 16S., R. 17E., S.B.	H. W. Schafer	"Barbara" 1	Abd. 1960	2,444
	Exploratory Geothermal Wells				
K	NW/SW Sec. 15, T. 13S., R. 14E., S.B.	Union Oil Co. of Calif.	"Veysey" 1	Idle	8,385
L	NW/SW Sec. 22, T. 15S., R. 14E., S.B.	Magma Energy, Inc.	"Bonanza" 1	Idle	1,531
M	SW/SE Sec. 35, T. 15S., R. 16E., S.B.	Magma Energy, Inc.	"Sharp" 1	Abd. 1972	1,850
N	NW/NW Sec. 31, T. 15S., R. 17E., S.B.	U.S. Bureau of Reclamation	"Mesa" 31-1	Idle	1,882
O	SW/NE Sec. 29, T. 16S., R. 14E., S.B.	Chevron Oil Co.	"Hulse" 1	Idle	1,949
P	NW/NE Sec. 32, T. 16S., R. 14E., S.B.	Chevron Oil Co.	"C. B. Jackson" 1	Idle	1,818
Q	SW/NW Sec. 33, T. 16S., R. 14E., S.B.	Chevron Oil Co.	"J. D. Jackson, Jr." 1	Idle	1,836
R	NW/SE Sec. 33, T. 16S., R. 14E., S.B.	Chevron Oil Co.	"Nowlin Partnership" 1	Testing	1,533
S	NW/SE Sec. 32, T. 16S., R. 14E., S.B.	Magma Energy, Inc.	"Holtz" 1	Testing	1,569
T	NE/SE Sec. 31, T. 16S., R. 14E., S.B.	Magma Energy, Inc.	"Holtz" 2	Disposal	1,524
U	NE/SE Sec. 34, T. 16S., R. 16E., S.B.	Magma Energy, Inc.	"Sharp" 2	Idle	1,977
V	NE/NE Sec. 5, T. 16S., R. 17E., S.B.	U.S. Bureau of Reclamation	"Mesa" 5-1	Disposal	1,834
W	NW/SE Sec. 6, T. 16S., R. 17E., S.B.	U.S. Bureau of Reclamation	"Mesa" 6-1	Testing	2,448
X	NE/SW Sec. 6, T. 16S., R. 17E., S.B.	U.S. Bureau of Reclamation	"Mesa" 6-2	Testing	1,831
Y	NW/NW Sec. 8, T. 16S., R. 17E., S.B.	U.S. Bureau of Reclamation	"Mesa" 8-1	Idle	1,829

Water Chemistry - The chemistry and isotopic composition of water samples from the Imperial Valley (Tables 1a and 1b) show a dominating influence by Colorado River water. Subsurface flow of the Colorado River water appears to have entered the valley from the southeast and moved to all parts of the area sampled, but the age of the ground water is unknown. Runoff water from the local mountains seems to have its greatest contribution in the north-easternmost samples, where isotopic and chemical differences are greatest.

Water from 30 of the wells was of the sodium-chloride type, and the remaining 18 samples were of the sodium-bicarbonate type. The occurrence of the sodium-bicarbonate water appears to be randomly distributed within the area sampled, but is restricted to depths of 150 to 300 m. Sulfate is a significant anion in some of the samples, and may reflect the occurrence of gypsum and anhydrite in the sediments.
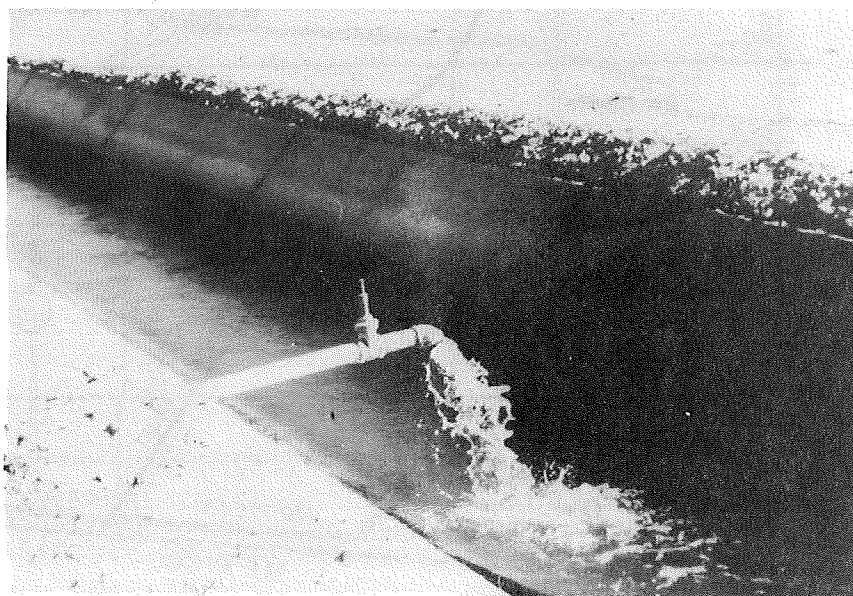
Discharge from the Phegley well (Sample 14) flows into Orita Drain. Artesian wells of this type supply domestic water needs for some farms, but a canal system from the Colorado River supplies the irrigation needs. The system of drains carries irrigation waste water and excess artesian water to the Salton Sea. Photo taken December 1970.

Generally, higher concentrations of major constituents correlate with higher temperature and greater depth. The chemistry of the subsurface water is primarily controlled by the solubility of minerals within the upper part of the sedimentary section, and the chemical indicators of temperature suggest that the water had never been in equilibrium with the rock of a high-temperature system.

There seems to be little fluid contribution to the shallow artesian water from the deep geothermal system thought to exist near Brawley (Combs, 1971). The high bicarbonate content of certain samples could be indicative of the high-temperature decomposition of calcite described by Muffler and White (1968). The high concentration of boron found in many analyses may also be a contribution from deeper, high-temperature water.
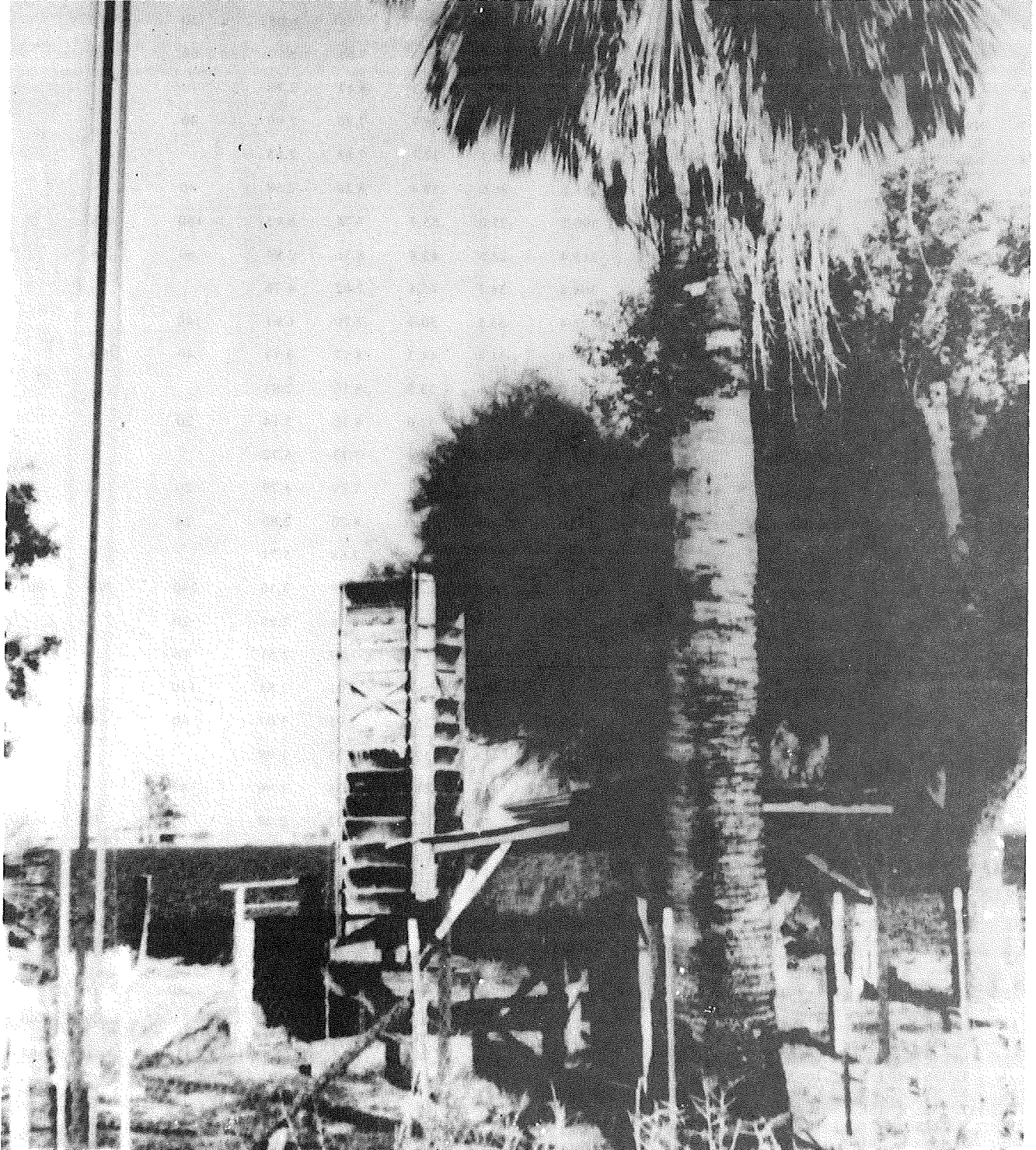
Magnolia School well (Sample 13) in the eastern Imperial Valley. The well has a standpipe to make efficient use of the artesian pressure, and a cooling tower to lower the water temperature for drinking. The 50.9°C water also supplies heat for the building during the winter. Photo taken December 1970.

CHEMISTRY OF THERMAL WATER

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Sample Number	Location S.B. B&M	Owner or Operator	Date Sampled (mo/dy/yr)	Producing Depth (m)	Alt. (m)	Water Temp. (°C)	pH	Conductivity (mmho/cm)	Discharge (l/min)	δO18 (⁰/oo)	δH2 (⁰/oo)
1	NW/SW Sec. 23 T. 12S., R. 15E.	D. Brownell	12/15/70	86.9- 99.1	-23.8	31.5	7.85	3.17			
2	SE/SE Sec. 27 T. 12S., R. 15E.	G. Brownell	12/15/70	125.0-131.1	-25.9	34.1	8.12	2.75		-7.3	-63
3	NE/NE Sec. 35 T. 12S., R. 15E.	Cowell	12/15/70	92.7-104.9	-19.8	33.0	8.13	2.61			
4	SW/SW Sec. 31 T. 12S., R. 16E.	P. Rebik	12/16/70	281.9	-7.6	39.1	7.79	6.08	20		
5	SE/NE Sec. 1 T.13S., R.15E.	Taylor	12/15/70	325.2-331.9	-19.8	55.2	7.66	6.90	64	-9.3	
6	SW/SW Sec. 3 T. 13S., R. 15E.	Mulberry School	12/14/70	271.3	-34.4	40.3	8.12	2.70			
7	NW/NW Sec. 5 T. 13S., R. 15E.	J. Williams	12/14/70	259.4-264.0	-43.3	35.7	7.80	2.89	40		
8	NW/NW Sec. 5 T. 13S., R. 15E.	Wiest Store	12/14/70	235.3-247.5	-42.1	37.7	7.88	2.55			
9	SW/SE Sec. 16 T. 13S., R. 15E.	M. Lunceford	12/14/70	231.6	-36.0	39.4	8.29	2.58	40		
10	SW/SE Sec. 23 T. 13S., R. 15E.	J. Ratliff	12/13/70	396.2	-25.0	55.7	7.74	6.15	160	-8.8	
11	SW/SW Sec. 24 T. 13S., R. 15E.	V. Butters	12/13/70	213.4	-22.6	42.8	8.36	2.84	60	-7.6	
12	NW/NW Sec. 32 T. 13S., R. 15E.	T. Shank	12/12/70	304.8	-38.7	43.5	7.82	4.76			
13	NE/NE Sec. 33 T. 13S., R. 15E.	Magnolia School	12/12/70	386.8-423.4	-33.5	50.9	7.70	6.61	140		
14	NW/SW Sec. 34 T. 13S., R. 15E.	M. Phegley	12/13/70	285.3-290.8	-31.4	44.3	8.17	3.14	40	-8.9	
15	SE/SE Sec. 6 T. 13S., R. 16E.	F. Schoneman	12/16/70	187.7	-11.6	33.3	8.16	2.83			
16	SE/SW Sec. 6 T. 13S., R. 16E.	T. Olesh	12/16/70	91.4	-15.2	32.0	8.12	3.14	20		
17	NW/NE Sec. 6 T. 14S., E. 15E.	N. Fifield	12/12/70	364.2-393.2	-40.2	51.4	7.77	6.72			
18	SW/SW Sec. 9 T. 14S., R. 15E.	J. Birger	12/11/70	117.3	-34.4	31.1	7.79	4.79	20		
19	NW/NW Sec. 11 T. 14S., R. 15E.	Moiola Feed Lot	12/13/70	198.1	-26.8	42.0	8.20	2.80	28		
20	SW/SW Sec. 12 T. 14S., R. 15E.	Mendiburu Feed Lot	12/13/70	356.9-375.8	-21.9	51.7	7.68	5.71			
21	NW/NE Sec. 15 T. 14S., R. 15E.	A. Gisler	12/11/70	355.1	-29.0	47.5	8.08	3.56	240	-9.9	-90
22	NW/SW Sec. 23 T. 14S., R. 15E.	J. Birger	12/11/70	228.6	-25.9	39.3	8.16	2.59	20		
23	NE/NE Sec. 27 T. 14S., R. 15E.	J. Birger	12/11/70	121.9	-26.8	31.8	7.87	2.51	16		
24	NW/NE Sec. 34 T. 14S., R. 15E.	Jenson	12/11/70	108.8	-26.8	29.5	8.01	2.83	120		
25	SW/SE Sec. 34 T. 14S., R. 15E.	Gaddis	12/11/70	185.9	-24.4	35.5	7.95	3.07	60	- 9.9	
26	SW/SE Sec. 4 T. 14S., R. 16E.	F. Borchard	12/10/70	118.9-139.0	-4.6	37.3	8.35	1.99			
27	SW/SE Sec. 4 T. 14S., R. 16E.	F. Borchard	12/10/70	139.3	-4.6	38.4	8.38	1.96	48		
28	SE/NE Sec. 11 T. 14S., R. 16E.	U.S.-B.L.M.	12/16/70	86.9	7.6	34.5	8.23	2.28		- 7.2	-62
29	NW/SE Sec. 16 T. 14S., R. 16E.	M. Axler	12/12/70	121.9	-5.2	25.4	8.17	1.41	4	-7.2	
30	NW/NE Sec. 21 T. 14S., R. 16E.	S. Stacey	12/10/70	133.2	-4.9	32.5	8.32	1.85	20		
31	NW/NW Sec. 22 T. 14S., R. 16E.	C. Singh	12/10/70	212.8-216.1	-2.1	41.7	7.91	4.95	20	-9.9	
32	SW NE Sec. 10 T. 15S., R. 15E.	Shawner	12/3/70	140.2	-22.6	31.6	7.77	3.08	108	-7.8	
33	SE/NE Sec. 14 T. 15S., R. 15E.	C. Allen	12/3/70	263.3	-13.7	40.0	8.14	2.60	40	-9.1	
34	SW NE Sec. 26 T. 15S., R. 15E.	J. DePaoli	11/29/70	240.8-289.6	-7.6	40.1	7.97	2.58		-9.4	-90
35	NE/NE Sec. 35 T. 15S., R. 15E.	Holtville Ice Co.	11/29/70	335.3	-5.5	44.6	7.96	4.33	116	-10.5	-94
36	NE NW Sec. 36 T. 15S., R. 15E.	City of Holtville	11/28/70	255.4-259.7	-4.6	29.0	7.77	1.71	12	-7.8	
37	SE/SE Sec. 7 T. 15S., R. 16E.	Hooke	12/3/70	202.4-211.8	-11.3	35.6	8.25	2.20	12		
38	SW NW Sec. 8 T. 15S., R. 16E.	G. Hoyt	12/3/70	144.8-148.7	-10.4	30.8	8.12	2.27	4		
39	SE SW Sec. 15 T. 15S., R. 16E.	R. Garewal	12/2/70	243.8	0	32.0	8.39	1.92		-7.2	

Sample Number	Location S.B. B&M	Owner or Operator	Date Sampled (mo/dy/yr)	Producing Depth (m)	Alt. (m)	Water Temp. (°C)	pH	Conductivity (mmho/cm)	Discharge (1/min)	Isotopes[1] δO18 (°/oo)	δH2 (°/oo)
40	SW/NW Sec. 19 T. 15S., R. 16E.	F. Strahm	12/2/70	254.2	-8.2	35.6	8.36	1.53	40	-7.4	
41	NE/SW Sec. 22 T. 15S., R. 16E.	D. Starr	12/2/70	228.6	0.3	34.7	8.15	2.88	12	-9.8	
42	SE/NW Sec. 23 T. 15S., R. 16E.	L. Foster	12/2/70	137.8-165.2	4.6	34.1	8.38	1.75	100	-8.2	
43	SW/SE Sec. 29 T. 15S., R. 16E.	A. Fusi	11/30/70	163.7-187.8	-3.0	30.6	8.26	1.19	8	-6.9	
44	SW/SE Sec. 30 T. 15S., R. 16E.	A. Fusi, Jr.	11/30/70	270.7-285.9	-3.0	39.7	8.17	2.26			
45	SE/NW Sec. 4	C. Ansiel	11/30/70	268.2-285.9	0	34.5	8.22	2.96			
46	NE/NE Sec. 14 T. 16S., R. 16E.,	Watton Labor Camp	12/1/70	343.8	5.2	43.0	8.09	3.29		-10.0	
47	NW/NE Sec. 15 T. 16S., R. 16E.	Alamo School (abd.)	12/1/70	263.3-267.3	3.7	37.2	8.33	2.21	16	-9.0	
48	NE/NW Sec. 9 T. 17S., R. 16E.	L. Bornt	12/9/70	184.1-2216.4	9.4	37.2	8.13	2.35		-10.3	

[1] Isotopic analyses by M. J. Reed, T. B. Coplen, and W. A. Klemm.

TABLE 1b. Chemical Constituents of Samples From Artesian Wells, Imperial Valley (in mg/l)[1]

Sample Number	Location	Li	Na	K	Mg	Ca	Sr	Fe	F	Cl	HCO₃	CO₃	SO₄	SiO₂	B	Calculated Dissolved Solids
1	NW/SW Sec. 23	0.50	670	5.5	23	32	1.0	0.24	1.9	620	360	2.3	450	32	2.6	2,200
2	SE/SE Sec. 27	0.24	530	3.7	9.7	19	0.4	0.09	1.5	510	290	3.4	300	36	2.7	1,710
3	NE/NE Sec. 35	0.28	510	3.8	11	19	0.57	0.05	1.6	520	290	3.5	280	33	2.7	1,680
4	SW/SW Sec. 31	0.68	1,200	7.7	11	37	1.7	0.25	1.3	1,700	290	2.0	60	27	8.9	3,350
5	SE/NE Sec. 1	0.63	1,100	9.4	14	43	1.6	0.03	1.3	1,200	400	2.5	620	33	9.7	3,440
6	SW/SW Sec. 3	0.17	500	3.0	4.2	9.7	0.25	0.19	2.0	450	480	6.0	120	38	2.4	1,620
7	NW/NW Sec. 5	0.32	620	5.4	11	11	0.25	0.20	1.4	230	1,300	7.7	100	36	2.6	2,330
8	NW/NW Sec. 5	0.20	530	4.5	8	8.7	0.18	0.28	1.4	200	1,200	8.7	53	43	5.8	2,060
9	SW/SE Sec. 16	0.18	490	3.1	3.3	9.9	0.14	0.10	1.9	400	540	9.8	120	30	2.4	1,610
10	SW/SE Sec. 23	0.56	980	8.7	10	29	0.95	0.12	1.3	960	450	3.2	540	33	3.7	3,020
11	SW/SW Sec. 24	0.17	500	2.9	3.3	8.7	0.16	0.09	1.4	450	470	10	130	29	1.8	1,610
12	NW/NW Sec. 32	0.13	900	4.5	12	19	1.2	0.17	1.2	820	680	4.9	160	30	5.7	2,640
13	NE/NE Sec. 33	0.51	1,100	8.9	14	29	1.4	0.19	1.0	1,400	550	3.5	270	32	2.2	3,410
14	NW/SW Sec. 34	0.14	570	3.4	4.0	8.8	0.21	0.12	1.9	380	830	13	100	44	4.9	1,960
15	SE/SE Sec. 6	0.32	560	3.8	10	21	0.87	0.03	1.2	610	250	3.2	250	22	2.5	1,730
16	SE/SW Sec. 6	0.41	580	4.1	9.3	23	0.83	0.04	1.0	660	270	3.1	240	31	4.7	1,830
17	NW/NE Sec. 6	0.23	1,200	6.9	15	40	1.2	0.32	1.0	1,300	890	6.9	310	35	2.0	3,810
18	SW/SW Sec. 9	0.17	1,000	5.9	45	52	1.3	0.19	1.2	1,200	560	3.3	490	36	3.7	3,400
19	NW/NW Sec. 11	0.12	520	3.1	4.2	10	0.13	0.20	2.0	340	810	12	81	31	5.5	1,820
20	SW/SW Sec. 12	0.42	940	8.0	10	33	0.75	0.11	1.2	1,000	380	2.3	550	33	6.8	2,970
21	NW/NE Sec. 15	0.15	610	3.7	4.2	22	0.47	0.19	1.6	490	800	11	130	36	13	2,120
22	NW/SW Sec. 23	0.11	500	3.0	3.9	8.7	0.07	0.12	2.3	350	740	10	87	37	2.6	1,740
23	NE/NE Sec. 27	0.09	530	4.2	15	26	0.49	0.24	1.7	330	700	4.4	280	24	3.7	1,920
24	NW/NE Sec. 34	0.11	590	4.2	13	29	0.59	0.60	1.3	530	740	6.3	190	33	2.8	2,140
25	SW/SE Sec. 34	0.11	620	4.6	17	30	1.3	0.34	1.3	420	650	5.4	370	24	2.7	2,150
26	SW/SE Sec. 4	0.12	390	2.0	2.1	6.2	0.20	0.05	2.9	200	610	12	120	23	1.1	1,370
27	SW/SE Sec. 4	0.11	390	2.1	2.0	4.8	0.12	0.07	3.3	170	640	14	130	23	7.6	1,390
28	SE/NE Sec. 11	0.25	420	3.0	5.2	12	0.36	0.03	1.3	500	200	2.9	130	30	9.0	1,310
29	NW/SE Sec. 16	0.08	310	2.2	5.3	13	0.33	0.10	1.6	300	310	3.1	57	18	0.8	1,020
30	NW/NE Sec. 21	0.08	380	2.0	3.0	7.6	0.31	0.06	2.6	300	440	7.4	100	28	2.8	1,270
31	NW/NW Sec. 22	0.36	900	5.7	8.2	31	0.61	0.22	1.7	1,200	270	2.4	130	28	2.7	2,580
32	SW/NE Sec. 10	0.12	670	4.9	17	22	0.95	0.12	1.8	600	670	3.4	190	37	1.9	2,220
33	SE/NE Sec. 14	0.11	490	2.9	4.0	11	0.50	0.16	2.0	320	790	10	84	33	2.5	1,750
34	SW/NE Sec. 26	0.12	500	3.2	4.7	11	0.47	0.19	2.0	300	790	6.9	110	26	3.6	1,760
35	NE/NE Sec. 35	0.21	790	4.6	6.1	20	0.72	0.08	1.4	950	370	3.6	150	29	3.6	2,330
36	NW/NW Sec. 36	0.04	350	2.5	7.9	15	0.44	0.32	1.7	290	490	2.1	79	23	3.2	1,270
37	SE/SE Sec. 7	0.11	460	2.5	3.5	9.1	0.15	0.12	2.8	260	710	11	110	38	4.4	1,610
38	SW/NW Sec. 8	0.08	510	3.3	8.6	16	0.39	0.42	1.4	280	880	9.4	130	24	6.7	1,870
39	SE/SW Sec. 15	0.12	420	2.2	2.7	7.6	0.10	0.10	3.9	220	600	12	160	25	2.7	1,460
40	SW/NW Sec. 19	0.05	320	1.8	2.7	6.5	0.11	0.16	3.2	72	650	12	100	35	1.2	1,200
41	NE/SW Sec. 22	0.16	570	3.7	5.5	17	0.44	0.14	2.2	600	430	5.4	170	22	2.9	1,830
42	SE/NW Sec. 23	0.13	370	2.1	2.0	6.7	0.09	0.04	3.4	160	580	12	140	23	3.5	1,300
43	SW/SE Sec. 29	0.04	260	2.0	2.5	7.1	0.25	0.40	2.9	40	580	7.6	110	21	1.9	1,040
44	SW/SE Sec. 30	0.09	450	2.5	3.3	9.0	0.18	0.20	2.3	260	690	9.4	130	41	6.7	1,600
45	SE/NW Sec. 4	0.12	610	3.5	5.2	11	0.31	0.24	1.6	490	850	13	74	22	3.2	2,080
46	NE/NE Sec. 14	0.25	560	3.6	3.5	17	0.57	0.05	2.1	630	310	3.8	120	26	3.4	1,680
47	NW/NE Sec. 15	0.10	420	2.4	2.7	10	0.41	0.05	2.3	310	510	9.3	130	25	2.2	1,420
48	NE/NW Sec. 9	0.11	450	2.9	4.2	17	0.70	0.12	1.7	400	370	4.4	180	29	1.5	1,460

[1] Chemical analyses by J. B. Rapp, M. J. Reed, and U.S.G.S. Central Laboratory.

Sample Number	Measured Temperature (°C)	Cristobalite	Silica Temperatures (°C) Chalcedony	Quartz	Cation Temperatures (°C) Empirical Na. K, Ca $\beta = 1/3$	$\beta = 4/3$
1	31.5	32.3	51.0	82.1	88.7	89.7
2	34.1	37.2	56.3	87.1	83.5	85.4
3	33.0	33.6	52.4	83.4	85.2	85.4
4	39.1	25.6	43.7	75.1	86.1	105.5
5	55.2	33.6	52.4	83.4	94.2	108.1
6	40.3	39.4	58.8	89.4	81.5	93.0
7	35.7	37.2	56.3	87.1	96.1	114.5
8	37.7	44.8	64.6	94.9	94.7	111.4
9	39.4	29.7	48.2	79.4	82.9	93.4
10	55.7	33.6	52.4	83.4	96.5	113.9
11	42.8	28.4	46.7	78.0	81.0	94.3
12	43.5	29.7	48.2	79.4	78.3	98.5
13	50.9	32.3	51.0	82.1	94.5	116.3
14	44.3	45.8	65.7	95.9	83.3	101.4
15	33.3	17.9	35.2	67.1	82.6	84.7
16	32.0	31.0	49.6	80.8	83.8	85.6
17	51.4	36.0	55.0	85.9	81.9	99.5
18	31.1	37.2	56.3	87.1	79.3	85.6
19	42.0	31.0	49.6	80.8	81.6	93.9
20	51.7	33.6	52.4	83.4	93.7	106.7
21	47.5	37.2	56.3	87.1	79.5	83.7
22	39.3	38.3	57.6	88.3	82.1	95.6
23	31.8	21.1	38.8	70.4	86.0	82.6
24	29.5	33.6	52.4	83.4	83.0	81.4
25	35.5	21.1	38.8	70.4	84.7	84.2
26	37.3	19.5	37.0	68.8	76.1	86.4
27	38.4	19.5	37.0	68.8	79.1	94.0
28	34.5	29.7	48.2	79.4	84.2	86.0
29	25.4	10.7	27.4	59.5	80.2	70.9
30	32.5	27.0	45.2	76.6	75.6	81.5
31	41.7	27.0	45.2	76.6	83.4	95.2
32	31.6	38.3	57.6	88.3	86.9	94.5
33	40.0	33.6	52.4	83.4	80.1	88.6
34	40.1	24.1	42.1	73.6	83.0	92.3
35	44.6	28.4	46.7	78.0	81.6	96.5
36	29.0	19.5	37.0	68.8	80.9	73.2
37	35.6	39.4	58.8	89.4	77.7	87.1
38	30.8	21.1	38.8	70.4	81.5	85.0
39	32.0	22.6	40.4	72.0	76.5	85.8
40	35.6	36.0	55.0	85.9	76.7	79.6
41	34.7	17.9	35.2	67.1	82.5	88.8
42	34.1	19.5	37.0	68.8	78.4	85.7
43	30.6	16.2	33.4	65.3	84.3	78.9
44	39.7	42.7	62.4	92.8	78.2	87.1
45	34.5	17.9	35.2	67.1	81.5	97.9
46	43.0	24.1	42.1	73.6	81.9	87.6
47	37.2	22.6	40.4	72.0	77.8	82.6
48	37.2	28.4	46.7	78.0	79.6	78.0

Sierra Valley, Plumas and Sierra Counties

Geologic Setting - Sierra Valley is an intermountain basin of the Basin and Range structural province, and is situated just east of the crest of the Sierra Nevada. Late Pliocene (post-Warner Basalt) block faulting created the valley, and its form has changed little since that time (Durrell, 1966). Sierra Valley was occupied by a large lake from late Pliocene until late Pleistocene, when it and Mohawk Lake, downstream, were drained by the Feather River (Durrell, 1966). Headward erosion by the river has not yet reached Sierra Valley, and none of the lake sediments have been dissected. A geothermal test well, drilled in the center of the valley, penetrated 400 m of lake sediments and 250 m of rhyolite tuff and breccia (possibly Miocene Delleker Formation) before entering the biotite granite basement.

The altitude of Sierra Valley is approximately 1,500 m, and the shoreline of the former lake lies at about 1,550 m. The valley is bordered by structural blocks of Cretaceous granitic rocks and Tertiary andesite and basalt. Several northwest trending faults cut the valley sediments and the igneous rocks on both sides of the valley. It is not known whether the faults are still active, but recent faults are visible from the air because they disrupt the ground-water flow and the vegetation patterns in the valley. Average precipitation is about 50 cm/yr and a great deal of runoff is collected from the surrounding mountains. The ground-water table is near the surface in most of the valley, and extensive marshes exist in the central and northern portions of the valley. Nine samples were collected from artesian wells and springs (Figure 3, Tables 2 and 2a).

Water Chemistry - Fluid from Campbell Hot Springs (Sample 9), is a sodium-bicarbonate-chloride type water issuing from Tertiary andesite. Water from a cold artesian well (Sample 8) is of the sodium-bicarbonate type, thought to represent local meteoric water. The remaining seven samples, from hot artesian wells, are sodium-chloride type water.

All the samples from the hot artesian wells are chemically very similar, indicating that they are only various dilutions of the same thermal source. It appears that deep circulating ground water is rising along a northwesterly striking fault in the

area of Sample 5, and that hot water (above 130°C) then moves into the permeable sand, which is tapped by the well. Leakage from the fault into other aquifers may feed the other wells.

There is little likelihood that a significant quantity of high-temperature water is in this area. Thermal energy transfer seems localized along a bedrock fracture zone, and the deep circulation of ground water appears to be the major means of heat convection to the surface.
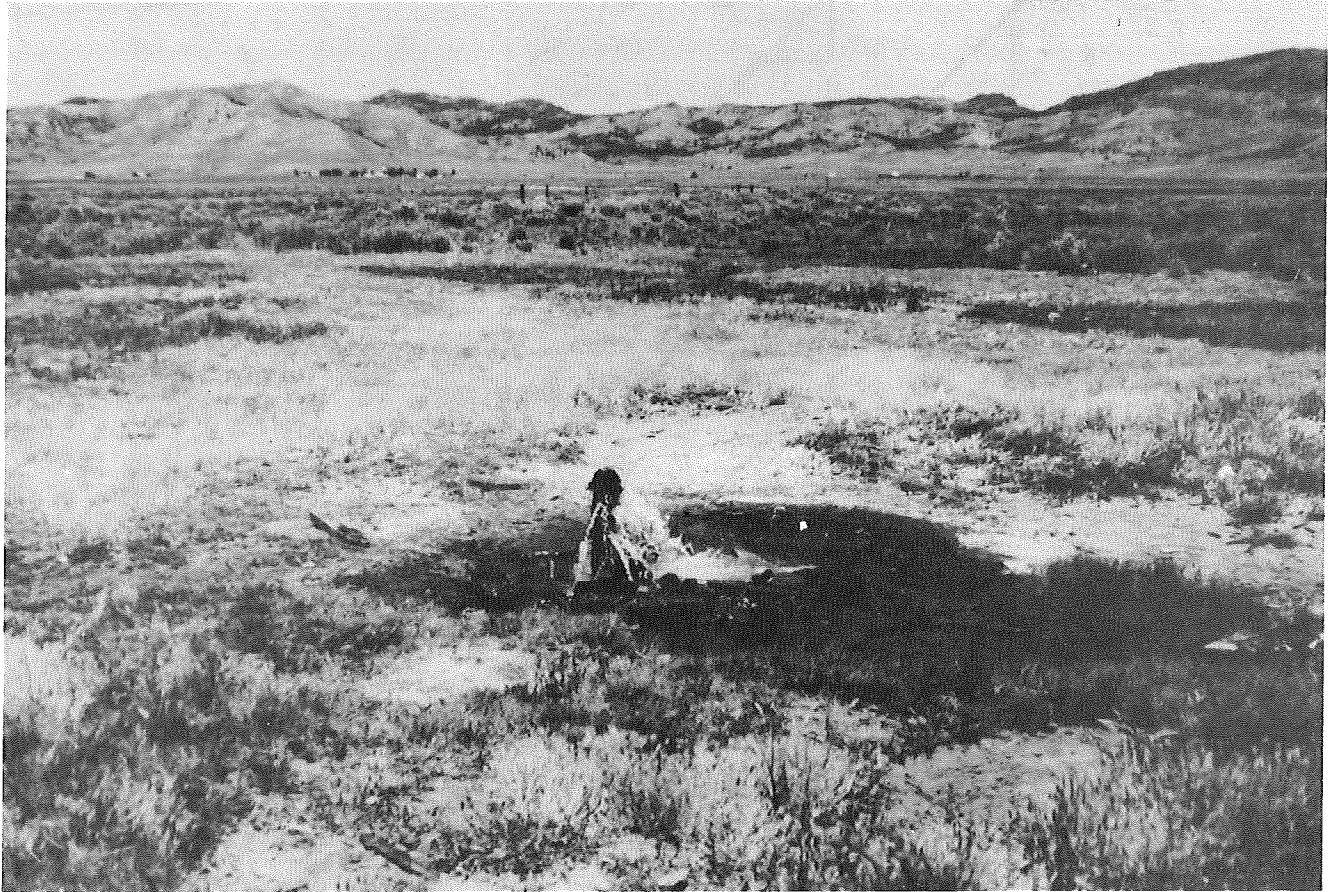
The northern Marble Hot Springs well (Sample 1) in the northwestern part of Sierra Valley. Water at 73.2°C leaks through holes in the corroded steel pipe. This was formerly the site of resort baths, but is now used for watering cattle. Photo taken June 1973.

TABLE 2. Artesian Wells and Springs, Sierra Valley

Sample Number	Location M.D. B&M	Owner	Date Sampled (mo/dy/yr)	Producing Depth (m)	Alt. (m)	Water Temp. (°C)	pH	Conduc- tivity (mmho/cm)	Dis- charge (1/min)	Isotopes[1] δO18 (°/oo)	δH2 (°/oo)
1	NW/SE Sec. 13 T. 22N., R. 14E.	Marble Hot Springs	6/20/73	104	1,486	73.2	8.19	3.87	100	-14.44	-117.8
2	SW/SE Sec. 13 T. 22N., R. 14E.	Marble Hot Springs	6/20/73	99	1,486	70.3	7.96	3.74	80	-14.32	-117.5
3	NW/NE Sec. 32 T. 22N., R. 15E.	W. Hagge	6/27/73	213	1,486	39.8	7.61	2.39	2.5	-14.87	-119.1
4	NW/NE Sec. 32 T. 22N., R. 15E.	W. Hagge	6/28/73	182	1,486	38.6	7.48	1.62	2	-15.66	-122.2
5	NE/SW Sec. 32 T. 22N., R. 15E.	G. Filipini	6/20/73	335	1,487	94.2	7.97	4.72	50	-13.93	-117.8
6	SE/SE Sec. 32 T. 22N., R. 15E.	W. Hagge	6/28/73	274	1,487	44.1	8.00	2.65	4	-14.64	-118.5
7	SW/NW Sec. 5 T. 21N., R. 15E.	G. Filipini	6/22/73	244	1,489	51.3	7.42	2.71	8	-14.91	-118.9
8	SW/SW Sec. 9 T. 21N., R. 15E.	A. Genasci	6/22/73	122	1,498	18.2	7.68	0.198	12	-14.75	-110.6
9	NW/NE Sec. 19 T. 20N., R. 15E.	Campbell Hot Springs	6/19/73	spring	1,530	36.8	10.13	0.596	1	-14.84	-111.4

[1] Isotopic analyses by T. S. Presser.
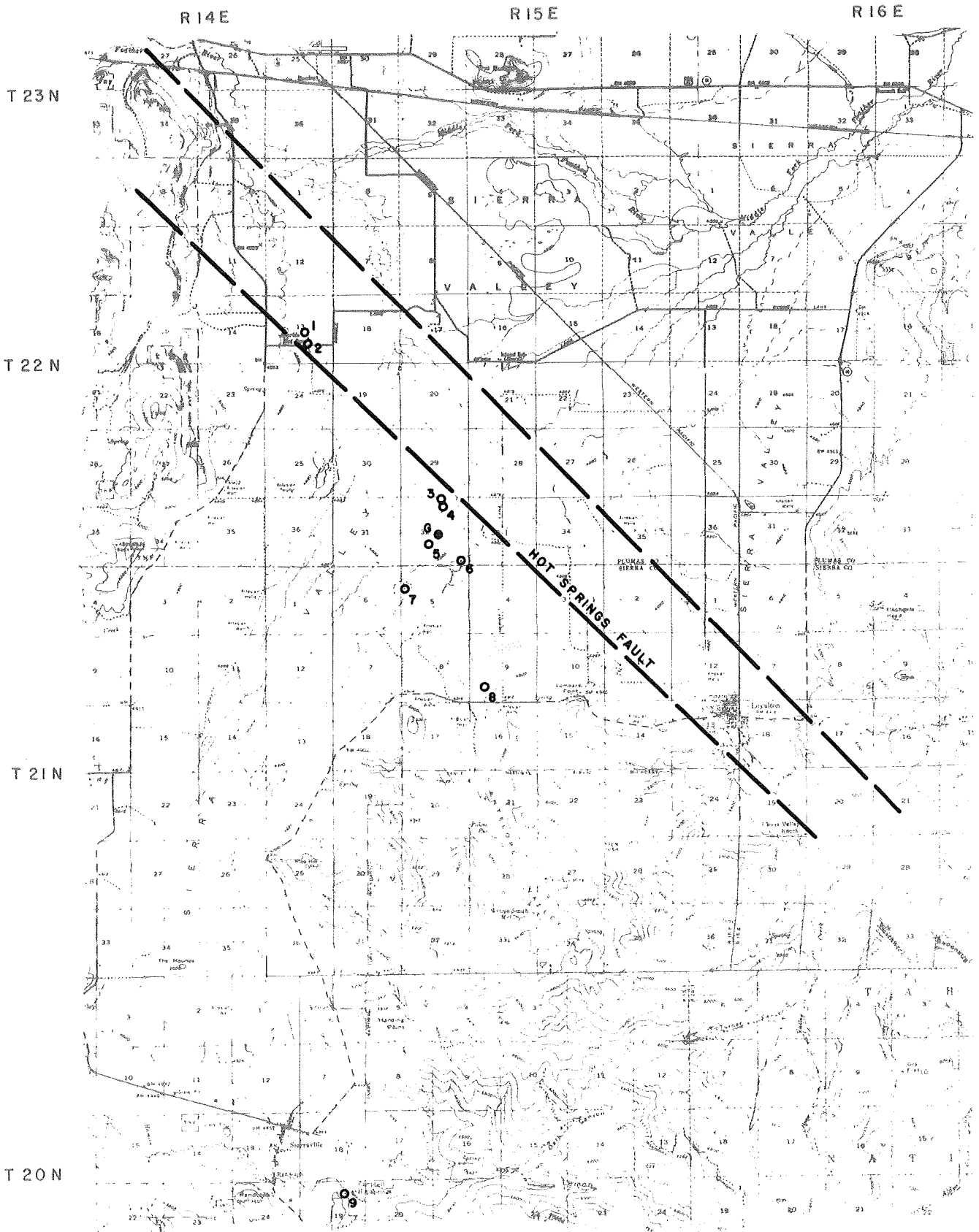
FIGURE 3. SAMPLE LOCATIONS IN SIERRA VALLEY, CALIFORNIA

QUATERNARY FAULTS   ● GEOTHERMAL WELL "FILLIPINI" 1   ○ SAMPLE LOCATIONS
                                         G   6

TABLE 2a. Chemical Constituents of Thermal Waters, Sierra Valley (in mg/l)[1]

Sample Number	Location	Li	Na	K	Rb	Cs	Mg	Ca	Mn	Fe	F	Cl	HCO₃	CO₃	SO₄	SiO₂	B	Calculated Dissolved Solids
1	NW/SE Sec. 13	0.42	410	7.6	0.06	0.2	0.1	37	0.022	<0.06	2.2	460	41	0	340	60	7.4	1,370
2	SW/SE Sec. 13	0.40	400	7.4	0.06	0.2	0.1	38	0.03	<0.06	2.2	460	51	1	330	62	7.3	1,360
3	NW/NE Sec. 32	0.50	400	6.3	0.05	0.1	1.3	26	0.10	0.63	1.5	440	76	0	270	80	7.8	1,310
4	NW/NE Sec. 32	0.36	300	5.3	0.03	0.1	1.4	12	0.075	1.43	1.0	300	87	0	190	77	6.2	980
5	NE/SW Sec. 32	0.65	450	13	0.11	0.2	0.1	39	0.01	<0.06	2.6	540	50	1	370	98	8.8	1,570
6	SE/SE Sec. 32	0.48	420	8.5	0.05	0.2	0.6	20	0.06	<0.06	1.9	450	72	1	270	92	8.2	1,340
7	SW/NW Sec. 5	0.38	380	5.6	0.04	0.1	0.6	20	0.09	0.09	1.8	390	103	0	220	85	7.4	1,210
8	SW/SW Sec. 9	<0.01	38	3.9	<0.01	<0.05	4.0	5.5	0.013	0.15	<0.1	5.8	130	1	13	65	0.07	266
9	NW/NE Sec. 19	0.06	92	1.1	<0.01	<0.05	<0.1	2.0	<0.01	<0.06	<0.1	52	86	25	27	82	1.6	369

Trace Constituents Below Detection:

Co < 0.04
Ni < 0.04
Cu < 0.01
Zn < 0.01
Cd < 0.01
Pb < 0.06

[1] Chemical analyses by L. M. Willey, T. S. Presser, J. B. Rapp, and M. J. Reed.

TABLE 2b. Subsurface Temperatures of Thermal Waters Calculated from Chemical Indicators, Sierra Valley

Sample Number	Measured Temperature (°C)	Cristobalite	Silica Temperatures (°C) Chalcedony	Quartz	Quartz (steam loss)	Feldspars	Cation Temperatures (°C) Empirical Na,K,Ca β=1/3	β=4/3
1	73.2	60.1	81.4	110.5	110.0	46.3	111.7	91.9
2	70.3	61.7	83.2	112.1	111.4	46.1	111.1	90.1
3	39.8	74.6	97.3	125.1	122.5	37.2	107.3	93.3
4	38.6	72.6	95.1	123.1	120.8	43.5	113.1	102.3
5	94.2	85.6	109.4	136.1	131.8	73.7	130.8	111.7
6	44.1	82.1	105.6	132.6	128.8	51.3	119.6	111.6
7	51.3	77.8	100.9	128.3	125.2	33.7	105.8	94.8
8	18.2	64.0	85.7	114.5	113.4	186.8	166.9	85.4
9	36.8	75.9	98.7	126.4	123.6	23.1	94.9	75.6

Honey Lake Valley, Lassen County

Geologic Setting—Honey Lake Valley is a part of the Basin and Range structural province. The valley is bounded on the southwest by the Honey Lake fault and the uplifted granitic and volcanic Diamond Mountains block. There appears to have been more than 2,400 m of vertical offset on the Honey Lake fault since the late Pliocene (post-Warner Basalt). The valley is bordered on the northeast by the Pliocene basalts of Skedaddle Mountains and on the north by the Pliocene and Pleistocene basalts of the Modoc Plateau.

An unpublished gravity survey for the California Department of Water Resources indicated that granite basement lies at a depth of approximately 1,600 m below the center of the valley. An unsuccessful exploratory gas well drilled northwest of Herlong penetrated 250 m of Quaternary lake deposits, 820 m of interbedded sandstone and shale, and 140 m of andesite breccia and flows. Long lines of calcareous tufa deposits lead back toward the Skedaddle Mountains from both Wendel and Amedee Hot Springs on the northeastern shore of Honey Lake. The tufa deposits mark positions of former hot springs and the traces of two faults.

The valley is a closed drainage basin, and the entire basin has an average precipitation of about 6 cm/yr. The local basalts have a high permeability and supply significant recharge to the ground water in storage. Honey Lake is an alkali lake which occupies the lowest part of the basin throughout most of the year. The locations of the water-sample sites in Honey Lake Valley are shown on Figure 4.

Water Chemistry—The dilute water in Samples 1 and 4 (Tables 3a and 3b) is of the sodium-bicarbonate type, and the remaining three samples are sodium-sulfate type water. The sodium-bicarbonate type water is thought to represent local meteoric water. The chemical geothermometers give conflicting temperatures in this area. Because of extensive volcanism in the area, it is possible that a significant amount of volcanic ash is contained in the valley sediments. If the silica in solution were in equilibrium with cristobalite in the ash, this would explain higher concentrations of silica than expected from quartz solubility. The ash could also supply a higher than normal amount of potassium to the solution and affect the calculated temperatures from the cation ratios (Table 3c).

Samples from both Wendel and Amedee springs appear to be from the same thermal reservoir containing water above 140°C. Deep circulation of ground water in fault conduits seems to be the source of this thermal system.
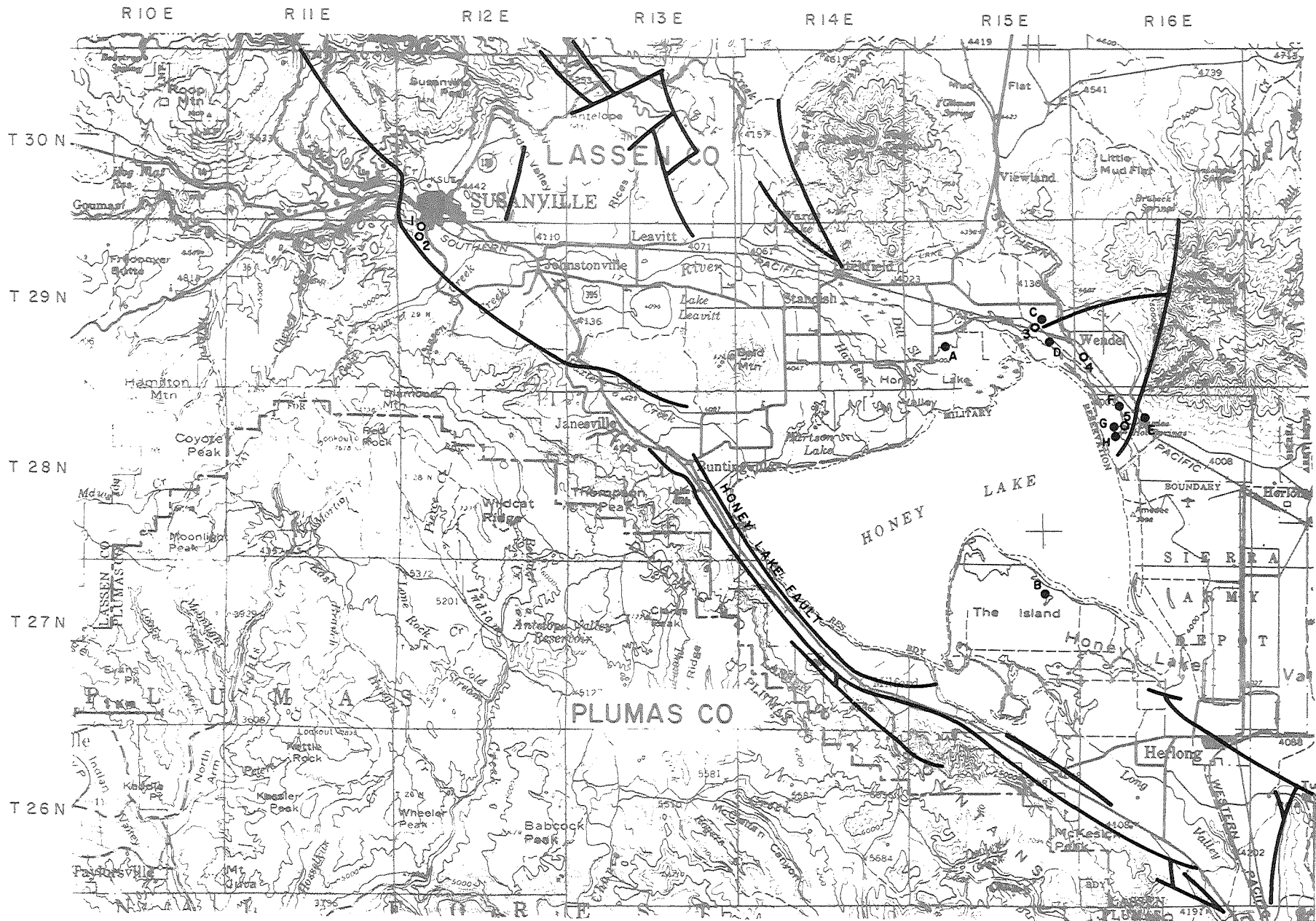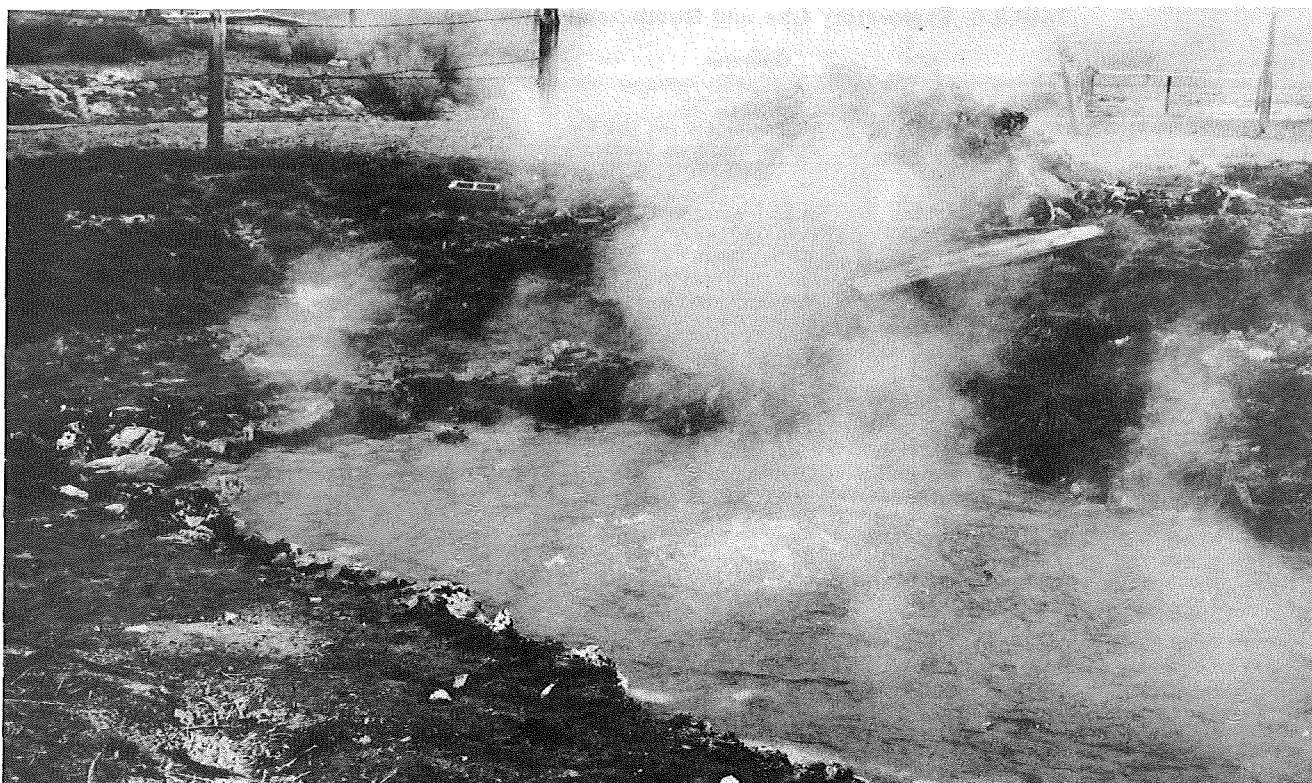
FIGURE 4. SAMPLE LOCATIONS IN HONEY LAKE VALLEY, CALIFORNIA

━━━━ QUATERNARY FAULTS   ● EXPLORATORY WELLS   ○ SAMPLE LOCATIONS
                              B   4

Boiling pool (95.6°C) at the main spring of Wendel Hot Springs (Sample 3). This pool is now surrounded by a cement block wall and supplies hot water to a greenhouse operation. Photo taken October 1973.

One of several springs at Amedee Hot Springs (Sample 5) on the eastern edge of Honey Lake Valley. The alignment of hot springs and the linear ridges of tufa indicate the locations of subsurface faults in this area. Water from the springs was boiling (95.1°C for Sample 5), and in some springs pieces of wood had a thin coating of cinnabar. Photo taken June 1973.

TABLE 3. Exploratory Gas and Geothermal Wells, Honey Lake Valley

Ident. Letter	Location	Operator	Well	Status	Total Depth (m)
	Exploratory Gas Wells				
A	SE/NW Sec. 32, T. 29N., R. 15E., M.D.	Sacramento Oil and Gas Co.	"Triami Cattle Corp" 2	Abd. 1962	256
B	Cen. NE Sec. 11, T. 27N., R. 15E., M.D.	Neaves Petroleum Developments	"Honey Lake Island" 1	Abd. 1963	1,211
	Exploratory Geothermal Wells				
C	NW/SE Sec. 23, T. 29N., R. 15E., M.D.	Magma Power Co.	"Wendel" 1	Idle	190
D	SW/NW Sec. 25, T. 29N., R. 15E., M.D.	Gulf Oil Corp.	"Honey Lake" 2-ST	Idle	1,538
E	SW/SW Sec. 4, T. 28N., R. 16E., M.D.	Magma Power Co.	"Amedee" 3	Abd. 1962	58
F	SE/NW Sec. 5, T. 28N., R. 16E., M.D.	Gulf Oil Corp.	"Honey Lake" 1-ST	Abd. 1973	1,531
G	NW/NE Sec. 8, T. 28N., R. 16E., M.D.	Magma Power Co.	"Amedee" 1	Idle	268
H	SW/NE Sec. 8, T. 28N., R. 16E., M.D.	Magma Power Co.	"Amedee" 2	Idle	338

TABLE 3a. Wells and Springs, Honey Lake Valley

Sample Number	Location M.D. B&M.	Name	Date Sampled (mo/dy/yr)	Producing Depth (m)	Alt. (m)	Water Temp. (^{0}C)	pH	Conduc-tivity (mmho/cm)	Dis-charge (1/min)	Isotopes[1] δO^{18} (^{0}/oo)	δH^2 (^{0}/oo)
1	NE/NE Sec. 6 T. 29N., R. 12E.	Roosevelt Swimming Pool	7/18/73	90(?)	1,295	35.8	8.01	0.254	pumped		
2	SE/NE Sec. 6 T. 29N., R. 12E.	Church of the Latter Day Saints	7/18/73	169-181	1,268	48.8	7.87	1.07	800 pumped	-14.48	-113.4
3	SW/SE Sec. 23 T. 29N., R. 15E.	Wendel Hot Springs	7/17/73	spring	1,231	95.6	8.38	3.34	1,200	-14.09	-118.8
4	NE/SW Sec. 30 T. 29N., R. 16E.	Southern Pacific Railroad	7/17/73	93	1,223	28.2	8.33	0.332	300 pumped		
5	NW/NE Sec. 8 T. 28N., R. 16E.	Amedee Hot Springs	7/17/73	spring	1,219	95.1	8.43	2.86	500		

[1] Isotopic analyses by T. S. Presser.

TABLE 3b. Chemical Constituents of Thermal Waters, Honey Lake Valley (in mg/l)[1]

Sample Number	Location	Li	Na	K	Rb	Mg	Ca	Zn	F	Cl	HCO$_3$	CO$_3$	SO$_4$	SiO$_2$	B	Calculated Dissolved Solids
1	NE/NE Sec. 6	<0.01	20	3.8	<0.01	3.4	19	0.043	<0.1	2.0	120	1	11	53	<0.02	233
2	SE/NE Sec. 6	0.05	140	4.6	0.02	1.6	24	0.009	1.2	64	68	1	190	62	1.4	558
3	SW/SE Sec. 23	0.12	280	7.5	0.04	<0.1	18	0.015	4.1	190	50	1	360	120	5.5	1,040
4	NE/SW Sec. 30	0.01	58	8.0	0.01	2.2	6.0	<0.005	0.2	17	112	1	32	42	0.22	279
5	NW/NE Sec. 8	0.08	250	5.5	0.02	<0.1	14	<0.005	4.4	160	44	2	300	95	4.0	879

Trace Constituents Below Detection:

Cs <0.1, Mn <0.01, Fe <0.06, Cd <0.01, Co <0.05, Cu <0.02, Ni <0.04, Pb <0.1

[1] Chemical analyses by L. M. Willey, T. S. Presser, J. B. Rapp, and M. J. Reed.

TABLE 3c. Subsurface Temperatures of Thermal Waters Calculated from Chemical Indicators, Honey Lake Valley

Sample Number	Measured Temperature (^{0}C)	Cristobalite	Silica Temperatures (^{0}C) Chalcedony	Quartz	Quartz (steam loss)	Feldspars	Cation Temperatures (^{0}C) Empirical Na,K,Ca $\beta=1/3$	$\beta=4/3$
1	35.8	54.2	75.0	104.5	--	273.3	177.1	52.6
2	48.8	61.7	83.2	112.1	111.4	82.6	123.2	72.9
3	95.6	97.3	122.3	147.6	141.5	68.7	126.3	104.3
4	28.2	43.8	63.5	93.9	--	224.6	189.5	114.8
5	95.1	83.9	107.5	134.3	130.3	56.3	118.4	97.6

Surprise Valley, Modoc County

Geologic Setting—Surprise Valley is a graben lying between the horsts of the Warner Mountains on the west and the Hays Canyon Range on the east. At least 2,000 m of sediments and volcanic debris have accumulated in the valley, and the crest of the Warner Mountains is up to 1,500 m above the valley floor. Vertical displacement on the Surprise Valley fault, which marks the western edge of the valley, is thus greater than 3,500 m. Scarps in the alluvium indicate recent movement, and radiometric ages suggest faulting began less than 15 million years ago

(Duffield and McKee, 1974).

Tertiary rhyolite flows and obsidian bodies crop out in the Fandango Valley of the northern Warner Mountains and also near the southern end of the range (Duffield and Fournier, 1974). It is possible that the volcanic rocks are related to a shallow crustal magmatic heat source.

Surface and ground water are supplied by runoff mainly from the Warner Mountains; and streams, springs, and artesian wells are numerous on the western side of the valley. The eastern side is an alkali desert with few springs and wells. Surprise Valley forms a closed basin, and lakes have occupied the basin since late Tertiary time. At present, three shallow alkali lakes are on the valley floor during most of the year. Figure 5 shows the locations of wells and springs sampled for this study. Sample 2 was collected from the site of a violent steam eruption in 1951 (White, 1955) but only quiet hot springs activity has occurred since that time.

Water Chemistry—All but one of the samples from Surprise Valley are sodium-sulfate type water (Tables 4a and 4b). The sample from Fort Bidwell (Sample 1) is a sodium-bicarbonate type water.

The chemical compositions and temperature indicators of the samples

View northward of the Lake City mud eruption area on the west side of Surprise Valley. Lakes in the foreground occupy craters formed during mud and steam eruptions in 1951. Hot springs presently discharge beneath the lakes and in the surrounding marsh. The Warner Range in the background has been uplifted along the Surprise Valley fault. Photo by R. E. Franson, Dec. 1960.

indicate shallow aquifers, with water up to approximately 170°C. The great depth of the valley fill makes it possible for a deeper geothermal reservoir to exist, but it is not reflected in the surface water chemistry.

Duffield and Fournier (1974) have applied various mixing models to chemical analyses from Surprise Valley wells and springs, and they calculate temperatures of 220°C for the Leonards Hot Springs and Fort

Bidwell areas. The sources of thermal waters are aligned in zones sub-parallel to the sides of the valley, and faults in these zones act as conduits for the water rising through the thick valley fill.

Abandoned well (Sample 1) on the Fort Bidwell Indian Reservation. Water at 45.1°C flows from holes in the corroded steel pipe. Photo taken October 1973.
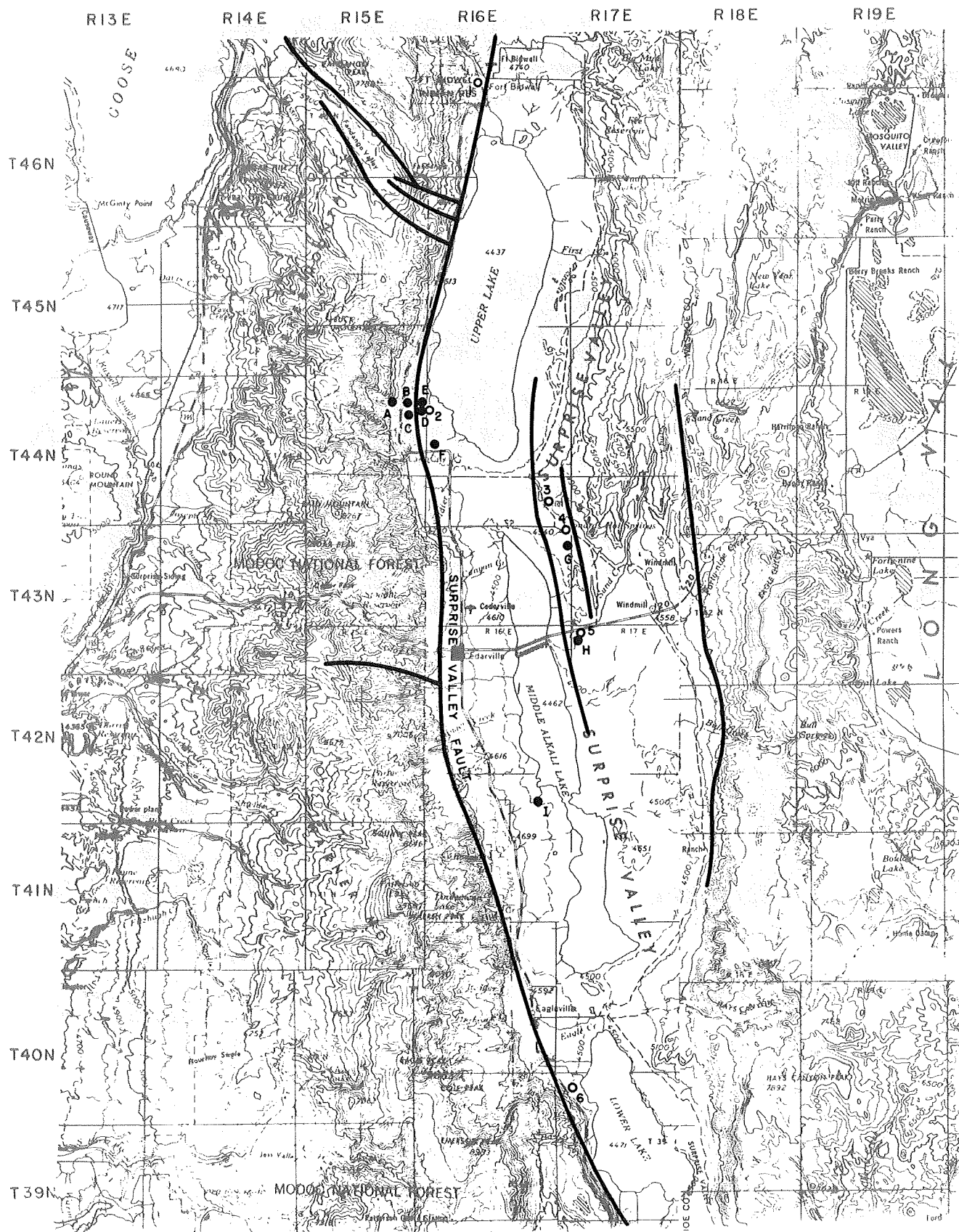
FIGURE 5. SAMPLE LOCATIONS IN SURPRISE VALLEY, CALIFORNIA

QUATERNARY FAULTS ● GEOTHERMAL WELLS ○ SAMPLE LOCATIONS
F 3

Hot spring vent within one of the craters in the Lake City mud eruption area. The craters are surrounded by ridges of ejected material which are now less than 2 m high. Many of the springs produce boiling water, and Sample 2 was collected at 96.5°C. Photo taken July 1973.

Seyferth Hot Springs (Sample 3) on the east side of Surprise Valley have a temperature of 85.4°C. The springs are thought to overlie a northerly trending subsurface fault. Photo taken July 1973.

Leonards Hot Springs (Sample 4) on the east side of the valley produce water at 61.8°C. These springs supply water to Leonards Pool (now abandoned) 0.6 km southwest of the springs. Photo taken July 1973.

View eastward of springs in the area of the Hot Springs Motel (formerly Cedar Plunge) on the east side of Middle Alkali Lake. Many springs in this complex produce boiling water which is thought to be rising along a concealed fault. Fault blocks of the Hays Canyon Range are visible in the distance, and a large Quaternary landslide appears on the front of the range. Photo by R. E. Franson, December 1960.

DIVISION OF OIL AND GAS
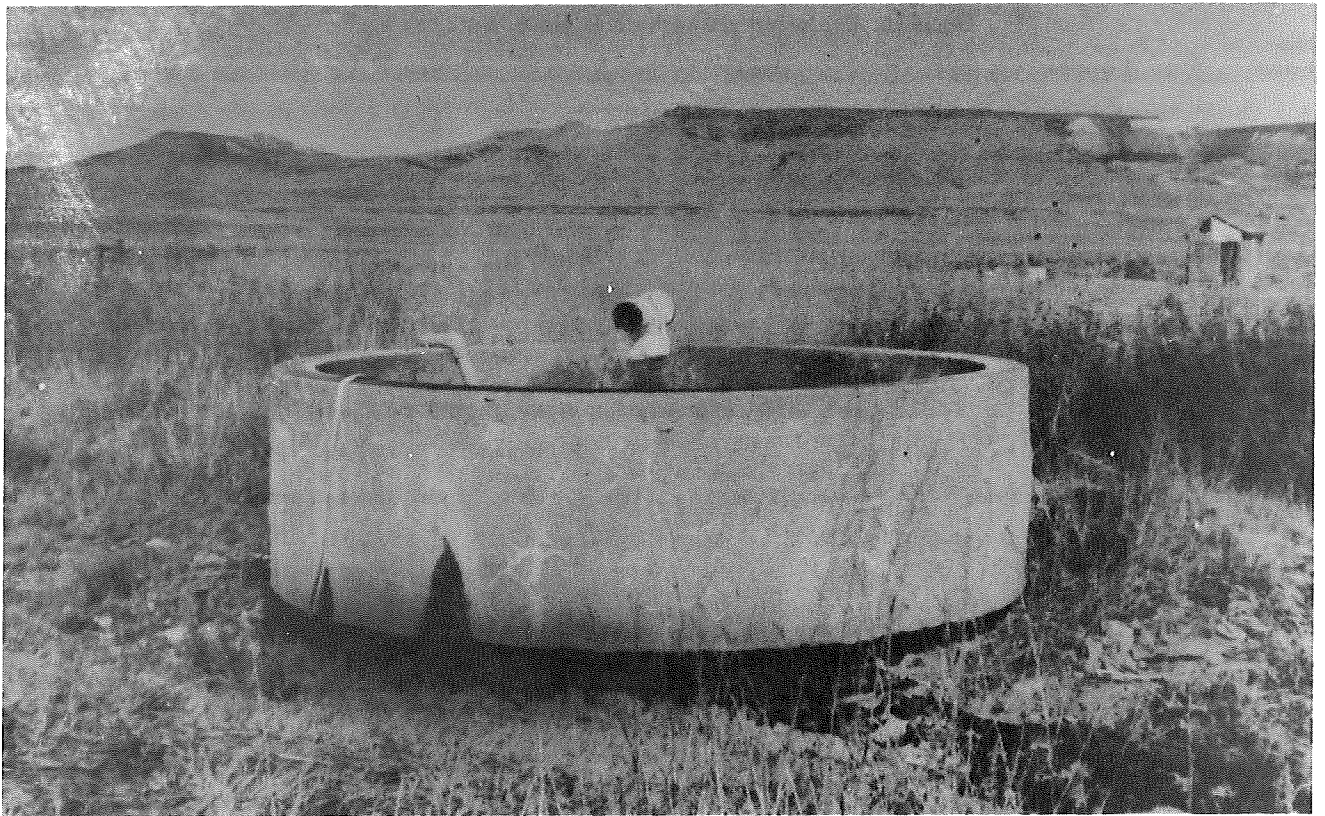
Hot Springs Motel well (Sample 5), formerly Cedar Plunge, discharges boiling water (98.1°C). This well supplies water for swimming pool and space heating needs. Photo taken August 1972.
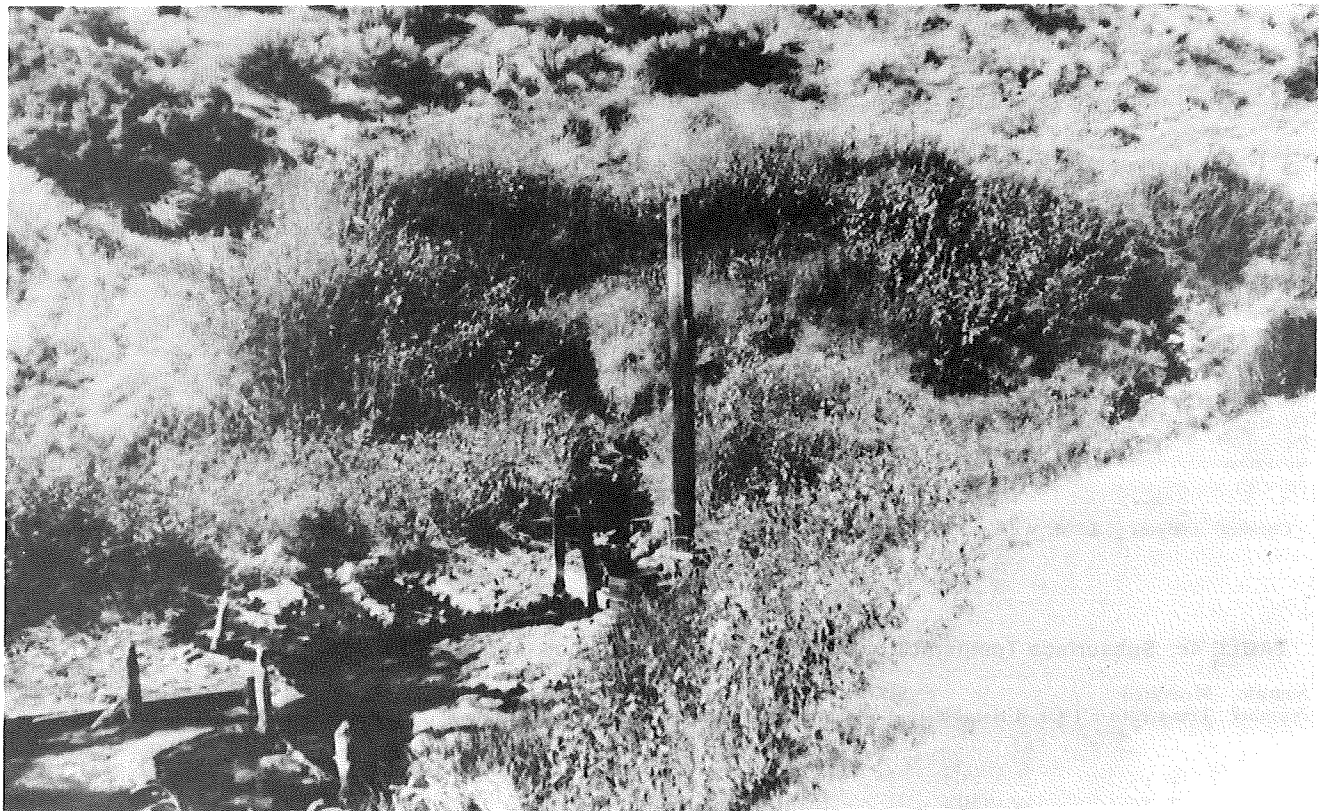
Menlo Hot Springs (Sample 6) discharge water at 57.4°C. The springs issue from a small landslide at the foot of a scarp along the Surprise Valley fault. Photo taken August 1973.

CHEMISTRY OF THERMAL WATER

TABLE 4. Exploratory Geothermal Wells, Surprise Valley

Ident. Letter	Location	Operator	Well	Status	Total Depth (m)
A	NE/NE Sec. 23, T. 44N., R. 15E., M.D.	Magma Energy, Inc.	"Phipps" 2	Idle	1,508
B	NW/NW Sec. 24, T. 44N., R. 15E., M.D.	Magma Energy, Inc.	"Phipps" 1	Idle	386
C	SW/NW Sec. 24, T. 44N., R. 15E., M.D.	Magma Energy, Inc.	"Parman" 1	Idle	655
D	SW/NE Sec. 24, T. 44N., R. 15E., M.D.	Magma Energy, Inc.	"Parman" 3	Blowout 1962	28
E	SE/NE Sec. 24, T. 44N., R. 15E., M.D.	Magma Energy, Inc.	"Parman" 2	Idle	600
F	SE/SW Sec. 30, T. 44N., R. 16E., M.D.	Gulf Oil Corp.	"Surprise Valley" 1-ST	Idle	2,085
G	SE/SE Sec. 13, T. 43N., R. 16E., M.D.	Gulf Oil Corp.	"Surprise Valley" 2-ST	Abd. 1973	1,982
H	SW/SW Sec. 6, T. 42N., R. 17E., M.D.	Magma Energy, Inc.	"Cedarville" 1	Abd. 1962	224
I	NW/NE Sec. 11, T. 41N., R. 16E., M.D.	American Thermal Resources	"Goodwin" 1-11	Abd. 1974	2,135

TABLE 4a. Springs and Artesian Wells, Surprise Valley

Sample Number	Location M.D. B&M	Name	Date Sampled (mo/dy/yr)	Depth (m)	Alt. (m)	Water Temp. (°C)	pH	Conductivity (mmho/cm)	Discharge (1/min)	Isotopes[1] δO^{18} (°/oo)	δH^2 (°/oo)
1	NW/NE Sec. 17 T. 46N., R. 16E.	Fort Bidwell Reservation	7/26/73		1,414	45.1	7.85	0 733	400		
2	SW/NE Sec. 24 T. 44N., R. 15E.	Lake City Mud Explosion	8/16/73	pool	1,366	96.5	7.44	3.74	0	-14.79	-113.0
3	NW/NW Sec. 12 T. 43N., R. 16E.	Seyferth Hot Springs	7/26/73	spring	1,417	85.4	7.66	3.28	500	-14.05	-121.2
4	NE/NE Sec. 13 T. 43N., R. 16E.	Leonards Hot Springs	7/25/73	spring	1,390	61.8	7.82	2.59	150		
5	NE/SW Sec. 6 T. 42N., R. 17E.	Hot Springs Motel	7/27/73	27	1,372	98.1	8.40	2.66	300	-13.81	-117.0
6	NE/NE Sec. 7 T. 39N., R. 17E.	Menlo Hot Springs	8/23/73	spring	1,384	57.4	8.91	0.808	500	-15.30	-112.3

[1] Isotopic analyses by T. S. Presser.

TABLE 4b. Chemical Constituents of Thermal Waters, Surprise Valley (in mg/l)[1]

Sample Number	Location	Li	Na	K	Rb	Mg	Ca	Mn	Zn	F	Cl	HCO₃	CO₃	SO₄	SiO₂	B	Calculated Dissolved Solids
1	NW/NE Sec. 17	0.03	110	9.5	0.01	0.1	4.2	<0.01	<0.005	2.2	31	131	1	86	82	0.61	458
2	SW/NE Sec. 24	0.24	320	15	0.08	<0.1	7.7	<0.01	<0.005	7.6	220	112	0	320	200	6.3	1,210
3	NW/NW Sec. 12	0.15	300	9.0	0.04	<0.1	28	0.01	<0.005	5.4	220	63	0	370	110	7.6	1,110
4	NE/NE Sec. 13	0.13	330	8.5	0.03	0.6	26	0.09	<0.005	5.2	220	82	1	390	110	7.6	1,180
5	NE/SW Sec. 6	0.10	280	5.5	0.03	<0.1	16	<0.01	0.014	5.1	200	57	2	320	100	5.7	991
6	NE/NE Sec. 7	<0.02	100	1.4	<0.01	<0.1	5.1	<0.01	<0.05	3.8	25	27	34	120	53	0.93	370

Trace Constituents Below Detection:

Cs <0.1
Fe <0.06
Cd <0.01
Co <0.05
Cu <0.02
Ni <0.04
Pb <0.1

[1] Chemical analyses by L. M. Willey, T. S. Presser, J. B. Rapp, and M. J. Reed.

TABLE 4c. Subsurface Temperatures of Thermal Waters, Calculated from Chemical Indicators, Surprise Valley

| Sample Number	Measured Temperature (°C)	Silica Temperatures (°C) Cristobalite	Chalcedony	Quartz	Quartz (steam loss)	Feldspars	Cation Temperatures (°C) Empirical Na,K,Ca $\beta=1/3$	$\beta=4/3$
1	45.1	75.9	98.7	126.4	123.6	167.2	178.8	141.2
2	96.5	130.4	159.1	180.0	168.1	109.7	160.4	160.6
3	85.4	92.2	116.7	142.6	137.2	76.3	129.0	101.0
4	61.8	92.2	116.7	142.6	137.2	66.2	124.4	101.9
5	98.1	86.7	110.7	137.2	132.7	49.6	114.5	95.8
6	57.4	54.2	75.0	104.5	--	31.0	95.9	64.6
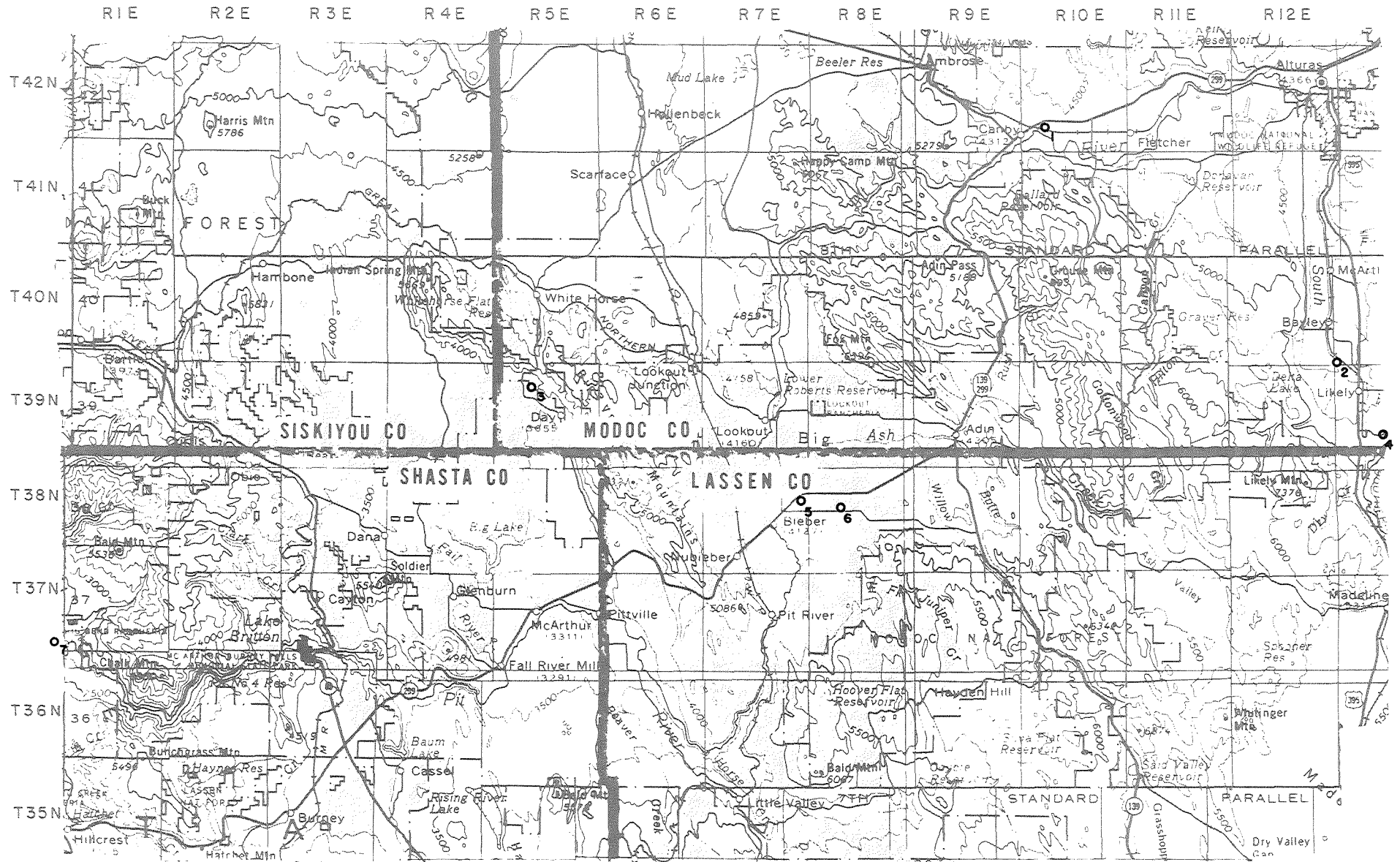
FIGURE 6. SAMPLE LOCATIONS IN MODOC PLATEAU, CALIFORNIA

o₅ SAMPLE LOCATIONS

Modoc Plateau, Modoc, Lassen, and Shasta Counties

Geologic Setting—The Modoc Plateau is an area of extensive flood basalts and pervasive normal faulting; a large number of the faults trend in a northerly to northwesterly direction. Tertiary volcanic rocks cover the area. Volcanism and faulting have continued into the Holocene with a diminishing rate of activity (Macdonald, 1966). The area has been uplifted to altitudes between 1,500 m and 1,800 m above sea level.

Highly permeable flood basalts control the hydrology of the Modoc Plateau. Through most of the region the water table is at an altitude of 1,220 m to 1,250 m, and most of the surface flow is drained to the water table in areas with an altitude over 1,250 m (Macdonald, 1966). The plateau receives an average precipitation of about 25 cm/yr, but in some areas there is no surface flow at all.

The Likely fault zone is a large, northwesterly striking structural feature cutting across the Modoc Plateau southwest of Alturas. The fault appears to have normal vertical offset, but it is unclear if any horizontal offset has taken place (Duffield and Fournier, 1974). Kelly Hot Springs (Figure 6, Sample 1) may be associated with the Likely fault. A geothermal test well drilled near the spring penetrated 977 m of volcanic and sedimentary rocks, and the bottom of the well is possibly in the upper part of the Cedarville Series of Miocene age.

Hunt Hot Springs (Sample 7) issue from the contact between Eocene conglomerate of the Montgomery Creek Formation and the Jurassic Bagley Andesite. Samples 2 through 6 came from valleys covered with Quaternary continental sediments or pyroclastic rocks, and seem to be associated with buried faults.
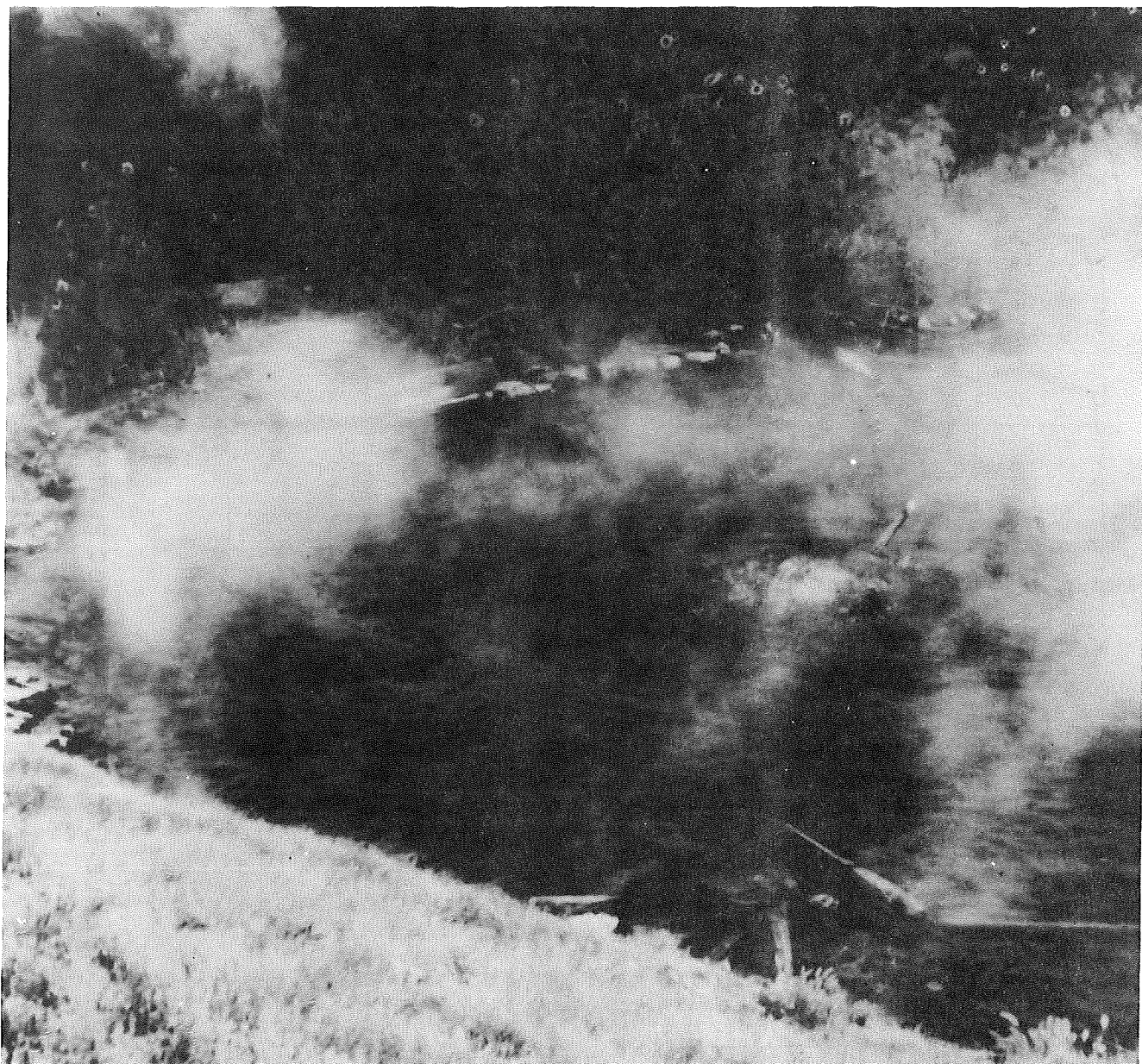
Kelly Hot Spring (Sample 1) forms a large boiling pool (91.5°C) northeast of Canby. Exploratory geothermal wells drilled both east and southwest of the spring were unsuccessful. Photo taken July 1973.
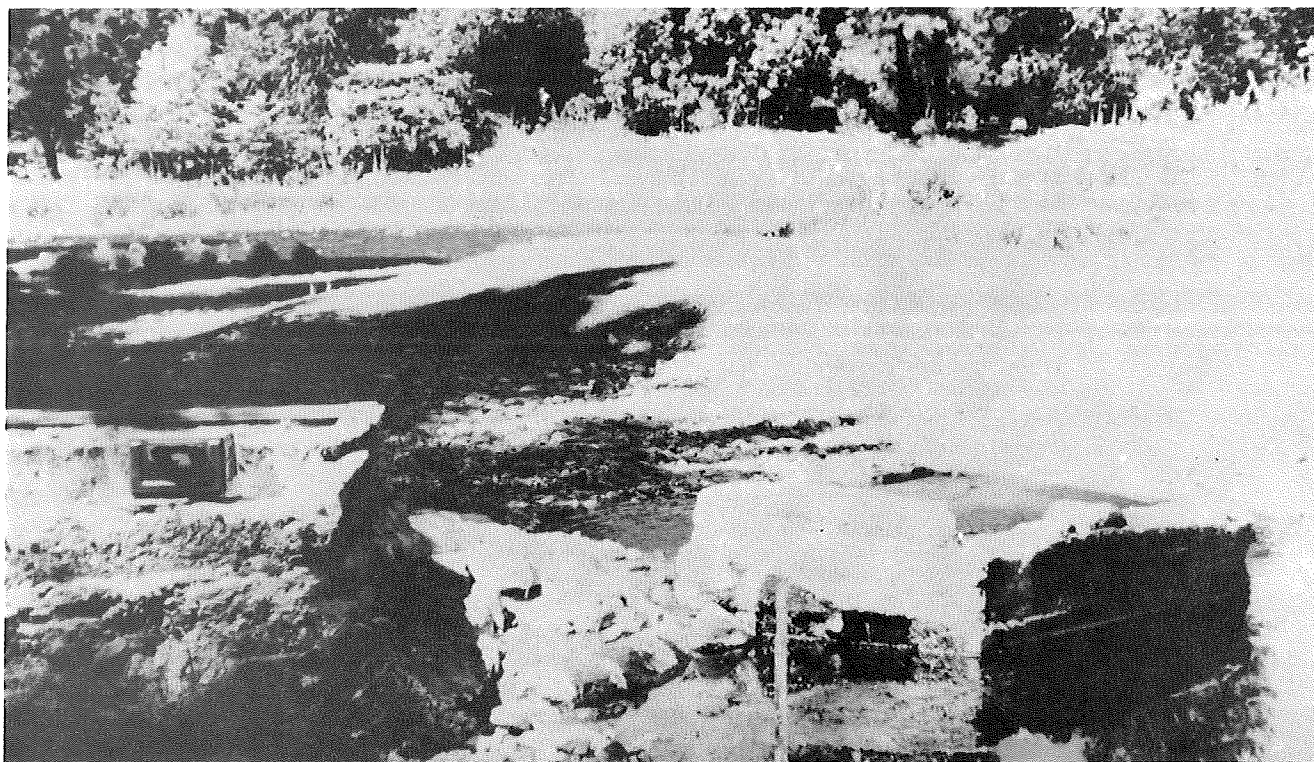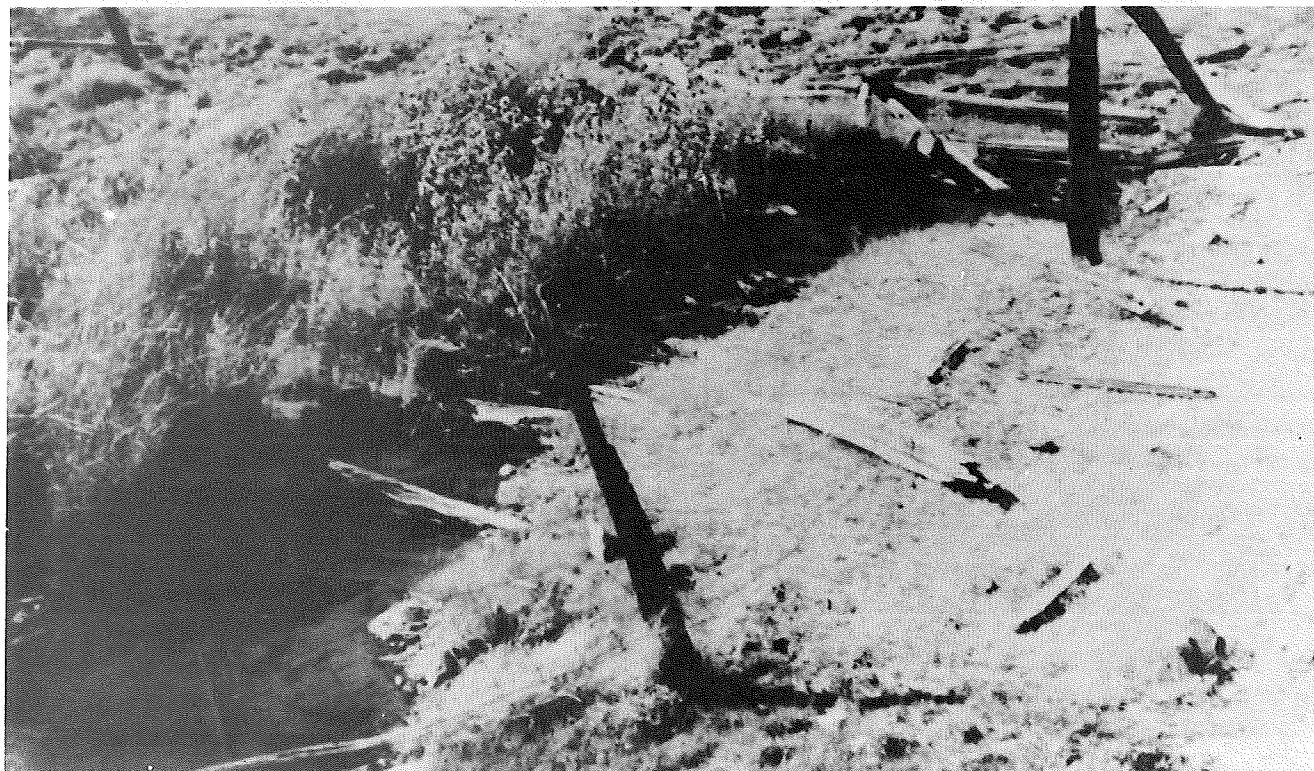
Hunt Hot Springs (Sample 7) discharge water at 57.6°C. The thermal water rises along the contact between Eocene conglomerate and Jurassic meta-andesite.

Water Chemistry—Sample 2, from the Williams Ranch well, is a dilute, sodium-bicarbonate type water, and the remaining samples are more concentrated sodium-sulfate type waters (Tables 5 and 5a). The chemical indicators of temperature give values below 155°C for all the samples (Table 5b). It is possible that all the samples in this group are mixtures of cold near-surface water and deeper thermal water.

Little Hot Springs (Sample 3) discharge water at 75.7°C from many small springs along a linear trend. Photo taken July 1973.

CHEMISTRY OF THERMAL WATER

Hot springs on the east side of West Valley Reservoir (Sample 4) issue from thin alluvium covering volcanic rocks of the western Warner Range. Photo taken July 1973.

Bassett Hot Spring (Sample 5) discharges water at 79°C to a large swimming pool. The spring issues from fractures in a well-indurated continental sandstone. Photo taken August 1973.
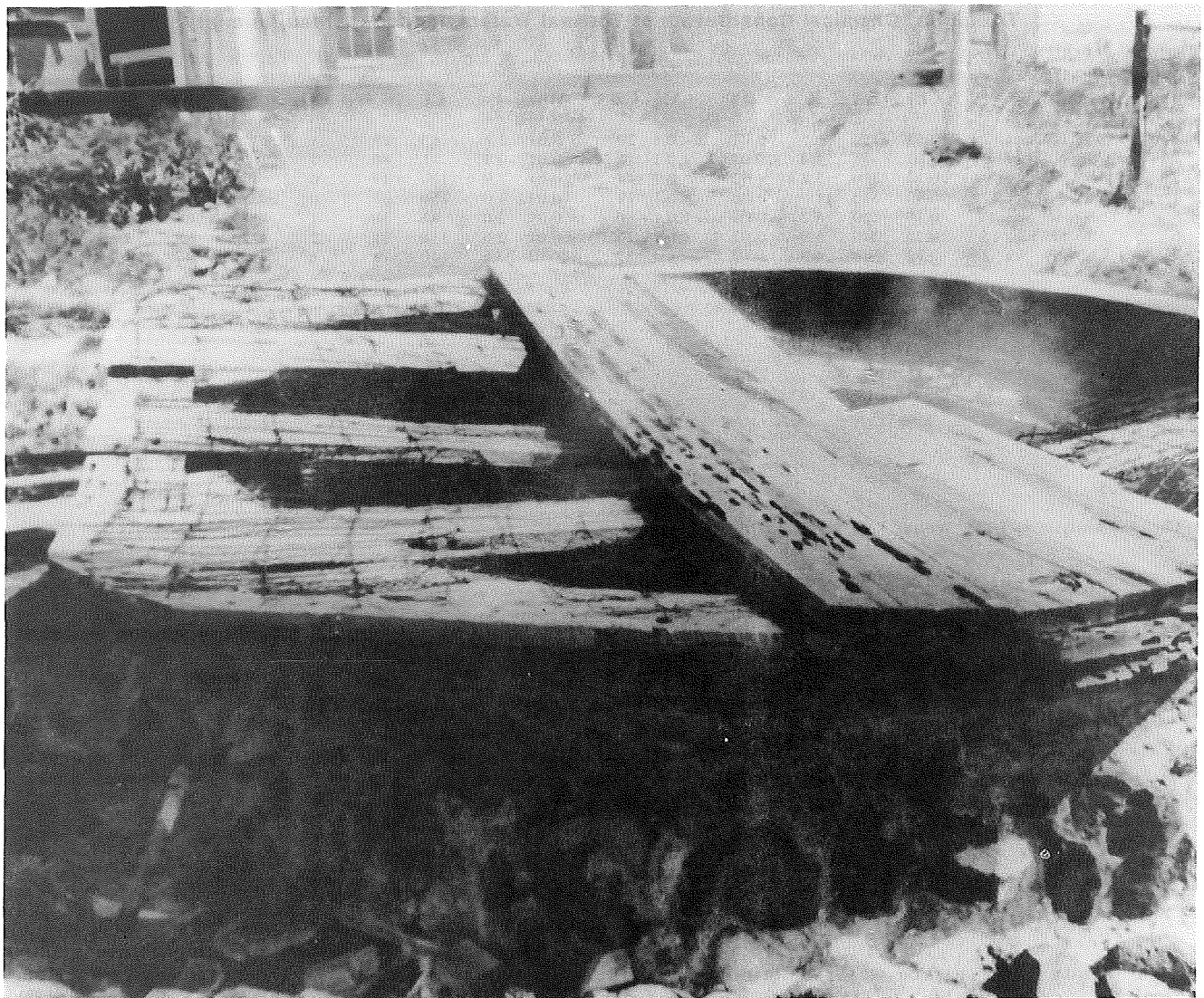
Kellog Hot Spring (Sample 6) supplies water at 78.4°C to now–abandoned bath houses. The spring comes up in a cement-lined basin. Photo taken May 1971.

All these samples could come from hot water rising along faults, since faulting is pervasive in the plateau and the sampling localities are close to mapped or inferred faults. Because of the highly permeable basalts underlying most of the region, the hot springs must also be rising along structural barriers to the ground-water flow.

TABLE 5. Hot Springs and Artesian Well, Modoc Plateau

Sample Number	Location M.D. B&M.	Name	Date Sampled (mo/dy/yr)	Producing Depth (m)	Alt. (m)	Water Temp. (°C)	pH	Conduc-tivity (mmho/cm)	Dis-charge (1/min)	Isotopes[1] δO[18] (°/oo)	δH[2] (°/oo)
1	NE NW Sec. 29 T. 42N., R. 10E.	Kelly Hot Spring	7/23/73	spring	1,326	91.5	8.08	2.77	1,250	-13.54	-115.1
2	SW NW Sec. 31 T. 40N., R. 13E.	Williams Ranch Well	7/24/73	30-38	1,347	43.8	8.40	0.333	pumped		
3	NW SW Sec. 9 T. 39N., R. 5E.	Little Hot Springs	8/22/73	spring	1,082	75.7	7.59	2.49	300	-14.20	-116.9
4	NW NE Sec. 29 T. 39N., R. 14E.	W. Valley Res. Hot Spring	7/24/73	spring	1,460	77.3	7.79	2.98	12	-14.13	-118.5
5	NW SE Sec. 12 T. 38N., R. 7E.	Bassett Hot Spring	8/14/73	spring	1,265	79.0	8.53	2.33	200	-14.67	-116.2
6	SW SE Sec. 15 T. 38N., R. 8E.	Kellog Hot Spring	8/22/73	spring	1,277	78.4	8.63	2.59	15	-14.09	-115.5
7	NW SW Sec. 25 T. 37N., R. 1W.	Hunt Hot Springs	8/21/73	spring	503	57.6	8.75	2.59	32	-13.30	-93.5

[1] Isotopic analyses by T. S. Presser.

TABLE 5a. Chemical Constituents of Thermal Waters, Modoc Plateau (in mg/l)[1]

Sample Number	Location	Li	Na	K	Rb	Mg	Ca	Mn	F	Cl	HCO₃	CO₃	SO₄	SiO₂	B	Calculated Dissolved Solids
1	NE/NW Sec. 29	0.15	250	6.5	0.02	<0.1	20	<0.01	2.1	160	45	1	300	110	3.8	899
2	SW/NW Sec. 31	<0.01	49	3.4	<0.01	<0.1	4.2	<0.01	0.4	11	80	3	28	52	0.22	231
3	NW/SW Sec. 9	0.17	230	5.2	0.02	0.2	44	0.01	1.9	120	49	0	400	87	3.9	941
4	NW/NE Sec. 29	0.40	330	11	0.06	<0.1	19	0.012	4.0	150	63	0	510	130	4.5	1,220
5	NW/SE Sec. 12	0.10	220	3.2	0.01	<0.1	30	<0.01	2.0	93	30	1	370	68	2.5	820
6	SW/SE Sec. 15	0.12	240	5.9	0.02	<0.1	30	<0.01	2.6	110	31	2	370	85	3.2	880
7	NW/SW Sec. 25	0.12	300	4.3	0.02	<0.1	52	<0.01	3.6	140	49	6	520	47	12.8	1,130

Constituents Below Detection:

Cs < 0.1
Fe < 0.06
Cd < 0.01
Co < 0.05
Cu < 0.02
Ni < 0.04
Pb < 0.1
Zn < 0.005

[1] Chemical analyses by L. M. Willey, T. S. Presser, J. B. Rapp, and M. J. Reed.

TABLE 5b. Subsurface Temperatures of Thermal Waters Calculated from Chemical Indicators, Modoc Plateau

Sample Number	Measured Temperature(°C)	Silica Temperatures (°C)				Feldspars	Cation Temperatures (°C) Empirical Na,K,Ca	
		Cristobalite	Chalcedony	Quartz	Quartz (steam loss)		β=1/3	β=4/3
1	91.5	92.2	116.7	142.6	137.2	66.8	122.8	95.1
2	43.8	53.4	74.0	103.6	--	144.7	153.9	89.8
3	75.7	79.1	102.2	129.6	126.3	58.0	110.8	69.3
4	77.3	102.1	127.7	152.4	145.4	83.6	137.8	120.0
5	79.0	66.3	88.2	116.7	115.4	33.0	96.1	61.9
6	78.4	77.8	100.9	128.3	125.2	63.2	117.2	82.0
7	57.6	48.7	68.9	98.9	--	32.2	96.0	62.8

CONCLUSIONS

A study of surface-water chemistry is applicable to the evaluation of the heat source through the use of chemical temperature in-

About the Author
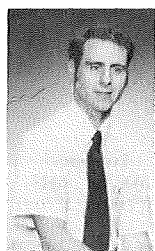
Marshall J. Reed graduated from the University of California, Berkeley with a B.A. degree in geology. He also holds an M.A. degree in geology from the University of California, Riverside, where he is currently working on his Ph.D. Marshall has experience in teaching as well as in research. From October 1972 to February 1975, he worked for the California Division of Oil and Gas as assistant geothermal officer. Marshall is presently employed by the U.S. Geological Survey in Menlo Park. He is affiliated with the Geological Society of America, California Academy of Sciences, and Geochemical Society.

dicators. Temperatures determined from water chemistry are the minimum temperatures for the system, since they give the temperature of last reaction between the water and surrounding rocks. Mixing of geothermal water and shallow, low-temperature water will usually result in the calculation, from chemical indicators, of temperatures lower than the actual subsurface temperatures. With an adequate knowledge of the geologic environment, a mixing model can be used to separate the contributions from shallow ground water and thermal water sources.

Most of the thermal waters sampled have calculated subsurface temperatures between 80° and 150°C. Water in this temperature range contains sufficient energy for industrial or domestic heating and cooling, or light industrial processing. Several of the water sources sampled in this study supply water used for space heating.

At the present time, 180°C is the minimum efficient temperature for electrical power generation from flashed steam. None of the samples

analyzed gave any geochemical indication of temperatures above 180°C. The existence of higher temperatures must be demonstrated by other methods. There is sufficient geochemical and structural information on Sierra Valley and Honey Lake Valley to conclude that these areas probably do not contain fluid above 180°C, and, therefore, will not be useful for electrical generation.

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