CHEMICAL ANALYSES OF THERMAL AND NONTHERMAL SPRINGS IN LASSEN VOLCANIC NATIONAL PARK AND VICINITY, CALIFORNIA

J. Michael Thompson

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Menlo Park, California

Abstract

Most thermal waters issuing in Lassen Volcanic National Park (LVNP) are acidic (pH $\leq$3.5), low-Cl (concentrations $\leq$ 30 mg/L) hot springs which are characteristic of vapor-dominated hydrothermal systems and, as such, are not useful for liquid chemical geothermometry. Thermal waters at Drakesbad and in Little Hot Springs Valley, hot spring localities characterized by neutral pH and low Cl containing water, may have equilibrated in shallow aquifers so that temperatures estimated by both the Na-K-Ca and Na-Li geothermometers approach the measured spring temperatures of 65° to 95°C. Waters rich in chloride (>2000 mg/L), such as those at Growler Hot Spring and Morgan Hot Springs, situated south of LVNP, are the most appropriate springs for liquid chemical geothermometry and indicate subsurface temperatures between 220° and 230°C. The chemical and thermal characteristics of these springs may result either from boiling at depth and subsequent mixing with meteoric water or from conductive cooling during lateral flow. In either case ~220° to 230°C thermal water probably originates inside LVNP and flows south to Morgan Hot Springs.

Introduction

Hot Springs, fumaroles, and other active hydrothermal manifestations in Lassen Volcanic National Park (LVNP) are situated primarily in the southwestern (Sulphur Works, Bumpass Hell, and Little Hot Springs Valley) and southern (Devil's Kitchen, Drakesbad, Terminal Geyser) part of the Park. Interpretation of chemical characteristics of thermal waters issuing from hot springs and fumaroles in LVNP and vicinity can provide insights about the nature of the volcanically associated hydrothermal system. Waring (1915) reported three thermal water analyses - two from LVNP (Bumpass Hell and Devil's Kitchen) and one from Morgan Hot Springs, which is situated outside LVNP approximately seven km south of Bumpass Hell (fig. 1). Day and Allen (1925) reported chemical analyses of waters from 23 acidic hot springs collected exclusively from LVNP during their studies of the then erupting Lassen Peak and surrounding area. White and others (1963) reported analyses from two hot springs in the vicinity of LVNP - an acidic spring from Bumpass Hell and a neutral spring in the vicinity of Morgan Hot Springs, probably Growler Hot Spring. Ghiorso (1980) reported chemical analyses for 34 hot springs, pools, and mud pots in LVNP; these analyses are the most numerous compilation of acidic thermal features in LVNP. Thermal springs within the boundaries of LVNP are predominantly acidic (Waring, 1915; Day and Allen, 1925; and Ghiorso, 1980) and can be characterized by White and others' (1963) definition of "acid sulfate springs associated with volcanism", while thermal waters from Morgan Hot Springs and Growler Hot Spring can be classified as "thermal waters from geyser areas in volcanic environments" (White and others, 1963). Individual springs at Bumpass Hell and Morgan Hot Springs were used by White and others (1963) as examples for the two types of water.

FIELD ANALYSIS

Field analyses included temperature measurements and determination of pH, dissolved ammonia, and hydrogen sulfide (as either H_2S or HS^{1-}). Temperature measurements of hot spring waters were obtained with a maximum reading, total immersion, mercury-in-glass thermometer; those of nonthermal springs were obtained with a conventional, total immersion, mercury-in-glass thermometer. Determinations of pH were made with E.M. Colorphast pH strips. Dissolved ammonia and hydrogen sulfide concentrations were determined with a Bausch and Lomb (B and L) Minispec 20[1] spectrophotometer and B and L spectrokits using methods based on APHA (1975) procedures 418B and 428C, respectively. The B and L spectrokit for hydrogen sulfide is specific for dissolved H_2S or HS^{1-} and does not detect other forms of reducible sulfur; therefore, its results may be different from those obtained using an iodometric titration. A visual discharge estimate was made for each spring where the complete discharge could be observed.

LABORATORY ANALYSES

Silica was analyzed at 640 nm by a modification of the molybdenum blue spectrophotometric procedure described by Shapiro and Brannock (1956) using 10 mL of spring water sample diluted in the field to approximately 60 mL and then brought to 100 mL total volume immediately prior to the determination.

Boron was determined spectrophotometrically by the carmin procedure at 600 nm (Brown and others, 1970).

Bicarbonate was determined as alkalinity titrimetrically using a constant drive buret, a combination pH glass electrode, a specific ion - pH meter, a strip chart recorder, and standardized sulfuric acid (0.05N). The laboratory pH was taken as the pH at the start of the alkalinity titration.

Sulfate was determined by a spectrophotometric titration using the thorin procedure (Brown and others, 1970) at 520 nm.

Chloride was determined by potentiometric titration using the same equipment as the alkalinity determination except that a silver billet electrode, a double junction reference electrode, and standardized silver nitrate (.015N) replaced the combination pH electrode and acid used for the alkalinity determination above.

Fluoride was determined by an Orion ion specific electrode; TISAB II was mixed 1:1 with all samples and standards.

Bromide was determined spectrophotometrically at 590 nm by a modification of the phenol red method (APHA, 1975): the oxidizer concentration was increased 2x and the developing time was reduced to approximately two minutes.

Sodium and lithium were determined simultaneously by flame emission spectroscopy (FES) in a fuel rich, air-acetylene flame with added potassium ion (0.1 percent v/v) at 589.0 nm and 670.8 nm, respectively.

Potassium was determined by FES in a fuel rich, air-acetylene flame with added cesium ion (0.1 percent v/v) at 766.5 nm.

Rubidium and cesium were also determined simultaneously by FES in a fuel rich, air-acetylene flame with added potassium ion (0.1 percent v/v) at 780.0 and 852.1 nm, respectively.

Calcium and magnesium were determined simultaneously by atomic absorption spectroscopy (AAS) in a stoichiometric air-acetylene flame with added La(III) (1.0 percent v/v) at 422.7 and 285.2 nm, respectively.

Barium and strontium were determined simultaneously by AAS in a nitrous oxide-acetylene flame with added potassium ion (0.1 percent v/v) at 553.5 and 460.7 nm, respectively.

Iron and manganese were determined simultaneously by AAS in an oxidizing, background corrected, air-acetylene flame at 248.3 and 279.5 nm, respectively.

Zinc was determined by AAS in an oxidizing, background corrected, air-acetylene flame with added potassium ion (0.1 percent v/v) at 213.9 nm.

Aluminum was determined by AAS in a nitrous oxide-acetylene flame with added potassium (0.1 percent v/v) at 309.3 nm.

Hydronium ion was determined as acidity titrimetrically using the same equipment as the alkalinity determination above except that standardized sodium hydroxide (0.025M) was used rather than sulfuric acid. The laboratory pH was also taken at the start of the titration.

Arsenic was determined by AAS in a stoichiometric, background corrected, air-acetylene flame at 193.7 nm.

RESULTS AND DISCUSSION

Spring waters were collected using methods similar to those described in Thompson (1979a and b) and Thompson and Hutchinson (1980). Analyses of 64 hot springs, one nonthermal spring which is apparently a highly diluted thermal water, and four background, nonthermal spring are reported here (table 1). Because water samples from acidic hot springs are not usually representative of any deep thermal fluids, neutral springs are preferred for liquid chemical geothermometry. Except for Growler Hot Spring and the unnamed springs at Morgan Hot Springs, all the thermal waters in the LVNP area contain <30 mg Cl L^{-1} (table 1) which are characteristic of surficial waters from vapor-dominated hydrothermal systems.

Calculated geothermometer temperatures are reported in table 2. At Bumpass Hell, Devil's Kitchen, Boiling Springs Lake, and Terminal Geyser calculated temperatures using different geothermometers (table 2) are not consistent. Waters from acidic hot springs such as those from Bumpass Hell, Devil's Kitchen, and Boiling Springs Lake are usually derived from shallow thermal fluids which often are oxidized in the near surface or surface environment. These fluids condense with water at the surface forming an acidic solution which dissolves the surrounding country rock; hence, the chemistry of the hot springs is independent of the shallow hydrothermal system, but dependent upon the country rock.

At Drakesbad, having low Cl and pH neutral spring waters, the calculated Na-K-Ca (Fournier and Truesdell, 1973) and Na-Li (Fouillac and Michard, 1981) geothermometers yield temperatures that are close to the measured spring temperatures. In Little Hot Springs Valley (LHSV) eight out of fourteen neutral springs have calculated Na-K-Ca temperatures near the measured spring temperatures and at Sulphur Works five out of eight neutral springs have Na-K-Ca temperatures near the measured temperatures. For both of these areas (LHSV and Sulphur Works), however, most of the calculated Na-Li temperatures are invalid because they are significantly lower than the measured temperature (table 2). The Mg corrected Na-K-Ca temperatures (Fournier and Potter, 1978) are essentially the same as the Na-K-Ca temperatures for Drakesbad, LHSV, and Sulphur Works because the indicated Na-K-Ca temperatures are quite low and the Mg/Mg+K+Ca equivalent ratio is low, generally around 0.10. Apparently, the rate of flow of this local, dilute thermal water at Drakesbad is sufficiently slow so that a chemical equilibrium (as defined by agreement of different geothermometers) is established between the country rock and the water. The origin of this thermal water is probably local. It does not appear to be associated with any deep thermal fluid, and its source is probably shallow. This shallow groundwater may be heated by a gaseous thermal fluid (steam and CO_2µ) and/or by a high local heat flow. A similar situation may exist at LHSV and Sulphur Works because the Na-K-Ca geothermometer (Fournier and Truesdell, 1973) indicates temperatures near those measured.

Growler Hot Spring and Morgan Hot Springs contain high concentrations of dissolved Na, Cl, and As. Diller (1889) proposed that the Cl in these waters initially originated in marine sediments. Taft and others (1940) reported that Late Cretaceous marine sandstones, shales, and conglomerates are deposited in the Chico Formation that outcrops approximately 33 km west and 33 km southwest of Morgan Hot Springs. This formation may underlie part of LVNP. White and others (1963) proposed that any water having a Cl/Br weight ratio less than 330 is likely to be connate. The Cl/Br weight ratio for these waters, calculated fron the data in table 1, ranges from 111 to 254 with a mean of 157, well below the 330 suggested by White and others (1963) for connate waters, indicating these waters may have a connate contribution, probably not exceeding 15 percent.

Morgan Hot Springs and Growler Hot Spring are also the only thermal areas in the vicinity of LVNP having thermal waters which consistently indicate high subsurface temperatures (>150°C) by liquid chemical geothermometry: the adiabatic silica geothermometer (Fournier and Rowe, 1966) indicates temperatures between 176° and 187°C and the Na-K-Ca geothermometer indicates temperatures between 213° and 230°C. Nehring and others (1979) reported that sulfate geothermometer temperatures are near 230°C for many of these same springs. Disparity between the silica, Na-K-Ca, and sulfate geothermometers may be caused by mixing of different types of water or by precipitation of silica. At Growler Hot Spring and Morgan Hot Springs the descrepancy apparently is caused by silica deposition.

Chloride and silica contours (figures 2 and 3) were drawn for the thermal springs at Growler Hot Spring and Morgan Hot Springs. The Cl contours (figure 2) indicate that the most concentrated thermal water is found at Growler Hot Spring and that the thermal water becomes diluted as it flows southward to Morgan Hot Springs. The silica contours (figure 3) indicate the same pattern of water movement; however, the percentage loss of silica is much greater than that of chloride. The Cl/SiO_2 ratio changes between the two hot spring areas; at Growler Hot Spring (LJ-79-14, Table 1) the Cl/SiO_2 weight ratio is 8.71, whereas at Morgan Hot Spring (LT-79-15) the ratio is 17.86: a relative change of over 100 percent!

Morgan Hot Springs water may also be slightly diluted compared to water at Growler Hot Spring. From unpublished data of D. E. White (written communication, 1982) and the chemical data acquired during this study (table 1), the chloride concentrations at Growler Hot Spring reported in table 3 vary from a high of 2510 mg/L (June 1951) to a low of 2270 mg/L (July 1975). This range in chloride concentrations suggests that Growler Hot Spring water may contains as much as 10 percent meteoric water if the water containing 2510 mg Cl/L is representative of the undiluted thermal water and the 2270 mg Cl/L is the most diluted water. Generally, though, the water is only diluted ~5 percent. Because chloride concentrations are easy to determine and very precise (relative standard deviation, RSD, is about 1 percent), chloride is preferred over other conservative species (such as B and As) which may much higher RSD's. Unfortunately, no other analyses of Growler Hot Spring water are available for collection times between the cessation of White's study and the initiation of the current one, a period of 20 years.

Beale (1981) reported Cl concentrations as high as 2100 mg/L in waters from the Walker "O" No. 1 well at Terminal Geyser. This well was drilled to a depth of >1200m immediately east of a fault (the Terminal Geyser Fault, Clynne, Brook, and Muffler, written communication, 1982) extending from near Drakesbad through Boiling Springs Lake and Terminal Geyser. The fault terminates just south of Terminal Geyser. The northern portion of the fault terminates after intersecting the Hot Springs Creek Fault (Clynne, Brook, and Muffler, 1982) which extends from west of Devil's Kitchen to south of Kelly Camp. From the surficial hydrothermal expressions along the faults, the greatest activity occurs at Devil's Kitchen and the activity decreases towards Terminal Geyser; however, all of the current hydrothermal activity is predominately acid sulfate (White and others, 1963) and no high Cl waters are found. Temperature measurements reported by Beale (1981) for the Walker "O" No.1 well at Terminal geyser suggest that thermal water at temperatures $\geq 170^{\circ}C$ flows laterally along the Terminal Geyser Fault and possibly along the Hot Springs Creek Fault. Upward leakage of this fluid may give rise to the thermal features at Devil's Kitchen, Boiling Springs Lake, and Terminal Geyser. The neutral springs located at Drakesbad may be heated by thermal fluids (steam, CO_2, and other such fluids) moving along these faults or by the high heat flow also associated with these faults.

No known neutral, high Cl hot springs issue south of Terminal Geyser; although, Domingo Springs, located approximately 7 km south of Terminal Geyser, contains ten times more Cl and six times more B than typical cold springs (table 1). More importantly, the Cl and B concentrations at Domingo Spring are 100 times less than the Cl and B concentrations found in the Walker "O" No. 1 well (Thompson, unpublished data, 1982). Thus, Domingo Springs may be the outlet or one of the outlets for the high Cl thermal water for the Walker "O" No.1 well at Terminal Geyser (Beale, 1981).

All of the chemical data supports the initial model proposed by

Truesdell and Hulston (1980) and elaborated by Muffler and others (1982) who have described the Lassen geothermal system as a vapor-dominated reservior which discharges steam and gas in LVNP. The vapor-dominated reservoir is centered beneath Bumpass Hell and is underlain by a thermal brine which discharges south of LVNP at Growler Hot Spring and Morgan Hot Springs and below Terminal Geyser. Isotopic data (Truesdell and Hulston, 1980), suggest that the thermal water discharging at Growler Hot Spring flows there from the vicinity of Bumpass Hell without any significant dilution.

White, Hem, and Waring (1963) reported analyses of Tuscan and Wilbur Springs in their description of "spring waters similar in composition to oil-field brines of the sodium chloride type." In addition to containing relatively high Na and Cl compositions, these waters are also characterized by relatively high B and NH_3 concentrations. Both Tuscan and Wilbur Springs are located in the sedimentary rocks of the Great Valley Sequence and it is probable that the B and NH_3 in these waters have been derived from organic material in the sediments (Barnes, 1970). The high B and NH_3 in the waters issuing at Growler Hot Spring and Morgan Hot Springs also are likely to have been derived from sedimentary material, most probably the Late Cretaceous Chico Formation. This also supports Diller's (1889) conclusions that the high Cl concentrations originate from marine sediments. It cannot be presently determined where or how this high Cl water enters the hydrothermal system.

CONCLUSIONS

The chemical data supports the previously published models for the Lassen geothermal system. Thermal water discharging at Morgan Hot Springs and Growler Hot Spring and the deep thermal water at Terminal Geyser probably originate inside Lassen Volcanic National Park near Bumpass Hell. The temperature of the parental brine beneath Bumpass Hell is ~230° to 240°C. The deep Terminal Geyser water may be diluted by as much as 100 times before discharging at Domingo Springs. The thermal waters at LVNP may have interacted with sedimentary rocks, as indicated by the Cl/Br weight ratio that is lower than seawater and the relatively high concentrations of NH_3 and B. Thermal decomposition of organic material contained in the Chico Formation may provide both the NH_3 and B.

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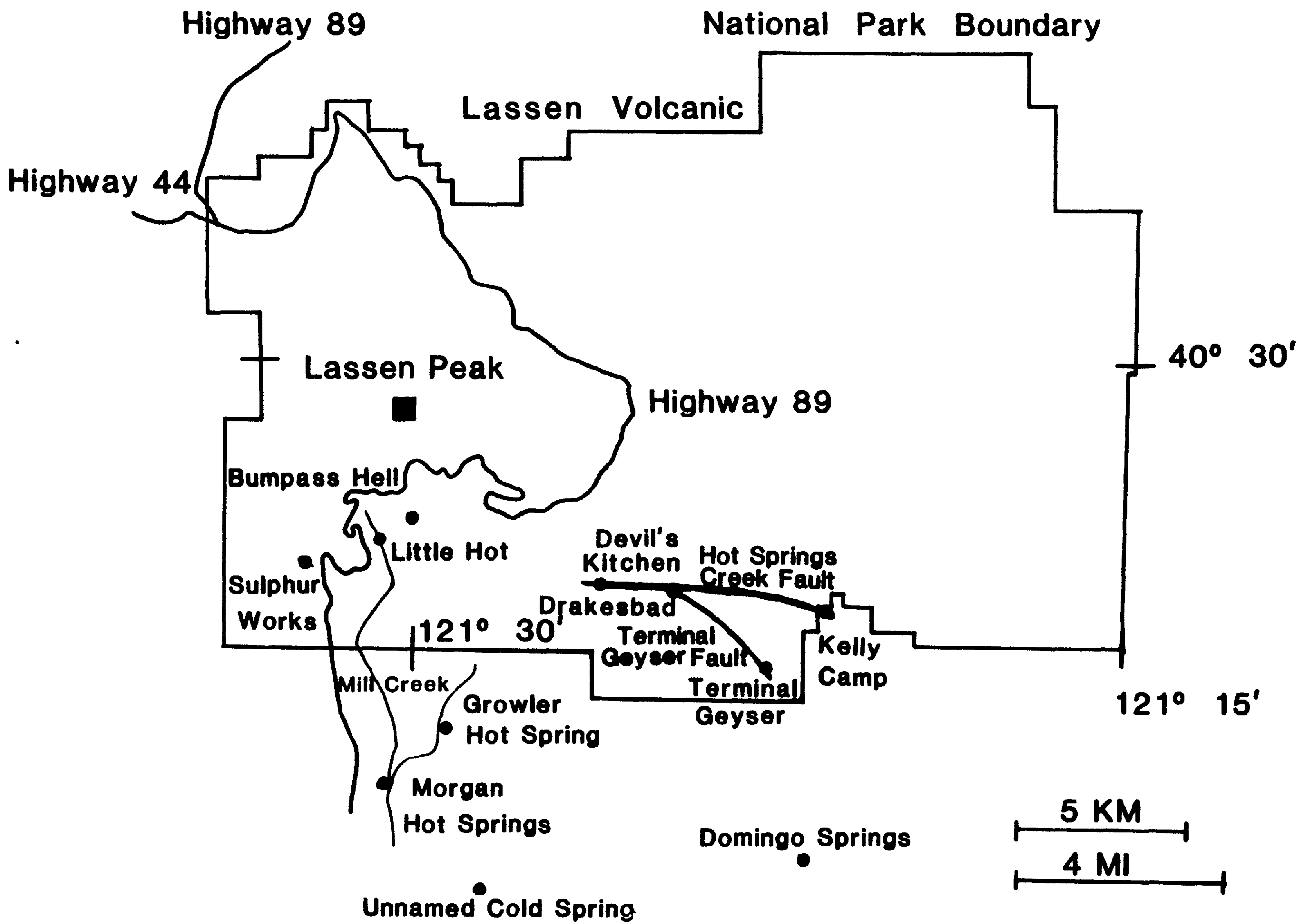
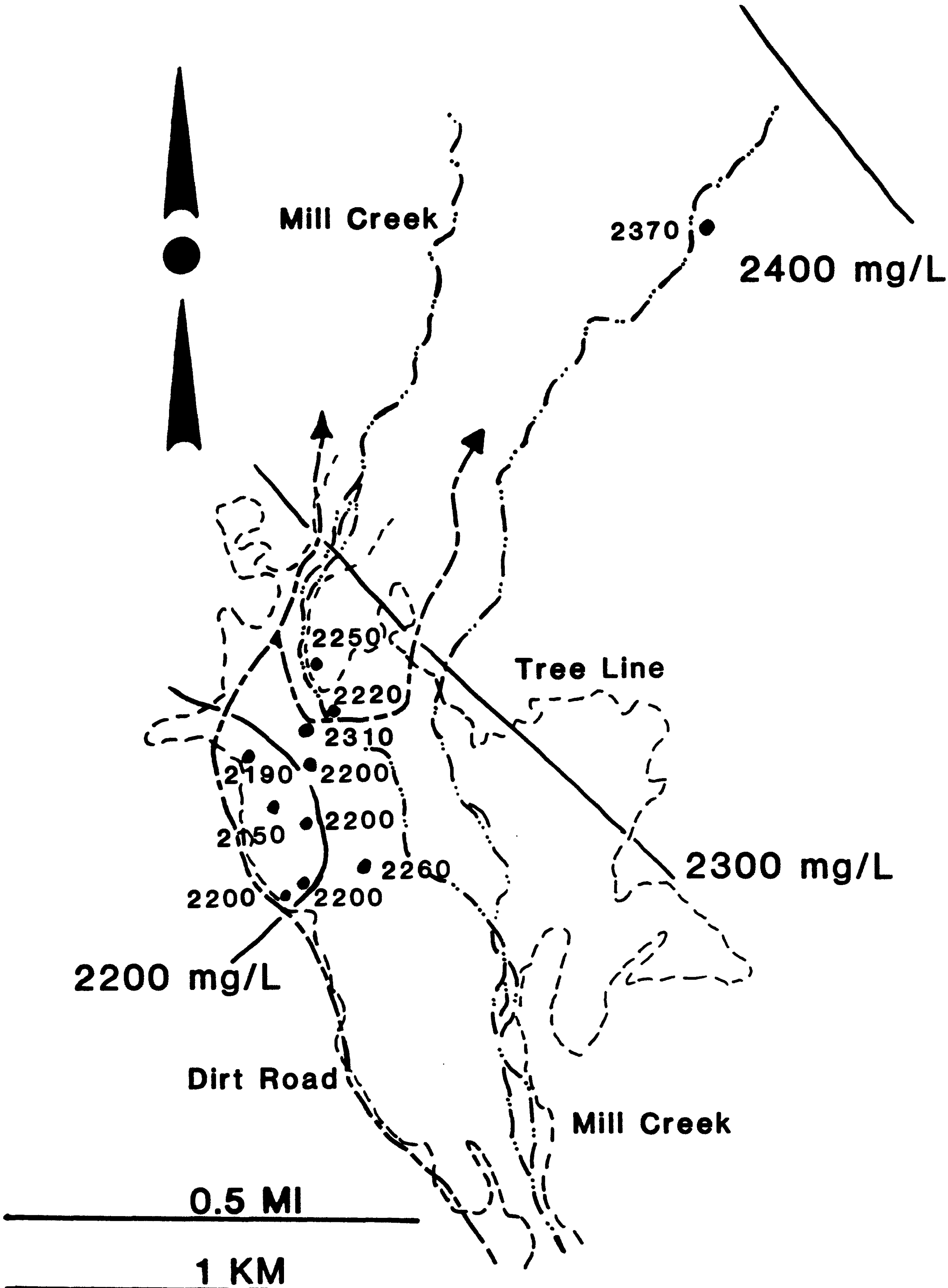
LOCATION MAP OF THERMAL AREAS NEAR LASSEN PEAK



CHLORIDE CONTOURS AT MORGAN HOT SPRINGS



SILICA CONTOURS AT MORGAN HOT SPRINGS

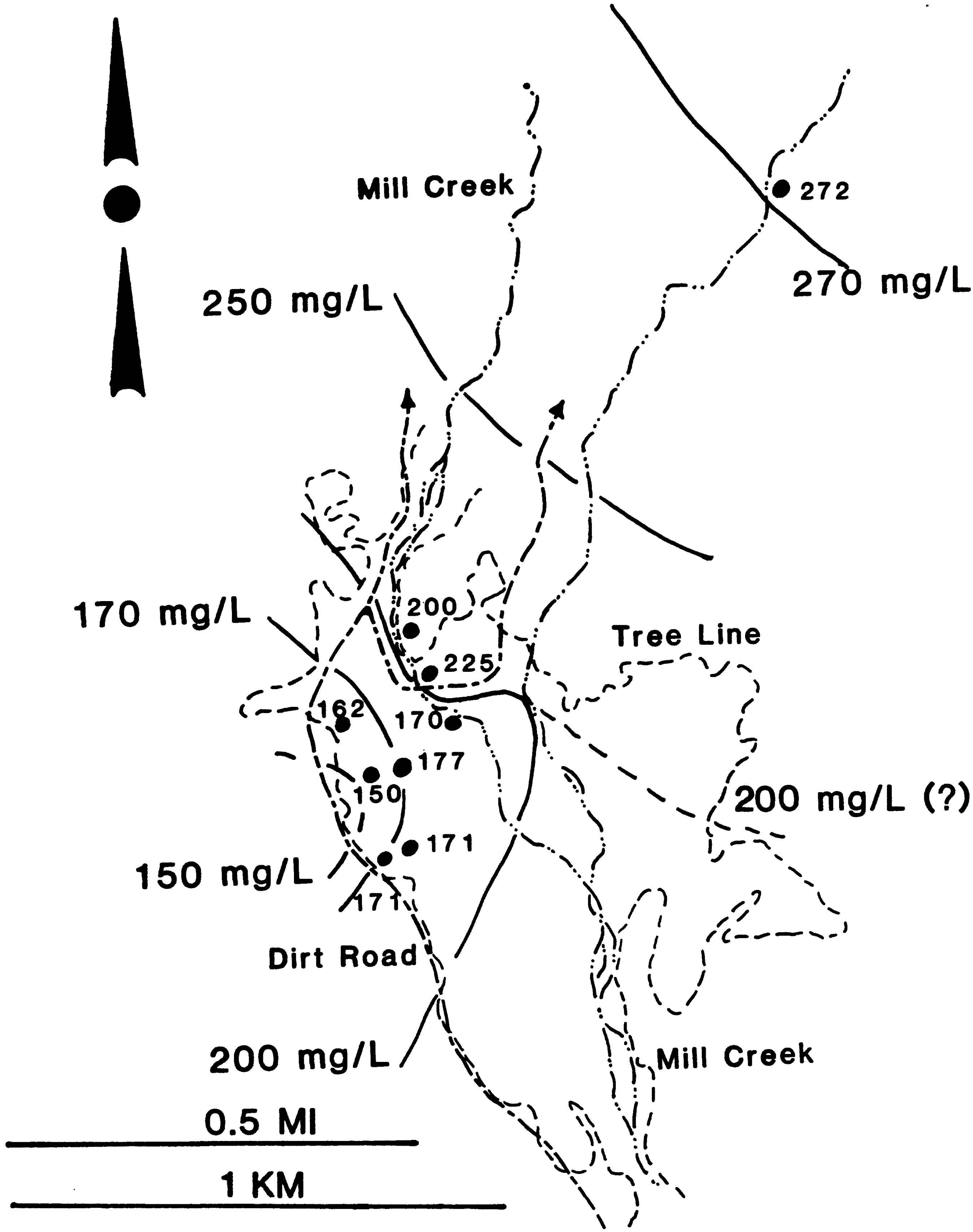


Table 1.--Lassen Area Thermal Springs
(Analyses in mg/L)

Sample	Date	Name and/or Description	Lat.	Long.	Est. flow gal/min	Temp	field pH	lab pH	SiO_2	Fe	Mn	Ca	Mg	Sr
		Boiling Springs Lake - Terminal Geyser												
J7902	31 July 79	Boiling Springs Lake, SE end, LVNP	40°26.09	121°23.65'	seep	94	<2	2.31	242	63	--	21.6	15.2	--
M76195	Aug 76	Terminal Geyser, LVNP	40°23.38'	121°23.80'	1	92	4.5	6.65	46	--	--	8.20	1.90	--
J7903	31 July 79	Terminal Geyser,LVNP	40°23.38'	121°23.80'	25	95	5.20	7.63	64	<.1	<.04	9.25	1.49	--
J8101	25 Sep 81	Terminal Geyser, NVNP	40°23.38'	121°23.80'	ne	95	--	--	30	--	--	9.91	3.01	--
		Bumpass Hell												
J7504	16 July 75	unnamed spring	40°27.48'	121°30.15'	ne	93	2.0	2.36	96.4	--	--	7.09	2.5	--
J7505	16 July 75	unnamed spring, northern section	40°27.53'	121°29.95'	1/3	90	1.7	1.95	193	--	--	1.1	1.76	--
M7921		unnamed spring	40°27.32'	121°30.00'	--	--	--	2.59	182	--	--	8.5	5.5	--
J7912	1 Aug 79	Big Boiler at outlet	40°27.45'	121°30.59'	5	55	2.18	2.55	215	10	.12	19.5	6.05	--
J7913	1 Aug 79	Main area composite	40°27.44'	121°30.10'	6	52.5	2.10	2.36	236	12	.20	34.5	6.56	--
		Devil's Kitchen												
J7506	16 July 75	unnamed spring, nr Hot Creek, fry pan	40°26.48'	121°29.95	ne	95	4.5	4.18	41.5	--	--	9.10	.45	--
J7507	17 July 75	NW hill slopes 200m beyond J7506	40°26.54'	121°26.07'	ne	94	7.0	6.89	114	--	--	6.1	1.4	--
J7508	17 July 75	large fumarole 25m from cr nr brdg	40°26.49'	121°25.95'	3/4	95	1.9	7.81	213	--	--	45	4.0	--
M76239	Aug 76	lowest spring in Devil's Kitchen	40°26.51'	121°25.90'	1	71	6	8.03	--	--	--	21	10.7	--
J7601	1 Sep 76		40°26.49'	121°25.91'	2	68	2.5	3.26	171	6.1	.08	10.5	6.4	--
J7602	1 Sep 76		40°26.51'	121°25.90'	1/2	73	5.6	7.88	183	<.04	.08	12.2	13.2	--
J7904	31 July 79	branches covering top, LM-79-337	40°26.56'	121°26.06'	2	93	6.8	7.05	60	.41	.07	14.7	3.4	--
J7905	31 July 79	same as LM-79-290*	40°26.54'	121°26.07'	ne	--	--	6.12	166	.1	.07	9.2	.9	--
J7906	31 July 79	same as LM-79-336*	40°26.55'	121°26.02'	ne	--	--	3.77	72	1.3	.05	13.2	2.7	--
J7907	31 July 79				ne	--	--	3.12	165	11.7	.11	18.5	8.0	--
J7908	31 July 79				ne	--	--	6.16	40	1.3	<.04	10.9	7.2	--
		Drakesbad												
M76232	Aug 76	Highest spring feeding swimming pool	40°26.60'	121°24.22'	2	65	6.5	7.11	142	--	--	38	6.1	.4
J7603	1 Sep 76	Highest spring feeding swimming pool	40°26.60'	121°24.22'	1	66	6.8	8.13	144	<.04	.06	38.6	9.6	.6
		Little Hot Springs Valley												
M76129b	Aug 76	Travertine depositing spg in upper val	40°27.29'	121°31.09'	1	66	6.5	7.82	101	--	--	192	14	2.6
M76162	Aug 76	E side creek, main area of activity	40°26.68'	121°30.83'	1	93	4.5	7.47	115	--	--	23	3.4	--
M76169	Aug 76	E side creek, main area of activity	40°26.65'	121°30.80'	1	91	5	6.83	117	--	--	39	3.6	--
J7604	2 Sep 76	Travertine depositing spg in upper val	40°27.29'	121°31.09'	1		6.7	7.74	100	<.04	.40	208	14.5	3.1
J7605	2 Sep 76	same as LM-76-131	40°27.28'	121°31.05'	0.5	69	--	7.59	91	.02	.49	255	15.8	3.3
J7606	2 Sep 76	same as LM-76-141	40°26.83'	121°31.77'	1/4	81	6.8	8.50	84	.63	.20	58	9.5	.6
J7607	2 Sep 76	same as LM-76-169, depositing FeS_2	40°26.65'	121°30.80'	ne	91	5.9	7.02	116	.10	.18	41	3.9	.8
J7608	2 Sep 76	same as LM-76-162,	40°26.68'	121°30.83'	1/3	94	6.5	7.55	95	<.02	.04	16.4	2.7	--
J7609	2 Sep 76	same as LM-76-164	40°26.66'	121°30.80'	1/8	94	3.8	3.51	162	17.6	.81	44.3	14.9	--
J7610	2 Sep 76	same as LM-76-004	40°26.62'	121°30.47'	2	95	4.8	8.32	133	<.02	.65	114	8.7	1.4
J7707	Sep 77	same as LM-76-004	40°26.62'	121°30.47'	--	--	--	7.89	172	--	--	59.2	6.5	.93
J7909	1 Aug 79	spring depositing MnO_2, LM-76-169	40°26.65'	121°30.80'	1	93	5.65	6.59	123	.34	.15	25.7	4.1	--
J7910	1 Aug 79	E side crk, blw mudpot, nr noisy fumar	40°27.18'	121°30.94'	1	88	5.6	6.19	152	<.04	.16	39.7	4.02	--
J7911	1 Aug 79	small warm spg on W side crk, N end	40°27.18'	121°30.98'	2	55	6.7	7.07	133	1.4	--	102	5.6	--

Table 1.--Lassen Area Thermal Springs (cont.)

(Analyses in mg/L)

Sample	Ba	Na	K	Li	Rb	Cs	NH_4	HCO_3	SO_4	Cl	F	Br	B	H_2S	Zn	H	Al	As
Boiling Springs Lake - Terminal Geyser																		
J7902	--	6.4	1.25	<.05	--	--	--	0	710	13	.55	--	1.6	--	--	15.9	28	--
M76195	--	8	3.0	<.01	--	--	--	33	48	3	<.1	--	1.6	--	--	--	--	--
J7903	--	7.5	1.33	<.05	--	--	--	24	16	26	.19	--	1.4	--	--	--	<.4	--
J8101	--	7.3	2.01	.01	--	--	--	19	52	.5	.19	--	1.5	--	--	--	--	--
Bumpass Hell																		
J7504	--	8.0	3.9	<.01	--	--	1.65	0	458	<.5	.3	--	.7	1.5	--	8.8	--	--
J7505	--	4.0	4.1	<.01	--	--	1.45	0	--	<.5	<.1	--	<.1	1.2	--	25.4	--	--
M7921	--	5.4	7.0	<.01	--	--	--	0	340	2	<.1	--	.17	--	--	--	--	--
J7912	--	22.1	6.60	<.05	--	--	--	0	364	5.7	.33	--	1.1	--	--	7.2	16.2	--
J7913	--	32.8	10.2	<.05	--	--	--	0	547	5.2	.28	--	1.6	--	--	10.6	17.6	--
Devil's Kitchen																		
J7506	--	5.1	1.7	<.01	--	--	1.4	0	58	<.5	.32	--	.6	--	--	.2	--	--
J7507	--	23.5	4.4	<.01	--	--	.54	39	42	<.5	.37	--	.7	--	--	--	--	--
J7508	--	43	13.2	<.01	--	--	1.0	32	237	<.5	.31	--	1.4	--	--	.4	--	--
M76239	--	34	19	.04	--	--	--	219	26	4	.18	--	2.4	--	--	--	--	--
J7601	--	2.0	7.2	.015	--	--	--	0	226	.5	.17	--	.3	--	--	1.6	--	--
J7602	--	34	17.4	.04	.15	.07	--	234	18	1.4	.32	--	1.4	--	--	--	--	--
J7904	--	12	1.1	<.05	--	--	1.0	82	78	16	.22	--	<.1	.03	--	--	.73	--
J7905	--	35.2	3.9	<.05	--	--	2.6	46	64	11	.31	--	1.5	.015	--	--	<.4	--
J7906	--	8.1	1.1	<.05	--	--	1.45	0	44	17	.22	--	<.1	.015	--	1.3	.66	--
J7907	--	14.9	4.4	<.05	--	--	5.3	0	179	4.8	.33	--	.6	.025	--	3.0	7.6	--
J7908	--	6.0	1.3	<.05	--	--	.75	37	55	6.7	.27	--	<.1	.10	--	--	.34	--
Drakesbad																		
M76232	0.4	45	10.9	.03	.12	.07	--	129	145	3.0	.15	--	1.4	--	--	--	--	--
J7603	.5	41	10.3	.03	.10	.06	--	130	132	0.9	.15	--	.6	.3	--	--	--	--
Little Hot Springs Valley																		
M76129b	1.3	72	16.0	.03	.13	.08	--	310	472	2	.69	--	.8	--	--	--	--	--
M76162	--	96	14.2	.01	--	--	--	41	294	3	.75	--	5.1	--	--	--	--	--
M76169	--	74	20.9	.01	--	--	--	24	330	2	<.1	--	1.0	--	--	--	--	--
J7604	2.4	70	15.5	.02	.09	.06	--	351	487	0.9	.54	--	.15	--	--	--	--	--
J7605	1.7	65	14.8	.02	.06	.08	--	275	517	0.7	.52	--	<.1	--	--	--	--	--
J7606	.8	102	5.2	.01	.09	.06	--	297	194	5.5	.49	--	.2	--	--	--	--	--
J7607	.4	78	19.8	.01	.14	.06	--	23	292	1.5	.12	--	.5	.4	--	--	--	--
J7608	--	100	14.3	.01	--	--	--	54	3	4.5	.66	--	3.9	.3	--	--	--	--
J7609	--	98	14.9	.08	--	--	--	0	511	0.5	.70	--	.5	1.4	--	1.8	--	--
J7610	1.2	93	15.8	.02	.08	.08	--	182	429	1.4	.30	--	.3	--	--	--	--	--
J7707	1.6	91	14	<.01	.04	<.01	--	87	373	4.3	.22	--	.1	--	--	--	--	--
J7909	--	87	11.9	<.05	--	--	3.5	19	301	5.2	.84	--	4.2	.03	--	--	.44	--
J7910	--	55	15.3	<.05	--	--	1.2	12	220	3.3	.35	--	.3	.01	--	--	<.4	--
J7911	--	68	9.1	<.05	--	--	5.3	425	101	6.2	.50	--	<.1	--	--	--	<.4	--

Table 1.--Lassen Area Thermal Springs (cont.)
(Analyses in mg/L)

Sample	Date	Name and/or Description	Lat.	Long.	Est. flow gal/min	Temp	field pH	lab pH	SiO_2	Fe	Mn	Ca	Mg	Sr
		Growler Hot Spring and Morgan Hot Springs												
J7501	16 July 75	Growler Hot Spring	40°23.64'	121°30.41'	3	95	8.3	7.95	231	--	--	80	.05	.77
7502	16 July 75	Spg across crk from "Little Growler"	40°23.29'	121°30.84'	1	85	7.2	7.16	101	--	--	92	.45	1.0
J7503	16 July 75	Hottest spring in meadow	40°23.05'	121°30.77'	2	88	7.2	7.41	177	--	--	90	.80	1.0
J7614	3 Sep 76	unnamed spring	40°23.27'	121°30.75'	1	94	7.1	7.84	172	<.04	<.04	85.5	.47	1.3
J7615	3 Sep 76	"Little Growler"	40°23.24'	121°30.74'	1	96	7.1	7.64	184	5.72	.08	85.5	1.4	1.5
J7616	3 Sep 76	unnamed spring	40°23.11'	121°30.81'	2	89	7.4	7.98	170	<.04	<.04	86	.11	1.6
J7914	1 Aug 76	Growler Hot Spring	40°23.64'	121°30.41'	5	95	7.45	7.85	272	.04	<.01	81	.07	.9
J7916	1 Aug 76	"Little Growler" (same as J7615)	40°23.24'	121°30.74'	2	95	7.25	8.08	225	.01	.03	93.7	.47	1.1
J7918	1 Aug 79	Upstream of "Little Growler"	40°23.27'	121°30.75'	2	93	6.9	7.69	200	<.01	.02	91.9	.40	1.1
T7914	24 Aug 79	unnamed spring	40°23.27'	121°30.75'	5	94	--	7.70	126	--	--	88.1	.32	--
T7915	24 Aug 79	unnamed spring	40°23.24'	121°30.74'	ne	96	--	7.90	122	--	--	94.4	.31	--
T7916	24 Aug 79	unnamed spring	40°23.23'	121°30.78'	1/4	87	--	7.32	156	--	--	88.9	1.2	--
T7917	24 Aug 79	unnamed spring	40°23.21'	121°30.79'	1/4	85	--	7.56	162	--	--	111.	1.69	--
T7918	24 Aug 79	unnamed spring	40°23.17'	121°30.81'	1/6	82	--	7.85	150	--	--	128.	3.71	--
T7919	24 Aug 79	unnamed spring	40°23.17'	121°30.77'	1	88	--	7.66	146	--	--	99.8	.57	--
T7920	24 Aug 79	unnamed spring	40°23.17'	121°30.74'	ne	18	--	9.72	75	--	--	16.8	4.31	--
T7921	24 Aug 79	unnamed spring	40°23.12'	121°30.70'	ne	71	--	7.28	193	--	--	83.3	1.60	--
T7922	24 Aug 79	unnamed spring	40°23.13'	121°30.67'	ne	20	--	8.02	62	--	--	20.0	4.41	--
T7925	24 Aug 79	unnamed spring	40°23.10'	121°30.76'	ne	82	--	7.60	171	--	--	104.	1.46	--
T7926	24 Aug 79	unnamed spring	40°23.09'	121°30.78'	ne	95	--	7.60	171	--	--	103.	.32	--
		Sulphur Works												
J7509	17 July 75	in midst of main hot area	40°26.96'	121°32.16'	seep	86	1.9	2.34	213	--	--	8.8	9.8	--
J7510	17 July 75	on N side of trail	40°26.96'	121°32.16'	1/2	38	4.0	3.10	102	--	--	.96	1.70	--
M76116	Aug 76	Travertine depositing spring blw S. W.	40°26.88'	121°32.03'	2	83	6.5	7.72	154	--	--	159	37.5	--
J7611	2 Sep 76	same as M76116 (previous sample)	40°26.88'	121°32.03'	4	84	6.9	8.10	140	<.02	.40	188	38	--
M7657	Aug 76	FeS_2 depositing spg in protalus grp	40°27.65'	121°31.52'	1/2	87	6	7.69	123	--	--	11.6	2.0	--
J7613	3 Sep 76	same as M7657 (previous sample)	40°27.65'	121°31.52'	1/4	91	6.2	8.16	112	<.04	<.04	13.6	2.1	--
M7676	Aug 76	FeS_2 depositing spg in upper S. W.	40°27.27'	121°31.77'	1	81	7	8.24	52	--	--	127	28.2	.29
J7612	3 Sep 76	same as M7676 (previous sample)	40°27.27'	121°31.77'	1/4	88	7.2	8.25	39	.10	.80	115	26.5	.32
		Cold Springs												
T7901	21 Aug 79	1/4 mi South of Mill Creek Bridge	40°20.75'	121°35.53'	10	12	5.9	6.95	34	--	--	4.8	2.2	--
T7902	22 Aug 79	Headwaters of Nanny Creek	40°23.69'	121°32.54'	ne	9	5.8	6.45	26	--	--	5.0	1.1	--
T7903	22 Aug 79	Creek on Brokeoff Mountain	40°	121°	ne	5	4.7	--	50	--	--	2.3	.14	--
T7911	24 Aug 79	N side Wilson Lake road nr Childs Mdw	40°20.37'	121°28.10'	ne	10	6.5	6.74	39	--	--	11.6	7.6	--
T7912	24 Aug 79	Domingo Springs	40°21.66'	121°20.84'	ne	10	5.9	7.00	40	--	--	5.3	2.9	--

* Location in Muffler, Jordan, and Cook (1983).

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Table 1.--Lassen Area Thermal Springs (cont.)
(Analyses in mg/L)

Sample	Ba	Na	K	Li	Rb	Cs	NH_4	HCO_3	SO_4	Cl	F	Br	B	H_2S	Zn	H	Al	As
Growler Hot Spring and Morgan Hot Springs																		
J7501	1.2	1,450	203	11.2	2.48	3.3	.27	65	73	2,273	2.3	13.4	105	1.8	--	--	--	11.0
J7502	1.7	1,380	165	8.2	2.13	3.2	.43	44	123	2,313	3.0	11.4	90	1.2	--	--	--	24.3
J7503	1.5	1,370	165	8.0	2.07	3.2	.39	62	98	2,290	2.8	11.5	81	--	--	--	--	9.7
J7614	1.0	1,460	182	7.9	1.44	2.08	--	61	98	2,210	2.7	17	85	--	--	--	--	9.6
J7615	1.0	1,470	173	7.4	1.47	2.14	--	76	99	2,220	2.5	15	82	1.1	--	--	--	10.1
J7616	1.5	1,520	179	7.5	1.56	2.28	--	66	99	2,340	2.5	21	86	2.1	--	--	--	9.2
J7914	2.5	1,340	173	6.3	1.67	2.22	9.5	55	110	2,370	2.3	10.1	84	.02	<.01	--	<.4	11.0
J7916	3.0	1,260	162	6.1	1.43	2.09	13	68	123	2,210	3.0	14.5	14	.035	.01	--	.2	10.6
J7918	3.1	1,280	166	6.4	1.46	2.10	11.5	63	72	2,250	2.9	12.5	25	.01	<.01	--	.2	10.3
T7914	--	1,260	159	7.1	1.47	2.1	--	70	113	2,270	2.5	--	74	--	--	--	--	--
T7915	--	1,240	155	7.1	1.20	1.8	--	50	101	2,280	2.6	--	74	--	--	--	--	--
T7916	--	1,220	141	6.8	1.16	1.8	--	43	107	2,200	2.6	--	71	--	--	--	--	--
T7917	--	1,180	149	6.7	1.29	2.0	--	108	107	2,190	2.6	--	72	--	--	--	--	--
T7918	--	1,140	141	6.4	1.19	1.8	--	134	113	2,150	2.5	--	72	--	--	--	--	--
T7919	--	1,190	141	6.7	1.22	1.9	--	46	104	2,200	2.6	--	72	--	--	--	--	--
T7920	--	15.3	2.6	.06	<.05	<.02	--	56	46	58	.27	--	.7	--	--	--	--	--
T7921	--	1,150	144	6.7	1.10	1.6	--	45	101	2,260	2.1	--	68	--	--	--	--	--
T7922	--	23.9	3.6	.11	<.05	<.05	--	50	42	46	.30	--	1.2	--	--	--	--	--
T7925	--	1,150	144	6.7	1.83	1.9	--	60	97	2,200	2.3	--	70	--	--	--	--	--
T7926	--	1,150	143	6.8	1.29	2.0	--	60	97	2,200	2.6	--	70	--	--	--	--	--
Sulphur Works																		
J7509	--	11	8.3	<.01	--	--	30	0	938	<.5	.35	--	4.4	.2	--	12.4	--	--
J7510	--	1.5	5.0	<.01	--	--	.41	0	153	<.5	.39	--	<.1	--	--	3.0	--	--
M76116	1.6	70	14.4	.02	.14	.08	--	267	494	2	.52	--	1.2	--	--	--	--	--
J7611	2.0	68	13.7	.02	.12	.07	--	115	514	.5	.47	--	.5	--	--	--	--	--
M7657	--	28	8.4	.01	--	--	--	78	77	2.5	.15	--	.9	--	--	--	--	--
J7613	--	35	10	<.01	--	--	--	94	66	1.6	.25	--	<.1	--	--	--	--	--
M7676	.8	3	3.0	<.01	.09	.05	--	269	237	2	.52	--	.8	--	--	--	--	--
J7612	1.3	3	2.7	<.01	.08	.06	--	230	246	2.5	.77	--	<.1	--	--	--	--	--
Cold Waters																		
T7901	--	2.2	1.2	<.01	--	--	--	60	8	2	.1	--	<.1	--	--	--	--	--
T7902	--	1.1	.7	<.01	--	--	--	48	2	2	.1	--	.17	--	--	--	--	--
T7903	--	3.4	1.9	<.01	--	--	--	12	33	2	.1	--	<.1	--	--	--	--	--
T7911	--	3.1	1.9	<.01	--	--	--	138	3	2	.1	--	<.1	--	--	--	--	--
T7912	--	12.0	2.6	<.01	--	--	--	78	2	21	.1	--	.6	--	--	--	--	--

Table 2. Calculated Geothermometer Temperatures

Sample Number	Measured Temperature	Silica		Na-K		Na-K-Ca		Na-Li[4]
		Adabatic[1]	Cond.[1]	F and T[1]	Revised[2]	Not cor.[1]	Mg cor.[3]	
Boiling Springs Lake and Terminal Geyser								
J7902	94	180	193	277	281	14	14	234
M76195	92	100	98	417	364	53	53	89
J7903	95	114	114	262	271	29	29	218
J8101	95	84	80	344	323	38	38	94
Bumpass Hell								
J7904	93	132	135	495	405	63	63	89
J7905	90	167	177	854	553	99	50	133
M7921	92	--	--	--	--	--	--	--
J7912	55	173	185	361	333	69	69	126
J7913	52.5	179	191	370	338	75	75	100
Devil's Kitchen								
J7606	95	97	94	387	348	32	32	116
J7607	94	140	144	271	277	82	82	36
J7608	95	173	184	367	337	81	81	13
M76239	71	--	--	542	428	109	60	85
J7601	68	161	169	406	359	84	60	62
J7602	73	164	174	511	413	120	60	85
J7904	93	111	111	174	210	21	21	173
J7905	--	159	167	196	226	73	73	96
J7906	--	119	120	223	245	20	20	210
J7908	--	159	167	359	332	54	54	155
Drakesbad								
M76232	65	151	158	317	307	79	79	56
J7603	66	152	158	325	311	75	73	61
Little Hot Springs Valley								
M76129b	66	134	138	301	297	62	62	35
M76162	93	140	145	235	253	109	109	13
M76169	91	141	146	349	326	107	107	5
J7604	--	134	137	300	296	59	59	21
J7605	69	129	132	306	299	53	53	23
J7606	81	126	128	117	165	56	56	15
J7607	91	141	146	327	312	104	104	7
J7608	94	131	134	230	250	118	118	14
J7609	94	158	166	239	256	95	80	66
J7610	95	148	154	255	267	75	75	69
J7707	--	161	170	240	257	85	85	11
J7909	93	144	149	224	245	98	98	10
J7910	88	154	162	346	324	91	91	72
J7911	55	148	154	221	243	57	57	61

Table 2. Calculated Geothermometer Temperatures (continued).

Sample Number	Measured Temperature	Silica Adabatic[1]	Silica Cond.[1]	Na-K F and T[1]	Na-K Revised[2]	Na-K-Ca Not cor.[1]	Na-K-Ca Mg cor.[3]	Na-Li[4]
Growler Hot Spring and Morgan Hot Springs								
J7501	95	177	190	227	248	230	230	234
J7502	85	134	138	206	233	217	217	206
J7503	88	163	172	207	233	218	218	205
J7614	94	161	170	211	237	222	222	197
J7615	96	165	174	204	231	218	218	190
J7616	89	160	169	204	231	219	219	188
J7914	95	187	202	216	240	223	223	184
J7916	95	176	188	215	240	219	219	187
J7918	93	169	180	216	240	221	221	190
T7914	94	145	150	213	238	219	219	201
T7915	96	143	149	212	237	217	217	203
T7916	87	156	163	201	230	213	213	200
T7917	85	158	166	213	238	215	215	202
T7918	82	154	161	210	236	212	212	201
T7919	88	152	159	205	232	212	212	201
T7920	18	121	122	256	267	168	73	168
T7921	71	118	119	212	237	217	217	204
T7922	20	113	112	237	255	168	78	182
T7925	82	161	169	212	237	215	215	204
T7926	95	161	169	211	236	214	214	206
Sulphur Works								
J7509	86	173	184	672	485	86	3	72
J7510	38	135	138	4114	994	12	12	22
M76116	83	155	163	287	288	62	62	21
J7611	84	150	157	284	285	57	57	22
M7657	87	144	149	362	334	91	91	29
J7613	91	139	144	351	327	96	96	21
M7676	81	105	104	837	547	2	2	155
J7612	88	94	91	769	523	1	1	155

1 Truesdell (1976)
2 Fournier (1979)
3 Fournier and Potter (1979)
4 Fouillac and Michard (1981)

Table 3. Chemical analyses of Growler Hot Spring [temperature in °C, discharge estimates in gallons/minute, analyses in mg/L]

Date	24 Jun 47	29 Jun 49	1 Jun 51	7 Sept 54	16 July 75	1 Aug 79
Temperature	95	95.4	95	96	95	95
discharge	8-10	nr*	8	7	3	2
pH	7.77	7.8	7.93	7.4	8.3	7.3
SiO_2	230	233	--	111	231	225
Fe	--	0.2	--	--	--	0.1
Mn	--	--	--	--	--	0.3
As	--	2.2	--	--	11	11.
Ca	--	79	--	82.5	80	93.7
Mg	--	0.8	--	3.4	.05	.47
Sr	--	14	--	14	.77	1.1
Ba	--	--	--	--	1.2	2.5
Na	--	1,400	--	1,380	1,450	1,340
K	--	196	--	187	203	173
Li	--	9.2	--	8.35	11.2	6.3
NH_4	--	1	--	--	--	9.5
HCO_3	--	52	--	57	65	55
SO_4	--	79	--	123	73	110
Cl	2,430	2,430	2,510	2,400	2,270	2,370
F	--	1.5	--	--	2.3	2.3
B	--	88	--	86	105	84
Analyst	White	Brannock	White	Kramer	Thompson	Thompson

* Not recorded