THE LASSEN GEOTHERMAL SYSTEM

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Abstract The Lassen geothermal system consists of a central vapor-dominated reservoir underlain by hot water that discharges peripherally at lower elevations. The major thermal upflow at Bumpass Hell (elevation 2,500 m) displays numerous superheated fumaroles, one of which in 1976 was 159°C. Gas geothermometers from the fumarole areas and water geothermometers from boiling Cl-bearing waters at Morgan Hot Springs (elevation 1,530 m; 8 km south of Bumpass Hell) and from 176°C waters in a well 12 km southeast of Bumpass Hell both indicate 230-240°C for the deep thermal water. With increasing distance from Bumpass Hell, gases are progressively depleted in H_2S relative to CO_2 and N_2, owing to oxidation of H_2S to pyrite, sulfur, and sulfates and to dilution with atmospheric N_2. H_2O/gas ratios and degree of superheat of fumaroles can be explained by mixing of steam of maximum enthalpy (2,804 J g^{-1}) with near-surface water and with the condensate layer overlying the vapor-dominated reservoir.

Introduction The Lassen geothermal system is located in the southernmost part of the Cascade Range, a linear belt of Quaternary volcanoes that extends from southern British Columbia to northern California (Muffler, Bacon, and Duffield, 1982, figure 1). The Lassen geothermal system has by far the most conspicuous surface hydrothermal manifestations of any geothermal system in the Cascades. However, most of the system is located in Lassen Volcanic National Park (LVNP) and is therefore not available for commercial development except perhaps in peripheral, hot-water zones outside LVNP.

Geologic setting The Cascade Range in the Lassen region is a broad ridge of late Pliocene and Quaternary volcanic rocks consisting primarily of pyroxene andesite flows and pyroclastic rocks with subordinate basalt flows, silicic flows, and silicic pyroclastic rocks. The regional basement probably consists of Mesozoic granitic and metamorphic rocks overlain by a thin sequence of Late Cretaceous marine sedimentary rocks which are in turn overlain by the Pliocene Tuscan Formation (Anderson, 1933; Lydon, 1968), a broad apron of andesitic debris flows with minor interbedded lava flows, ash-flow tuffs, and alluvial material deposited 3.5-2 m.y. ago (Lydon, 1961; Gilbert, 1969).

Late Pliocene and Holocene volcanic rocks overlying the Tuscan Formation were extruded primarily from long-lived major volcanic centers, at least three of which have been recognized in the Lassen region (figure 1):

- Dittmar volcanic center, active from perhaps 1.2 to 2.5 m.y.;
- Maidu volcanic center, active between 1.8 and 1.0 m.y. (Wilson, 1961);
- Lassen volcanic center, active from 0.6 m.y. to the present.

Each volcanic center evolved in three stages: (1) an initial cone-building period of andesite lava flows and pyroclastic rocks, (2) a later cone-building period of thick siliceous andesite lava flows, and (3) eruption of dacite to rhyolite domes and flows flanking the main composite cone. Silicic magma chambers related to the late domes and flows provided potent heat sources for hydrothermal convection systems within the cores of each of the main cones. However, the silicic magma chambers of the Dittmar and Maidu volcanic centers have cooled, and their hydrothermal systems are extinct. The present hydrothermal system at Lassen is associated with the active silicic volcanism of the Lassen volcanic center.

Flows and pyroclastic rocks of Stages 1 and 2 of the Lassen volcanic center were extruded primarily from a composite cone centered near Sulphur Works (Williams, 1932) during the period 0.6 to 0.35 m.y. (G. B. Dalrymple, personal commun., 1977-82). After a hiatus of approximately 0.1 m.y., at least 15 vents in a broad zone on the northeastern flank of this composite cone extruded flows and domes of dacite and rhyodacite, forming a dome field of approximately 130 km^2. The most recent events were the emplacement of the dacite dome of Lassen Peak approximately 11,000 years ago (Crandell, 1972), the eruption of rhyodacite pyroclastic flows and domes at Chaos Crags approximately 1,050 years ago (Crandell and others, 1974; D. A. Trimble, USGS, personal commun., 1982), and the relatively small eruption at the summit of Lassen Peak in 1914-1917 (Day and Allen, 1925; Loomis, 1926). Concurrent with this silicic volcanism, basalt and mafic andesite shield volcanoes grew to the north and east of the Lassen volcanic center, and mixing of silicic and basaltic magmas

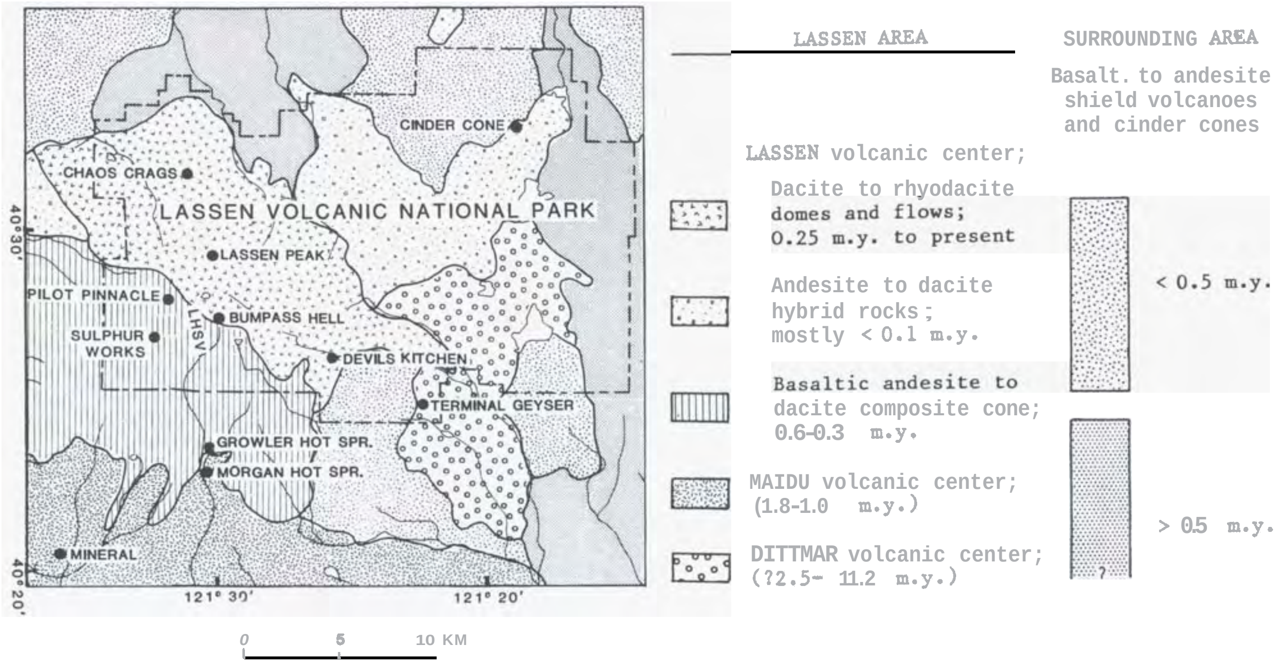

Figure 1.--Generalized geologic map of the Lassen region (adapted from Muffler, Clynne, and Cook, 1982). LHSV = Little Hot Springs Valley

produced intermediate lava flows on the east flank of the Lassen dome field (Eichelberger, 1975). The most recent eruption in this area was at Cinder Cone in 1850-51 (Finch and Anderson, 1930).

The long history of pyroclastic and dome-building eruptions in the Lassen dome field, the historical production of magma at two separate vents, and the existence of a major gravity low suggest that a partially molten silicic magma body still underlies the dome field (Heiken and Eichelberger, 1980).

The Lassen Geothermal System Geological and geochemical observations in the Lassen region all fit a model originally suggested by D. E. White (written commun., 1971) of a single large geothermal system with a central vapor-dominated reservoir (or reservoirs) underlain by a reservoir of hot water discharging at lower elevations (figure 2). The focus and major thermal upflow of the Lassen geothermal system is at Bumpass Hell along the contact between the andesitic composite cone and the dacite dome field of the Lassen volcanic center. Some of the outflow of hot water reaches the surface at Morgan and Growler Hot Springs to the south of LVNP and has been produced from the geothermal well Walker "O" No. 1 at Terminal Geyser in the southeast corner of LVNP.

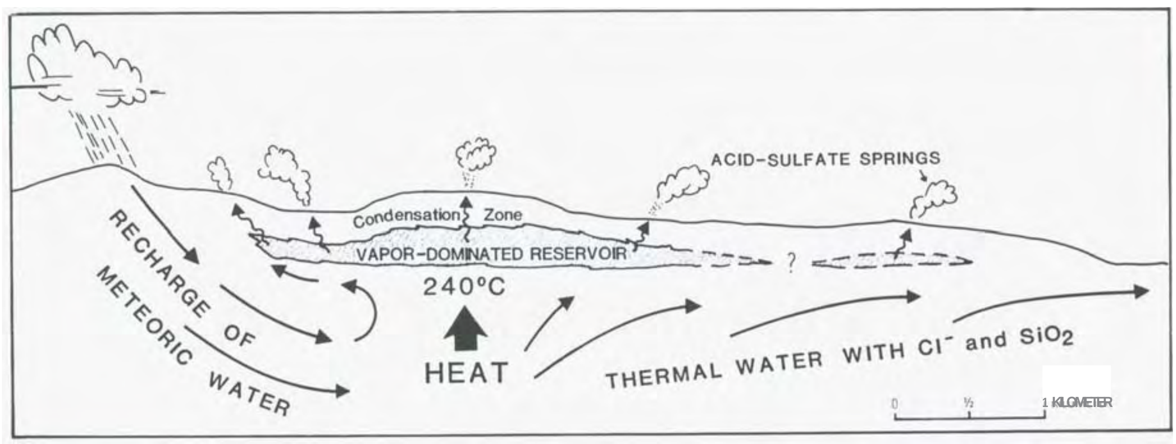

Figure 2.--Schematic cross-section of the Lassen geothermal system (adapted from Muffler, Clynne, and Cook, 1982)

Bumpass Hell (elevation 2,500 m) contains numerous superheated fumaroles, one of which in 1976 had a temperature of 159°C. Approximately 75 major fumaroles, acid-sulfate hot springs, and mudpots occur in Bumpass Hell (Muffler, Jordan, and Cook, 1982), plus a myriad of similar features too small to map. An area of approximately 0.13 km^2 is intensely altered to a white aggregate of opal and kaolinite ± alunite; the surface of the active part of Bumpass Hell is commonly covered with orange and yellow sulfates. Pyrite is common in many of the hot springs as linings of the vents and discharge channels, as scum floating on the surface of pools, and as dispersions in brown or black mudpots. Significant sinter does not occur, although a few springs show a weak deposit of silica around their rims and in the first few centimeters of their discharge channels. Silica is also found as bright-red mixtures with iron oxides in some drainages in the forest below acid-altered bare ground. Neither of these occurrences is indicative of a hot-water geothermal system. The acid-sulfate water from Bumpass Hell (table 1) is typical of hot springs related to a vapor-dominated reservoir in having low pH, high sulfate, and no significant Cl.

Table 1.--Chemical analyses of waters from thermal springs in and near LVNP. Constituents in mg L^{-1}; flow in L min^{-1}; n.d. = not determined. BH, Bumpass Hell; DK, Devil's Kitchen; SW, Sulfur Works; LHSV, Little Hot Springs Valley; TG, Terminal Geyser; GHS, Growler Hot Spring; MHS, Morgan Hot Springs.

	BH	DK	SW	LHSV	TG	GHS	MHS
Date	8/79	9/76	7/75	8/79	8/76	8/79	8/79
flow	20	8	seep	4	4	20	8
T(°C)	55	68	86	93	92	95	95
pH	2.2	2.5	1.9	5.65	4.5	7.45	7.25
si02	215	171	213	123	46	272	225
Al	16.2	nd	nd	.4	nd	.4	.2
Fe	10	6.1	nd	.34	nd	.04	.01
Mn	0.12	0.08	nd	.15	nd	.01	.03
As	nd	nd	nd	nd	nd	11	10.6
Ca	19.5	10.5	8.8	26	8.2	81	94
Mg	6.05	6.4	9.8	4.1	1.9	.07	.47
Sr	nd	nd	nd	nd	nd	.9	1.1
Ba	nd	nd	nd	nd	nd	2.5	3.0
Na	22.1	2.0	11	87	8	1340	1260
K	6.6	7.2	8.3	12	3	173	162
Li	0.5	0.015	0.01	.05	.01	6.3	6.1
Rb	nd	nd	nd	nd	nd	1.4	1.2
CS	nd	nd	nd	nd	nd	.6	.4
NH_4	nd	nd	30	3.5	nd	9.5	13
HCO_3	0	0	0	19	33	55	68
so4	364	226	938	301	48	110	123
Cl	5.7	0.5	0.5	5.2	3	2370	2210
F	0.33	0.17	0.35	.84	0.1	2.3	3.0
Br	nd	nd	nd	nd	nd	10	14.5
B	1.1	0.3	4.4	4.2	1.6	84	nd
H_2S	nd	nd	0.2	.03	nd	.02	.03
Calculated Geothermometer Temperatures							
Quartz Adiabatic[a]				158		187	176
Quartz Conductive[a]				166		202	188
Na-K-Ca[b]				95		223	219

a Equation from Truesdell, 1976
b Equation from Fournier and Truesdell, 1973

Fumaroles, acid-sulfate springs, and mudpots also are abundant in Little Hot Springs Valley just to the west and *230-400* m lower than Bumpass Hell. Several fumaroles in Little Hot Springs Valley are superheated, with a highest temperature of 125°C measured in 1976.

Devil's Kitchen (1,835 m) is an area of intense fumaroles, acid-sulfate springs, and mudpots (Muffler, Jordan, and Cook, 1982). Although a temperature of 106.6°C was measured in 1947 by D. E. White (written commun., 1982), at present the hottest fumaroles are superheated only by a degree or two. Several centimeters of sinter at two spots along the stream flowing through Devil's Kitchen indicate discharge of hot thermal water in the recent past.

Several other geothermal areas in LVNP also are characterized by fumaroles, mudpots, and acid-sulfate hot springs (see chemical analyses in table 1). Conspicuous among these are Sulphur Works (elevation 2,124-70 m), Pilot Pinnacle (2,516 m), Boiling Springs Lake (1,798 m), and Terminal Geyser (1,792 m). Steam discharging currently from these areas is either saturated or only slightly superheated.

Several springs near Sulphur Works and in Little Hot Springs Valley are relatively rich in HCO_3 and deposit travertine ($CaCO_3$). These springs are interpreted to be surface discharge from the zone of steam condensate that overlies the vapor-dominated reservoir.

Natural discharge from the hot-water part of the Lassen geothermal system occurs only at Morgan Hot Springs and Growler Hot Spring, both located in the canyon of Mill Creek at elevations of 1,530 and 1,570 m, respectively. These springs discharge moderate amounts of near-neutral water with significant Cl (table 1) and deposit conspicuous sinter. Na-K-Ca, sulfate-water isotope, and mixing model geothermometers indicate that the deep thermal water feeding these springs has a temperature of 220-240°C. Both Cl and SiO_2 concentrations decrease systematically south-southwest from Growler Hot Spring through Morgan Hot Springs (Thompson, 1982).

High-Cl hot water from the Lassen geothermal system has also been found in the Walker "O" No. 1 well (Beall, 1981) at Terminal Geyser. Samples taken during flow of the well on 10-11 October 1978 show Na, K, and Cl increasing with time to maximum values of 1,300, 180, and 2,200 mg L^{-1}, respectively; flow tests were terminated before the chemical constituents reached constant values. Measured pH ranged from 8.1 to 8.6. Temperatures taken in the plugged liner 10 months after the well was flowed reach a maximum of 176°C between 603 and 640 m and then decrease gradually to 124°C at the well bottom (1,222 m).

The Cl-bearing water found in Walker "O" No. 1 does not discharge in Terminal Geyser. This vent is not a true geyser but is a fumarole discharging into a small surface stream. Water discharged by Terminal Geyser (table 1) appears to be local precipitation heated by steam.

Thermodynamic evidence for steam sources High-temperature superheated geothermal fumaroles are uncommon, but during the California drought of 1976-77 high degrees of superheat were observed in three areas of LVNP. In late 1976 Big Boiler fumarole in Bumpass Hell reached 159°C, to our knowledge the highest temperature ever recorded from a geothermal (non-volcanic) fumarole. This temperature is close to the temperature (163°C) of steam decompressed adiabatically to Lassen surface pressure (0.75 bar abs) from saturated steam of maximum enthalpy (2,804 J g^{-1} at 235°C and 31 bar abs; figure 3). Steam of higher temperature and enthalpy (up to 260°C and 2,980 J g^{-1} at 5 bars abs; Truesdell and White, 1973) has been produced from wells at Larderello, Italy, by the isothermal decompression of saturated steam in the reservoir (flow in the wells is adiabatic). This isothermal decompression, however, is a result of drastically reduced pressures caused by rapid withdrawal of steam through wells. Isothermal decompression is unlikely to occur in a natural system because cooler rocks between the reservoir and the surface can be heated only to the temperature of the steam. Thus the limiting process in nature is adiabatic (isoenthalpic) decompression.

The range of superheat in the Lassen steam samples could have resulted from two processes: (1) adiabatic decompression of saturated steam with different temperatures, or (2) mixing of highly superheated steam with liquid water or with saturated steam of lower temperature. After mixing, the resulting steam would undergo further decompression to reach surface conditions. This second process is the simpler explanation and is in accord with the observed H_2O/gas ratios.

On a plot of H_2O/gas ratio vs. enthalpy (figure 4), the Lassen data fall on two trend lines that intersect at the point of maximum steam enthalpy (2,804 J g^{-1}). Line A consists of Big Boiler (Bumpass Hell) samples and trends toward a relatively high H_2O/gas end member; line B (from Bumpass Hell and other areas) trends toward a relatively low H_2O/gas end member. These two trends are also distinguished on a plot of percent H_2 vs. H_2O/gas ratio (figure 5). In this plot, one trend has a slope of 1, suggesting that H_2 was in equilibrium with H20 (at constant temperature and P_{CO_2}), and the other has a slope of infinity, suggesting lack of equilibrium due to short reaction times or low

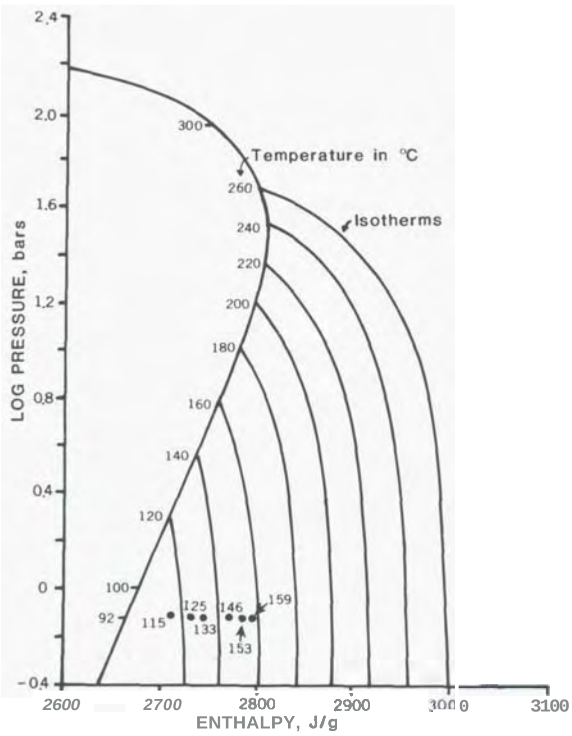

Figure 3.--Diagram showing the relations between saturated steam, the isothermal decompression paths of superheated steam, and the surface enthalpy, temperature, and pressure of superheated fumarolic steam from LVNP. Numbers give temperatures in °C.

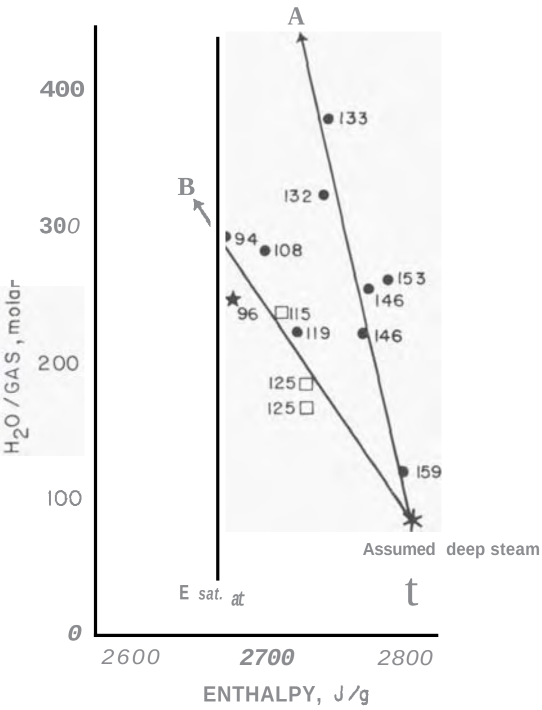

Figure 4.--Diagram showing the relations between H_2O/gas and enthalpy of steam samples from LVNP. Numbers give temperatures in °C. See figure 6 for explanation of symbols. Line A trends towards 235°C liquid water with 0.7 bar P_{CO_2} and 7,900 H_2O/gas. Line B trends towards 90°C liquid water with 1.1 bar P_{CO_2} and 3,900 H_2O/gas.

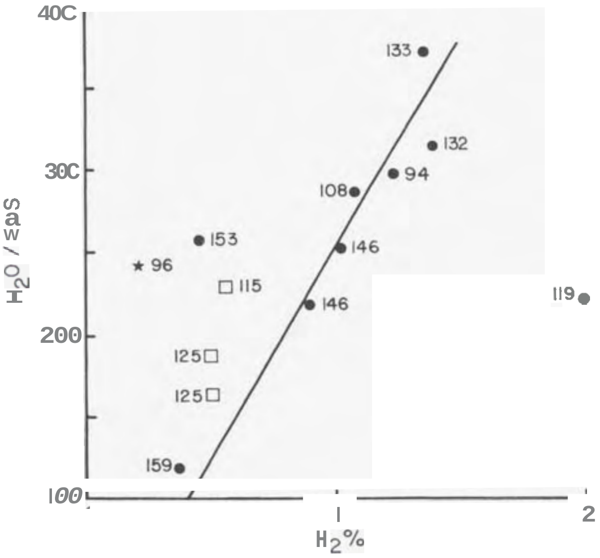

Figure 5.--Diagram showing relations between H_2O/gas and H_2 content of gas samples from fumarole areas in LVNP. Numbers give temperature in °C. See figure 6 for explanation of symbols. Hydrogen in geothermal systems appears to be generated by the dissociation of water (H_2O = H_2 + 1/2 O_2) with the pressure (fugacity) of oxygen controlled by mineral reactions.

temperature. Although the correspondence is not complete, 5 of the 7 points on the line with a slope of 1 lie on line A of figure 4, and 4 of the 5 points with a slope of infinity lie on line B.

This behavior of H_2 strongly suggests that steam samples falling along line B resulted from mixture of superheated steam and liquid water near the surface, where residence times were too short for H_2-H_2O equilibration. A possible low-temperature end-member would be 90°C water in equilibrium with CO_2 at 1.1 atm pressure and with a H_2O/gas ratio of 3,600. This heated, gas-charged water might reasonably saturate the near-surface zones of the fumarolic areas and be entrained into superheated steam as it flowed upward. The total pressure (water vapor + CO_2) of this liquid water would be 1.8 bars, which would allow the mixing to occur within 8 m of the surface by boiling-point-to-depth relations.

Steam samples along line A (figure 4) must mix at greater depths, where H_2 and H_2O can equilibrate after mixing. If this mixing occurs in the upper part of the deep reservoir near 235°C, the H_2O/gas ratio of the liquid water mixing with steam would have been 7,900 and the P_{CO_2} about 0.7 bar. The H_2O/gas ratio of reservoir steam with P_{CO_2} = 0.7 bar would be 50, close to the ratio of the hypothetical deep steam (H_2O/gas = 85).

Using these end members, we find that the steam samples along trend A are mixtures of superheated steam (2,804 J g^{-1} and 85 H_2O/gas) with 0.5–4.0 percent liquid water at 235°C, 1,014 J g^{-1} and 7,900 H_2O/gas. Those samples along trend B are mixtures of superheated steam with 2-6 percent liquid water at 90°C, 377 J g^{-1}, and 3,600 H_2O/gas. These fractions of liquid are so small they might not be detected by isotopic methods, but owing to the high gas content of the deep steam are readily distinguished by H_2O/gas ratios.

Stable isotopes of hydrogen and oxygen Isotopic analyses of samples collected from 1977 to 1981 provide extensive data supporting interpretations made by Truesdell and Hulston (1980) on limited data. The isotopic compositions of D and ^{18}O of meteoric waters in the Lassen region fall along a line defined by $\delta D = 8 \delta ^{18}O + 12$ (figure 6). This pattern largely reflects the prevailing south-southeast to north-northwest regional storm direction and is only locally affected by depletion of D and ^{18}O with increasing elevation. Cold waters southwest of the LVNP near Mineral are significantly heavier than spring waters north of the thermal features.

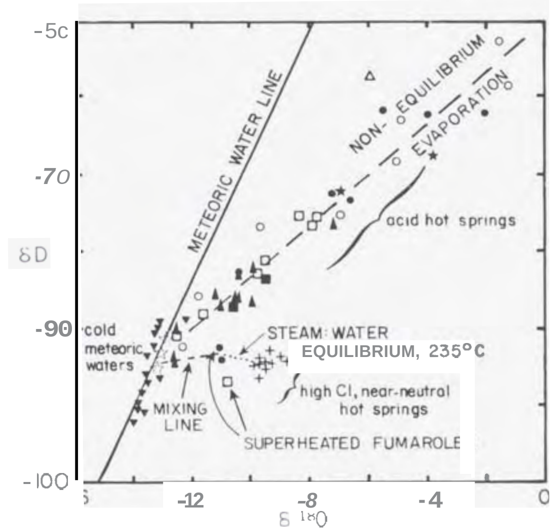

Figure 6.--Diagram showing relations between deuterium and ^{18}O for water and steam samples from LVNP and vicinity. ● , Bumpass Hell; □ , lower Little Hot Springs Valley; ☆ , Pilot Pinnacle and upper Little Hot Springs Valley; ○ , Sulphur Works; △ , Cold Boiling Lake; ▲ , Devil's Kitchen; ★ , Boiling Springs Lake; ■ , Terminal Geyser; + , Growler and Morgan Hot Springs; ▼ , meteroic water.

The thermal waters issuing from Morgan and Growler Hot Springs have δD values similar to meteoric waters on the andesitic composite cone, suggesting that recharge to the Lassen geothermal system occurs on the composite cone. These thermal waters exhibit an oxygen isotope shift of up to +4°/oo due to water-rock isotopic exchange at high temperature.

If, as shown above, the most superheated steam from Bumpass Hell is derived directly from a 235°C vapor-dominated reservoir by adiabatic expansion, steam in the reservoir would have the same isotopic composition as the highest-temperature samples (average δD = -93.4 and $\delta^{18}O$ = -10.93). The calculated composition of water in equilibrium with this steam at 235°C is δD = -95.0 and $\delta^{18}O$ = -9.09 (data in Truesdell et al., 1977). These calculated values are very similar to those measured for Growler Hot Spring waters (average δD = -94.6 and $\delta^{18}O$ = -9.27), indicating that the water of Growler Hot Spring is deep reservoir water mixed with only a minor amount of local meteoric water. A balance calculation based on the ^{18}O data indicates that the thermal component is about 95%. Morgan Hot Springs have $\delta^{18}O$ = -9.7, which corresponds to 84% thermal water.

Waters from the acid-sulfate hot springs and drowned fumaroles define a line of nonequilibrium surface evaporation of steam at temperatures of 70-90°C (figure 6; Craig, 1963; Truesdell and Hulston, 1980).

Gas Geochemistry Analyses of major gases from fumarole areas of LVNP are depicted on figure 7. The gas compositions can all be derived by two major near-surface processes that remove H_2S from a reservoir gas composition very near to the composition of gas from Big Boiler in Bumpass Hell. The first process is oxidation of H_2S either to pyrite (FeS_2) or to elemental sulfur without involving oxygen from air (either directly or dissolved in water). The second

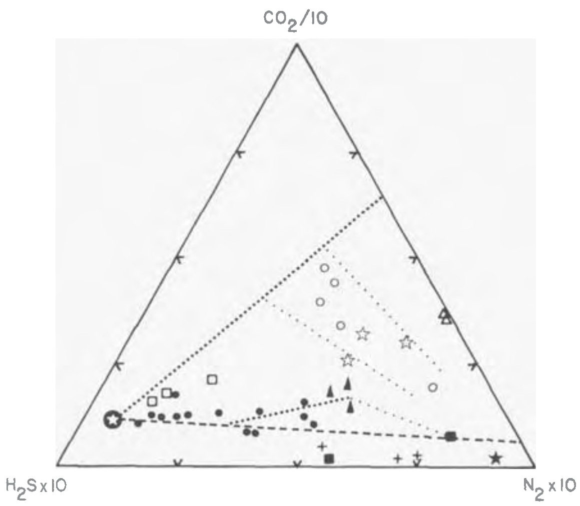

Figure 7.--Triangular plot of CO_2-H_2S-N_2 in gas samples from LVNP and vicinity. ✪, reservoir gas composition; ...., oxidation of H_2S to pyrite or elemental sulfur; - - - -, oxidation with air or air dissolved in water to produce sulfates; ········, near-surface addition of air without reaction with H_2S. See figure 6 for explanation of other symbols.

process involves oxidation with air or air dissolved in water to produce sulfates; this reaction is accompanied by admixture of N_2. The intersection of the lines representing these processes gives an estimate of the ratio of CO_2-H_2S-N_2 in the reservoir. The three samples plotting nearest the reservoir composition are from the hottest fumaroles in Bumpass Hell and Little Hot Springs Valley; all are over 125°C. The reconstructed composition of the gas in the vapor-dominated reservoir (from figures 5 and 7) is (in mol percent) CO_2, 92.7; H_2S, 6.6; H_2, 0.01; NH_3, 0.075, N_2, 0.6; Ar, 0.013; O_2, 0.0; and CH_4, 0.05, with a H_2O/gas ratio of 85 (figure 4).

Gases from Boiling Springs Lake, Terminal Geyser, Growler Hot Spring, and Morgan Hot Springs appear to originate from the hot-water reservoir rather than the vapor-dominated reservoir. High H_2O/gas ratios (2,000-4,000) and high H_2S/CO_2 ratios indicate that the water has previously been degassed by formation of a vapor phase at high temperature (235°C). When this degassed water approaches the surface and boils a second time, the steam that is formed is depleted in total gas and in CO_2 relative to H_2S (the latter because H_2S is more soluble in water than is CO_2).

Temperatures calculated using the gas geothermometer of D'Amore and Panichi (1980) are given in table 2. Within the uncertainties in the calculation (± 15°C), the temperature determined from the calculated reservoir gas composition is compatible with the 220-240°C calculated from Na-K, Na-K-Ca, and sulfate isotope relations for Growler Hot Spring waters. The temperatures from Little Hot Springs Valley and Bumpass Hell appear somewhat high, probably due to near-surface loss of CH_4. Temperatures from Sulphur Works and Pilot Pinnacle are somewhat low, apparently due to the great loss of H_2S (see figure 7).

Table 2.--Temperatures in °C calculated by the geothermometer of D'Amore and Panichi (1980) for gases from fumaroles and hot springs in LVNP and vicinity. Temperature for the reservoir is calculated from the reservoir gas composition given in the text.

Reservoir	Bumpass Hell	Little Hot Springs Valley	Sulphur Works
244	248	265	201

Pilot Pinnacle	Devil's Kitchen	Terminal Geyser	Growler Hot Spg
212	237	233	242

A physical model for the Lassen geothermal system New geologic, chemical, and isotopic data combined with thermodynamic and physical constraints on the production of superheated steam allow us to add considerable detail to the previously suggested model of the Lassen geothermal system as a central vapor-dominated reservoir underlain by hot water that discharges peripherally at lower elevations. The critical observations are:

1. Oxygen isotopic data suggest that recharge to the Lassen geothermal system is local and probably on the composite cone of Lassen volcanic center.
2. These data further suggest that the Morgan-Growler water and the Bumpass Hell superheated steam separated at about 235°C and have undergone little alteration in isotopic composition during passage to the surface.
3. Considerations of the H_2O/gas and H_2O/H_2 ratios and the temperatures of the superheated steam suggest that the highest temperature samples (mostly from Big Boiler at Bumpass Hell) consist of adiabatically decompressed samples of saturated 235°C reservoir steam with small (≃ 0.5%) additions of condensate from the top of the reservoir.
4. Gas chemistry suggests that this highest-temperature steam is the least altered sample of deep steam; gas equilibration temperatures are near 235°C.
5. Hot water compositions at Morgan and Growler Hot Springs give geothermometer temperatures of 220-240°C and show progressive dilution away from LVNP.

These observations support a model in which cold meteoric water from the composite cone of the Lassen volcanic center in LVNP flows underground and is heated by a cooling intrusion related to the silicic volcanic activity of the past 0.25 m.y. Geothermal liquid at approximately 235°C at depth boils to form an overlying vapor-dominated reservoir, steam from which leaks upward to feed the fumaroles in LVNP. Part of the geothermal water flows laterally to the south to feed the Morgan and Growler Hot Springs and to the southeast where it is encountered in the Walker "O" No. 1 well at Terminal Geyser. Most of the steam that flows to the thermal areas of LVNP mixes with local ground water to form acid hot springs, but some steam in relatively large conduits undergoes adiabatic decompression with small addition of deep or surface waters to form superheated fumaroles. Assuming boiling point-depth relations in the condensate layer, the top of the 235°C vapor-dominated reservoir is probably near 2,100 m elevation. The bottom of the vapor-dominated reservoir is roughly constrained by the elevation of the springs at Growler Hot Spring (1,570 m). This gives a thickness of the two-phase vapor-dominated zone at Lassen of only 500-600 m, comparable to parts of Larderello, Italy, but much thinner than the two-phase reservoir at The Geysers, California.

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