QUANTITATIVE ANALYSIS OF THE HYDROTHERMAL SYSTEM IN LASSEN VOLCANIC NATIONAL PARK AND LASSEN KNOWN GEOTHERMAL RESOURCE AREA

By M. L. Sorey and S. E. Ingebritsen

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ACKNOWLEDGEMENTS

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ABSTRACT

The Lassen hydrothermal system is in the southern Cascade Range, approximately 70 kilometers east-southeast of Redding, California. The conceptual model of the Lassen system is termed a liquid-dominated hydrothermal system with a parasitic vapor-dominated zone. The essential feature of this model is that steam and steam-heated discharge at relatively high elevations in Lassen Volcanic National Park (LVNP) and liquid discharge with high chloride concentrations at relatively low elevations outside LVNP in the Lassen Known Geothermal Resource Area (KGRA) are both fed by an upflow of high-enthalpy, two-phase fluid within the Park. Liquid flows laterally away from the upflow area towards the areas of high-chloride discharge, and steam rises through a vapor-dominated zone to feed the steam and steam-heated features. Numerical simulations show that several conditions are necessary for the development of this type of system. These include (1) the existence of large-scale topographic relief that allows thermal fluids to discharge in regions of significantly different elevation, (2) the occurrence of an initial period of convective heating within a zone of upflow followed by some change in hydrologic or geologic conditions that initiates a period of drainage of liquid from portions of the upflow zone, and (3) the existence of low permeability barriers that inhibit the movement

of cold water into the vapor zone.

The geometric model in these simulations corresponds to an areally restricted flow regime that connects the Bumpass Hell area in LVNP with regions of chloride hot springs in the Mill Creek canyon in the KGRA south of LVNP. Measurements of streamflow and chloride concentration at several sites along Mill Creek and Canyon Creek indicate that the total flow of thermal water discharging at the surface in Mill Creek Canyon is close to 17 kilograms per second (kg/s). An unknown amount of thermal water may flow out of this canyon in shallow and deep groundwater aquifers. Our modeling shows that the permeability-thickness product for a 1 km-wide reservoir transmitting 20 kg/s of thermal water beneath Mill Creek Canyon would be about 32 darcy-meters.

Simulations of thermal fluid withdrawal in the Mill Creek Canyon were carried out in order to determine the effects of such withdrawal on portions of the hydrothermal system within the Park. The nature of such effects is for pressure and liquid saturation to decrease beneath the vapor-dominated zone, resulting in a temporary increase and subsequent decrease in the rate of upflow of steam into the vapor zone. Within the vapor-dominated zone, the changes in steam upflow are damped by condensation and pressure increases. The degree to which the net upflow of steam changes as a result of fluid withdrawal depends on the production and injection rates, the nature of the functions relating relative permeability to liquid saturation, and on the extent of two-phase conditions in the lateral flow zone before development. In cases where the lateral conduit was initially single-phase, the simulated effects of geothermal development on pressures and steam flow in the vapor-dominated zone beneath LVNP were significant. In cases involving an extensive two-phase region in the lateral conduit such effects were negligible. Injection of all or part of the produced fluid allows higher production rates to be sustained but generally does not prevent the propagation of induced pressure changes in the lateral flow zone under the Park. Fluid withdrawal also reduces or reverses the simulated discharge of thermal water from Morgan and Growler Hot Springs in Mill Creek Canyon.

Additional information on the locations and properties of thermal-fluid reservoirs inside and outside the Park is needed to refine our model of the Lassen hydrothermal system. Such information may be obtainable only from test drilling and associated borehole measurements. Wells drilled into lateral outflow conduits at or near the Park boundary could also be useful in monitoring changes in pressure and temperature induced by geothermal development activities.

INTRODUCTION

Numerous areas within Lassen Volcanic National Park (LVNP) and the adjacent Lassen Known Geothermal Resource Area (KGRA) contain fumaroles and hot springs. These features are manifestations of an underlying hydrothermal system that is heated by recently crystallized and partially molten silicic intrusions associated with the abundant accumulations of young volcanic rocks in the Lassen area. Existing data from studies by the U. S. Geological Survey and from a privately drilled 1,200-meter (m)-deep well at Terminal Geyser suggest that subsurface hydrologic connections exist between widely separated areas of steam and steam-heated discharge within the Park and areas of high-chloride hot-water discharge in the KGRA to the south. As a result, the potential exists for changes in flow rates and temperatures of thermal discharge features inside and outside the Park in response to fluid production for geothermal energy development outside the Park.

A quantitative study of the Lassen hydrothermal system was undertaken in order to evaluate the potential impact of geothermal development within the Lassen KGRA on thermal discharge within LVNP. This study included hydrologic and geochemical field investigations and numerical simulations based on a simplified geometric model. The analysis of this model applies to the evolution of the present-day Lassen system as well as the possible effects of fluid production for geothermal development. Explanations of technical terms used in this report are given in the Glossary at the end of this report.

LASSEN HYDROTHERMAL SYSTEM

Geologic Setting

Lassen Volcanic National Park is located at the southern end of the Cascade Range, near the boundaries of the Cascade, Klamath Mountains, Great Valley, Sierra Nevada, and Modoc Plateau physiographic provinces (figure 1). 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 minor basalt flows and silicic flows and pyroclastics (Muffler and others, 1982). The regional basement probably consists of Mesozoic granitic and metamorphic rocks overlain by a thin sequence of marine rocks of the Late Cretaceous Chico Formation. The late Cretaceous rocks are probably overlain by the Eocene Montgomery Creek Formation, a series of sandstones, conglomerate, and shales, and by the Late Pliocene Tuscan Formation, a widespread series of lahars, tuffs, and tuff breccias. Late Pliocene to Holocene volcanic rocks, of unknown thickness, overlie the Tuscan Formation in the vicinity of LVNP. The rather high concentrations of Na, Cl, B, and NH_3 in thermal waters discharging in Mill Creek Canyon in the Lassen KGRA suggest that these waters have some component that flowed through the Chico Formation (Thompson, 1983), which in turn implies a deep root to the Lassen hydrothermal system.

The dominant structural trend in the Lassen region is northwest-southeast. It is expressed by a series of normal faults with offset beginning contemporaneously with late Pliocene volcanism

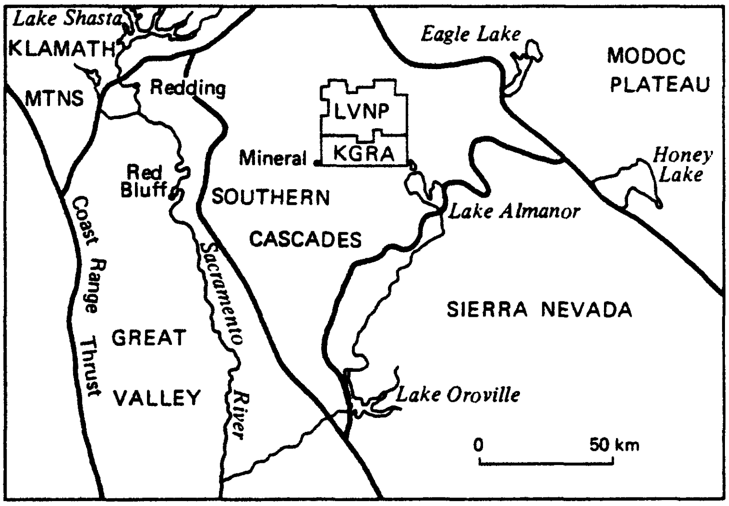

Figure 1. Map of physiographic provinces in Northern California and adjacent states (after Fenneman, 1928) and location of Lassen Volcanic National Park (LVNP) and Lassen Known Geothermal Resource Area (KGRA).

(figure 2). Faults in younger rocks show progressively less displacement, and many late Pleistocene rocks show little or no displacement (Clynne, 1983). The volcanic plateau formed by the young volcanic rocks of LVNP may fill a portion of a graben structure extending continuously from Hat Creek Valley on the north to the Lake Almanor Depression on the south (Heiken and Eichelberger, 1980). Although the orientations of most of the major valleys within LVNP may be fault-controlled, offset has been demonstrated for only two faults in the LVNP area (figure 3). Clynne (1983) referred to these two young normal faults as the "Hot Springs Creek Fault" (northernmost) and the "Terminal Geyser Fault" (southernmost). The structural significance of the large-scale ring features outlined in figure 2 is speculative. They are visible on Landsat and digital terrain tape imagery and are defined geomorphically by valleys, drainage patterns, and other lineaments. It has been suggested that the outer ring ("Sifford Peak Depression") is the surface expression of a Late Pliocene caldera (Rich, written commun., 1975; Ingebritsen and Rojstaczer, 1983) or a "volcano-tectonic collapse structure" (Friedman and Frank, 1978). The alignment of the three younger Pleistocene volcanic centers along the outer ring and the surface manifestations of the present-day Lassen hydrothermal system along the inner ring (figure 2) suggests that these features may have provided some structural control over subsequent intrusive and hydrothermal activity.

Late Pliocene to Holocene volanic rocks in the Lassen region were extruded from three long-lived volcanic centers (figures 2 and

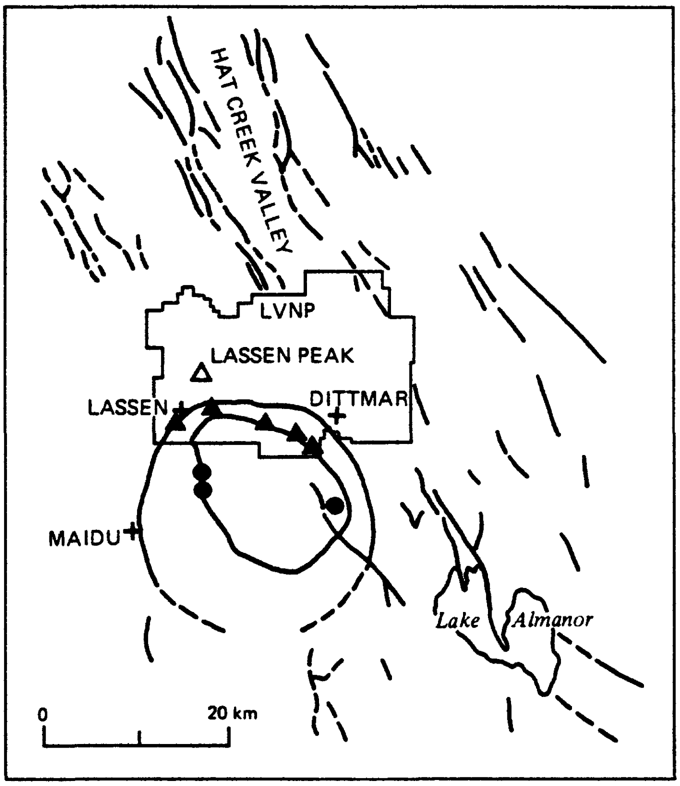

Figure 2. Map of the Lassen region showing northwest-trending structural features, ring features suggestive of volcano-tectonic collapse structures, major Pleistocene volcanic centers (crosses), and areas of present-day thermal fluid discharge (triangles and dots).

3): the Dittmar, Maidu, and Lassen volcanic centers (Muffler and others, 1982; Clynne, 1983). Each of these centers evolved in three stages: (1) an initial cone-building period of andesitic lava flows and pyroclastic rocks, (2) a later cone-building period of thick siliceous andesitic lava flows, and (3) eruption of dacitic to rhyolitic domes and flows on the flanks of the main composite cone. The silicic magma chamber associated with the Lassen volcanic center (0.6 m.y. to present) provides the heat source for the present-day Lassen hydrothermal system centered near Bumpass Hell. The area of young (0.25 m.y. to present) volcanic rocks extruded from the Lassen center includes Lassen Peak (11,000 years b.p.), Chaos Crags (1,050 years b.p.), and Cinder Cone (133 years b.p.).

Geochemical Characteristics

Surficial hydrothermal features in the Lassen region are confined to the southern half of LVNP and to the Lassen KGRA. They include fumaroles and acid-sulfate hot springs at relatively high elevations in LVNP and neutral-pH, high-chloride hot springs at relatively low elevations in the KGRA. The steam and steam-heated features occur for the most part near the contact between the andesitic composite cone and the dacitic dome field of the Lassen volcanic center (figures 3 and 4). The thermal features at Devils Kitchen, Drakesbad, and Terminal Geyser occur along the "Hot Springs Creek Fault" and "Terminal Geyser Fault". High-chloride thermal water discharges at Morgan Hot Spring along Mill Creek and at Growler Hot Spring along Canyon Creek, and has been

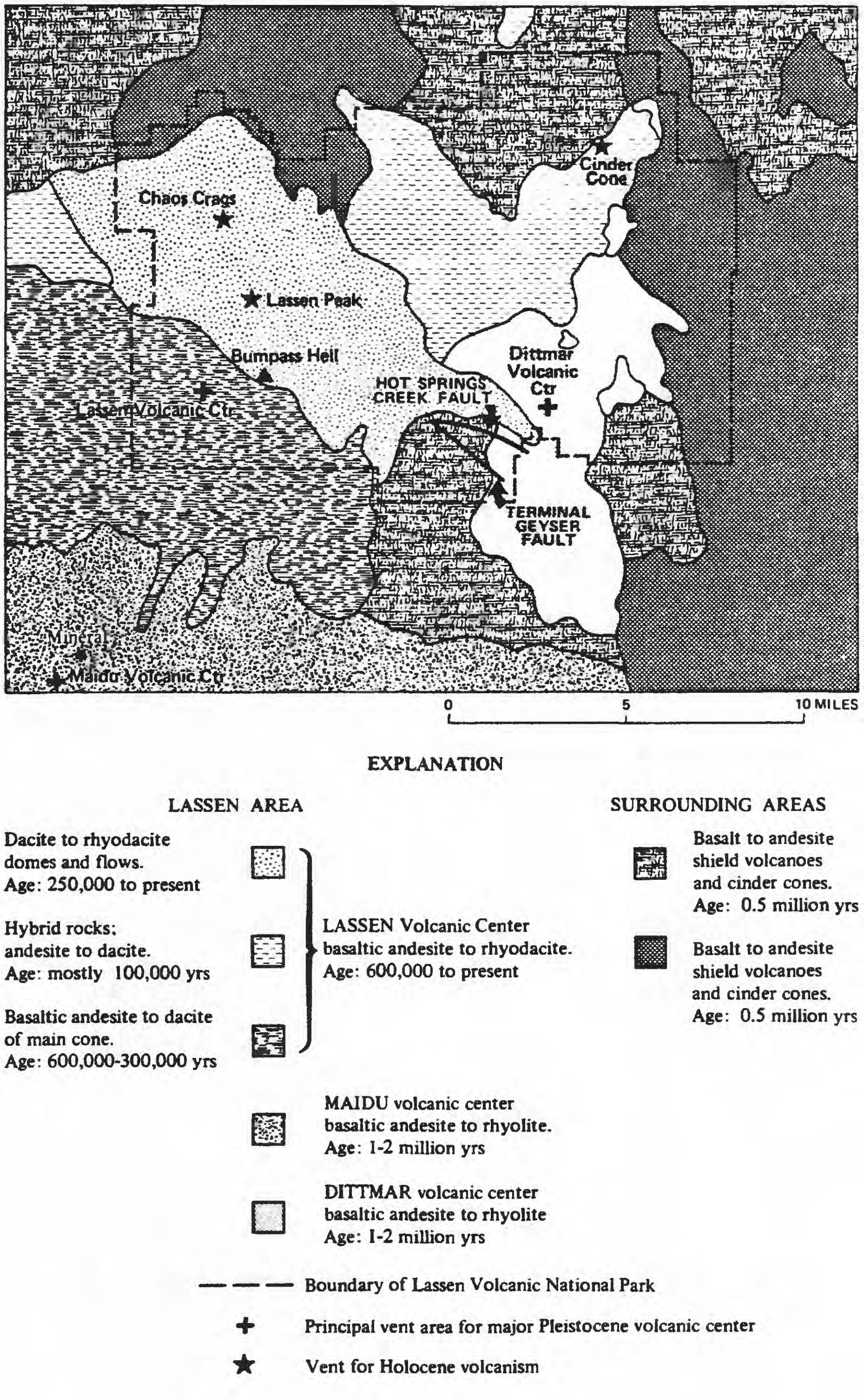

Figure 3. Generalized geologic map of the Lassen region (adapted from Muffler and others, 1983).

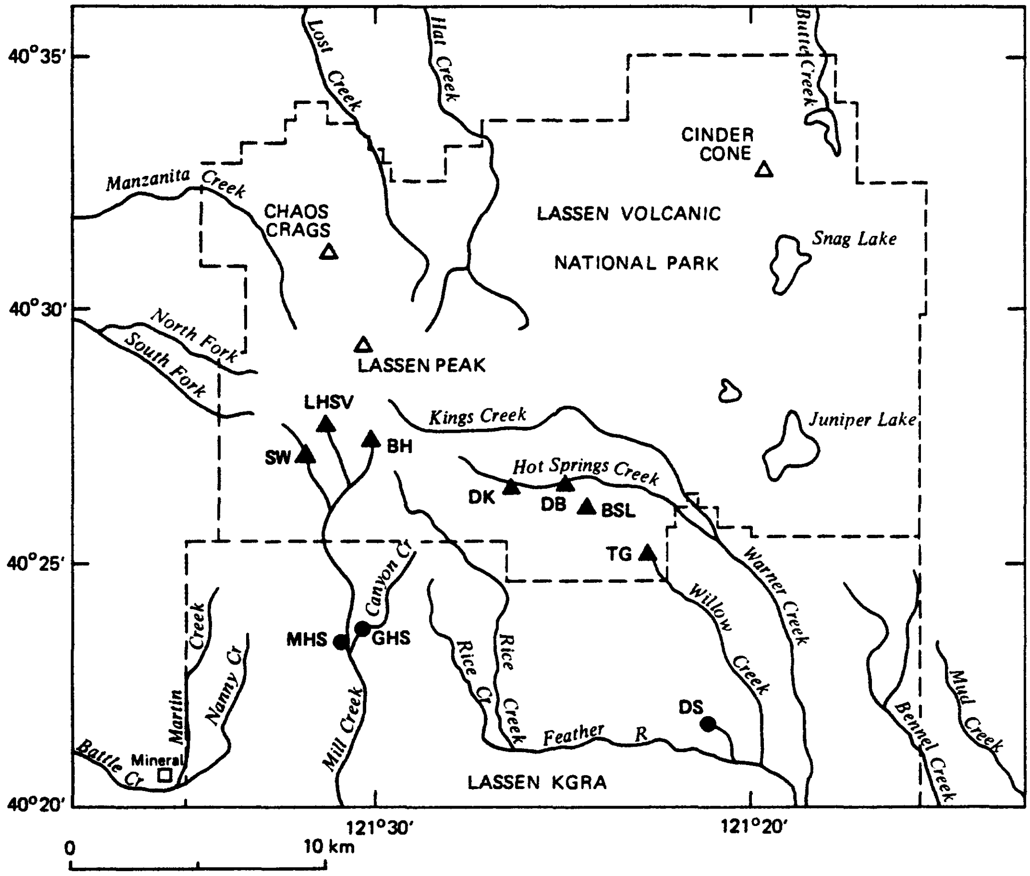

Figure 4. Map showing areas of thermal-fluid discharge and major streams in the Lassen region. Areas with fumaroles, steam-heated springs, and/or low-chloride, conductively heated springs are shown as triangles (BH = Bumpass Hell, LHSV = Little Hot Springs Valley, SW = Sulphur Works, DK = Devils Kitchen, DB = Drakesbad, BSL = Boiling Springs Lake, TG = Terminal Geyser). Areas with high-chloride thermal water discharge (GHS = Growler Hot Spring, MHS = Morgan Hot Springs) and spring discharge containing chloride contents significantly above background (DS = Domingo Spring) shown as dots.

detected in an aquifer at depths near 500 m in the Walker "O" No. 1 well drilled at Terminal Geyser (Beall, 1981). Some or all of the high-chloride water flowing under Terminal Geyser may eventually discharge at Domingo Spring, where chloride concentrations are approximately 10 times higher than in other cold springs in the KGRA (Thompson, 1983). It should be noted that additional flows of thermal water may exist under the northern half of LVNP and beyond; their presence could be masked by flow of cold ground water in overlying aquifers.

Typical values for the concentrations of selected ions in thermal waters are listed in table 1. The generally acidic, low-chloride character of all but the waters at Growler and Morgan Hot Springs and water produced from the well at Terminal Geyser is indicative of some degree of vapor-dominated conditions at depth. Such conditions occur where liquid mobility is low and steam is the pressure controlling fluid phase. Vapor-dominated zones are generally overlain by zones of steam condensate and cold groundwater in which the vertical pressure distribution is near hydrostatic and from which acid-sulfate and bicarbonate waters discharge.

The composition of gas in steam discharging from various thermal areas shows variations in H_2S, CO_2, and N contents and in ^{13}C and ^{34}S isotopic ratios which indicate that steam and gas discharging at Devils Kitchen, Boiling Springs Lake, Terminal Geyser, and Morgan and Growler Hot Springs is derived from underlying hot-water reservoirs rather than from the vapor-

Table 1. Typical concentrations of selected ions in thermal waters in Lassen Volcanic National Park and Lassen KGRA. Data from Thompson (1983), except for the Walker "O" No. 1 well (from J.M. Thompson, written communication, 1983).

Location	Temp. °C	pH	SO_4 mg/L	SiO_2 mg/L	Na mg/L	Cl mg/L	B mg/L
Bumpass Hell	53-93	2.2	400	96-236	4-33	2-6	1
Sulphur Works	83-93	1.9-7.2	940	39-213	3-70	1-3	1-4
Little Hot Springs Valley	55-93	3.8-6.8	101-517	84-172	55-102	1-6	.1-5.1
Devils Kitchen	71-95	1.9-7.0	226	40-213	2-43	.5-1.6	.3-2.4
Drakesbad	65	6.7	140	143	43	2.0	1.0
Boiling Springs Lake	94	2	710	242	6.4	13	1.6
Terminal Geyser	93	5.0	16-52	30-64	7.5	3-26	1.5
Morgan Hot Springs	82-95	7.2	110	150-184	1300	2210	80
Growler Hot Springs	95	8.0	90	250	1400	2320	95
Walker "O" No. 1 Well	86*	7.4	81	133	1220	2180	62
Domingo Spring	10	7.0	2	40	12	21	0.6

*Temperature of surface sample. Subsurface temperature of production zone = 176°C (Beall, 1981).

dominated zone underlying the Bumpass Hell-Sulphur Works area (Janik and others, 1983). This means that vapor-dominated conditions do not extend continuously under the entire southwestern part of the Park. Depletion of H_2S and an increase in the proportion of CO_2 and N with increasing distance from Bumpass Hell suggests that the thermal features between Devils Kitchen and Terminal Geyser and at Growler and Morgan Hot Springs are connected to the vapor-dominated zone under Bumpass Hell by liquid-dominated lateral flow zones. The well at Terminal Geyser intercepted such a flow zone at a depth of approximately 500 m.

Results of applying quartz, cation, and sulfate-water isotope geothermometers to hot-spring waters in LVNP and Lassen KGRA are summarized in table 2. Geothermometer temperatures from steam-heated waters are not indicative of reservoir temperatures at depth, because fluid discharge from steam-heated features is a combination of condensed steam and shallow nonthermal groundwater. Leaching of near-surface rocks by low-pH waters can produce fairly high concentrations of SiO_2 in acid-sulfate springs, leading to erroneously high silica geothermometer temperatures. The low-chloride, neutral-pH spring waters at Drakesbad yield cation temperatures that are consistent with the measured spring temperatures, suggesting that these waters are not steam-heated but rather heated by conduction from an underlying higher-temperature fluid reservoir. Some of the neutral-pH springs at Sulphur Works and Little Hot Springs Valley may also be conductively heated.

Table 2. Calculated geothermometer temperatures and measured temperatures for hot springs and a thermal well in Lassen Volcanic National Park and Lassen KGRA.

Location	Measured °C	SiO_2 (Conductive) °C	Na-K-Ca (Mg corrected) °C	Sulfate Isotope °C
Bumpass Hell	53-93	135-191	50-75	--
Sulphur Works	38-91	91-184	57-96	--
Little Hot Springs Valley	55-93	128-170	53-118	--
Devils Kitchen	71-95	94-184	20-82	--
Drakesbad	65-66	158	73-79	--
Boiling Springs Lake	94	193	14	--
Terminal Geyser	92-95	98-114	29-53	--
Morgan Hot Springs	82-95	138-188	212-222	235
Growler Hot Springs	95	190-202	220-233	235
Walker "O" No. 1 Well	176	154	225	--

Data from Thompson (1983).

Data from Nehring and others (1979).

Data from J. M. Thompson, written communication, 1983.

Waters from the high-chloride sources yield cation and sulfate geothermometer temperatures between 212° and 235°C. Lower estimates from the quartz geothermometer suggest some degree of silica deposition and/or mixing with near-surface waters. Minor differences in Cl and SiO_2 between waters at Growler Hot Spring and Morgan Hot Spring support the suggestion of mixing (Thompson, 1983), though the higher concentrations at Growler Hot Spring could also be attributable to concentration by boiling. However, the geothermometer results and the similar chemical characteristics of waters from the various high chloride discharges indicate that they may be derived from a common source.

Superheated steam temperatures of up to 159°C were measured in the Big Boiler fumarole at Bumpass Hell during the California drought of 1976-1977. Muffler and others (1982) pointed out that this temperature is close to the temperature (163°C) of steam decompressed adiabatically from saturated steam at maximum enthalpy (235°C and 31 bars) to a land surface pressure of 0.75 bars. A similar steam reservoir temperature of 244°C was calculated by Muffler and others (1982) using the gas geothermometer of D`Amore and Panichi (1980). The inferred vapor-dominated reservoir temperature is similar to the calculated cation and sulfate geothermometer temperatures for waters from Morgan Hot Spring and Growler Hot Spring and from the well at Terminal Geyser, suggesting that these waters may have circulated outward from a common upflow zone below Bumpass Hell.

Further evidence for a common source for these fluids is provided by stable isotope concentrations (Janik and others, 1983). As shown in figure 5, the thermal water issuing from Growler Hot Spring has a deuterium value similar to those for meteoric waters on the composite cone of the Lassen volcanic center ($\delta D = -95$) and exhibits an oxygen isotope shift of about +4 ‰, probably owing to water-rock interaction at high temperature. The isotopic content of condensed steam from Big Boiler is closely similar to that calculated for steam in equilibrium with the Growler water at 235°C, as indicated by the dotted line in figure 5. Slightly lighter values of ^{18}O in waters toward the southern end of the Morgan Hot Spring area suggest dilution of this thermal water with about 16 percent non-thermal water. Such dilution is also indicated by tritium contents near 1.01 TU at Morgan, compared to 0.2 TU at Growler. Waters from the acid-sulfate hot springs show systematic differences in D and ^{18}O which define a non-equilibrium surface evaporation line at temperatures of 70° - 90°C.

Geophysical Characteristics

The regional geophysical setting is characterized by a large gravity low centered in the northeastern part of LVNP, magnetic anomalies centered over various volcanic vents, low heat flow northward from LVNP and variable heat flow within LVNP and the Lassen KGRA, and continuing seismicity of moderate magnitude. Published electrical surveys and heat flow measurements offer the most direct information regarding the Lassen hydrothermal

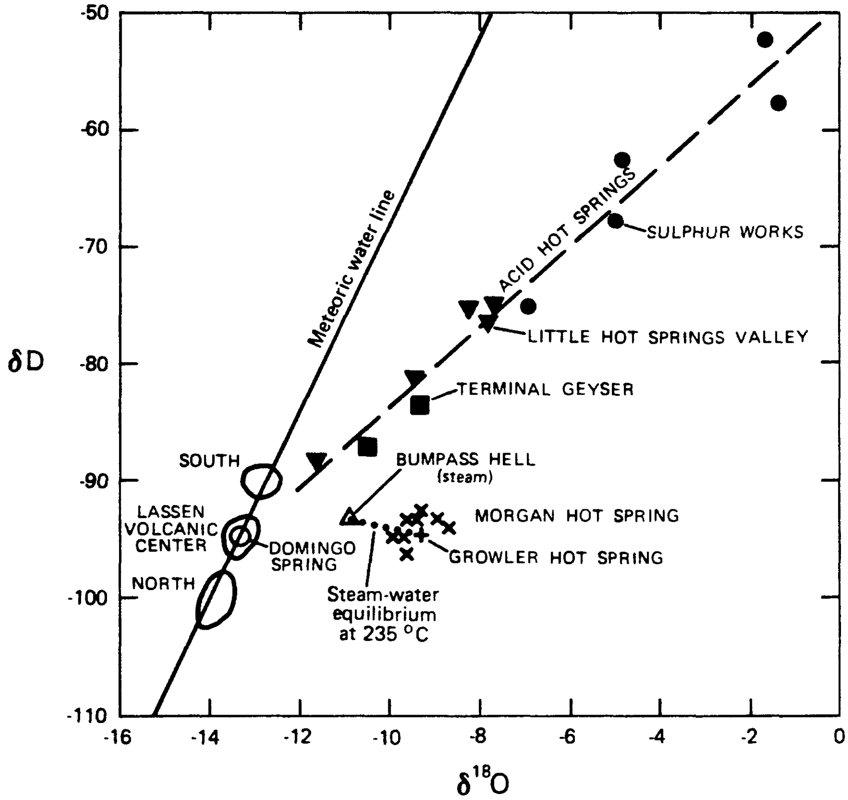

Figure 5. Diagram showing relationship between deuterium (D) and ^{18}O for water and steam samples from the Lassen region (adapted from Muffler and others, 1983; and Janik and others, 1983). Data for cold waters from the Lassen volcanic center and from areas to the north and south of the Lassen volcanic center fall within the areas outlined along the meteoric water line.

system but have thus far been restricted to the more accessible areas in the southernmost part of the Park (AMT surveys) and the Lassen KGRA (AMT surveys and heat-flow measurements). The low heat flow measured north of LVNP can be interpreted as being caused by regional ground water flow towards the springs at Rising River (Mase and others, 1982).

Relevant electrical data are contained in AMT maps at 7.5 and 27 hertz (Christopherson and Pringle, 1981). At 7.5 hertz the depth of penetration ranges from 600 - 2000 m and at 27 hertz it is about half as deep, depending on the resistance of the material. Areas of resistivity less than 16 ohm-meters are inferred to be underlain by thermal waters and/or hydrothermally altered rock. There are at least two such areas of low resistivtiy within LVNP that are suggestive of lateral flow of thermal water southward from Sulphur Works and southeastward from Drakesbad (figure 6). The network of AMT stations did not extend north of a line between Brokeoff Mountain and Drakesbad. Within the KGRA, the low resistivity zones south of Morgan Hot Spring, which are also discernable on the 7.5 hertz map, may be caused by water moving southward in aquifers at depths within those penetrated by these surveys. The AMT data show no evidence of high-temperature, high chloride water underlying the central part of the Lassen KGRA.

Temperature profiles and calculated heat flows for nine shallow holes (100 - 250 m deep) in Lassen KGRA were presented by Mase, Sass, and Lachenbruch (1980). Hole locations and heat-flow

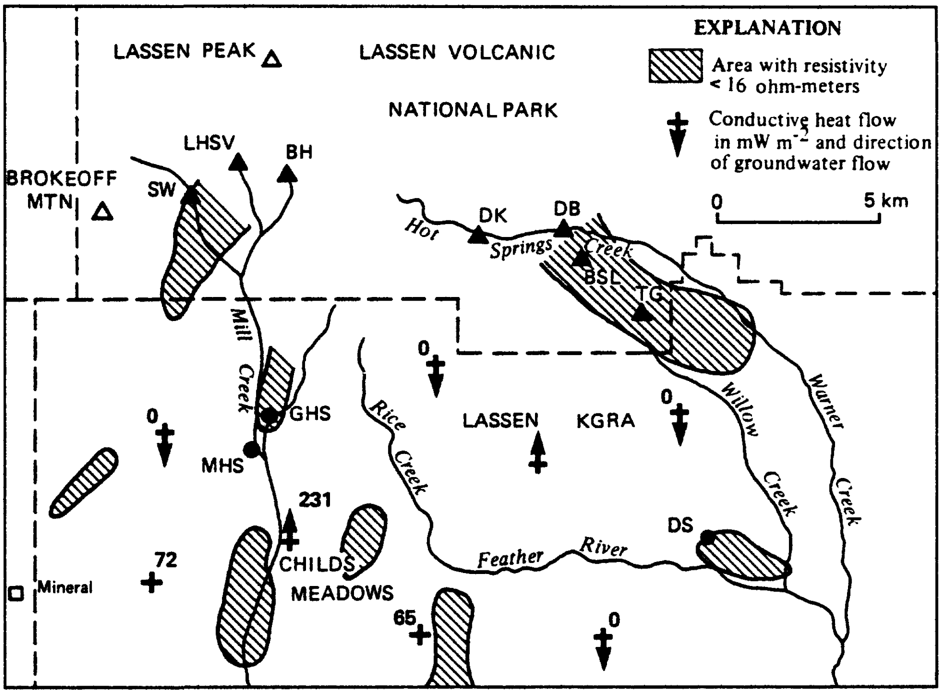

Figure 6. Map showing areas of apparent resistivity less than 16 ohm-meters, based on AMT map at 27 hertz and electric line oriented east-west (adapted from Christopherson and Pringle, 1981), and measured heat flow (Mase and others, 1980). Areas of thermal-fluid discharge are shown as triangles within LVNP and as dots within Lassen KGRA (see figure 4 for explanations of abbreviations used).

values are plotted in figure 6. For two of the holes, conductive gradients were interpreted to represent a regional heat flow of 65 - 75 mW m^{-2}. Downward arrows, shown for five of the holes drilled near topographic highs, signify that the measured gradients were affected by ground water downflow. Upward arrows, shown for two of the holes drilled in topographic lows, signify that the gradients were affected by ground water upflow. In one of the latter two holes, drilled at the northern end of Childs Meadows, the convective disturbance is minimal and the average gradient and conductive heat flow are near 90°C/km and 230 mW m^{-2}, respectively. This anomalously large heat flow may be caused by thermal water flowing southward in an aquifer at depths greater than 200 m beneath Mill Creek or Childs Meadows.

The only hole drilled deeper than 250 m in the Lassen region is the 1200 m-deep Walker "O" No. 1 well at Terminal Geyser. The temperature profile in this well measured 10 months after flow testing in 1979 (figure 7) shows a zone of constant temperature between 396 m and 655 m and a zone of cooler temperatures below 655 m. The chemical characteristics of fluids from this well and its temperature reversal with depth indicate that it is drawing from a reservoir of laterally flowing hot water.

The thermal regime below 1200 m near Terminal Geyser probably resembles the extrapolated temperature profile which joins the line with a slope of 50°C/km and a land surface intercept at 10°C. This represents a condition in which the regional heat flow is near that delineated for the KGRA and the thermal

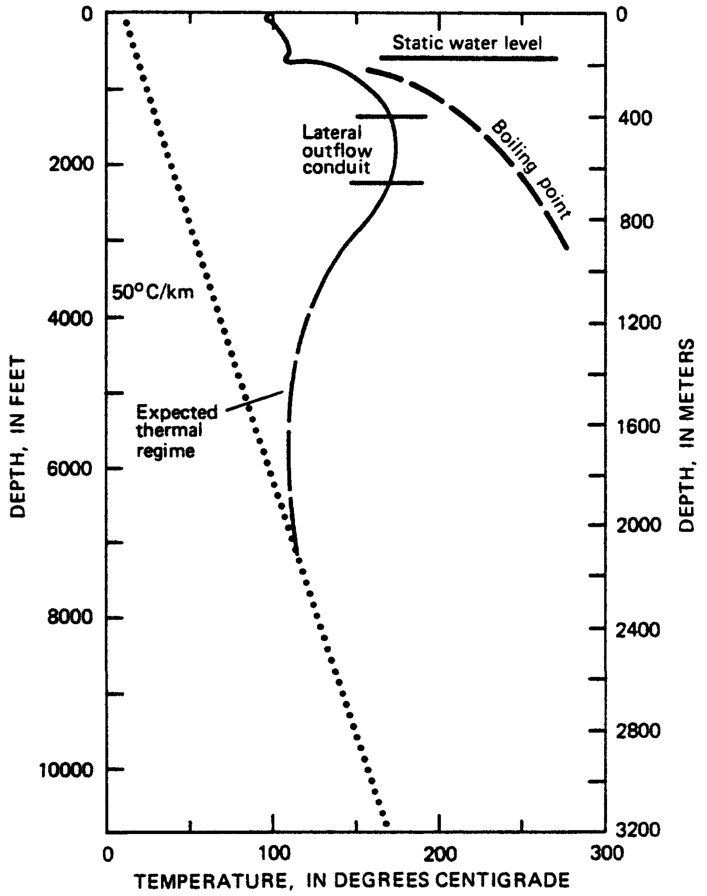

Figure 7. Measured temperature profile (solid curve) in the Walker "O" No. 1 well at Terminal Geyser, showing the position of an inferred lateral outflow conduit, and the extrapolated temperature profile (dashed curve) assuming a regional gradient of 50°C/km). Also shown is the position of the boiling-point curve referenced to static water level measured by Eureka Resources.

disturbance caused by the lateral flow of hot water at shallower depths has not penetrated below about 2 km.

The existence of a vapor zone at near-atmospheric pressures is indicated by the isothermal nature of the temperature profile above 400 m-depth, the relatively deep static water level, and the proximity of this well to the Terminal Geyser "drowned fumarole". As discussed above, geochemical evidence implies that such a vapor zone is not continuous westward to the Bumpass Hell area; it is more likely to result from localized boiling and phase separation above the hot-water reservoir. Between Drakesbad and Terminal Geyser this reservoir may be confined to the "Terminal Geyser Fault" zone, which could provide a permeable connection between volcanic rocks of different ages and compositions. The ultimate point(s) of discharge of this thermal water are speculative; the presence of chloride concentrations significantly above background levels in springs within the eastern half of the KGRA has been detected only at Domingo Spring.

Conceptual Model

The evidence discussed above is consistent with the generalized model for the Lassen system illustrated in figure 8. We refer to such systems as liquid-dominated hydrothermal systems with parasitic vapor-dominated zones. Other examples occur in geothermal areas with moderate to great topographic relief, such as the Valles Caldera in New Mexico and Tongonan in the

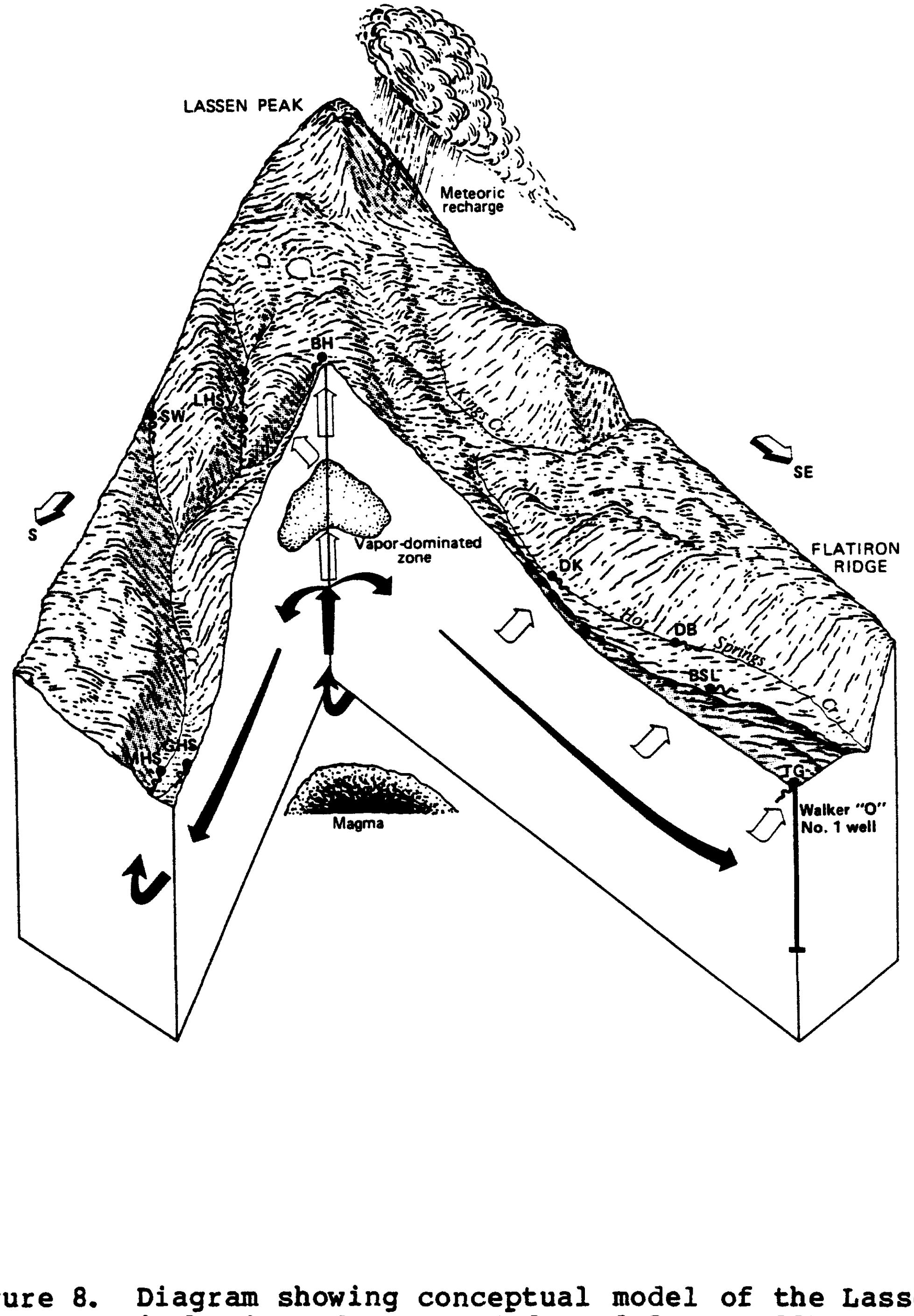

Figure 8. Diagram showing conceptual model of the Lassen hydrothermal system (adapted from Muffler and others, 1983). Zones of hot-water and steam flow shown by solid and open arrows, respectively.

Philippines (Grant, 1979). The essential feature of such systems is the separation of steam and liquid in the upflow zone, with steam rising through an overlying vapor-dominated zone and liquid flowing away laterally. This differs from a true vapor-dominated system such as The Geysers where the rate of fluid flow through the system is small and the vertical extent of vapor-dominated conditions is on the order of kilometers.

The conceptual model for the Lassen system involves recharge of meteoric water on the composite cone of the Lassen volcanic center, addition of heat to this fluid by conduction from a residual silicic magma chamber and possibly from small amounts of magmatic steam, and upwelling of high-enthalpy fluid within a central upflow zone. Lateral outflow from this central upflow zone feeds the surficial hydrothermal features, which lie along two orientations - Bumpass Hell to Morgan-Growler Hot Spring and Bumpass Hell to Terminal Geyser. Avenues of permeability for such upflow may be associated with contact zones between the older andesitic rocks and the younger dacitic intrusives. The discharge of steam and condensate from adjacent thermal areas at Bumpass Hell, Little Hot Springs Valley, and Sulphur Works may be fed by an areally extensive zone of upflow beneath the region encompassing these features, or by a less extensive zone of upflow from which steam and condensate flow through lateral conduits connecting one or more of these areas at relatively shallow depths. Another possibility is that Little Hot Springs Valley and Sulphur Works represent "satellite" parasitic vapor-dominated zones fed by a deeper lateral flow zone.

Within the central upflow zone, boiling commences when pressures reach saturation values for the existing fluid temperatures. Without avenues for lateral flow of liquid toward discharge areas at lower elevations, boiling would occur only near the land surface and discharge would occur as chloride hot springs. Remnants of sinter deposits at Devils Kitchen suggest that such discharge occurred during the past in areas currently characterized by steam and steam-heated discharge (L.J.P. Muffler, oral commun., 1982). However, if liquid can flow laterally away from the upflow zone, the phase separation depicted in figure 8 may occur. Within the vapor-dominated zone, steam is the pressure-controlling phase and the vertical pressure distribution is near vapor-static. Pressures in this zone are balanced by the weight of liquid in the overlying zone of steam condensate and shallow groundwater, although some excess pressure must exist to drive steam and steam-heated ground water through the condensate zone to the land surface.

The general pressure-depth relations for this model are shown in figure 9. The thickness of the vapor-dominated zone and pressures within it depend on the elevation difference between steam-heated and high-chloride discharge areas and on the pressure gradient required to drive the lateral outflow. The lateral pressure gradient is a function of the lateral flow rate and the permeability and geometry of the conduits transmitting

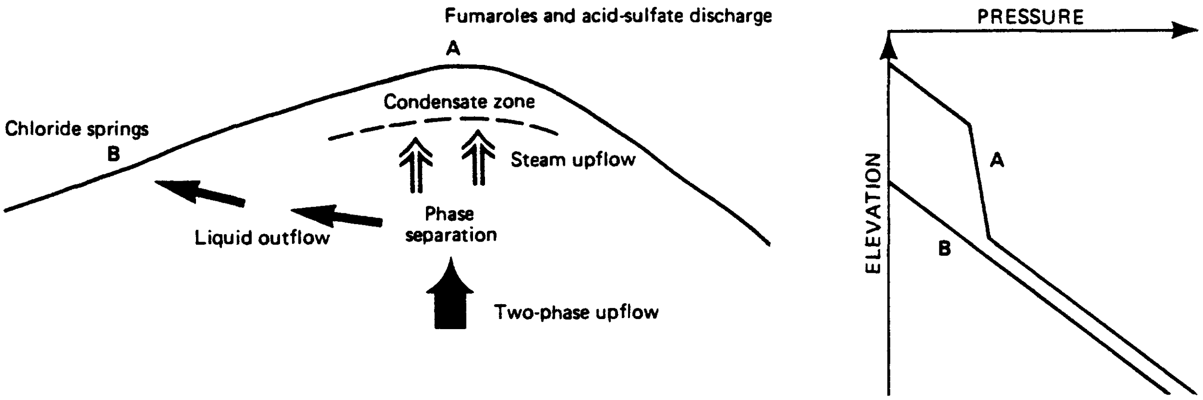

Figure 9. Diagram showing generalized pressure-elevation relations for liquid-dominated hydrothermal systems with parasitic vapor-dominated zones (after Grant, 1979).

this flow. Pressures at the base of the condensate layer are close to those within the vapor-dominated zone.

Quantitative constraints on the Lassen hydrothermal system are few. Calculations based on liquid and gas geothermometry and on the thermodynamic analysis of superheated steam at Bumpass Hell place pressures and temperatures in the central vapor-dominated zone within the ranges 31-34 bars and 235-240°C, respectively. If pressures in the condensate zone followed boiling point-depth relations from the land surface, the top of the vapor zone would be at a depth of about 350 m and at an elevation of 2150 m. The elevations of the hot springs in Mill Creek Canyon are near 1550 m, so the thickness of the inferred vapor zone may be approximately 600 m. Temperatures in the lateral flow conduits decrease away from the upflow zone owing to conductive heat loss. Such loss is affected by fluid flow rates, the depth of the conduits, and the length of time lateral flow has been taking place. Between Bumpass Hell and Terminal Geyser, temperatures in the lateral flow conduit apparently decrease from 240°C to 176°C, while the temperature decrease between Bumpass Hell and Morgan and Growler Hot Spring is such that conduit temperatures beneath the hot springs are equal to or greater than the measured spring temperatures (≥95 °C).

The available data suggest that areally restricted zones of lateral flow are oriented between the central upflow zone beneath Bumpass Hell and the Growler-Morgan Hot Springs area and between Bumpass Hell and the Terminal Geyser area. Thermal discharge features are confined to these orientations, and the resistivity data from the Lassen KGRA and the southernmost part of LVNP (figure 6) are also consistent with this interpretation. Extension of the Bumpass Hell to Terminal Geyser flow zone to Domingo Spring seems reasonable. However, to delineate the geometry of permeable conduits within these flow zones and to assess the possibility of a more extensive reservoir of thermal fluid beneath the Lassen KGRA, deeper and more extensive drilling is required. Possible candidates for such conduits include fault zones (such as extension of the "Terminal Geyser Fault"), brecciated zones between different flows from the Lassen volcanic center, and fracture zones related to cooling or preexisting zones of weakness.

The additional constraints needed to obtain estimates of hydraulic properties of conduits for lateral and vertical flow from modeling simulations are provided by measurements of the rate of discharge of thermal water at the land surface. Calculations of chloride flux in Mill Creek, Canyon Creek, and at Domingo Spring, discussed in the next section of this report, indicate that the total surficial discharge of thermal water in these areas is near 17 kg/s. Fluid discharge from areas of fumaroles and acidic hot springs within LVNP is more difficult to quantify, but should be of lesser magnitude than the mass flow of high-chloride hot springs.

MEASUREMENTS OF THERMAL FLUID DISCHARGE

A set of measurements of streamflow and chloride concentration in Mill Creek, Canyon Creek, and at Domingo Spring was obtained in August, 1983, in order to estimate the discharge of high-chloride thermal water within Lassen KGRA. Such measurements are necessary in areas where hot-spring discharge is hard to gage directly or where a large fraction of the thermal discharge occurs as seepage into streams. Additional streamflow measurements and samples for chemical analysis were obtained at Sulphur Works and Bumpass Hell to allow the sulfate flux from steam-heated springs in these areas to be estimated.

Mill Creek Canyon

Streamflow was gaged at four sites on Mill Creek, at one site on a tributary that flows into Mill Creek from Morgan Mountain, and at three sites on Canyon Creek. Site locations are shown in figure 10. Current-meter velocity measurements and discharge calculations were made by W. F. Shelton of the Redding Field Office, Water Resources Division, USGS, and an integrated water sample for chemical analysis was obtained at each site using a churn splitter. Chloride concentrations in each sample were determined by J. M. Thompson in Menlo Park (USGS, Geologic Division).

Measured streamflow, temperature, and chloride concentration and calculated chloride flux and seepage are listed in table 3 for

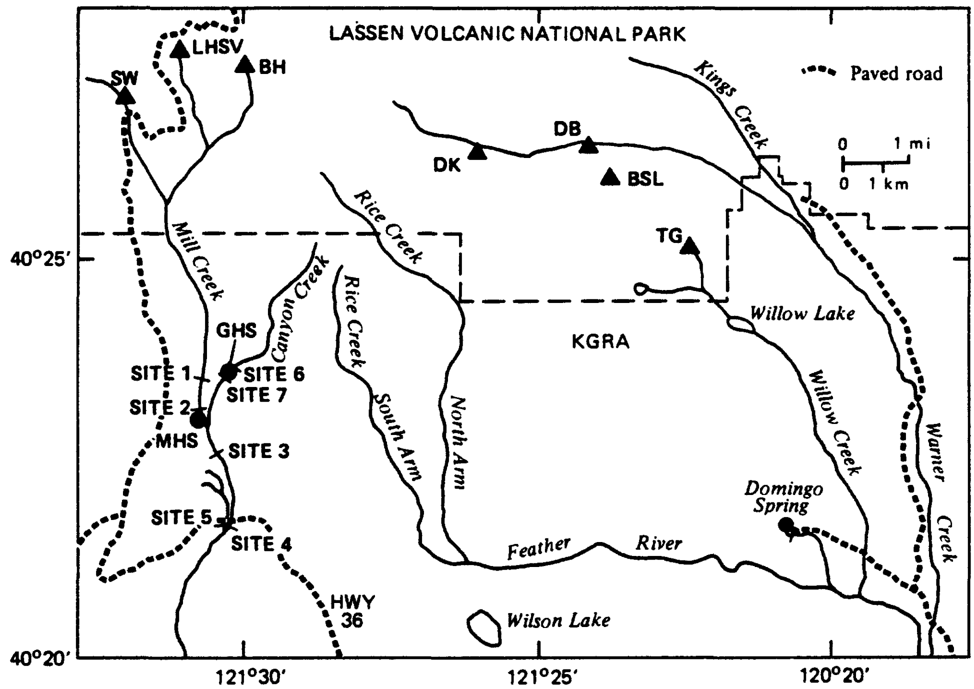

Figure 10. Map showing locations of sites where stream gaging and water sampling were carried out in order to estimate the discharge of thermal water within Lassen KGRA. Sites indicated by bar across stream (see table 3 for data on each numbered site). Areas of hot springs and fumaroles within LVNP and within Lassen KGRA shown as triangles and dots, respectively (see figure 4 for explanations of abbreviations used).

Table 3. Measured streamflow, temperature, and chloride concentration and calculated chloride flux and thermal water inflow to Mill Creek and Canyon Creek within Lassen KGRA.

	Site Location	Date/Time	Streamflow L/s (rating)*	Temp. °C	Chloride mg/L	Chloride flux g/s	Thermal water inflow** L/s
1.	Mill Ck. 0.6 miles above bridge in Morgan Meadow	8/4/83 1015-1050	4,020 (poor)	10	0	0	0
2.	Mill Ck. 75 ft below bridge in Morgan Meadow	8/4/83 0830-0910	4,080 (fair)	8	1.7	6.93	3.1
3.	Mill Ck. 0.5 mi below confluence with Canyon Creek	8/4/83 0745-0810	4,590 (fair)	8	6.9	31.7	14.2
4.	Mill Ck. 100 ft below bridge at Highway 36	8/4/83 0630-0700	4,840 (good-fair)	7	6.4	31.0	13.9
5.	Mill Ck. tributary from Morgan Mt. at Hwy. 36	8/4/83 1230-1300	85 (fair)	20	68	5.78	2.6
6.	Canyon Ck. 150 ft above Growler Hot Spring	8/2/83 1345-1415	306 (good)	14	0	0	0
7.	Canyon Ck. 100 ft below Growler Hot Spring	8/2/83 1300-1330	295 (fair-poor)	14	9.1	2.68	1.2
8.	Canyon Ck. 0.3 mi above confluence with Mill Creek	8/4/83 1130-1210	292 (good)	14	21	6.13	2.6

*Accuracy rating (see text for corresponding error ranges).

**Calculated as chloride flux / 2,230 mg/L for Mill Creek (based on the average chloride concentration in springs at Morgan Hot Spring) and as chloride flux / 2,320 mg/L for Canyon Creek (based on the average chloride concentration in springs at Growler Hot Spring).

the sites along Mill Creek and Canyon Creek. Error ranges assigned to the ratings good, fair, and poor are ± 5 percent, ± 8 percent, and ± 10 percent, respectively. Measurement accuracy at these sites is affected by the rocky nature of the streambeds and the rather high stream stages. Along Mill Creek, the increase in measured flow between sites 2 and 3 is caused by addition of tributary inflow. Along Canyon Creek, the apparent decrease in flow between upstream and downstream sites may be caused by loss of water to bank storage or ground water recharge, although differences in the measured flow may not be significant.

Chloride flux at each site was calculated by multiplying measured stream flow by chloride concentration in the stream. Chloride flux is seen to increase along Mill Creek between sites 1 and 3 and to remain constant between sites 3 and 4. Along Canyon Creek, chloride flux increases monotonically between sites 6 and 8. Increases in chloride flux result from addition of high-chloride thermal water from hot spring inflow and streambed seepage. The total rate of inflow of thermal water above each measuring site is estimated by dividing the chloride flux by the assumed chloride concentrations in thermal waters.

The data in table 3 show that the total rate of inflow of thermal water along Mill Creek above the bridge at Highway 36 is approximately 14 L/s, and that the total rate of inflow of thermal water along Canyon Creek is about 3 L/s. Subtracting the flow of thermal water in Canyon Creek from the Mill Creek total yields an estimate of 11 L/s for thermal water inflow from the Morgan Hot Spring area. For comparison, Thompson (1983) listed the estimated flow from springs at Morgan Hot Spring as 1.1 L/s and the flow from the main vent at Growler Hot Spring as averaging 0.25 L/s. In both cases, estimates based on the chloride-flux measurements are an order of magnitude greater than the totals for individual springs, presumably because of the addition of thermal water directly into the beds of these streams.

The relatively high estimated chloride flux at site 5 on the Mill Creek tributary at Highway 36 reflects the addition of thermal water from a ditch that carries water southward from a hot spring above the swimming pool in Morgan Meadow. This contribution (2.6 L/s) brings the estimated total discharge of thermal water in Mill Creek Canyon to 17 L/s. There may also be an undetected flow of thermal water in the ground water system southwestward from Highway 36 beneath Mill Creek and southeastward beneath Childs Meadow, as suggested by the high temperature gradient noted previously for the heat-flow hole at the northern end of Childs Meadow and by the areas of low resistivity shown in figure 6.

Domingo Spring

Measured chloride concentrations in waters issuing at Domingo Spring at 8^{o} - $10^{o}C$ are near 20 mg/L. This concentration is approximately ten times greater than chloride concentrations in other cold springs in the Lassen region, suggesting a component of high-chloride thermal water in springs at Domingo. These springs issue from Dittmar volcanics, near the southern-most contact with the younger volcanic rocks associated with Red Mountain. Approximately 5 miles to the northwest, the "Terminal Geyser Fault" intersects the Dittmar volcanic rocks and may provide a conduit for lateral flow of high-chloride thermal ground water at temperatures near 180°C. Comparison of the chloride concentration in waters from Domingo Spring with that in fluid produced from the Walker "O" No. 1 well at Terminal Geyser, implies a ratio of thermal to non-thermal water in this spring of 1 to 100. The measured total flow of springs at Domingo on August 3, 1983 at 1630 hrs was 266 L/s with an accuracy rating of fair. The calculated thermal component would then be 2.7 L/s. Although chloride concentrations in other cold springs in this area are near background levels, additional thermal water may flow from the Dittmar volcanics into the North Fork of the Feather River and Warner Creek. High flow rates in these streams would probably preclude detection of such a thermal component.

Thermal Areas Within LVNP

The total discharge of fluids from thermal areas within LVNP cannot be determined by the same seepage technique because of the loss of steam in fumaroles and the lack of conservative elements such as chloride in the steam-heated springs. However, measurements of the flux of sulfate ions in streams draining such areas may prove useful in estimating the total flow of condensed steam contained within the steam-heated springs. These springs may contain both condensed steam (high in sulfate) and shallow ground water (presumably low in sulfate). From such measurements and the estimated ratio of H_2S to steam in the upflow from the underlying vapor-dominated zone, the fraction of this upflow that condenses in the hot-spring waters can be estimated, by assuming that H_2S is completely converted to sulfate and that sulfate is not stored locally. However, local storage of sulfur as sulfate or at intermediate oxidation states (pyrite, native sulfur) is an important complicating factor. Significant amounts of pyrite and native sulfur accumulate in the acid-sulfate discharge areas, and are eventually oxidized and flushed out by rainfall or snowmelt. Therefore, a series of repeat measurements is necesssary to obtain a more reliable estimate of condensed steam discharge. Potentially, periodic measurements of the sulfate flux from areas such as Bumpass Hell and Sulphur Works might be used in conjunction with sulfur isotope analyses to delineate the degree of natural variability in condensed steam discharge and to detect changes in steam upflow.

At Sulphur Works, the measured streamflow and temperature in the north fork of West Sulphur Creek at the upstream end of the culvert under Highway 89 were 280 L/s and 6°C at 1000 hrs on August 3, 1983. At this time the 1-m diameter culvert was half full of water. The quality of this measurement was rated poor because of the degree of turbulence in the flow. Measurement accuracy should improve at lower flows and can be checked with additional measurements at the downstream end of the culvert. The sulfate concentration in the sample collected at the culvert was 13 mg/L. A secondary site for future gaging and sampling of more concentrated effluent was also selected. This point, where flow from the southeastern part of the thermal area passes through two metal drain pipes, is approximately 30 m up the foot path from the highway to the thermal area. Repair or replacement of these pipes, whose bottoms have been partially destroyed by sulfuric acid, will be required before discharge measurements can be made.

At Bumpass Hell, streamflow was measured and a sample was collected in the west fork of East Sulphur Creek at a site 20 m downstream from the foot bridge. The measured flow at 1220 hrs on August 3, 1983, was 57 L/s with a rating of good, and the measured temperature was 31°C. Sulfate concentration in the water from this site was 68 mg/L. Inspection of this channel and the one gaged at Sulphur Works indicates that installation of a flow-measuring structure (such as a weir or flume) would be difficult because of the steep, rocky nature of these streambeds.

To apply the method suggested above for estimating the discharge of condensed steam at Bumpass Hell and Sulphur Works, we use a molar ratio of H_2S to steam in the vapor-dominated zone of 0.0008 (Muffler and others, 1982). We then calculate that 1 mole of dissolved sulphate is derived from 1,250 moles of condensed steam. On a mass basis this converts to 232 mg of condensed steam for each 1 mg of dissolved sulfate. Multiplying the measured sulfate flux in milligrams per second by 232 yields an estimate of the flow of steam from the vapor-dominated zone that is condensed in the hot springs.

The estimated sulfate flux in the stream draining Bumpass Hell is 3900 mg/s, and the corresponding estimate for Sulphur Works is 3700 mg/s. The calculated discharge of steam condensate at each area is approximately 0.9 kg/s.

EVOLUTION SIMULATIONS

Numerical simulations of the evolution of the present-day Lassen hydrothermal system were used to provide estimates of rock properties and boundary conditions controlling heat and fluid flow and to generate initial conditions for subsequent simulations of the effects of fluid withdrawal on surficial thermal features. The basis for this analysis is the conceptual model illustrated in figure 8.

Numerical Model

The geometric configuration modeled in these simulations is shown in figure 11. It consists of a vertical slab of uniform width with a sloping upper boundary representing land-surface elevations between Bumpass Hell and Morgan and Growler Hot Spring. Fluid circulation is confined to the vertical conduits along the sides of the model and to the 200 m-thick lateral conduit. Circulation is driven by a specified mass inflow of hot water at the lower right, and discharge occurs at the upper right and left sides of the model. Along the base, a conductive heat flux of 85 mW m^{-2} was specified to represent the regional heat flow. With reference to the conceptual model shown in figure 8, the numerical model is restricted to the regions of upflow and lateral outflow and does not include the regions of downflow and magmatic heating.

A two-dimensional model was chosen in part because of computational difficulties and expense involved in three-

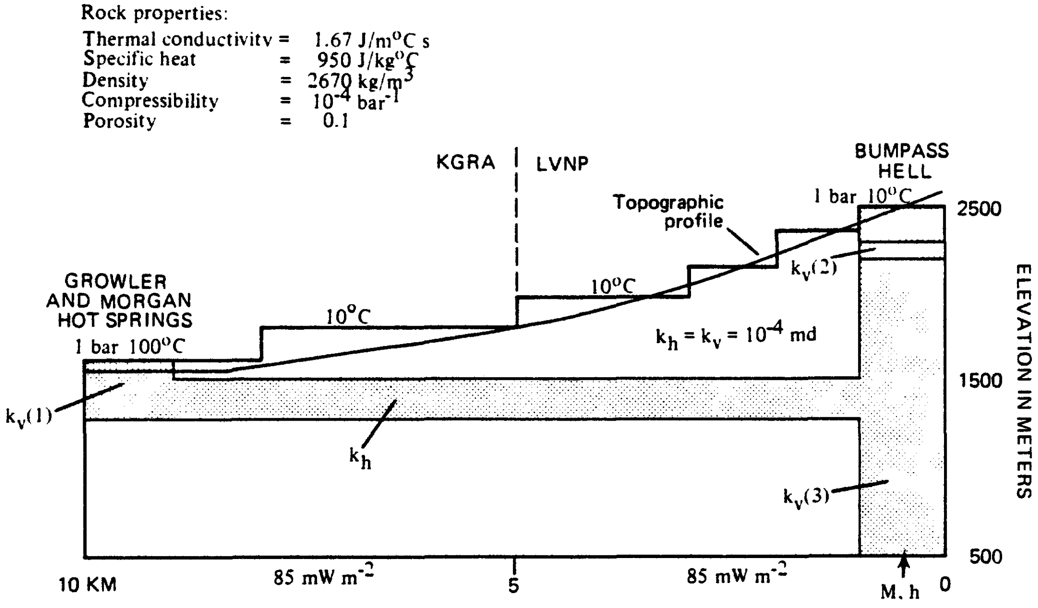

Figure 11. Diagram showing geometric model used in simulations of the Lassen hydrothermal system. Arrow indicates inflow of hot water with mass flow rate M and enthalpy h. Fluid flow is essentially confined to regions shown with dotted pattern. Upper rectangular boundary represents an approximation to the land surface profile between Bumpass Hell and Morgan-Growler Hot springs. Horizontal and vertical intrinsic permeabilities indicated by symbols k_h and k_v, respectively.

dimensional simulations of multiphase flow over geologic time periods. In addition, the lack of quantitative information regarding rock and fluid properties within the Lassen system does not justify using a more detailed model. The available data suggest there are two areally restricted flow regimes originating in the central upflow zone beneath Bumpass Hell. Our model corresponds to the southward-trending flow axis from which the discharge of high-chloride thermal water is reasonably well constrained (Bumpass Hell to Growler and Morgan Hot Springs). Inclusion of the southeastward-trending axis in the model would have added useful constraints provided by the known temperature and elevation of the lateral conduit beneath Terminal Geyser. However, excluding this part of the flow system saves considerably on computational requirements and should not alter the basic conclusions derived from these simulations.

For simplicity, the lateral conduit is assumed to be a horizontal stratum, 200 m in thickness, with its base at an elevation of 1300 m. These values were selected in part because they match those for the hot-water aquifer penetrated in the Walker "O" No. 1 well (figure 7). Constraints provided by the estimated vapor-dominated zone pressure of 31-34 bars and by the need for a pressure gradient within the conduit sufficient to drive the lateral outflow indicate that the lowest possible elevation for the base of such a conduit is about 1200 m, whether the conduit is horizontal or sloping.

The model width is 1 km, a value close to the average width of the glacially eroded Mill Creek Canyon. The rationale for this correspondence is the possibility that the width of the canyon is controlled by a zone of weakness associated with a structurally controlled fracture or fault zone. Alternatively, this conduit could represent a stratigraphic unit, such as a contact zone between successive flows from the Lassen volcanic center, and hence be thinner but more areally extensive than assumed here. Results from the numerical simulations depend to some extent on the conduit geometry used in the model, as discussed below.

A 10 by 13 array of variably spaced grid blocks was utilized for numerical solutions of heat and fluid flow in this model. This yielded an approximation to the actual land-surface topography, as shown in figure 11. The computer code used is a modified version of a three-dimensional, two-phase fluid and heat transport program described by Faust and Mercer (1979) and used in a recent analysis of the effects of potential geothermal development in the Valles Caldera (Faust, Mercer, and Thomas, 1983). With this program, solutions for fluid pressure and enthalpy at selected times are obtained by finite-difference techniques. Saturation and rock-fluid temperature solutions are obtained from the calculated pressures and enthalpies. Modifications to the original code were needed to improve the scheme for upstream weighting of fluid properties and relative permeabilities and to allow conductive heat flux to be specified as a boundary condition (Ingebritsen, 1983). Numerical simulations of the evolution of the Lassen system are made more difficult by the need for relatively small time steps during periods of transition from single to two-phase flow within total simulation times on the order of 10,000 years.

Evolution Processes

Evolution of the Lassen hydrothermal system is likely to have begun with a period in which mineralized hot water discharged at the land surface above the main region of upflow. This would have caused rock-fluid temperatures in the upflow zone to increase to levels such that vapor-dominated conditions could develop if pressures were subsequently reduced. During or some time after this period of upflow, deposition of silicate and carbonate minerals at shallow depths may have occurred to a degree sufficient to produce a caprock of low permeability. Such a feature is necessary to restrict inflow of cooler water during the depressurization and draining of liquid that accompanies the development of a vapor-dominated zone.

A parasitic vapor-dominated zone can develop below this caprock by several mechanisms that initiate a reversal in the direction of liquid flow, allowing water to drain from beneath the caprock as pressures are lowered to saturation levels and steam replaces liquid. Associated with each mechanism is lateral flow of thermal water away from the upflow zone toward discharge areas at lower elevations. For drainage to occur, the rate of outflow in the lateral conduit must exceed the rate of mass inflow to the system for some period of time.

Mechanisms considered in this study for inducing such a drainage process included: (1) an increase in the permeability of the lateral conduit; (2) a decrease in the rate of inflow to a value less than the flow rate established in the lateral conduit; (3) a lowering of the elevation of the hot-spring outlet, causing an increase in the lateral pressure gradient; (4) a gradual decrease in fluid viscosity as hot water flows away from the upflow zone and heats up the lateral conduit. Each of these mechanisms appears geologically or hydrologically plausible, but one or more could be considered more likely to have occurred in specific systems of this type.

Numerical simulations of the evolution of the Lassen hydrothermal system were continued until the pressure distribution reached conditions similar to those in figure 9, with pressures in the 31-34 bar range in the vapor-dominated zone, and temperatures in the lateral conduit had become relatively stable (changing less than 1°C per 1,000 years). The desired temperature and pressure distributions in the lateral conduit at this quasi-steady state condition were constrained only by the requirement that conduit temperatures at the left side of the model be above the surface boiling point of 95°C. Note that this condition is approximated by specifying a land-surface temperature of 100°C at the left side of the model. Factors affecting the simulated end-point conditions include the mass inflow rate M, inflow enthalpy h, horizontal and vertical permeabilities k_h and k_v, and the relative permeability-liquid saturation functions. Lack of information on values of most of these parameters and the complex interactions between thermodynamic and hydraulic processes in these simulations made considerable experimentation necessary to obtain combinations of parameter values that would produce the desired results.

Numerical Results

Typical results of simulations of the evolution of the Lassen hydrothermal system are shown in figures 12 and 13, for a case in which mechanism (1) was invoked after approximately 2100 years of upflow with no lateral flow. At this point, the permeability of the lateral conduit was increased from zero to 140 md. Values of other parameters used in this simulation are listed below.

$M = 20$ kg/s

$h = 1{,}125$ J/gm ($258^{\circ}C$)

$k_v(1) = 100$ md $= 1 \times 10^{-9}$ cm^2

$k_v(2) = 0.05$ md

$k_v(3) = 100$ md

$k_{rl} = [(S - 0.3)/0.65]^4$

$k_{rs} = [1-(S-0.3)/0.65]^2 \times [(1-(S-0.3)^2)/0.4225]$

where k_{rl} = liquid relative permeability, k_{rs} = steam relative permeability, S = liquid saturation, and the other terms are defined in figure 11. The initial temperature distribution corresponds to a uniform conductive heat input of 85 mW m^{-2}, and the initial pressures vary hydrostatically with depth (figures 12a and 13).

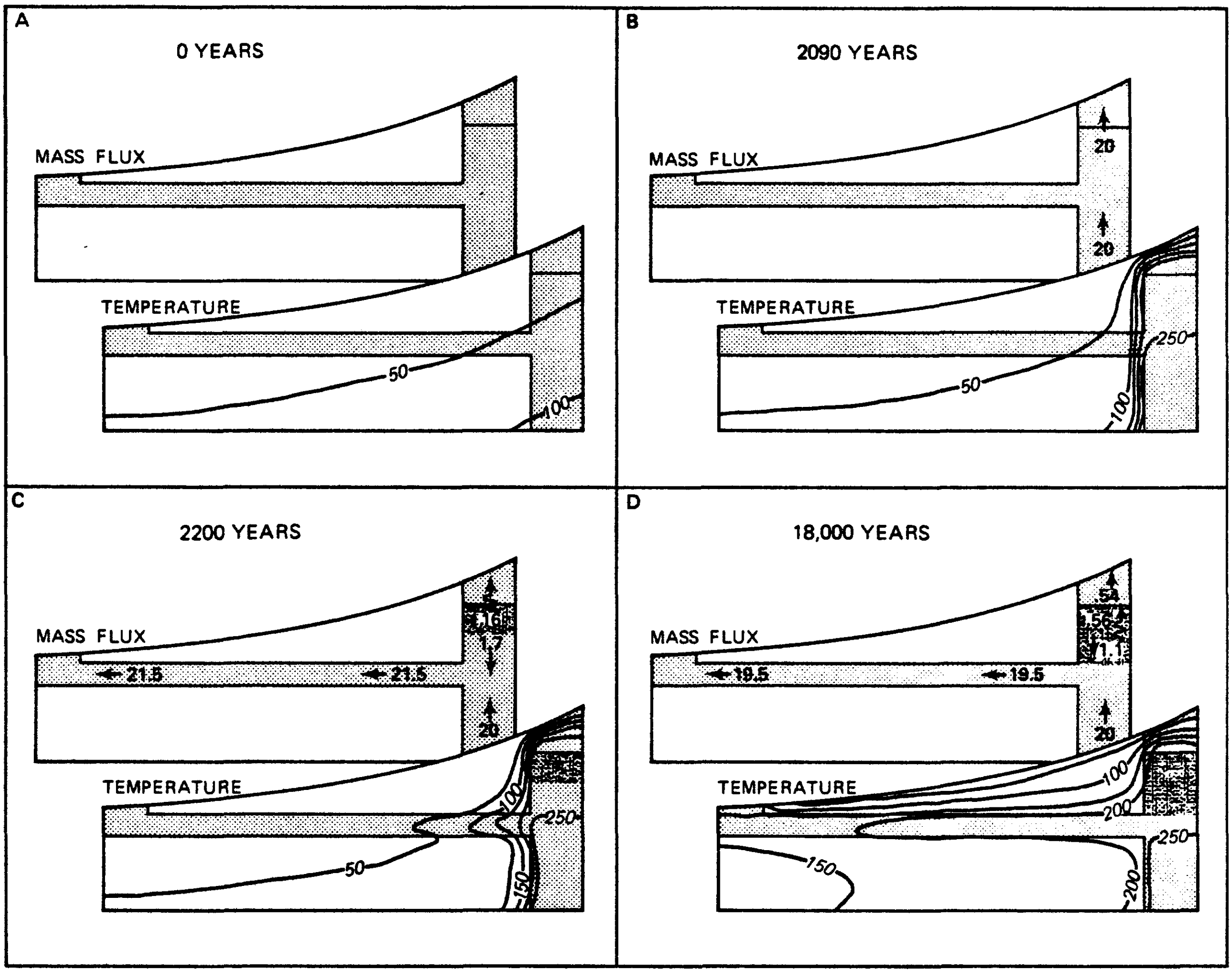

Figure 12. Diagrams showing mass flow vectors (straight arrows for liquid, wavy arrows for steam) and temperature distributions at selected times since upflow begins during evolution of a liquid-dominated hydrothermal system with a parasitic vapor-dominated zone. Mass input at lower-right corner set at 20 kg/s with enthalpy = 1,125 J/g (258°C). Permeability of lateral conduit increased from zero to 1.4 x 10^{-9} cm^2 at a simulation time of 2,090 years. Dotted pattern represents the region of vapor-dominated conditions.

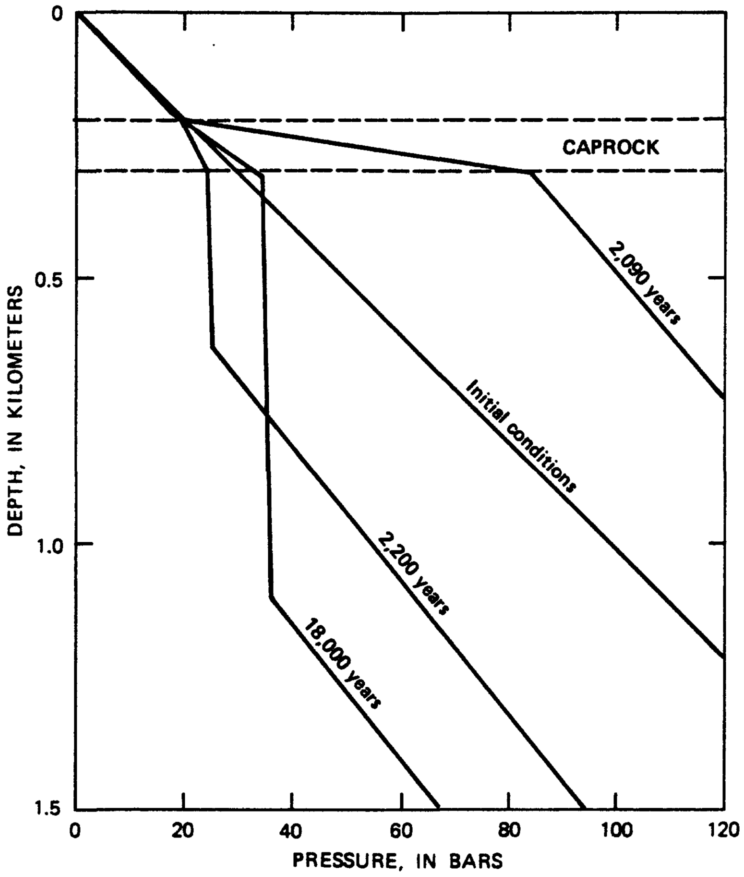

Figure 13. Diagram showing pressure profiles in the upflow column during evolution of a liquid-dominated hydrothermal system with a parasitic vapor-dominated zone. Profiles shown for a case in which lateral flow is initiated at 2,090 years by increasing the permeability of the lateral conduit (as in figure 12).

The upper part of the upflow conduit below the caprock layer is heated to temperatures of more than 200°C during the initial period of upflow with no lateral flow. One hundred and ten years after lateral flow is initiated (figure 12c), a vapor-dominated zone has begun to develop beneath the caprock layer as liquid drains toward the lateral conduit. The corresponding pressure distribution in this region is close to vapor-static, with pressures controlled mainly by the temperatures prevailing when drainage commences. Drainage continues for another 1,400 years until the vapor-dominated zone extends to the top of the lateral conduit. Subsequently, steam pressures slowly increase as liquid saturation decreases in the underlying two-phase region and the rate of steam upflow increases. Final pressures in the vapor zone in this case are near 34 bars. Temperatures in the lateral conduit increase slowly throughout the simulation as the hot-water front moves toward the low-elevation end of the model. Approximately 18,000 years are required for temperatures near the discharge end to rise to quasi-steady-state values of about 170°C.

Mass flow vectors at quasi-steady-state indicate a counterflow of liquid and steam within the vapor-dominated zone, with a net upflow of 0.54 kg/s. At the base of the caprock layer, some steam condenses and flows downward while the remainder flows into the caprock layer where it condenses before rising to the land surface. Note that in this simulation the net rate of upflow through the vapor and condensate zones is only about 3 percent of the lateral outflow rate. As discussed below, several factors influence the ratio of steam upflow to lateral outflow, including the mass inflow rate and enthalpy, the permeability of the caprock, and the form of the relative permeability functions.

The temperature distribution above and below the lateral conduit (figure 12d) shows the effects of conductive heat loss from the lens of hot water in the conduit. The time required to reach quasi-steady-state is controlled mainly by the lateral flow velocities and the thickness and thermal conductivity of the rock above the conduit. The greater the average velocity, the shorter the equilibration time and the higher the resultant quasi-steady-state temperatures along the conduit. For example, decreasing the inflow rate M from 20 kg/s to 10 kg/s changes the average lateral velocity by roughly the same factor and results in an equilibration time of 23,000 years and a conduit temperature at the left side of the model of about 100°C (Ingebritsen, 1983). If the average lateral velocity were halved by doubling the cross-sectional area of the conduit while keeping M = 20 kg/s, similar effects on the equilibration time and conduit temperature would have been observed.

Travel times for fluid flow between the upflow zone and the discharge end of the model under quasi-steady-state conditions can be calculated from the equation

$$t = \frac{A \bar{\rho} L \phi}{Q} \qquad (1)$$

where t = travel time in the lateral conduit, A = cross-sectional area of the conduit, $\bar{\rho}$ = average fluid density, L = length of conduit, ϕ = conduit porosity (0.1 in all simulations), and Q = mass flowrate in conduit (approximately equal to inflow rate M). For M = 20 kg/s, t = 240 years and for M = 10 kg/s, t = 500 years. For flow through a lateral conduit between Bumpass Hell and Terminal Geyser, a travel time of 180 years is calculated from (1), assuming a mass flow of 3 kg/s (the estimated thermal component at Domingo Spring), a conduit area of 200 m by 100 m, and a porosity of 0.1.

One particularly useful result of our simulations of the evolution of the Lassen hydrothermal system is the delineation of a relatively narrow range for possible values of the product of permeability and cross-sectional area of the southward-trending lateral-flow conduit. Necessary constraints are provided by the estimated pressure of 31-34 bars in the vapor-dominated zone and by the estimate from chloride flux measurements of approximately 20 kg/s for the total mass flowrate along this conduit. Simulations that yielded quasi-steady-state conditions matching these constraints provided estimates of k_h applicable to the conduit geometry used in the model. For the simulation illustrated in figures 12 and 13, the value of k_h is 140 md.

Two additional factors influencing the determination of conduit permeability are the possible presence of two-phase conditions in the conduit away (downstream) from the upflow zone, and the value of vertical permeability below the hot-spring discharge boundary ($k_v(1)$). For the simulation illustrated in figure 12d, two-phase flow extends about 4 km downstream from the upflow zone, and within this region the relative permeability to liquid averages about 0.35. Additional simulations with a much lower value of vertical permeability below the hot-spring discharge boundary ($k_v(1) = 0.6$ md) resulted in higher pressures and a reduced pressure gradient within the lateral conduit, and the absence of two-phase flow except immediately below the vapor-dominated zone. Fortuitously, the resulting increase in relative permeability to liquid is such that the value of k_h required to transmit the mass flowrate is only slightly greater (180 millidarcys). The presence or absence of an extensive two-phase region in the lateral conduit would have a strong influence on the rate of propogation of pressure changes induced by fluid withdrawal for geothermal development and is therefore an important feature of the Lassen hydrothermal system yet to be delineated.

The simulated net rate of upflow of steam within the vapor-dominated zone under quasi-steady-state conditions depends primarily on the value of caprock permeability ($k_v(2)$). Steam upflow increases as the caprock permeability is made greater. For example, the net rate of upflow for the simulation illustrated in figure 12d (for which $k_v(2) = 0.05$ md) is about 0.55 kg/s, whereas a simulation using $k_v(2) = 0.25$ md resulted in a net upflow of 1.4 kg/s. For values of caprock-layer permeability exceeding about 0.25 md, the rate of drainage of liquid across this layer prevented the development of a vapor-dominated zone in our model. Conversely, for values of $k_v(2)$ less than about 0.05 md, net rate of upflow from the vapor-dominated zone at quasi-steady-state becomes unrealistically low if pressures in the vapor-dominated zone are required to be in the range of 31-34 bars. Thus the range of values of caprock permeability for which the Lassen system could have evolved is reasonably well constrained.

Upflow above the caprock layer in our model becomes single-phase liquid, as temperatures drop and steam condenses. The net mass upflow of steam through the vapor-dominated zone is balanced by the mass upflow of liquid across the land surface, which represents the discharge of steam and steam condensate above the central vapor-dominated zone. Real-world complications involving separate channels for steam and liquid flow within the condensate zone are neglected in this model.

Two sets of relative permeability - saturation functions were used in these simulations in order to evaluate the effects of relative permeability on the natural state of the Lassen system and its response to development. The Corey functions listed above were developed for problems involving two-phase flow through porous media and are commonly used in geothermal reservoir engineering analyses. The other set of functions used in this study may be more applicable to two-phase flow through fractured media because they yield greater values of steam relative permeability (Sorey, Grant, and Bradford, 1980). These "fracture-flow" equations are listed below.

$$k_{rl} = [(S - 0.3)/0.65]^4$$

$$k_{rs} = 1 - k_{rl}$$

The final issue to be discussed with respect to simulations of the evolution of the Lassen hydrothermal system is that of the hydrogeologic mechanisms initiating this evolution. As noted previously, the results illustrated in figures 12 and 13 apply to mechanism (1), the increase in permeability of the lateral conduit. A slight variation of this mechanism that would yield similar results would be an increase in vertical permeability beneath the hot-spring discharge boundary. Such a change in permeability could result from tectonic activity or glacial erosion. Because total simulation times are on the order of 10,000 years, these changes could take place gradually without significantly altering the quasi-steady-state results.

Simulations involving mechanism (2), a decrease in the inflow rate M, yielded results similar to those in figures 12 and 13 except that quasi-steady-state conditions took about 25 percent less time to develop after drainage was initiated (Ingebritsen, 1983). This was because the lateral conduit was effectively preheated during an initial period with both upflow and lateral outflow. A decrease in high-enthalpy inflow during the evolution of the Lassen system could have resulted from some combination of (a) long-term changes in climate that caused a reduction in the rate of meteroic water recharge to the system, (b) diminution in the conductive heat input from a cooling magma body which reduced fluid temperatures at depth and fluid density differences driving the circulation system, and (c) sealing of flow conduits at depth due to mineral deposition.

Mechanism (3), a lowering of the elevation at which high-chloride thermal water discharges, was not simulated, but may have been involved to some extent in the development of the part of the Lassen system beneath the glacially eroded Mill Creek Canyon. For glacial action to effect such a lowering, the system must have been active before the end of the last major glacial period (10,000 years ago). This mechanism appears to have been effective in a related situation at the Valles Caldera, where high-chloride water discharges within the fault-controlled San Diego Canyon and evidence of a gradual lowering of the elevation of hot-spring discharge of about 200 m is preserved by travertine deposits on a granitic intrusive at Soda Dam (Frank Trainer, oral commun., 1983).

Mechanism (4) does not involve any change in rock properties or boundary conditions; it involves only the decrease in fluid viscosity that occurs as the lateral conduit is heated by the flow of hot water away from the upflow region. As fluid viscosity decreases, the rate of flow in the lateral conduit tends to increase. Simulations using this mechanism did not yield the desired quasi-steady-state results, however, because the initial hydrostatic pressure distribution (for a sloping upper boundary) produces such a large lateral pressure gradient that almost all the specified mass inflow (M) flows out the lateral conduit. Consequently, flow rates within the upflow zone above the lateral conduit were too small to heat this region sufficiently for a high-temperature vapor-dominated zone to form. Evidently, some change in rock properties and/or boundary conditions was necessary for the evolution of the Lassen hydrothermal system.

DEVELOPMENT SIMULATIONS

Simulations of the effects of geothermal development were also carried out with the geometric model shown in figure 11, representing the flow system between Bumpass Hell and Morgan and Growler Hot Spring. Initial conditions based on the evolution simulations were chosen so that temperatures in the lateral conduit outside the Park would be suitable for geothermal electric power generation (near 200°C). This necessitated mass inflow rates of about 20 kg/s. Quasi-steady-state results from four different cases were used as initial conditions for development. Two of these cases involved an extensive region of two-phase flow in the lateral conduit, one for each of the two sets of relative permeability functions referred to previously, and two involved single-phase flow in the conduit away from the region of phase separation, one for each of the relative permeability functions. One additional variable considered in the development simulations was the vertical permeability of the caprock layer above the vapor-dominated zone.

The results from the development simulations indicate that under certain conditions fluid production from lateral outflow conduits could alter the surficial discharge of thermal fluids within LVNP and the Lassen KGRA. The numerical model used in these simulations is simplified, and involves a lateral conduit of limited areal extent. If subsurface data were available for constructing a more detailed and realistic model of the Lassen system, modeling analyses might be expected to show somewhat different results in terms of the timing and magnitude of effects on surface features. However, results obtained with the present model concerning the type of induced changes and the conditions necessary for such changes are considered valid.

Production-Injection Schemes

The production-injection scheme used in our simulations (figure 14) consists of a production grid block centered 1.5 km outside the Park boundary and injection blocks centered 1 km upstream (towards the Park) or 1 km downstream from the production block.

As shown in table 4, development simulations were carried out for production rates of 50, 100, and 250 kg/s. For reservoir temperatures near 200°C, these production rates correspond with electrical power generation of about 5, 10, and 25 MW_e, respectively. Without reinjection, a production rate of 100 kg/s caused pressures in the production block to fall below a realistic cutoff point of 3 bars after periods of 11-21 years. This reflects limitations imposed by the permeability and cross-sectional area of the conduit. Although the average value of permeability - thickness for the lateral conduit in our model (32 darcy-meters), is comparable to values found for exploited geothermal fields at Wairakei and Broadlands in New Zealand, the conduit width (1 km) and production area (1 km^2) are near minimum values for commercial geothermal-electric development.

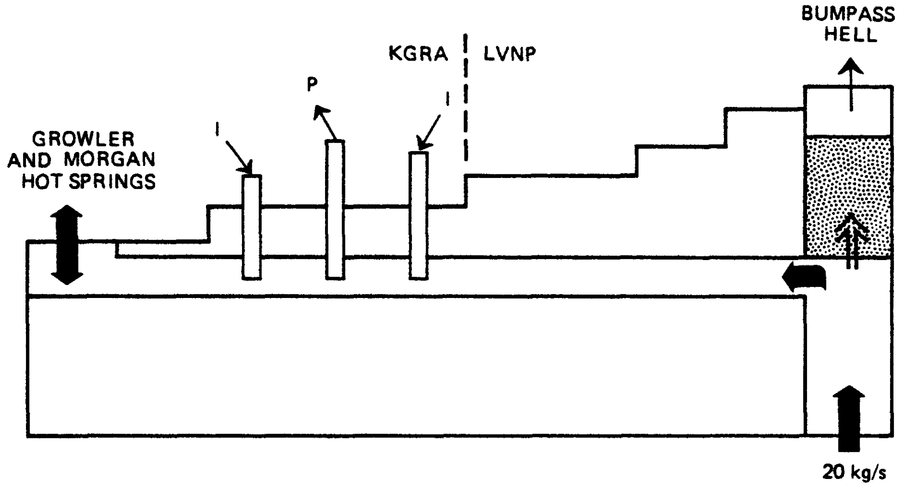

Figure 14. Diagram showing locations of production (P) and injection (I) wells in simulations of the effects of geothermal development from a lateral conduit beneath Mill Creek Canyon. Arrows show directions of liquid (solid) and steam (open) flow. Vapor-dominated zone shown by dotted pattern.

Table 4. Results of development simulations in terms of times required for pressures and temperatures in the production block to reach limits of 3 bars and 150°C, respectively, and the resultant change in discharge of the high-chloride hot springs.

Run	Production[1] Rate, kg/s	Injection[2] Rate, kg/s Upst.	Dnst.	$k_v(1)$[3] md	Relative[4] Permeability Functions	Time to pressure limit, yrs.	Time to temperature limit, yrs.	Hot Spring[5] Discharge kg/s
1	50	0	0	100	Corey	>300	>300	-31
2	50	0	0	100	Fracture	>300	>300	-27
3	50	0	0	0.6	Corey	55	47	-1.6
4	50	0	0	0.6	Fracture	63	55	-2.3
5	50	0	40	100	Corey	>300	>300	9.5
6	50	0	40	0.6	Corey	>300	270	13
7	50	40	0	0.6	Corey	>300	240	11
8	50	0	50	0.6	Corey	>300	>300	20
9	50	50	0	0.6	Corey	>300	175	19
10	100	0	0	100	Corey	11	10	-40
11	100	0	0	100	Fracture	18	16	-50
12	100	0	0	0.6	Fracture	21	18	-2.2
13	100	80	0	0.6	Corey	>300	100	1.8
14	250	200	0	100	Corey	>300	36	-40
15	250	200	0	0.6	Corey	42	36	-1.9

[1] Production block centered 1.5 km south of Park boundary (figure 14).

[2] Injection blocks centered 0.5 km south of Park boundary (upstream) and 2.5 km south of Park boundary (downstream).

[3] Vertical permeability of conduit beneath high-chloride hot springs. Horizontal permeability of lateral-flow conduit = 140 md for runs with $k_v(1)$ = 100 md, and 180 md for runs with $k_v(1)$ = 0.6 md. Vertical permeability of caprock layer = 0.05 md for all runs listed.

[4] See text for forms of relative permeability equations.

[5] Flow rate across constant pressure boundary at left side of model. Negative sign indicates downflow. Value listed applies to a development time of 50 years, or when the 3-bar pressure limit or the 150°C temperature limit was reached, whichever was smaller.

A production rate of 250 kg/s could be sustained for nearly 40 years with reinjection at 80 percent of the production rate. For production rates greater than 250 kg/s with 80 percent reinjection, either production-block pressures fell below 3 bars or production-block temperatures fell below a realistic cutoff point of 150°C within a period of 40 years. Temperature declines in the production block result from breakthrough of lower temperature water from injection (at 100°C) or induced recharge (at 10°C) across the constant-pressure boundary at the left side of the model. In simulations with a reinjection rate equal to 100 percent of the production rate, pressures in the production block did not fall significantly, but the decline in production-block temperature was still a limiting factor.

Effects on Hot Springs in Lassen KGRA

During all of the development simulations, except for those with a reinjection rate equal to the production rate, the rate of fluid flow across the constant-pressure boundary in the vicinity of Morgan and Growler Hot Spring changed (table 4). Initially, approximately 20 kg/s discharged at this boundary. Depending upon the specified production-injection rates and the vertical permeability beneath the boundary ($k_v(1)$), the simulated flow either decreased in magnitude or reversed direction in response to production. A reversal in direction corresponds to disappearance of hot-spring discharge and induced recharge of cold water from the land surface. The simulated rate of induced recharge was greater and the pressure declines in the lateral conduit less for cases with a high value of $k_v(1)$ than for cases with a low value of $k_v(1)$. An additional consideration is that if the southward-trending lateral-flow conduit actually extends further south than Morgan Hot Springs, induced "recharge" of thermal fluid from areas not included in our model could lessen, but not eliminate, the negative effects of fluid production on hot-spring discharge.

Effects on Thermal Discharge in LVNP

Fluid production from the lateral conduit in our model causes pressure declines that tend to propagate both upstream (toward the Park) and downstream from the production area. The rates and magnitudes of pressure changes induced within portions of the conduit beneath LVNP vary significantly depending on the difference between the specified production and injection rates, the relative permeability functions used, and, most significantly, the extent of two-phase conditions in the conduit before development starts. For cases in which pressure declines can propagate into the region of phase separation beneath the central vapor-dominated zone, the net rate of steam upflow into the vapor-dominated zone is observed to increase significantly and then decrease within 20 years. Such increases in the steam upflow rate are partially damped within the vapor zone itself by condensation and accompanying pressure rises. Nevertheless, these simulations indicate that under certain conditions the discharge of steam and steam condensate at the land surface above the central vapor-dominated zone in LVNP could be noticeably affected by geothermal development outside the Park.

The plots in figures 15 and 16 show transient variations in net upflow of steam into and out of the vapor-dominated zone during selected development runs. These runs involved single-phase liquid conditions in the lateral conduit away from the central upflow zone before development; in each case, changes in steam upflow in the vapor-dominated zone are observed in response to fluid production. For runs in which the lateral conduit initially contained an extensive region of two-phase flow (those listed in table 4 with $k_v(1)$ = 100 md), the effects of fluid production do not propagate as far back as the central upflow zone because of the high effective fluid compressibility in the two-phase portion of the lateral conduit and the induced recharge of water from the land surface at the left side of the model. It should be noted that although boiling and two-phase flow are induced in and near the production area in runs in which the lateral conduit is initially single-phase, the drop in pressure to saturation values for the initial temperatures is transmitted relatively rapidly and hence can reach the central upflow zone during the development period.

The development runs plotted in figure 15 involve production of 50 kg/s with no reinjection and show the effects of varying the relative permeability functions and the vertical permeability of the caprock layer on induced changes in steam upflow. Run 1a, in which the caprock permeability was increased by a factor of five to 0.25 md, is not listed in table 4 because it yielded results

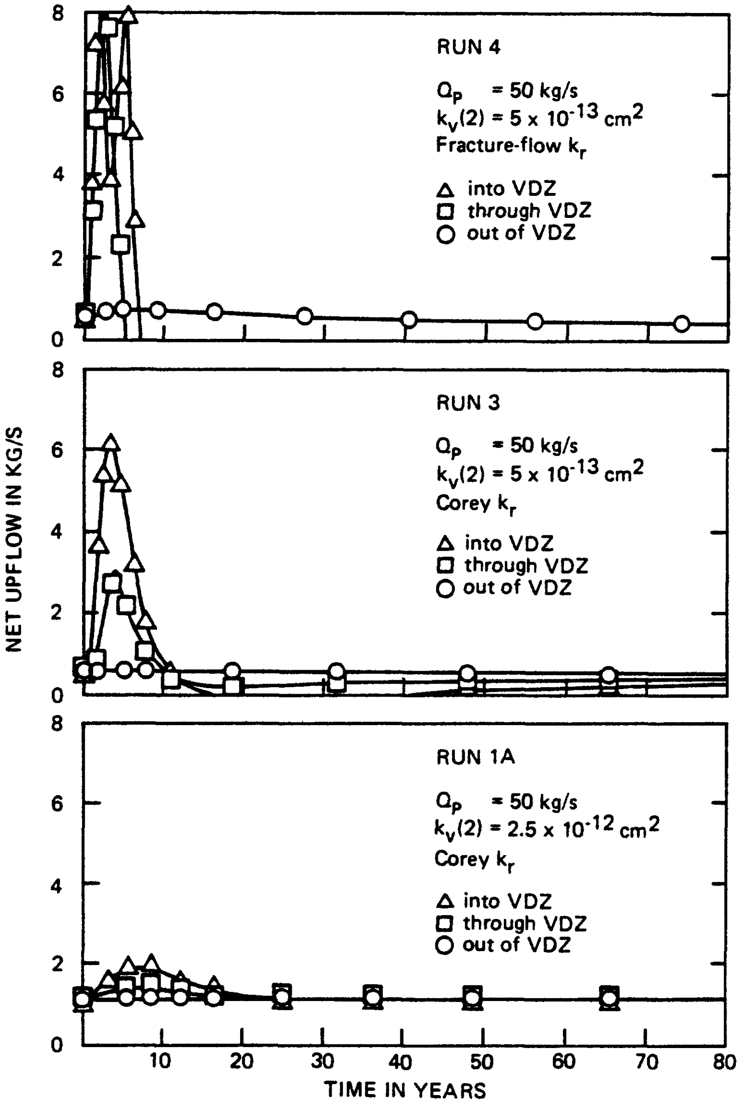

Figure 15. Diagrams showing net mass upflow in the vapor-dominated zone (VDZ) during development simulations involving production of 50 kg/s without reinjection for cases with single-phase initial conditions in lateral conduit. Production starts at 0 years and ceases if the pressure limit of 3 bars is reached (see table 4 for additional details).

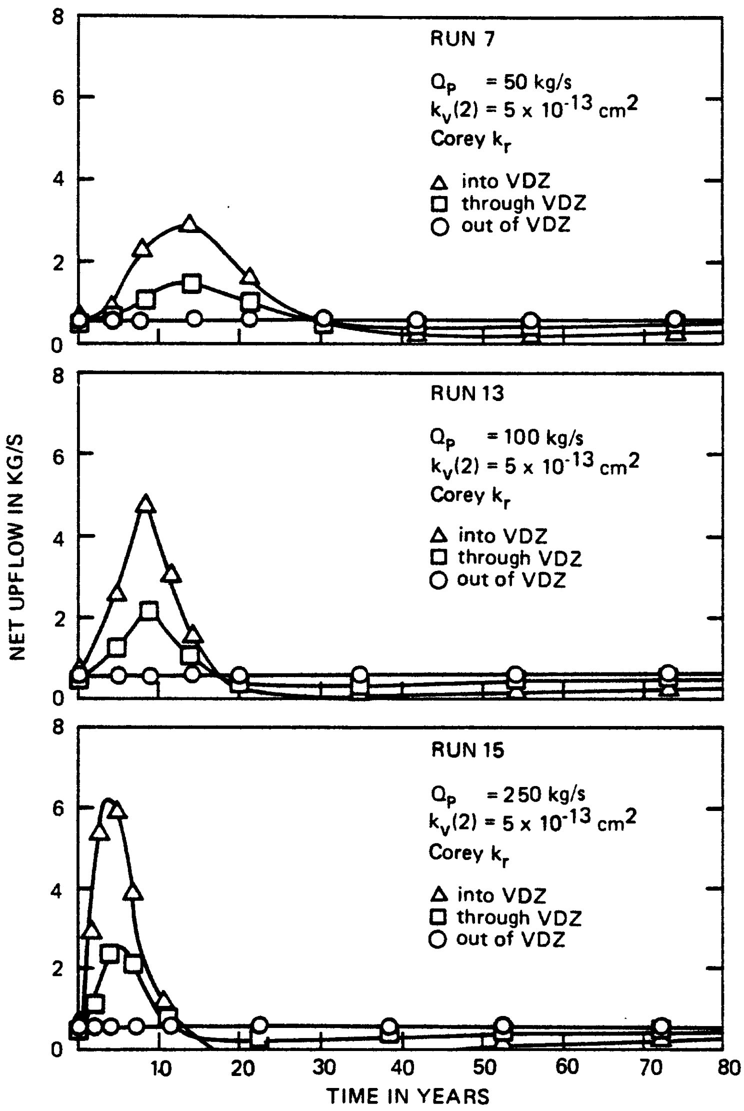

Figure 16. Diagrams showing net mass upflow in the vapor-dominated zone (VDZ) during development simulations involving production rate Q_p with reinjection at 80 percent of Q_p for cases with single-phase initial conditions in lateral conduit. Production starts at 0 years and ceases if the pressure limit of 3 bars is reached (see table 4 for additional details on each run).

similar to those shown for Run 1. Using the higher value of $k_v(2)$, the initial rate of steam upflow from the quasi-steady-state simulation is nearly twice the value for the lower $k_v(2)$ cases, but changes in net upflow during development are more subdued and continue for a longer period of time. This relatively subdued response is partly due to differences in the initial pressure-temperature distributions in the lateral conduit, which for run 1a involved less overpressure with respect to the corresponding saturation pressures than for run 3. The degree of overpressure affects the magnitude of pressure decline that can propagate from the production area before boiling occurs.

Changes in steam upflow are most pronounced for the case with fracture-flow relative permeability functions. Here, although the temporary increase in steam flow is greatly damped by condensation within the vapor-dominated zone, the increase in steam flow into the caprock amounts to about 32 percent of the initial flow rate. The oscillation seen within the first five years of production may represent a shift in the dynamic balance between steam upflow, liquid downflow, and pressures and saturations near the base of the vapor-dominated zone.

The development runs plotted in figure 16 involve production rates of 50, 100, and 250 kg/s with 80 percent reinjection upstream from the production block. The magnitude of the temporary rise in steam upflow increases and the time required to reach maximum steam upflow decreases as the production rate increases. The critical factor in these simulations is actually the difference between the production and injection rates, so that results for run 13 with a net withdrawal rate of 50 kg/s are comparable to those for run 3 with a production of 50 kg/s and no reinjection.

The temporary increases in steam upflow seen in these simulations are followed by decreases to levels at or below the initial flow rates. Pressures in the region of phase separation beneath the vapor-dominated zone continue to decline during the entire development period. At early times, corresponding decreases in liquid saturation and increases in steam relative permeability dominate and cause the rapid rise in steam upflow. After 5 - 10 years, liquid saturation and steam relative permeability stabilize and the continued pressure decline beneath the vapor-dominated zone causes the rate of steam upflow to decrease. Within the vapor zone itself, steam relative permeability remains nearly constant so that changes in steam upflow can occur only if the vertical pressure gradient changes. Thus, the observed initial increase in steam flow through the vapor zone is accompanied by condensation of steam and resultant pressure increases. This condensation of excess steam results in the vapor zone acting as a buffer between rather large changes in the region of phase separation and smaller changes at the base of caprock.

Simulated changes in net steam upflow into the caprock were in all cases very small compared to changes within and below the vapor-dominated zone. This reflects primarily the relatively low value of vertical permeability applied to the caprock layer. As the value of $k_v(2)$ is increased, the ratio of change in steam upflow into the caprock to change in steam upflow at the base of the vapor-dominated zone increases. Although low values of caprock permeability appear to have been necessary to allow a vapor-dominated zone to evolve, it is possible that higher permeability channels transmitting steam upwards through the condensate zone could have developed after the vapor-dominated zone was established. A more detailed model that includes separate channels for steam and liquid flow above the vapor-dominated zone is required to adequately quantify changes in steam flow at the land surface induced by geothermal development. Such changes are likely to be larger in magnitude than those found in our simulations.

Reinjection

Reinjection of produced fluids (or injection of water from another source) is often cited as a means for protecting surficial discharge features from the effects of geothermal development. Our results indicate that such protection may be difficult to achieve. As discussed above, an injection rate equal to the production rate was required to avoid diminution in the flow of hot springs located downstream from the production area in our simulations. However, with either upstream or downstream injection rates equal to production rates, simulated pressure changes propagated within the lateral conduit back under the Park (figure 17a). Injection of 100 percent of the produced fluid downstream from the production block is accompanied by pressure declines at all grid blocks to the right of the injection block, resulting in the same type of response in the vapor-dominated zone shown in figures 15 and 16. In contrast, the same rate of fluid injection upstream from the production block causes a pressure rise to propagate under the Park, resulting in a sharp decrease in steam upflow owing to an increase in liquid saturation beneath the vapor-dominated zone.

For injection rates equal to 80 percent of production rates, the corresponding plots (figure 17b) show that pressures in the lateral conduit under the Park are lowered regardless of whether fluid is injected upstream or downstream of the production zone. These results suggest, however, that upstream injection of between 80 and 100 percent of the produced fluid could minimize or eliminate induced pressure changes in the lateral conduit beneath the Park. This might change with time, as the temperature changes associated with production and injection affect fluid mobility in the lateral conduit. In the case illustrated in figure 17, a constant reinjection rate equal to 89 percent of production (44.5 kg/s) leaves pressures beneath the Park essentially unchanged after 40 years.

Further experimentation with a combination of upstream and downstream reinjection showed that upstream reinjection at 30

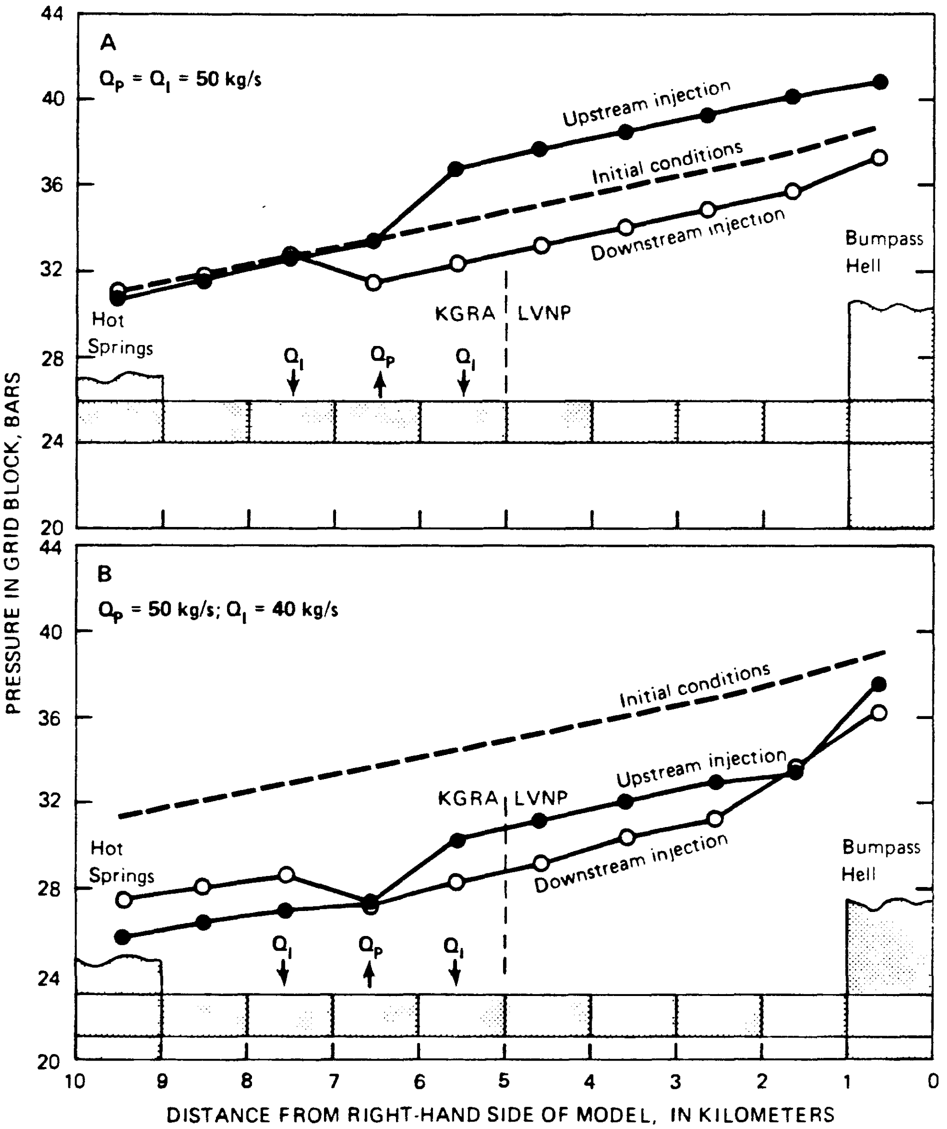

Figure 17. Plots of grid-block pressures within the lateral conduit for development simulations involving a production rate of 50 kg/s and injection rates of 50 kg/s (A) and 40 kg/s (B), either upstream or downstream from the production block. Results apply to a development time of approximately 40 years.

percent of the production rate (15 kg/s) combined with downstream reinjection at 70 percent of the production rate (35 kg/s) also left pressures beneath the Park unchanged after 40 years. In addition, because the total injection rate is equal to the production rate, this production-injection scheme maintains the flow of hot springs downstream from the production area.

Additional Considerations

If flow in the lateral conduit trending southward from Bumpass Hell is now mostly two-phase within LVNP, fluid production from such a conduit within the KGRA may have no significant effect on thermal features in the Park for realistic development periods. Our simulations showed that induced pressure changes did not propagate rapidly enough through several kilometers of two-phase fluid to reach the central upflow zone. However, because the speed of pressure propagation through the conduit is controlled by the conduit permeability and the fluid compressibility, the inhibiting influence of the large effective compressibility of a two-phase fluid mixture can be partly offset if the permeability were actually much larger than the values used in our simulations. Such would be the case, for example, if the southward trending conduit were much thinner and/or narrower than assumed in our model. As noted previously, our simulations together with the chloride flux measurements can only be used to constrain the permeability-cross-sectional area product for such a conduit.

Along the flow axis trending southeastward from Bumpass Hell, fluid in the lateral conduit beneath Terminal Geyser (figure 7) is single-phase liquid, and it appears that upflow from this conduit boils and undergoes phase separation near the elevation of the measured water level. Similar conditions may exist at other thermal areas along this axis of lateral outflow, and steam and steam-heated thermal features in some of these areas could be affected by fluid withdrawal for geothermal development along the extension of this flow axis outside the Park. The type of changes induced in surficial discharge in such areas should be qualitatively similar to those observed in our development simulations.

Interpretation of resistivity and heat flow data (figure 6) suggests that lateral outflow from the Lassen hydrothermal system could extend southward beyond the Morgan Hot Spring area. Fluid production for geothermal development from conduits located at greater distances from LVNP could be expected to have a lesser impact on thermal features within LVNP. For a conduit with uniform properties, the time required for a given pressure change to reach the central upflow zone beneath Bumpass Hell from production areas located at different distances varies as the square of the distance. Thus, the effects of production from wells near the southern edge of the Lassen KGRA might be expected to take approximately four times as long to reach the central upflow zone as the results of our simulations have indicated. Such an inference must be qualified by the sensitivity of this analysis to the actual conduit geometry and properties, which can be adequately delineated only by test drilling.

Changes in surficial discharge from thermal areas within LVNP caused by future geothermal development outside the Park may be difficult to distinguish from changes related to natural processes, such as seasonal variations in precipitation, seismic events or intrusive activity. For example, the discharge rates and temperatures of the fumaroles tend to increase during dry years and decrease during wet years. Although periodic monitoring of sulfate discharge from these thermal areas may help in establishing the natural level of fluctuations, the need for monitoring pressures and temperatures in wells drilled at or near the Park boundary is clear. Such monitoring could detect changes induced by fluid production before such effects propagate extensively through the hydrothermal system beneath the Park, or help to delineate the causes of observed changes in thermal features within the Park.

CONCLUSIONS

Existing data support a conceptual model of the Lassen hydrothermal system in which boiling and phase separation occur within a central upflow zone beneath Bumpass Hell, giving rise to an upflow of steam through a parasitic vapor-dominated zone and lateral flow of liquid toward discharge areas outside LVNP.

The simplest model accounting for the distribution of areas of steam and steam-heated discharge within LVNP and areas of discharge of high-chloride thermal water in the Lassen KGRA involves lateral outflow of thermal water from the central upflow zone along two axes, one leading southward from Bumpass Hell to Growler and Morgan Hot Springs in Mill Creek Canyon and the other leading southeastward to Terminal Geyser and Domingo Spring. Quantitative constraints on this conceptual model include estimates of temperature and pressure in the central vapor-dominated zone and the underlying region of phase separation of 235^{o} - 240^{o}C and 31 - 34 bars, and estimates of the lateral outflow of thermal water in Mill Creek Canyon and at Domingo Spring of 17 L/s and 2.7 L/s, respectively.

Numerical simulations of heat and fluid flow in a two-dimensional vertical cross-section representing the Bumpass Hell to Growler and Morgan Hot Springs axis indicate that the present-day Lassen hydrothermal system could have evolved from an initial period of upflow and convective heating by several processes that initiate a period of lateral outflow at rates greater than the rate of upflow from depth and, consequently, result in draining of liquid beneath a low-permeability caprock layer. Although formation of a thick parasitic vapor-dominated zone takes place over periods on the order of 1,000 years, much longer times are required for temperatures within the lateral outflow conduit to stabilize. From the evolution simulations, a value for the permeability-thickness product of the lateral conduit beneath Mill Creek Canyon of approximately 32 darcy-meters can be estimated, asssuming a conduit width of 1 km and a total throughflow rate of 20 kg/s.

Other factors influencing the present state of the Lassen system and its response to geothermal development include the vertical permeability of channels through which thermal water discharges at Growler and Morgan Hot Spring, the vertical permeability distribution within the condensate layer overlying the central vapor-dominated zone, and the applicable relative permeability-saturation functions.

The effects of fluid production for geothermal development from the lateral conduit beneath Mill Creek Canyon were simulated for production rates of 50 - 250 kg/s, with and without reinjection at 80 and 100 percent of production rates. Production with less than 100 percent reinjection is likely to cause a diminution in the discharge of thermal water in Mill Creek Canyon and possibly a reversal from upflow of hot water to downflow of cold water. The magnitude of such effects depends on the vertical permeability of channels between the springs and the underlying lateral conduit. Our simulations also indicate that thermal discharge features within LVNP could be affected by geothermal development outside the Park if fluid flow within the lateral outflow conduits is initially single-phase liquid. In the cases simulated, pressure declines propagated relatively rapidly through the conduit toward the central upflow zone, causing a temporary rise in steam upflow that was damped by condensation within the vapor-dominated zone. If lateral conduits presently contain extensive regions of two-phase flow, production-induced pressure declines are unlikely to propagate far enough to affect thermal features within LVNP, unless the cross-sectional area of such conduits is much less than assumed in our model.

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GLOSSARY: Technical Nomenclature

AMT (audio-magnetotelluric) surveys: use of measurements of the frequency and strength of the earth's natural magnetic and electric fields to determine variations in electrical resistivity.

Development simulations: numerical simulations of fluid production and reinjection and related changes in pressure, temperature, and fluid discharge.

Evolution simulations: numerical simulations of the natural evolution of the present-day Lassen hydrothermal system.

Effective fluid compressibility: change in fluid volume due to phase change accompanying change in pressure.

Finite-difference techniques: algebraic approximations to partial differential equations describing conservation of mass and energy. Algebraic equations applied to finite-sized grid blocks are solved by computer simultaneously for all grid blocks.

Fluid enthalpy (h): internal energy plus (pressure/density). For liquid water at temperatures of up to 200 $^{\circ}C$, the value of enthalpy in cal/gm is approximately equal to the temperature in $^{\circ}C$.

Liquid saturation (S): ratio of volume of liquid to total pore volume. S varies from 0 (all steam) to 1 (all liquid).

Multiphase flow: simultaneous flow of steam and liquid water through a region of the earth. Both phases assumed to exist at same pressure and temperature (on the saturation or boiling curve).

Numerical model: geometric configuration representing some region of the earth that is subdivided into grid blocks and given specified values of temperature, pressure, and/or flow around its surface to enable numerical simulations to be performed.

Numerical simulations: Computer-generated solutions to algebraic equations describing heat and fluid flow within the earth.

Permeability (k): refers in this report to the intrinsic permeability of rock, expressed in units of millidarcys (md) = 10^{-11} cm^2. Permeability rather than hydraulic conductivity is used in geothermal modeling because permeability does not vary with temperature.

Reinjection: commonly used terminology for injection of fluid associated with simultaneous production of fluid from a geothermal reservoir for energy conversion. Used interchangeably with the term "injection."

Relative permeability (k_{rl}, k_{rs}): fractional reduction in effective permeability to liquid or steam phase due to the presence of the other phase. Steam and liquid relative permeabilities are treated as functions of liquid saturation and vary from 0 to 1.

Tritium Unit (TU): ratio of tritium (^3H) to hydrogen (H), multiplied by 10^{-18}.

Two-phase zone: applied to part of the lateral flow conduit in which fluid is boiling and both liquid and steam phases are mobile. Liquid saturations and liquid relative permeabilities in this zone are significantly larger than within the parasitic vapor-dominated zone.

Upstream weighting: numerical proceedure that assigns properties of fluid in the upstream node to fluid flowing into the downstream node to assure convergence of numerical solutions in problems involving transport of heat (or solutes).

Vapor-dominated zone: applied to part of the upflow region in which liquid saturations and liquid relative permeabilities are so small that steam is the pressure-controlling fluid phase and the vertical pressure distribution is close to vapor-static (pressure increases with depth due only to the weight of overlying steam).

δD: ratio R of deuterium (^2H) to hydrogen (H) expressed in delta notation, where

$$\delta D = \left[\frac{R\ Sample}{R\ Standard} - 1 \right] \times 1{,}000,$$

in parts per thousand (‰). Standard is designated Standard Mean Ocean Water (SMOW).

$\delta^{18}O$: ratio of oxygen 18 (^{18}O) to oxygen (^{16}O) in delta notation.