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NUMERICAL SIMULATIONS OF THE HYDROTHERMAL SYSTEM AT LASSEN VOLCANIC NATIONAL PARK

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ABSTRACT

The hydrothermal system in the vicinity of Lassen Volcanic National Park contains a central region of fluid upflow in which steam and liquid phases separate, with steam rising through a parasitic vapor-dominated zone and liquid flowing laterally toward areas of hot spring discharge south of the Park. A simplified numerical model was used to simulate the 10,000 - 20,000-year evolution of this system and to show that under certain circumstances fluid withdrawal from hot-water reservoirs south of the Park could significantly alter the discharge of steam from thermal areas within the Park.

INTRODUCTION

Thermal discharge from the Lassen hydrothermal system occurs in fumaroles and steam-heated springs within Lassen Volcanic National Park (LVNP) and in high-chloride neutral-pH hot springs within the Lassen Known Geothermal Resource Area (KGRA) south of the Park. Existing geochemical and geophysical data indicate that these features are connected to and fed by a single convection system at depth. Thus fluid production for geothermal energy development south of LVNP could potentially cause changes in flow rates and temperatures in discharge vents within the Park. The numerical simulations discussed in this paper were carried out in an effort to predict the magnitude of such changes.

Although the general nature of the Lassen system has been delineated, critical data regarding the location and properties of thermal-fluid reservoirs are lacking. Therefore, numerical simulations of the evolution of the present-day Lassen hydrothermal system were carried out to provide estimates of the rock properties and boundary conditions controlling heat and fluid flow. Our simulation model is idealized and involves a relatively simple geometric configuration. Nevertheless, the results of this study indicate that under certain circumstances fluid production from reservoirs within Lassen KGRA could induce significant changes in steam discharge within LVNP. Such development is also likely to reduce or eliminate the discharge of hot springs within Lassen KGRA.

THE LASSEN HYDROTHERMAL SYSTEM

The Lassen area is in north-central California, approximately 50 km east of Redding and 20 to 30 km northwest of Lake Almanor (figure 1). It is at the southern end of the Cascade Range, which here is reduced to a broad ridge of Late Pliocene and Quaternary volcanic rocks, primarily pyroxene andesite flows and pyroclastics with minor basaltic and silicic flows and pyroclastics (Muffler and others, 1982).

Surficial hydrothermal features in the Lassen region are confined to the southern half of LVNP and to the Lassen

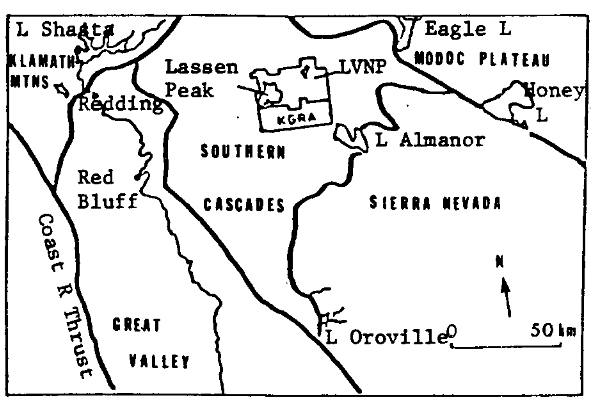

Figure 1. Physiographic provinces in Northern California and adjacent states and locations of Lassen Volcanic National Park (LVNP) and Lassen Known Geothermal Resource Area (KGRA).

KGRA (figure 2). They include fumaroles and acid-sulphate hot springs at relatively high elevations in LVNP and neutral-pH high-chloride hot springs at relatively low elevations in the KGRA. Although these features are widely separated, they are fed by a single convection system at depth. The Lassen system is similar in this respect to other high-temperature hydrothermal systems in regions of moderate to great relief, including the Valles Caldera in New Mexico and the Tongonan area in the Philippines. We refer to such systems as liquid hydrothermal systems with parasitic vapor-dominated zones (LHSPVZ). The essential characteristic of these systems is that steam and liquid phases separate within a zone of upflow, with steam rising through a parasitic vapor-dominated zone and liquid flowing laterally to discharge at lower elevations.

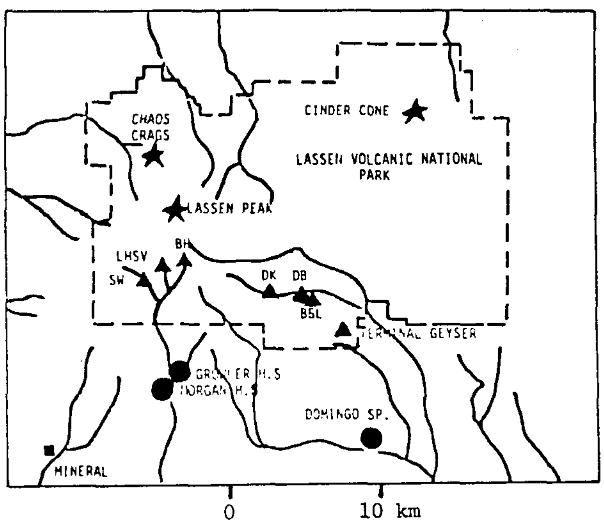

Figure 2. Map of areas of thermal fluid discharge and streams in the Lassen region. Areas of fumaroles, steam-heated springs, and low-chloride conductively heated springs shown as triangles (BH = Bumpass Hell, LHSV = Little Hot Springs Valley, SW = Sulphur Works, DK = Devils Kitchen, DB = Drakesbad, BSL = Boiling Springs Lake). Areas of high-chloride thermal water discharge shown as dots.

A generalized conceptual model for the Lassen system and other LHSPVZ is illustrated in figure 3. As seen in the accompanying diagram of pressure versus elevation, steam is the pressure-controlling phase within the vapor-dominated zone and the vertical pressure gradient in this zone 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. The thickness of the vapor-dominated zone depends upon the difference in elevation between the steam-heated and high-chloride discharge areas, and on the pressure gradient required to drive the lateral outflow.

Studies of gas and stable isotope composition (Janik and others, 1983) and geothermometry (Thompson, 1983) indicate that thermal fluids in the Lassen region circulate outward from a common upflow zone beneath Bumpass Hell (figure 2). Recharge to the system occurs on the composite cone of the Lassen volcanic center that includes Lassen Peak. Fluid is heated at depth by conduction from the residual silicic magma chamber associated with this long-lived (0.6 m.y. to present) volcanic center, and possibly by small amounts of magmatic steam. The resulting high-enthalpy fluid circulates upward along the contact between the andesitic composite cone and the dacite dome field of the Lassen center (Muffler and others, 1982).

With the exception of Morgan and Growler Hot Springs, hot spring waters in the Lassen area are generally acidic and low in chloride (Thompson, 1983), indicating some degree of vapor-dominated conditions at depth. The widely separated areas of steam-heated discharge could be surface expressions of a single laterally extensive vapor-dominated zone or expressions of a number of "satellite" parasitic vapor zones. However, the composition of gas in steam discharging from the various thermal features suggests that vapor-dominated conditions do not extend continuously under the entire southwestern part of LVNP (Janik and others, 1983), and that the thermal features between Devil's Kitchen and Terminal Geyser and at Morgan and Growler Hot Springs are connected to the vapor-dominated zone beneath Bumpass Hell by liquid-dominated lateral flow zones. The 1200 m deep Walker "O" No. 1 well at Terminal Geyser - the only well drilled deeper than 250 m in the Lassen region - intercepts such a lateral flow zone at a depth of approximately 500 m (Beall, 1981).

Most of the lateral outflow eventually discharges in regions of high-chloride springs in the canyon of Mill Creek (at Morgan and Growler Hot Springs) and at Domingo Springs, where elevated chloride levels indicate a component of high-chloride thermal water. Available data supports a model of two areally restricted orientations of thermal fluid circulation in the Lassen system, between Bumpass Hell and Morgan and Growler Hot Springs and Bumpass Hell

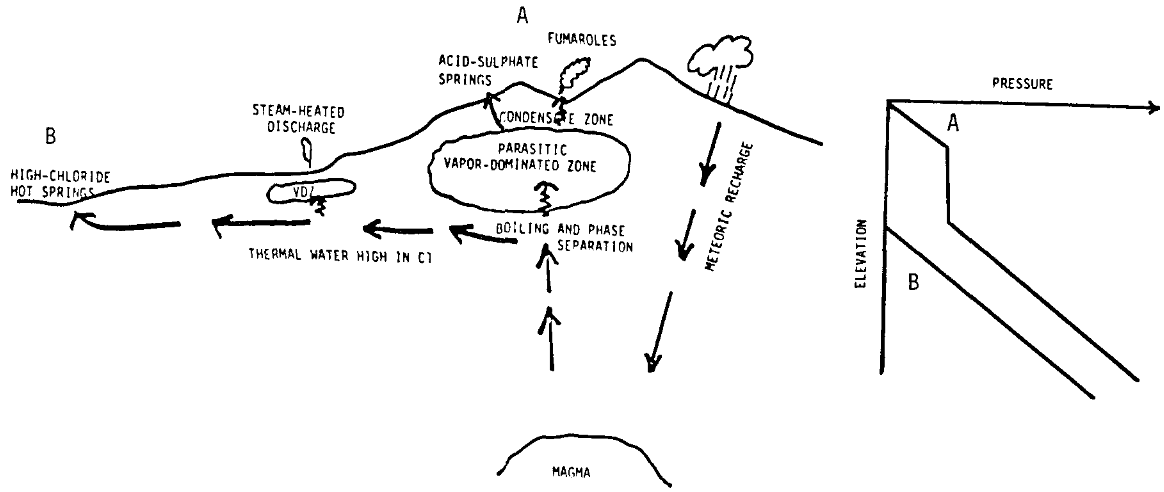

Figure 3. Generalized conceptual model of the Lassen hydrothermal system and other liquid-dominated systems with parasitic vapor-dominated zones, and corresponding pressure -elevation relations in the upflow region A and outflow region B.

and Terminal Geyser. Extension of the Bumpass Hell - Terminal Geyser orientation to Domingo Springs seems reasonable. All of the surface manifestations of the Lassen hydrothermal system lie along these orientations, and resistivity data (Christopherson and Pringle, 1981) show no evidence of high-temperature, high-chloride water underlying the central part of Lassen KGRA between the two flow zones. The areally restricted flow zones imply avenues of relatively high permeability leading away from the upflow zone beneath Bumpass Hell. Such avenues of permeability could be fault controlled.

Although the general nature of the Lassen system is well understood, quantitative constraints on this model are few. Temperatures and pressures in the vapor-dominated zone beneath Bumpass Hell are inferred to be near 235 °C and 31 bars, on the basis of superheated steam temperatures of up to 159 °C measured in the overlying fumarolic area during the California drought of 1976-1977 (Muffler and others, 1982). Temperatures in the lateral flow zone beneath Terminal Geyser intercepted by the Walker "O" well are approximately 176 °C (Beall, 1981), and high-chloride spring temperatures in the Morgan and Growler Hot Springs area are near-boiling.

Preliminary estimates of the rate of lateral outflow in the Lassen system were made based on data collected in the course of this study. Measurements of streamflow and chloride concentration at selected sites in the Morgan and Growler Hot Springs area indicate that the total flow of thermal water discharging at the surface is approximately 17 kg/s. This figure probably represents most of the lateral outflow along the Bumpass Hell - Morgan and Growler Hot Springs orientation; however, an anomolously high heat flow value (Mase and others, 1980) and low resistivity values (Christopherson and Pringle, 1981) in the Child's Meadow area south of Morgan and Growler suggest that an additional, unknown quantity of thermal fluid flows past the hot springs area in the subsurface. Some or all of the thermal fluid flowing under Terminal Geyser may eventually discharge at Domingo Springs. Measurements of chloride flux in Domingo Springs indicate a thermal component of approximately 2.7 kg/s. Additional thermal fluid from the Bumpass Hell - Terminal Geyser orientation may flow into the North Fork of the Feather River and Warner Creek, where relatively high flowrates could preclude detection of a thermal component.

NUMERICAL MODEL

The geometric configuration used in numerical simulations of the Lassen hydrothermal system is shown in figure 4. 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 Springs. 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. A conductive heat flow along the base of

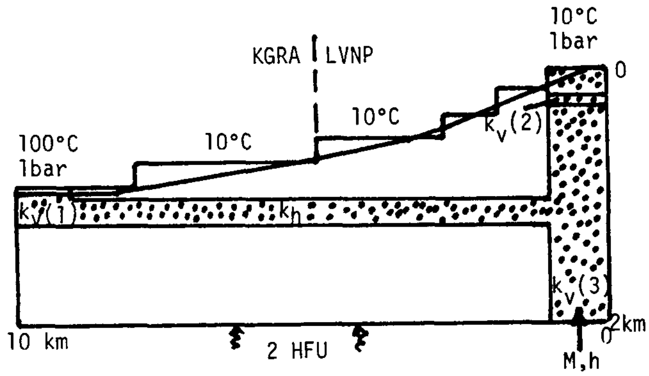

Figure 4. Geometric model used in simulations of the Lassen hydrothermal system. Arrow indicates inflow of hot water at mass flow rate M and enthalpy h. Fluid flow confined to regions with dotted pattern and across portions of the upper boundary held at 1 bar pressure. Upper boundary represents finite difference approximation to land surface between Bumpass Hell and Morgan and Growler Hot Springs. Horizontal and vertical permeabilities indicated by symbols k_h and k_v, respectively. The model width is 1 km.

85 mW m^{-2} represents the regional heat flow (Mase and others, 1980). With reference to the conceptual model shown in figure 3, 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-dimensional simulations of multiphase flow over the time periods on the order of 10,000 years. 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 do suggest that there are two areally restricted flow regimes originating from the central upflow zone beneath Bumpass Hell. Our model corresponds with the Bumpass Hell - Morgan and Growler Hot Springs orientation, which represents the most likely target for geothermal exploration and development in Lassen KGRA, and for which the discharge of high-chloride thermal fluid is reasonably well constrained. Inclusion in the model of the Bumpass Hell - Terminal Geyser orientation would have added useful constraints provided by the known temperature and elevation of the lateral conduit beneath Terminal Geyser. However, exclusion of this part of the flow system saves considerably on computational requirements and should not alter the basic conclusions derived from the numerical simulations.

For simplicity, the lateral conduit is assumed to be flat-lying at an average elevation of 1400 m and to be 200 m in thickness. These values match those for the hot-water aquifer penetrated in the Walker "O" No. 1 well. Modeling the lateral conduit at significantly greater depths would have resulted in the evolution of a vapor-dominated zone with pressures considerably in excess of the desired 31 bar-level. The model width of 1 km is the value suggested by the average width of the glacially eroded Mill Creek Canyon.

The computer code used in the numerical simulations 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. Modifications 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.

EVOLUTION SIMULATIONS

Simulations of the evolution of the Lassen hydrothermal system provided insight into the conditons required for the development of LHSPVZ in general, as well as estimates of the rock properties and boundary conditions controlling heat and fluid flow in the Lassen system. The simulations indicate that several conditions are necessary for the development of parasitic vapor-dominated zones: large-scale topographic relief that enables thermal fluids to discharge in regions of significantly different elevations; a change in hydrologic or geologic properties that initiates a period of drainage from a zone of high temperature; and low permeability barriers that inhibit drainage of cool water from surrounding regions into the evolving vapor-dominated zone. The evolution of LHSPVZ are discussed in greater detail by Sorey and Ingebritsen (1983).

Initial conditions for the evolution simulations were a temperature distribution corresponding to a uniform conductive heat input of 85 mWm^{-2} and a hydrostatic pressure distribution. Evolution simulations were carried out until the pressure distribution reached conditions similar to those in figure 3, with pressures near 31 bars 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 temperatures at the left side of the model be above the surface boiling point of 95 °C. 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. The lack of information on values of most of these parameters and the complex interactions between thermodynamic and hydraulic processes in the simulations made considerable experimentation necessary to find combinations of parameter values that would produce the desired results.

The evolution simulations suggest that times required for the evolution of the present-day Lassen hydrothermal system are of the same order of magnitude as the age of the volcanism which produced Lassen Peak (11,000 years). Quasi-steady-steady-state mass flux and temperature distributions for one of the evolution runs are shown in figure 5. Values of various parameters associated with this solution are listed below and defined in figure 4.

$M = 20$ kg/s
$h = 1{,}125$ J/gm (258 °C)
$k_h = 1.4 \times 10^{-9}$ cm^2
$k_v(1) = 1 \times 10^{-9}$ cm^2
$k_v(2) = 5 \times 10^{-13}$ cm^2
$k_v(3) = 1 \times 10^{-9}$ cm^2

Corey relative permeability functions

Mass flow vectors at quasi-steady-state (figure 5) show 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 lower permeability caprock layer [$k_v(2)$] overlying the vapor-dominated zone, some of the steam condenses and flows downward while the remainder flows into the caprock layer where it condenses before rising to the land surface. Although separate flows of steam and steam condensate at the land surface are not simulated, the net mass upflow of steam through the vapor-dominated zone is balanced by the mass upflow of liquid across the surface.

The parameter values listed above lead to a quasi-steady-state configuration involving a zone of two-phase flow conditions in the lateral conduit extending to the Park boundary. The presence of an extensive two-phase region in the lateral conduit would have a strong influence on the rate of propagation of pressure changes induced by fluid withdrawal, and whether such a region exists is as yet unknown.

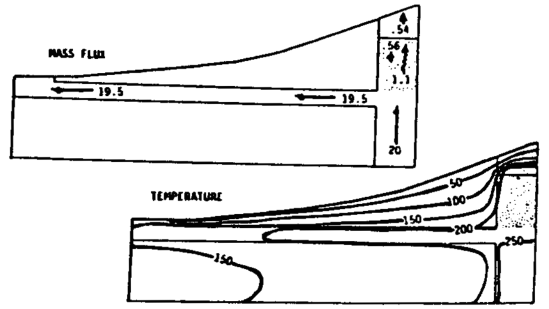

Figure 5. Quasi-steady state results from simulation of the evolution of the Lassen hydrothermal system, showing mass flow vectors (straight arrows for liquid, wavy arrows for steam) and the temperature distribution. Dotted pattern represents region of vapor-dominated conditions. Units of mass flow are kg/s.

Simulations with a much lower value of $k_v(1)$ (6×10^{-12} cm^2) and a slightly increased value of k (1.8×10^{-9} cm^2) resulted in higher conduit pressures and the absence of two-phase flow except immediately below the vapor-dominated zone. Quasi-steady-state results were also generated using the relative permeability functions suggested for fractured media by Sorey, Grant, and Bradford (1980) in place of the porous-media derived Corey functions.

Four quasi-steady-state results from the evolution simulations were used as initial conditions for simulations of fluid withdrawal for geothermal electric power generation. 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 k (2) of the caprock layer above the vapor-dominated zone.

DEVELOPMENT SIMULATIONS

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. In the absence of reinjection, it was not possible to sustain production rates greater than 50 - 100 kg/s for periods of about 50 years without causing pressures in the production block to fall below a realistic cutoff point of 3 bars. This reflects limitations imposed by the permeability and cross-sectional area of the conduit. Conduit permeability is constrained from the evolution simulations to the range 1.4×10^{-9} to about 2.0×10^{-9} cm^2, if the rate of mass outflow along the Bumpass Hell to Morgan-Growler Hot Springs axis is indeed near 20 kg/s, as suggested by the chloride flux measurements discussed above. The average value of permeability - thickness for the lateral conduit in our model would then be 34 darcy-meters, a value comparable to those found for exploited geothermal fields at Wairakei and Broadlands in New Zealand.

Production rates greater than 100 kg/s can be sustained with reinjection at 80 percent of the production rate. The maximum production rate sustainable for more than 30 years is near 250 kg/s; for greater rates either production-block pressures fall below 3 bars or production-block temperatures fall below a realistic cutoff point of 150 °C. Such declines in temperature in the production block are due to the injection of lower temperature water.

The development scheme involved a production block centered 4.5 km from the left side of the model and 1.5 km outside the Park boundary (see figure 4). Reinjection was specified either in the block centered 1 km upstream (towards the Park) from the production block or the block centered 1 km downstream from the production block.

During the development simulations, the rate of fluid flow across the constant-pressure finite-difference block representing Morgan and Growler Hot Springs changes. Depending on the specified production-injection rates and the value of $k_v(1)$, the simulated flow across this boundary either decreases in magnitude or reverses in direction in response to production. A reversal in direction corresponds with the disappearance of hot-spring discharge and induced recharge of cold water from the land surface. For given production-injection rates, 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 $k_v(1)$.

Fluid production from the lateral conduit induces pressure drops that propogate upstream (toward the Park) as well as 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, on the extent of two-phase conditions in the conduit before development starts. For cases in which pressure declines can propogate into the region of phase separation beneath the central vapor-dominated zone, the net rate of steam upflow into the vapor-dominated zones is observed to increase significantly and then decrease within a time frame of less than 20 years. Such increases in upflow rate are damped within the vapor zone itself by condensation and accompanying pressure rises so that the observed changes in steam flow into the caprock layer are delayed and reduced in magnitude.

The plots in figure 6 show transient variations in net upflow of steam into and out of the vapor-dominated zone during selected development runs involving single-phase initial conditions in the lateral conduit away from the upflow zone. In each case, changes in steam upflow in the vapor-dominated zone are observed in response to fluid production. Although boiling and two-phase flow are induced in and near the production area in these runs, the drop in pressure to saturation values for the initial temperatures is transmitted relatively rapidly through the single-phase portions of the conduit and hence can reach the upflow zone during the development period. In runs in which the lateral conduit initially contained an extensive region of two-phase flow, the effects of fluid production did not propogate as far back as the upflow zone because of the low hydraulic diffusivity in the two-phase portion of the lateral conduit.

The development runs plotted in figure 6 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. With the higher value of $k_v(2)$ in Run 3, the initial rate of steam upflow from the quasi-steady-state simulation is about twice the value for the lower $k_v(2)$ cases, but changes in net upflow during development are more subdued and spread out over a longer period of time. This response may be due in part to differences in the initial pressure-temperature distributions in the lateral conduit, which for run 3 involved less overpressure with respect to the corresponding saturation

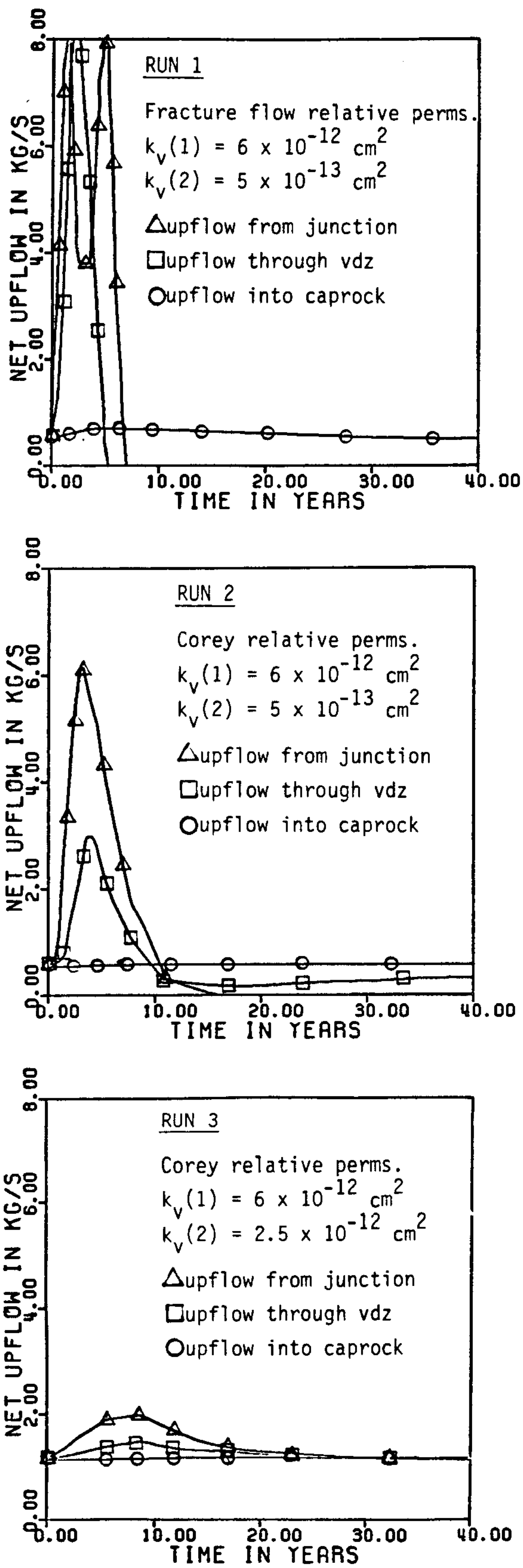

Figure 6. Development simulations involving production of 50 kg/s without reinjection. Production starts at 0 years.

pressures than for runs 1 and 2. The degree of overpressure affects the magnitude of pressure decline that can propogate 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.

Results for development runs involving reinjection were qualitatively similar to the results in figure 6. Changes in net steam upflow increased with the production rate and, hence, the difference between production and injection.

Temporary increases in steam upflow seen in these simulations are followed by decreases to levels at or below 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 produce the observed rapid rise in steam upflow. After about 5 - 10 years, liquid saturation and steam relative permeability tend to stablize 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 only occur if the vertical pressure gradient changes. Thus the observed increase in steam flow through the vapor zone at early times is accompanied by condensation of steam and resultant pressure increases, with more condensation and larger pressure increases at lower levels than at higher levels to increase the gradient. This condensation of excess steam results in the vapor zone acting as a buffer between relatively large changes in the region of phase separation and smaller changes at the base of the caprock.

Simulated changes in net steam upflow into the caprock layer ranged from 0 to

32 percent of the initial rate, and were in all cases very small compared with changes within and below the vapor-dominated zone. This primarily reflects 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 the change in steam upflow at the base of the vapor zone increases. The value for caprock permeability of 2.5×10^{-12} cm^2 used in run 3 is near the upper limit for successful simulation of the evolution of the Lassen system. However, a more detailed model involving separate channels for steam and liquid flow through the condensate zone would be required to adequately describe the 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.

Although no changes in pressure or upflow within the vapor-dominated zone were observed during development runs involving an extensive region of two-phase flow initially in the lateral conduit, such changes could occur if the permeability of the lateral conduit were at least an order of magnitude larger than the value used in these simulations. Higher permeability is possible if the conduit were thinner or less areally extensive than modeled. On the other hand, if outflow conduits at Lassen are more areally extensive than modeled in this study, conduit permeabilities may by lower and the speed of pressure propogation slower than our simulations indicate. In either event, the need for additional test drilling to delineate such conduits and to provide access for monitoring pressure and temperature changes near the Park boundary seems evident.

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