MODELING FLUID FLOW AND HEAT TRANSFER AT BASIN AND RANGE FAULTS: PRELIMINARY RESULTS FOR LEACH HOT SPRINGS, NEVADA

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ABSTRACT

The hydrothermal systems of the Basin and Range Province are often located at or near major range-bounding normal faults. The flow of fluid and energy at these faults is affected by the advective transfer of heat and fluid from and to the adjacent mountain ranges and valleys. This paper addresses the effect of the exchange of fluid and energy between the country rock, the valley fill sediments, and the fault zone, on the fluid and heat flow regimes at the fault plane. For comparative purposes, the conditions simulated are patterned on Leach Hot Springs in southern Grass Valley, Nevada. Our simulations indicate that convection can exist at the fault plane even when the fault is exchanging significant heat and fluid with the surrounding country rock and valley fill sediments. The temperature at the base of the fault decreases with increasing permeability of the country rock. Higher groundwater discharge from the fault and lower temperatures at the base of the fault are favored by high country rock permeabilities and fault transmissivities. Preliminary results suggest that basal temperatures and flow rates for Leach Hot Springs can not be simulated with a fault 3 km deep and an average regional heat flow of 150 mW/m^2 because the basal temperature and mass discharge rates are too low. A fault permeable to greater depths or a higher regional heat flow may be indicated for these springs.

INTRODUCTION

A number of geothermal systems occur in the Basin and Range Province of the western United States. Many of these systems are typically structurally-controlled, dynamic flow systems rather than reservoir systems (Yeamans, 1983). Hot springs associated with these systems occur along permeable vertical paths located at or near major range-bounding faults (Blackwell and Chapman, 1977). In general terms, they reflect deep groundwater flow in a region of high background heat flow. However, in most cases the manner in which fluid and heat transfer at a fault plane is affected by groundwater flow and energy transport to and from the surrounding country rock is not completely understood. For geothermal systems already under exploitation, and those under investigation, it is important to understand the nature of hydrodynamic processes within fault zones. It is equally important to understand how properties such as country rock permeability, regional heat flow, and fault depth affect the flow regime within the fault, and especially the output of fluid and energy at the surface. The purpose of this paper is to examine these factors in the framework of conditions similar to those found at Leach Hot Springs in Nevada.

In many previous investigations of heat transfer and fluid flow at fault zones, faults have been viewed as channels which input or discharge heat from a geothermal reservoir (e.g. Goyal and Narasimhan, 1982; Bodvarsson et al., 1982). In other cases, faults have been modeled as permeable slabs embedded in impermeable rock (e.g. Murphy, 1979; Sorey, 1978; Lowell, 1979), without consideration of the input of fluid and energy from country rock to the fault zone. Forster and Smith (1989) characterized the relationship between country rock permeability, fluid and energy transfer from country rock to valley faults, and the discharge temperature of thermal springs. More recently, López and Smith (1994) have studied the interplay between convective circulation in a fault plane and topographically-driven groundwater flow in a setting with a vertical fault surrounded by moderately high topographic relief. They showed that in a plot of fault permeability versus country rock permeability, there are well-defined regions leading to four different fluid and heat flow regimes: conductive, advective, steady convective, and unsteady convective. High temperature springs are more likely to reflect convective fluid circulation along strike of the fault than deep groundwater circulation that is driven up the plane of the fault by the regional topographic gradient on the water table.

Leach Hot Springs are located in Grass Valley, northwestern Nevada (Fig. 1). This valley is bounded by the north-trending Sonoma and East Ranges. According to Sorey and Olmsted (this volume), this is a region of relatively high regional conductive heat flow of 150 mW/m^2. The total flow rate at Leach Hot Springs is ~10 l/s and discharge temperatures are as high as 95 °C. Welch et al. (1981) provide a comprehensive review of the Leach Hot Springs area. The fault where the hot springs are located (Fig. 1), is a northeast trending structure. There is also a west-dipping buried basement scarpment having a more northerly trend and a throw of more than 800 m in the vicinity of Leach Hot Springs. The rocks in this region are slightly to moderately metamorphosed sedimentary, volcanic, and plutonic units. Fig. 1 shows that the fault is bounding the valley to the east and lower elevations of the country rock and the water table are found towards the center of the valley. A thick cover of consolidated to semi-consolidated sedimentary rocks and undeformed volcanic rocks fill the structural basin. The thickness of these permeable deposits is as much as 2 km. Silica geothermometers indicate a maximum temperature for the thermal water close to 140 °C, while alkali cations and sulfate-oxygen isotopes indicate a temperature between 150-180 °C.

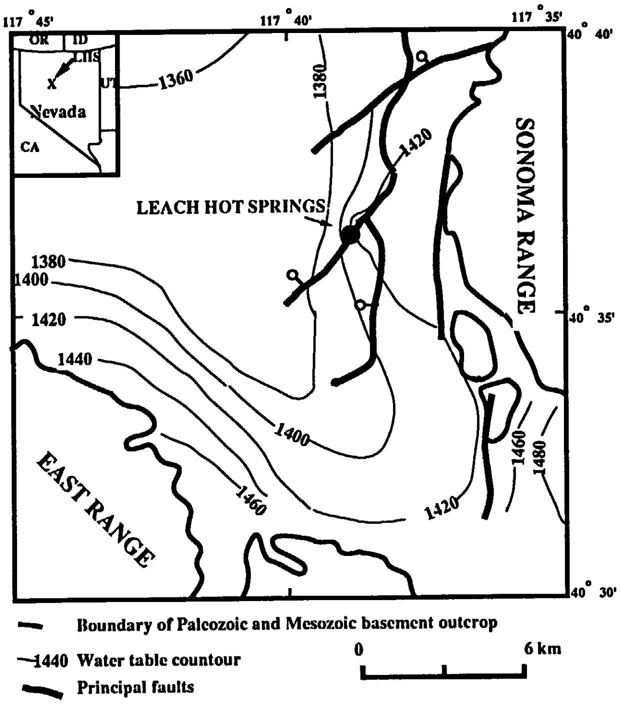

Figure 1. Simplified map showing the location of southern Grass Valley, Nevada, adjacent mountain ranges, main faults, and water table (after Sorey and Olmsted, 1994 and Welch et al., 1981).

Welch et al. (1981) modeled Leach Hot Springs in two dimensions using a numerical simulator that solved the coupled equations of fluid flow and heat transfer. They assumed the country rock was impermeable and represented the fault as a permeable channel. The fault was modeled as a linear feature transporting heat and fluid. They simulated different sections of the fault plane representing the upward and downward limbs of convective cells. For the section with upward flow at the fault, a source of hot water was located at the base of the fault. For the section with downward flow at the fault, a sink was located at the base of the fault. Thermal conductivities of rocks and sediments (3.4 and 1.7 W/m ^{o}K) were estimated from laboratory measurements. For a regional heat flow of 150 mW/m^2, their results suggested that in order to attain the maximum temperatures of 160-180 ^{o}C with fluid circulation in a single fault, the fault must be permeable to depths considerable greater than 3 km. They concluded that a more regional scale flow system with a laterally extensive deep reservoir may supply Leach Hot Springs. More recently, Pottorf (1988) has modeled Leach Hot Springs using a three-dimensional Discrete State Compartment (DSC) model. This method is based on dividing the domain into a small number of cells. The DSC model uses a continuity equation and iterative corrections of the input variables until the model output approximates the known values of fluid discharge and temperature. The modeled region included the Sonoma Range and the basin-bounding fault. Pottorf found that a fault depth of 5 km and a fault width of 100 m were needed to reproduce the observed temperature and flow rate of Leach Hot Springs. Our work focuses on both the advective transport of heat from the mountain ranges towards the fault and structural basin, and convection transport in the fault plane to study the fluid flow regime, the temperature field, and rates of groundwater recharge/discharge along the fault.

MATHEMATICAL AND NUMERICAL MODEL

The mathematical model we use is based on a three-dimensional numerical solution of the coupled equations of fluid flow and heat transfer (López and Smith, 1994). The boundary value problem is shown in Figure 2. The domain is patterned after Leach Hot Springs in terms of topographic relief on the water table, basal heat flow, rock and sediment thermal conductivity, and geological characteristics. Table 1 lists the values of the parameters used in the simulations. Heat and fluid flow is not allowed across the four lateral boundaries. The bottom boundary permits conductive heat transfer but it does not allow fluid flow because of a low permeability layer at the base of the model domain. The top surface has a specified fresh water head and ambient temperature, allowing the transfer of fluid and heat across the surface. A layer of permeable sediments fills the neighboring basin, permitting transfer of fluid and heat between the fault, country rock and the basin. The slope of the water table in the valley is 50 m in 6 km. The lateral extent of the model domain is 6 km.

Studies of fluid flow and heat transfer within fault zones (López and Smith, 1994) indicate that the permeability of the country rock, water table relief, transmissivity of the fault zone, and the width and depth of the fault, control the character of the flow regime at the fault plane. For the problem under consideration, the permeability of the sediments filling the basin can also play an important role in determining the flow regime. In this paper, the effect of some of these parameters are studied in order to characterize the hydrodynamic behavior of Basin and Range faults and, in particular, to find the conditions that can produce the Leach Hot Springs.

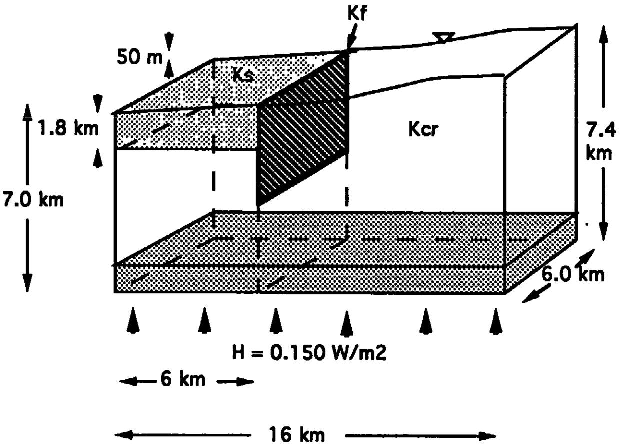

Figure 2. Conceptual model for groundwater flow and heat transfer at Basin and Range type faults. A low permeability basal boundary allows only conductive heat transfer. Several permeability and thermal conductivity regions can be recognized. They include the valley fill sediments Ks, the country rock Kcr, and the fault Kf. Problem dimensions, thermal conductivity, and basal heat flow are patterned on Leach Hot Springs, Grass Valley, Nevada.

TABLE 1. Typical Simulation Parameters

	Value
K_b, permeability of the basal unit	1.0×10^{-22} m^2
K_s, permeability of the valley fill sediments	1.0×10^{-15} m^2
H, basal heat flow	150 mW/m^2
G_l, thermal lapse rate	6.5 ^oC/km
T_{ref}, reference surface temperature	10 ^oC
θ_b, porosity of basal unit	0.01
θ_u, porosity of upper unit	0.10
λ_r rock thermal conductivity	3.40 W/m^oC
λ_s valley fill sediments thermal conductivity	1.70 W/m^oC
ρ_s, rock density	2.50 kg/m^3
a_L, longitudinal thermal dispersivity	10.0 m
a_T, transverse thermal dispersivity	10.0 m
b, fault width	50.0 m
T, fault transmissivity[1]	6.0×10^{-12} m^3

[1]Fault transmissivity is defined here as the product of permeability and the width of the fault zone.

CONVECTIVE FLOW REGIME WITHIN A FAULT PLANE

López and Smith (1994) document the region in country rock/fault permeability space where convection, advection, or conduction will be the dominant process within the fault plane. Their results indicate that cellular convection within the fault zone occurs at country rock permeabilities lower than approximately 1.0×10^{-15} m^2 and fault transmissivities higher than approximately 1.0×10^{-12} m^3. Fault transmissivity is defined as the fault permeability multiplied by the width of the fault. At higher country rock permeabilities than 1.0×10^{-15} m^2, regional groundwater flow from topographically higher areas leads to upflow everywhere along the fault trace. The exact positioning of the convective region in permeability space is determined mainly by the basal heat flow and fault depth. Values of fault transmissivity of 6.0×10^{-12} m^3 and country rock permeabilities lower than 1.0×10^{-15} m^2 are well within the steady convective region for a wide range of basal heat flows.

Figures 3 and 4 show the heat and fluid flow regime within the fault plane and along a plane perpendicular to the fault. The perpendicular plane intercepts the upward limb of the left convective cell about 500 m from the front boundary in Figure 2. For the simulation presented in Figures 3 and 4 the permeability of the country rock is 1.0×10^{-17} m^2, sediment permeability is 1.0×10^{-15} m^2, fault width is 50.0 m, fault depth is 3.0 km, fault permeability is 1.2×10^{-13} m^2, and fault transmissivity is 6.0×10^{-12} m^3. At the fault plane, two-well defined convective cells are formed and define regions of recharge and discharge of fluid along the fault trace (Fig. 3a). Heat is collected and transferred by the fluid flow, and discharged at the upward limbs of the convective cells (Fig. 3b). The heat flow arrows in Figure 3b represent the sum of the conductive and advective components of heat transfer. Heat fluxes at the fault springs can be up to two

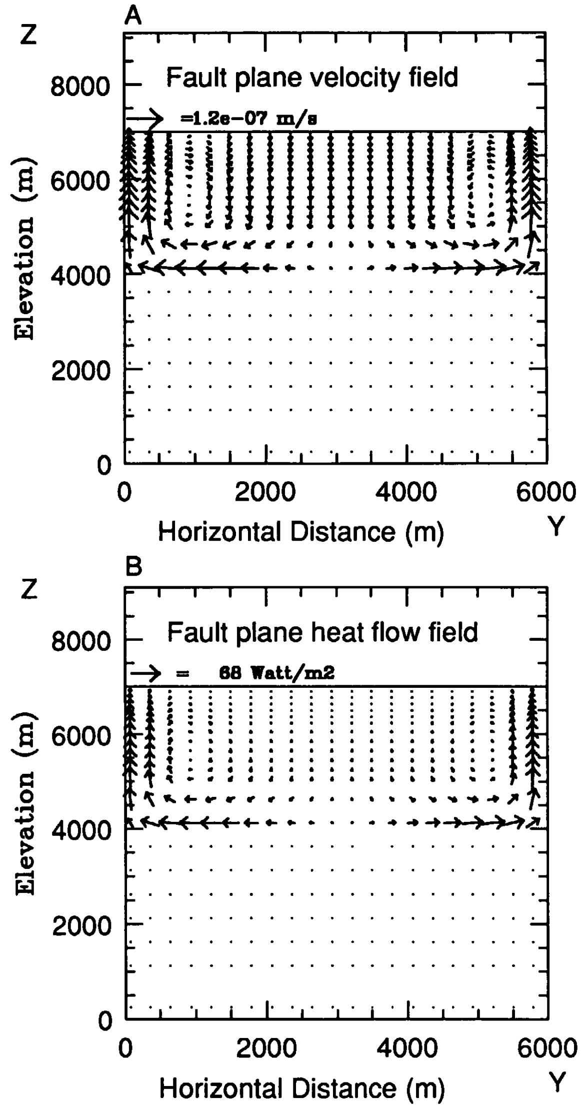

Figure 3. Patterns of ground water flow and heat transfer at the fault plane (a and b). Country rock permeability is 1.0×10^{-17} m^2, sediment permeability is 1.0×10^{-15} m^2, fault transmissivity is 6.0×10^{-12} m^3, and basal heat flow is 150 mW/m^2. Vector scales are linear.

orders of magnitude larger than the conductive heat flux entering the system at the base of the fault. Within the country rock, heat is transferred by advection from the mountains towards the fault and the valley fill (Fig. 4a and 4b). Some fluid and heat is transferred from the fault to the valley sediments. The magnitude of the mass discharge through the valley fill is close to the output at the fault (2.66 kg/s and 2.74 kg/s, respectively, in this case).

The temperature field within the fault plane and perpendicular to the fault plane provides important insight to the hydrogeological processes in this system. Figure 5 presents the temperature field in the fault plane (Fig. 5a) and

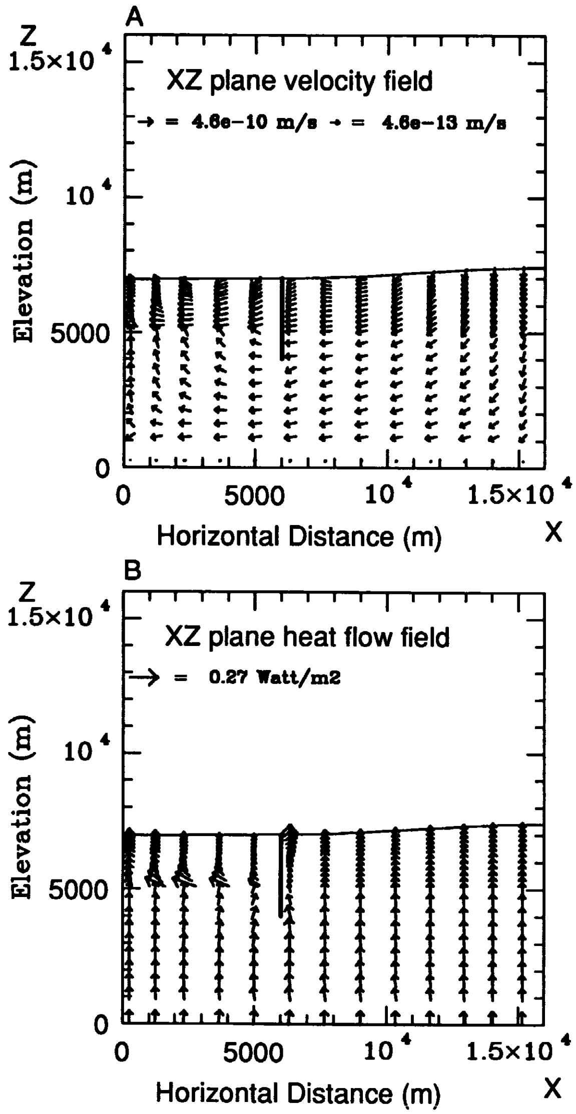

Figure 4. Patterns of ground water flow and heat transfer in a plane perpendicular to the fault, at the upward limb of the left convective cell (a and b). Country rock permeability, sediment permeability, fault transmissivity, and basal heat flow as in Figure 3. Vector scale is logarithmic for a and linear for b.

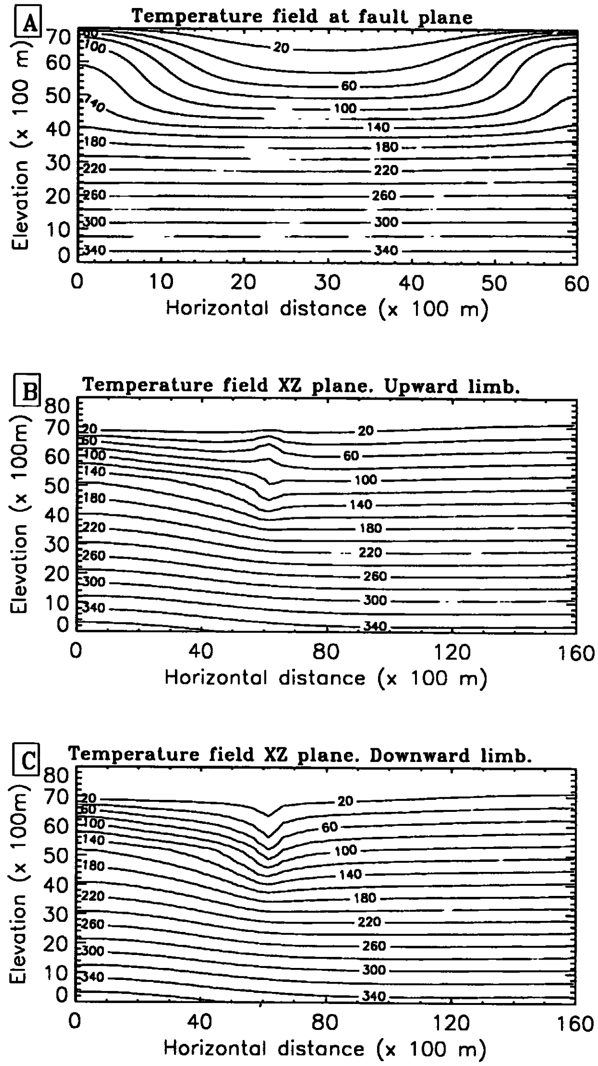

Figure 5. Temperature field for the simulation of Figures 3 and 4. a) Isotherms at the fault plane show the presence of two convective cells. b) A plane perpendicular to the downward limb of the convective cells show reduction in temperatures produced by the circulation of cold recharge fluid. c) A plane perpendicular to the upward limb of the convective cells shows reduction in temperature at the base of the fault and temperatures higher than the surroundings in the discharge regions.

in two planes perpendicular to the fault. One plane intercepts the upward limb of the left convective cell (Fig. 5b) and the other (Fig. 5c) intercepts the center of the fault (downward limb of convective cells). In Fig. 5a the cooling effect of the central recharge zone at the fault is observed in the isotherms. Upward flow is expressed in the high geothermal gradient near the discharge zone. In work in progress, we are relaxing the assumed condition of a specified temperature along the fault trace, and calculate the temperature of the discharging groundwater.

The profiles perpendicular to the fault (5b and 5c) show the refractive effect on the conductive component of the temperature field that is produced by the contrast in thermal conductivity between the sediments and the basement rocks. Figure 5b shows a cooling effect at the base of the fault. Within the upflow zone, the top of the fault is warmer than the surrounding country rock. For the downward flow region within the fault (Fig. 5c), the net effect of the recharging groundwater is to cool the system. Our simulations indicate that this cooling effect at the base of the fault occurs for both low country rock permeabilities

(1.0×10^{-19} m^2) and relatively high country rock permeabilities (1.0×10^{-16} m^2). For the particular case presented in Fig. 5, the average temperature at the base of the fault is 148 °C, several degrees lower than the surrounding country rock.

EFFECT OF COUNTRY ROCK PERMEABILITY AND FAULT TRANSMISSIVITY ON HOT SPRING THERMAL AND MASS DISCHARGE

The temperature field within the fault zone and the temperature and flow rates of the discharging springs are affected by the country rock permeability as well as by the fault transmissivity (López and Smith, 1994). In order to understand these effects, the permeability of the country rock was varied and the fault transmissivity held constant at 6.0×10^{-12} m^3. The country rock permeability and fault transmissivity values are within the range where steady convection dominates at the fault plane (López and Smith, 1994). In this paper we report the results of our initial simulations where the fault is permeable to a depth of 3 km.

Figure 6 shows the variations in the rate of fluid mass recharge and discharge at the fault, and the rate of fluid mass flow in the valley fill sediments. At low country rock permeabilities (lower than 5.0×10^{-18} m^2), groundwater recharge along the fault discharges as fault-controlled springs, in addition to leaking into the permeable valley fill sediments. Most of the fluid recharging the system enters along the fault trace, a minor amount enters from the country rock and the sedimentary fill close to the fault. For higher permeability country rock, the fluid recharged at the fault becomes less important and a major portion of fluid discharged at the fault originates from the country rock. The fluid fluxes are such, however, that a convective circulation pattern still occurs within the fault plane. The mass discharge through the valley fill also increases and becomes greater

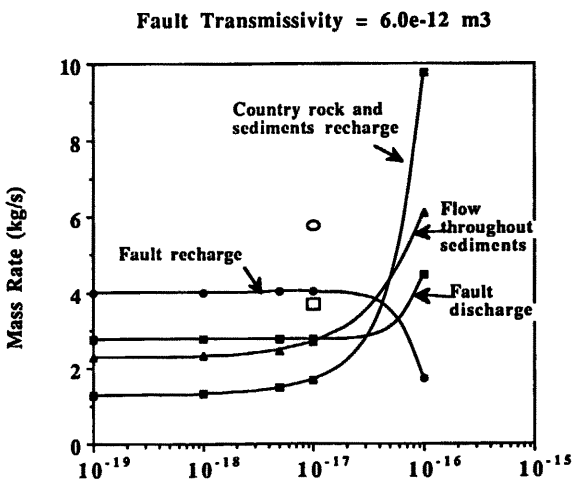

Figure 6. Variation in the mass rate of groundwater flow for different values of the country rock permeability, at constant fault transmissivity. Permeability of the valley fill sediments is 1.0×10^{-15} m^2.

than the fluid discharged at the fault. At a country rock permeability of 1.0×10^{-16} m^2, the flow through the sediments is 6.1 kg/s and the flow discharged along the fault is 4.4 kg/s.

The temperature at the base of the fault is important because it is the highest temperature encountered by the fluid circulating at the fault. It should be similar of the highest temperatures estimated from chemical geothermometers. Figure 7 shows the variations in the average temperature at the base of the fault as function of permeability of the country rock. The average temperature at the base of the fault is constant for low country rock permeabilities, but decreases rapidly for country rock permeabilities higher than 1.0×10^{-17} m^2. The effect of higher fluid flow within the country rock is to produce lower temperatures at the base of the fault. Heat is transferred from the country rock and the bottom of the fault and discharged at the springs. This behavior is observed in Fig. 3, 4, and 5 for the heat flow vectors and temperature field within the country rock and at the fault plane.

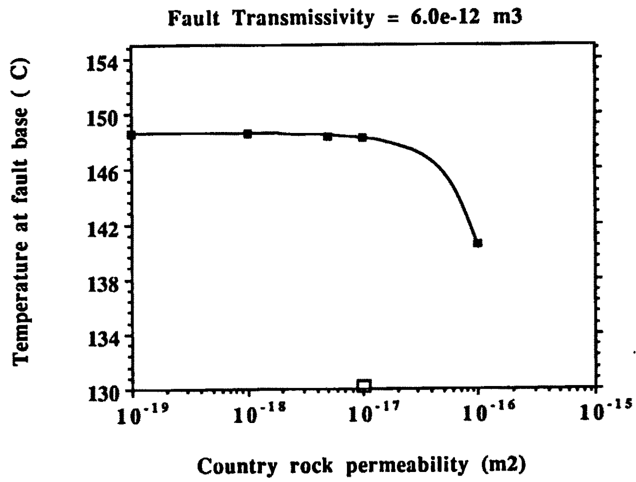

Figure 7. Temperature at the base of the fault for different values of the country rock permeability, at constant fault transmissivity. Permeability of the valley fill sediments is 1.0×10^{-15} m^2.

The temperatures and groundwater discharges estimated for Leach Hot Springs differ from the values found for a fault that is permeable to a depth of 3 km. Figure 6 suggests that in order to obtain a discharge at the fault of ~10 l/s, a country rock permeability considerable higher than 1.0×10^{-16} m^2 is needed. However, a high country rock permeability has a negative effect on the temperature at the base of the fault (Fig. 7). Temperatures lower than 140 °C are expected for country rock permeabilities higher than 1.0×10^{-16} m^2. In addition, higher permeability values are not consistent with the types of rocks found in this site. López and Smith (1994) showed that at either high permeabilities for the country rock (> 1.0×10^{-15} m^2), or at moderate permeabilities for the country rock, but lower permeabilities for the fault (< 1.0×10^{-13} m^2), an advective flow pattern is established within the fault plane, with the upward movement of groundwater everywhere along the fault trace. However, it does not seem possible to generate Leach Hot Springs in an advective regime at the fault plane because, at high country rock permeabilities the temperatures at the base of the fault are too low. Furthermore, for lower values of fault permeability, the mass fluxes discharged at the fault trace are too low.

Another possible way to obtain an increase in the groundwater discharge at the fault is to increase the transmissivity of the fault. The open symbols in Figures 6 and 7 correspond to a fault transimissivity of $1.0x10^{-11}$ m^3 instead of $6.0x10^{-12}$ m^3, and a country rock permeability of $1.0x10^{-17}$ m^2. A considerable increase in the fault discharge is observed, from 2.7 kg/s to 3.7 kg/s. Nevertheless, the temperature at the base of the fault decreases to 130 ^oC from 148 ^oC in the previous case (Fig. 5). An increase in fault transmissivity increases the groundwater discharge at the fault but decreases the temperature at the base of the fault.

Additional simulations are planned to better define the conditions that describe Leach Hot Springs. It is clear at this point that a single fault 3 km deep cannot produce these springs if a basal heat flow of 150 mW/m^2 is assumed. It is expected that a deeper fault, higher basal heat flow, or lower country rock thermal conductivities could yield higher basal temperatures. Another possible scenario is the existence of a deep zone of horizontal permeability linking the fault at Leach Hot Springs with the faults to the west of the basin, and the East Range (Fig. 1), as suggested by Welch et al. (1981). Simulations are underway to investigate these cross-basin flow and the effects of fault depth, permeability of the valley-fill sediments, fault dip, fault length, and heterogeneities in permeability within the fault plane on the mass discharge from thermal springs, spring temperatures, and temperatures at the base of the fault.

CONCLUSIONS

The preliminary work reported here allows the following conclusions:

1) Convective circulation at the fault plane occurs even when the fault is receiving fluid and heat from the country rock and transferring some of the fluid and heat to the valley fill sediments. At low country rock permeabilities groundwater is preferentially discharged at the fault trace. At the highest permissible values of country rock permeabilities within the convective regime, the fluid transferred to the sediments from the fault and the country rock is greater than the fluid discharged at the fault trace.

2) The effect of fluid circulation is to decrease the temperature at the bottom of the fault with respect to the surrounding country rock. The fluid transfers heat from the country rock and the base of the fault to the upper discharging parts of the system.

3) Higher temperatures at the base of the fault are favored by low country rock permeabilities and fault transmissivities. Higher discharges from thermal springs are favored by high country rock permeabilities and fault transmissivities.

4) It is not possible to model the Leach Hot Springs with a fault 3 km deep and the average heat flow in this site. A deeper fault or a higher heat basal flow could be producing these springs. The occurrence of several listric faults-instead of a singular fault would lead to higher flow rates but it will probably decrease the temperature at the base of the fault. These scenarios are currently under investigation.

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