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THERMAL CONSTRAINTS ON THE SEALING EFFICIENCY OF THE CAPROCK OVERLYING THE MEDICINE LAKE HYDROTHERMAL SYSTEM

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ABSTRACT

Medicine Lake volcano, a large Quaternary volcano located within the northern California segment of the Cascades Range, has been identified as the possible site of a 48.8 MW powerplant to be operated by the California Energy General Corporation. Recent research by the USGS and other institutions has focused on evaluating and understanding the sealing efficiency of the caprock overlying the hydrothermal system. The caprock consists of hydrothermally altered volcanic rock that isolates the hydrothermal system from shallow, low-temperature ground water. Water-level and fluid pressure measurements in shallow (<200 m) water wells, intermediate depth (up to 1400 m) temperature-gradient holes, and deep (up to 2600 m) exploratory geothermal production wells demonstrate that the hydraulic seal produced by the caprock results in a hydraulic head difference of more than 200 m between the shallow ground water system and the lower pressure geothermal reservoir. Equilibrium temperature measurements acquired from three exploratory production wells have been combined with thermal conductivity measurements on core samples to reveal three thermal regimes characterizing the Medicine Lake system. The upper 100 to 400 m are nearly isothermal, reflecting the rapid downward flow of cold (<20 °C) meteoric water through the shallow subsurface. From the base of this isothermal zone to depths as great as 800 m, temperatures increase steadily with depth, reflecting constant, conductive heat flow. This interval of conductive heat flow corresponds to the zone of argillic alteration identified by J. Hulen and S. Lutz of EGI as the caprock of the hydrothermal system. Below this interval the nearly isothermal conditions of the geothermal reservoir predominate, with temperatures exceeding 250 °C.

Mathematical models for the thermal effects of vertical water flow within the Medicine Lake system indicate that downward flow in the shallow subsurface is rapid, reaching rates of approximately 50 cm/yr, a result consistent with observations of this "rain curtain" effect in other young volcanic settings. In addition, the thermal models indicate that all of this flow terminates in the upper 100 meters of the zone of argillic alteration. Variations in heat flow below this point are best explained by conductive transients resulting from the evolving physical state and geometry of the hydrothermal system.

INTRODUCTION

Medicine Lake volcano is a large Pleistocene and Holocene shield volcano located approximately 50 km northeast of Mount Shasta in northeastern California (Figure 1). The volcano is thought to contain approximately 600 km^3 of eruptive material and is predominantly mafic in composition, even though several late Holocene silicic lava flows are found in the upper parts of the volcano (Donnelly-Nolan, 1988). Constructional volcanism has established a one km-wide rim encircling the shallow elliptical basin containing Medicine Lake itself (Hulen and Lutz, 1999). Geothermal exploration has been focused on Medicine Lake since the late 1980s, with the completion of 26 temperature-gradient holes in the surrounding region (Richard et al., 1998). Although there are few geothermal features at the surface, Medicine Lake volcano hosts a high temperature (up to 288 °C) liquid-dominated geothermal system (Iovenitti and Hill, 1997). The California Energy General Corporation (CalEnergy) has proposed to construct a 48.8 MW geothermal power plant at the Telephone Flat area within the constructional basin east of the lake.

Medicine Lake Region

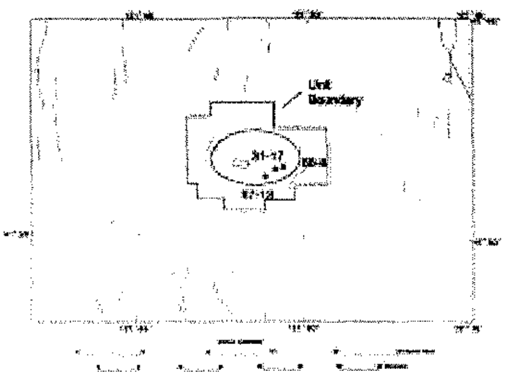

Figure 1. Map of the Medicine Lake region showing active faults, the constructional rim of the volcano, the geothermal unit boundary, an the location of the three deep wells discussed in this paper.

The primary reason for the absence of surface geothermal manifestations is the rapid flow of cooler ground water in the near surface. Much of this ground water flows down from the Medicine Lake highlands into the permeable volcanic rocks of the Modoc Plateau and contributes approximately 2% of the water discharging from the Fall River springs approximately 55 km south of Medicine Lake (Iovenitti and Hill, 1997). An important factor in the understanding of the Medicine Lake geothermal system is the degree to which the shallow ground water mixes with the higher temperature geothermal fluid. This paper presents results of a heat flow study at Medicine Lake which place quantitative constraints on the possible rates of flow between the shallow ground-water system and the deep hydrothermal system.

THERMAL DATA

Equilibrium pressure and temperature logs were acquired from three of the four deep exploratory wells at Medicine Lake (GMF 31-17, 68-8 and 87-13) in October of 1998 and August of 1999. Temperature data from the upper 1000 meters of these three wells are shown in Figure 2. All three wells have a shallow, nearly isothermal zone overlying a zone of high gradients in an apparently "conductive" profile which then transitions to near-isothermal conditions within the geothermal reservoir. In each well there are modest thermal disturbances at the fluid level. The shallow isothermal zone is substantially thinner in well 87-13, and there is evidence for downward flow in the annulus behind the casing from a depth of approximately 200 meters down to the fluid level at 270 meters. The fluid levels in 31-17 and 68-8 are 330 meters and 308 meters, respectively. Although only sparse data are available to map the water table within the vicinity of Medicine Lake, the available data indicate that the head difference between the shallow ground water and the equilibrium pressure recorded in these wells ranges from 210 to 270 meters (Iovenitti and Hill, 1997).

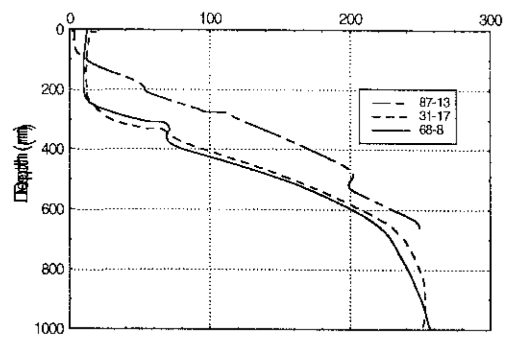

Figure 2. Temperature profiles for the upper 1000 m of the three wells discussed in the text.

The temperature profiles in these wells are consistent with observations from many other geothermal systems. The upper isothermal sections are typical for subsurface temperatures in young volcanic terranes. These features are a consequence of what is generally referred to as the "rain curtain" effect, whereby the rapid infiltration of water from snow melt and rainfall through the highly permeable volcanic rocks overcomes the background geothermal gradient and suppresses near surface temperatures (Swanberg et al., 1988; Blackwell and Steele, 1987). The approximately linear temperature profiles below the shallow isothermal sections reflect a transition to heat transfer dominated by conduction, with the return to curvature in the temperature profiles at greater depths reflecting predominantly advective heat transfer within the underlying hydrothermal system.

This thermal evidence for a conductive seal or caprock over the hydrothermal system is consistent with the observed contrast in hydraulic head between the shallow and deep system and the development of hydrothermal alteration with depth. As demonstrated by Bargar and Keith (1997), Hulen and Lutz (1999), and Lutz et al. (2000), hydrothermal alteration within the Medicine Lake subsurface is consistent with the development of a caprock. Within well 31-17, a shallow zone of little or no alteration dominated by the low temperature ground water evolves to an interval of zeolite-smectite or upper argillic alteration. At approximately 400 meters depth, the appearance of mixed-layer clays, chlorite, quartz and potassium feldspar mark the beginning of a lower argillic zone of alteration (Hulen and Lutz, 1999). By 800 meters depth, the appearance of epidote and the gradual disappearance of smectite mark the transition from argillic to propylitic alteration. According to Hulen and Lutz, this second transition forms the base of the caprock and the beginning of the geothermal reservoir. On the basis of alteration studies alone, it is difficult to identify the upper limit of the caprock. Abundant clay mineralization characterizes both the zeolite-smectite and the argillic zones of alteration.

In order to provide quantitative constraints on the sealing efficiency of the caprock to the Medicine Lake hydrothermal system and to develop a consistent tie between alteration patterns and the presence of an impermeable barrier, we have analyzed the thermal data with a recently developed analytical model for the thermal effect of vertical groundwater flow.

MATHEMATICAL MODEL

Existing models for the thermal effects of vertical ground-water flow assume constant fluid velocity through a layer with fixed thermal boundary conditions (e.g., Bredehoeft and Papadpolos, 1965). Models of this type cannot be used to represent conditions above the caprocks of hydrothermal systems, because the presence of a low permeability zone ensures a variable fluid velocity with depth. In order to estimate the rate and depth extent of downward ground-water flow at Medicine Lake, we have developed a one-dimensional mathematical model for the thermal effects of vertical groundwater flow that varies linearly from a maximum at the top of the layer to zero at the bottom (see a related discussion in Williams and Galanis, 1994).

In this model, the relevant equation for coupled heat and fluid transport is

$$\frac{d}{dz}\bullet\left(\lambda\frac{dT}{dz}\right)=-\rho_f c_f v(z)\frac{dT}{dz} \qquad (1)$$

where λ is the whole rock thermal conductivity (assumed constant over the interval), ρ_f is the fluid density, c_f is the fluid heat capacity, and $v(z)$ is the vertical fluid velocity as a function of depth. Over a layer from $z = 0$ to $z = L$, the following boundary conditions are applied. At $z = 0$, $T = 0$ and $v = v_0$. At $z = L$, $T = T_L$ and $v = 0$. The functional form of the vertical flow is

$$v(z) = v_0(z-L)/L \qquad (2)$$

In this model, mass is conserved by having the horizontal fluid velocity increase with depth at the same rate as the vertical velocity decreases with depth, and the one-dimensional thermal features of the problem are maintained by assuming the horizontal flow follows isotherms. Limitations of this assumption are discussed below. Equation (1) can be reduced to a non-dimensional form by defining $\xi = z/L$, $\Theta = T/T_L$, and a Peclet number (Clauser and Villinger, 1990)

$$Pe=\frac{\rho_f c_f v_0 L}{\lambda} \qquad (3)$$

The boundary conditions are then transformed to $\Theta = 0$ at $\xi = 0$ and $\Theta = 1$ at $\xi = 1$. The complete solution for nondimensional temperature is

$$\Theta=\frac{erf\left(\sqrt{\frac{Pe}{2}}(\xi-1)\right)+erf\left(\sqrt{\frac{Pe}{2}}\right)}{erf\left(\sqrt{\frac{Pe}{2}}\right)} \qquad (4)$$

where erf() is the error function. From this a dimensional vertical temperature gradient, $p = d\Theta/d\xi$, can be defined and works out to be

$$p=\frac{e^{\frac{Pe}{2}(\xi-1)^2}}{\sqrt{\frac{\pi}{2Pe}}\,erf\left(\sqrt{\frac{Pe}{2}}\right)} \qquad (5)$$

When dimensional variables are substituted into equation (5) the vertical temperature gradient becomes

$$\Gamma(z)=\Gamma_L \exp^{\frac{Pe}{2}\left(\frac{z}{L}-1\right)^2} \qquad (6)$$

where Γ is used to represent the vertical temperature gradient. Profiles of p are shown in Figure 3 for varying values of the Peclet number. The primary features of note are the transformation of the gradient profile with depth from concave to convex as the vertical velocity approaches zero and the match of the lower gradient values with the background conductive value established as a boundary condition.

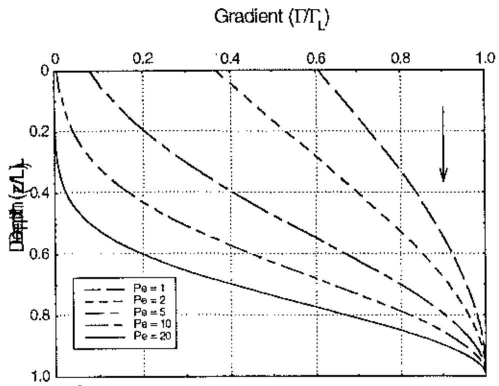

Figure 3. Profiles of dimensionless temperature gradient from Equation (6) for varying values of the Peclet number.

DISCUSSION

The model developed in the previous section has many limitations. Perhaps the most important of these to the present study is the assumption that the rate of decrease in downward flow rates from the surface to the caprock is linear. Although this adoption of a linear velocity profile yields a model that can accommodate the necessary decrease in velocity, the actual velocity profile is probably nonlinear. The long term downward flow rate is almost certainly constant down to the water table. From this point it decreases at a rate that reflects both the vertical stratification of permeability imposed by hydrothermal alteration and the structural influence of varying lithology and topography. Although the linear model provides a relatively straightforward functional form for solution of equation (1), other solutions of polynomial, sinusoidal or exponential form may prove both solvable and more realistic.

Another limitation of the model is the assumption that horizontal flow follows isotherms and does not contribute to the transport of heat. This constrains all of the increase in temperature and temperature gradient with depth to reflect the balance of advective and conductive heat transport in the vertical direction. Near the summit of Medicine Lake volcano, where nearly isothermal downflow dominates the shallow ground-water system, this is a reasonable approximation. In areas where lateral ground-water flow predominates, increases in temperature and temperature gradient with depth are the result of conductive heating of the water flowing along the base of the aquifer (Williams et al., 1994).

Despite these limitations, gradient profiles predicted by the model are consistent with the observed gradients. Figure 4 shows the predictions of the model for Peclet numbers of 12, 20 and 24 for a linear decrease in the vertical flow rate over a depth range from 50 to 450 meters. These model curves are plotted with gradients measured in wells 31-17 and 68-8. In both cases, despite some disturbance in the two wells at the fluid level, the model curves match the data quite well. In both wells, the model predicts termination of downward flow at a depth of approximately 450 meters. In well 31-17, this corresponds to the transition between the upper argillic and lower argillic zones identified by Hulen and Lutz (1999). Reductions in the temperature gradient below this depth probably reflect three-dimensional conductive and advective variations in heat transport near the top of the reservoir.

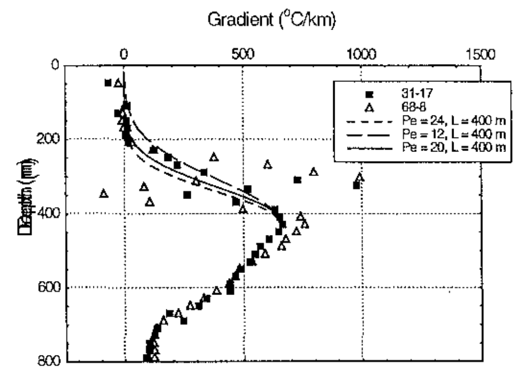

Figure 4. Temperature gradients from wells 31-17 and 68-8 compared with linear velocity model profiles for Peclet numbers ranging from 12 to 24 with flow terminating at a depth of 450 m.

For well 87-13, the base of the cool ground-water regime is much shallower. As shown in Figure 5, model curves for Peclet numbers ranging from 10 to 16 with the downward flow velocity decreasing to zero at a depth of 150 meters provide a good match to the data. One other significant difference in well 87-13 is the relatively constant gradient from the base of shallow ground water at 150 meters past 400 meters. This suggests that temporal and spatial variations in heat transfer within the upper part of the reservoir are limited in amplitude near the well site. More than 100 thermal conductivity measurements on core samples from wells at Medicine Lake yield a relatively constant average (1.7 ± 0.3 W/m•K), which allows for the direct correlation of gradient variations with heat flow variations.

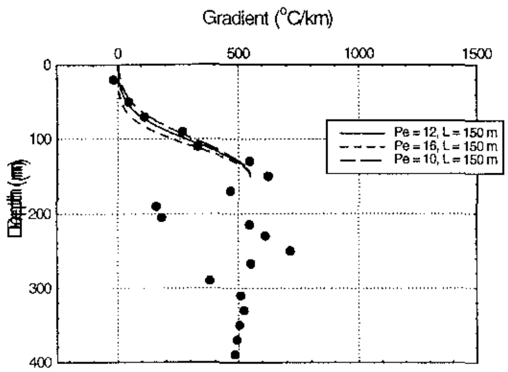

Figure 5. Temperature gradients from well 87-13 compared with linear velocity model profiles with Peclet numbers varying from 10 to 16 and with flow terminating at a depth of 150 m.

When representative values for thermal conductivity, heat capacity, and density are substituted into the Peclet number as defined in equation (3), the results for wells 31-17 and 68-8 yield surface flow rates of v_0 = 40 to 80 cm/yr. For well 83-17, the estimated flow rates are v_0 = 90 to 110 cm/yr. As reported by Iovenitti and Hill (1997), the long-term average precipitation within the Medicine Lake basin is 81 cm/yr. With the loss of some of this precipitation to the atmosphere, the true average value for v_0 is likely to be close to 50 cm/yr. The consistency of the predicted flow rates for wells 31-17 and 68-8 with the observed precipitation provides an additional confirmation of the applicability of the model. Although there may be some variation in v_0 within the basin, the estimate for well 83-17 is probably high. In all likelihood this modest difference is due to the deviation of the true velocity profile from a linear model.

CONCLUSIONS

The geothermal reservoir found in the Telephone Flat area of Medicine Lake volcano is isolated from the shallow ground-water system by an impermeable caprock. Several lines of evidence confirm the existence of this caprock, including a substantial difference in hydraulic head between the shallow ground water and the reservoir, the absence of any detectable geochemical signature of hydrothermal water (Mariner and Lowenstern, 1999), the presence of clays and other low permeability alteration products within the rock overlying the reservoir, and the apparent transition from advective to conductive thermal regimes within the caprock.

In this study we have examined equilibrium temperature logs from three wells which penetrate the reservoir and developed a simple mathematical model for the response of the vertical temperature gradients to the termination of downward ground-water flow within a caprock. Comparisons of model results with the data demonstrate the termination of flow within the argillic zone of hydrothermal alteration identified by Hulen and Lutz (1999) and thought by them to represent the process by which these permeable volcanic rocks are altered to form an impermeable seal. In the context of this study, termination of flow is taken to represent a decrease in vertical flow velocity below a level detectable by precision temperature measurements. This detectability level is probably on the order of 1 cm/yr, although the reversing curvature in the temperature logs below the depths considered by the model are almost certainly representative of a transition to an upwelling regime within the geothermal reservoir itself.

REFERENCES

Bargar, K.E., and Keith, T.E.C., (1997), Estimated temperatures for geothermal drill holes at Medicine Lake volcano, northeastern California, based on fluid-inclusion and hydrothermal mineralogy studies, *USGS Open-file Report* 97-716 (released June, 1999), 116 p.

Blackwell, D.D., and Steele, J.L., (1987), Geothermal data from deep holes in the Oregon Cascade Range, *Trans. Geotherm. Resour. Counc.*, v. 11, p. 317.

Bredehoeft, J.D., and Papadopulos, I.S. (1965), Rates of vertical groundwater movement estimated from the Earth's thermal profile, *Water Resour. Res*, v. 1, no. 2, p. 325-328.

Clauser, C., and Villinger, H., (1990), Analysis of conductive and convective heat transfer in a sedimentary basin, demonstrated for the Rhinegraben, *Geophys. J. Int.*, v. 100, p. 393-414.

Donnelly-Nolan, J.M., (1988), A magmatic model of the Medicine Lake volcano, California, *J. Geophys. Res.*, v. 93, p. 4412-4420.

Hulen, J.B., and Lutz, S.J., (1999), Altered volcanic rocks a hydrologic seals on the geothermal system of Medicine Lake volcano, California, *Geothermal Resour. Council Bull.*, v. 7, September/October, p. 217-222.

Iovenitti, J.L., and Hill, D.G., (1997), Baseline hydrogeology evaluation report for the Telephone Flat Project, Medicine Lake, California, *Weiss Associates, Report prepared for CalEnergy Corporation*, Emeryville, California, 34p.

Lutz, S.J., Hulen, J.B., and Schriener, A., Jr., (2000), Alteration, geothermometry, and granitoid intrusions in well GMF 31-17, Medicine Lake volcano, geothermal system, California, *Proc. 25th Stanford Geothermal Workshop,* this volume.

Mariner, R.H., and Lowenstern, J.B., (1999), The geochemistry of waters from springs, wells, and snowpack on and adjacent to Medicine Lake Volcano, northern California, *Trans. Geothermal Resour. Council*, v. 23, p. 319-322.

Richard, M., Shuster, D., and McClain, D., (1998), Medicine Lake milestones, *Bull. Geothermal Resources Council,* April/May, p. 70-75.

Swanberg, C.A., Walkey, W.C., and Combs, J., (1988), Corehole drilling and the 'rain curtain' phenomenon at Newberry Volcano, Oregon, *J. Geophys. Res.,* v. 93, p. 10,163-10,173.

Williams, C.F., and Galanis, S.P., Jr., (1994), "Heat-flow measurements in the vicinity of the Hayward fault, California", *USGS Open-file Report* 94-692.

Williams, C.F., Galanis, S.P., Jr., Grubb, F.V., and Moses, T.H., Jr., (1994), The thermal regime of the Santa Maria Province, California, *USGS Bulletin,* n. 1995, Chapter F, 25p.

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