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EVALUATING HEAT FLOW AS A TOOL FOR ASSESSING GEOTHERMAL RESOURCES

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ABSTRACT

Recent studies have highlighted an approximate proportionality between the rate of natural heat loss (both advective and conductive) and the electric power production capacity of geothermal reservoirs. This study investigates the possible reasons for these observations and addresses the question of whether heat flow measurements alone can be used to estimate the production potential of geothermal systems or at least provide a basis for assessing the magnitude of the resource. Results from a suite of numerical models for heat transport from reservoirs of varying shapes, sizes and depth extents support the hypothesis that the recoverable thermal energy of some reservoirs can vary over a wide range with little impact on the corresponding surface heat flux.

Transient effects due to cooling or warming over geologic time, as well as thermal anomalies arising from heat sources unrelated to fluid circulation, such as the shallow emplacement of magma, further complicate the relationship. For those geothermal reservoirs at or near a thermal steady state, near-surface heat flow measurements provide a direct measurement of the natural heat flux required to maintain the hydrothermal system and thus yield an approximate estimate of the potential renewable level of production. However, heat flow is best applied as a tool to estimate the thermal energy of a reservoir if the spatial distribution of the observed heat flow anomaly, or complementary geological, geochemical or geophysical data, can be used to constrain the reservoir's temperature and subsurface geometry.

INTRODUCTION AND BACKGROUND

Through the history of geothermal exploration and development a number of techniques have been applied to the problem of characterizing geothermal resources. Muffler and Cataldi (1978) identified four methods for assessing geothermal resources: surface heat flux, volume, planar fracture and magmatic heat budget. The volume method as developed by Nathenson (1975), White and Williams (1975), Muffler and Cataldi (1978) and Muffler et al. (1979) was quickly established as the standard approach in resource assessments conducted by the USGS and other organizations (e.g., Lovekin, 2004). The volume method is a self-consistent and accurate approach to geothermal resource assessments, provided adequate data are available on the size, depth and thermal state of potential geothermal reservoirs. This need for detailed information on the nature of potential geothermal reservoirs is a significant limitation on the applicability of the volume method, particularly for those reservoirs only known through surface and near-surface observations.

Consequently, the observation by Wisian et al. (2001), that there is a rough proportionality between the rate of natural surface heat loss (both advective and conductive) and electric power production capacity of geothermal reservoirs (Figure 1), raises the question of whether the proportionality can be applied in a new heat flux approach to geothermal resource assessments (e.g., Sanyal, 2004).

Figure. 1. Plot of installed geothermal reservoir production capacity versus surface heat loss from Wisian et al. (2001). Solid lines represent ratios of production equal to 10x and 1x surface heat loss.

Figure 1 reproduces the production capacity and surface heat loss data from Wisian et al. (2001). An important aspect of these observations is that the range of power production covers more than three orders of magnitude while the surface heat loss ranges over approximately two orders of magnitude, a result inconsistent with a strict proportionality. In some cases this may reflect incomplete development of a subset of producing geothermal fields or variations in the recovery factor, but consideration of the variables controlling both natural heat loss and reservoir thermal energy suggest this is not the sole explanation.

According to Muffler and Cataldi (1978), the electric power generation potential from an identified geothermal system depends on the thermal energy, H_R, present in the reservoir and the efficiency with which the reservoir thermal energy can be converted to electric power. (Both q and H have been used to represent reservoir thermal energy. In this paper H is used to avoid confusion with the common use of q for heat flow measurements.) This thermal energy is given by

$$H_R = \rho C V (T_R - T_{ref}) \quad (1)$$

where ρC is the volumetric specific heat of the reservoir rock, V is the volume of the reservoir, T_R is the characteristic reservoir temperature, and T_{ref} is a reference temperature, typically close to the average ground surface temperature. This thermal energy can be related to electric power production through application of recovery and conversion factors, but given the significant variability of recovery factors among geothermal fields (e.g. Muffler, 1979; Sanyal, 2004; Williams, 2004), the analysis here is restricted to comparisons of reservoir thermal energy to natural heat loss. For comparison with heat loss measurements, this thermal energy can be converted to thermal “power”, P_R, as

$$P_R = H_R / t \quad (2)$$

with t representing a period of exploitation. In the comparisons below t is taken to be 30 years.

The natural heat flux from a geothermal system is the combination of both its advective (e.g., fluid discharge from natural hot springs) and conductive parts. As noted by Wisian et al. (2001), the conductive part usually predominates and is the focus of this study. Near-surface conductive heat flow, q, is measured as

$$q = k \frac{dT}{dz} \quad (3)$$

where k is the thermal conductivity of the rock and dT/dz is the vertical temperature gradient.

Recognizing that ρ, C, and k are approximately constant for any given geothermal reservoir, P_R/q should be relatively constant as long as variations in dimensions of reservoirs are reflected in the magnitude of the surface heat flux. If these variations are not reflected in surface heat flow, P_R/q will vary. In order to address this issue quantitatively, a series of two-dimensional, finite-element, conductive heat flow models were evaluated for reservoirs of varying shape, volume and depth.

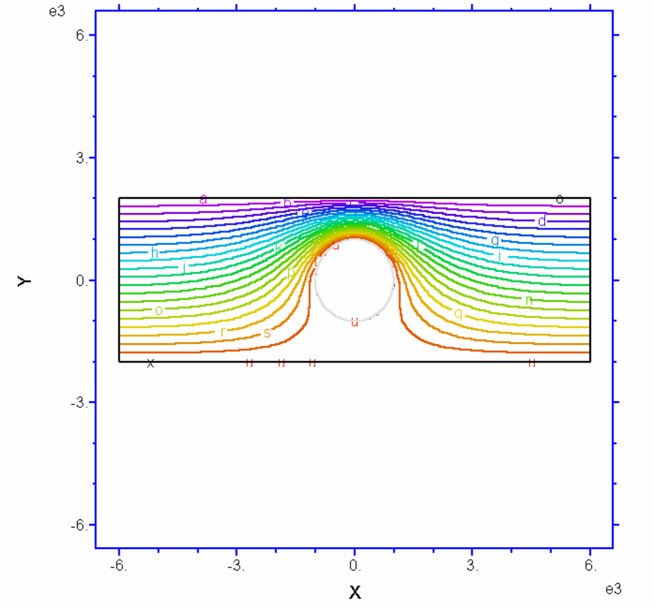

Figure 2. Temperature contours at 10 ^{o}C intervals for a 200 ^{o}C cylindrical reservoir of 1 km radius, with the top of the reservoir at 1 km depth. Lateral dimensions are in km.

CONSTANT TEMPERATURE RESERVOIRS

The models developed in this study determine subsurface temperatures and heat flow from constant temperature cylindrical and rectangular block reservoirs of varying size and depth. In each model the reservoir temperature was set at 200 ^{o}C, the surface temperature at 0 ^{o}C, and the thermal conductivity to 2.5 W m^{-1} K^{-1}. The background geothermal gradient was set to 50 ^{o}C km^{-1}, and the depth to the top of each reservoir was varied from 1000 to 3000 meters. The lateral extent of the rectangular block reservoirs ranged from 250 meters to 6000 meters for a reservoir thickness of 1000 meters. Those models with lateral extent substantially greater than the reservoir thickness can be considered representative of relatively thin, laterally extensive reservoirs, such as might be found in the strata of sedimentary basins. Those with lateral extent substantially less than their thickness are considered representative of subvertical, fault-hosted reservoirs such as those found in the Great Basin of the western United States.

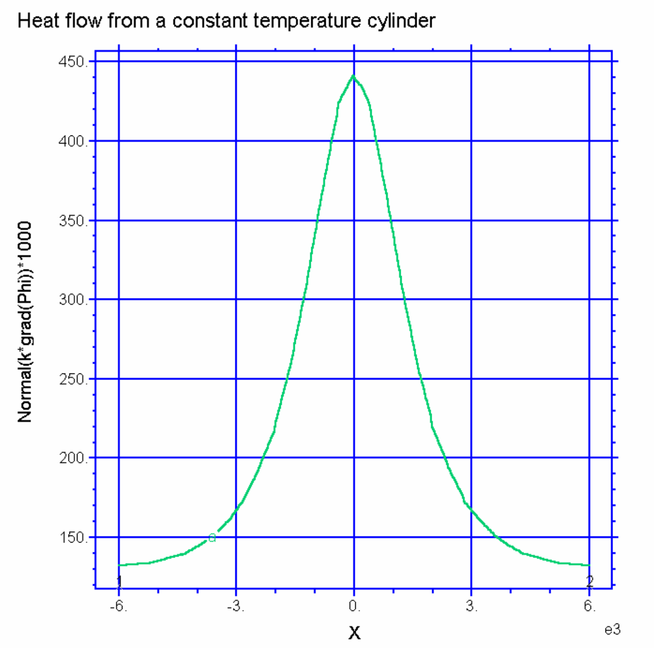

Figure 3. Surface heat flow for the cylindrical reservoir shown in Figure 2.

Figure 2 shows the temperature contours for a cylindrical reservoir with a top at a depth of 1 km and a radius of 1 km. The proximity of the model reservoir to the surface results in a substantial surface heat flow anomaly (Figure 3), with the total additional heat flux due to the geothermal reservoir equal to 1.1 MW for each meter of thickness out of the plane of the model. Figure 4 shows the temperature contours for a rectangular reservoir at 1 km depth with horizontal extent of 4 km and thickness of 1 km. The resulting heat flow anomaly (Figure 5) reflects the greater size and lateral extent of the reservoir.

Figure 6 is a summary of modeled thermal power versus heat loss for the two geometries where the top of the simulated reservoirs is varied from 1 to 3 km. Although the two-dimensional, constant temperature models represent an idealization, the correspondence with the data in Figure 1 is striking.

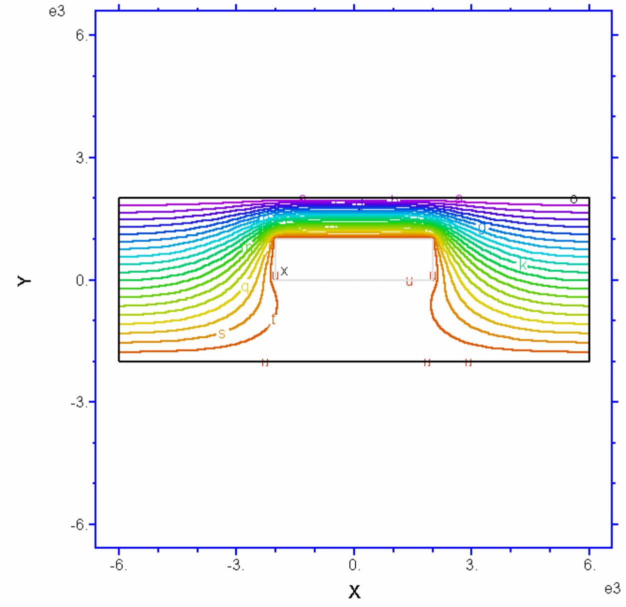

Figure 4. Temperature contours at 10 ^oC intervals for a 200 ^oC rectangular block reservoir of 4 km lateral extent, 1 km thickness, and the top of the reservoir at 1 km depth.

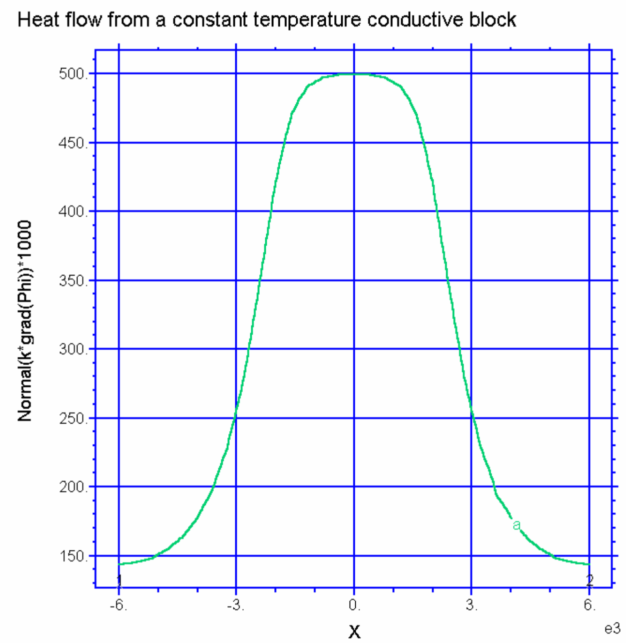

Figure 5. Surface heat flow for the rectangular block model shown in Figure 4.

For the cylindrical models, the heat loss from the varying reservoir sizes at a given depth is relatively insensitive to increasing reservoir volume. As a result, heat loss from the cylindrical reservoir increases by only a factor of 2.5 as the thermal power increases by more than two orders of magnitude. Also, increasing the depth to the top of the reservoir from 1 to 3 km (a typical range for producing geothermal systems) reduces the heat loss by an order of magnitude for the same thermal power.

The narrow rectangular block models follow the same trend as the cylindrical models, but as the width of the block grows, the resulting heat flow anomaly approaches a one-dimensional geometry and the relationship between heat loss and power rolls over toward the proportional lines. These results are consistent with the concept of reservoir thermal power relating directly to heat loss as suggested by Wisian et al. (2001), with the primary variation in the proportionality arising from the varying depth of the reservoir.

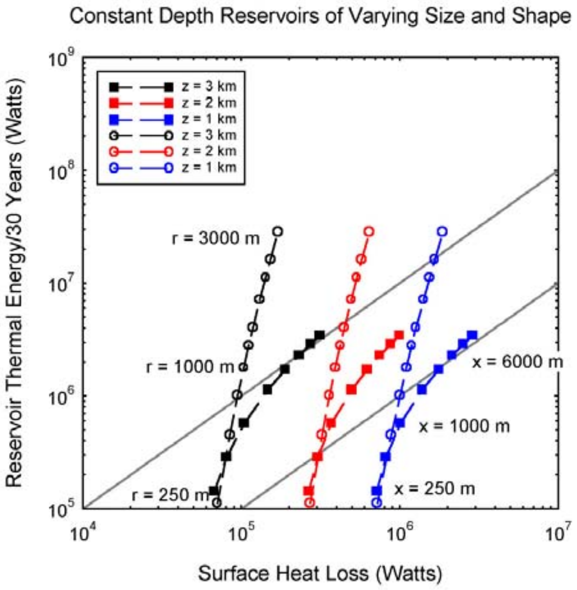

Figure 6. Plot of reservoir power versus surface heat loss for the 2-D models with top at z. Circles represent cylindrical models of radius r and squares block models with lateral extent x.

TRANSIENT MODELS

Other significant questions regarding heat flow and geothermal resources relate to the transient aspects of hydrothermal systems and heat transport through the crust. One question is whether near-surface heat flow measurements accurately represent deep thermal conditions. This is a relatively simple problem to investigate, and as noted by Urban et al. (1975), the critical parameter is the thermal time constant τ. This is defined as

$$\tau = \frac{z^2}{4\alpha} \qquad (4)$$

where z is the depth to the reservoir and α is the thermal diffusivity. Surface heat flow will be close to equilibrium with the thermal state of a new reservoir at 1 km depth in approximately 8000 years. For a reservoir at 3 km, the equivalent time constant is approximately 70,000 years. For a reservoir at 5 km the time constant is approximately 200,000 years. This lag in surface heat flow is equally true for systems that have been active and then started to cool due to loss of permeability. The life spans of hydrothermal systems have been estimated to range from 10,000 years to nearly 1 My (Stein and Cathles, 1997), so heat flow measurements over a deep geothermal reservoir are less like to reflect thermal conditions in the reservoir.

On the other hand, given their lower anomalous heat flow, deeper geothermal reservoirs should be longer lived and perhaps more common than the more easily identified shallow reservoirs. The high heat flow from a shallow reservoir mines a large amount of heat very rapidly from the surrounding crust and shortens the duration of high reservoir temperatures (unless renewed by magmatic heat input). This is illustrated through application of a two-dimensional time-dependent model for heat transfer through a hydrothermal convection system. In this model, adapted from the one-dimensional convection model presented by Lachenbruch and Sass (1977), the rate of convective heat transport is given by a value of thermal conductivity in the reservoir many times that of the surrounding crust.

Figure 7 shows the mean reservoir temperature as a fraction of its initial value for a block reservoir 1 km wide and varying depth with convection extending to 5 km below the top of the reservoir. The results show strong depth dependence in the decline of the mean reservoir temperature after 1 My, with shallow reservoirs losing temperature much more rapidly than deeper reservoirs. This loss of temperature is a direct consequence of the higher heat loss to the surface required from a shallow reservoir.

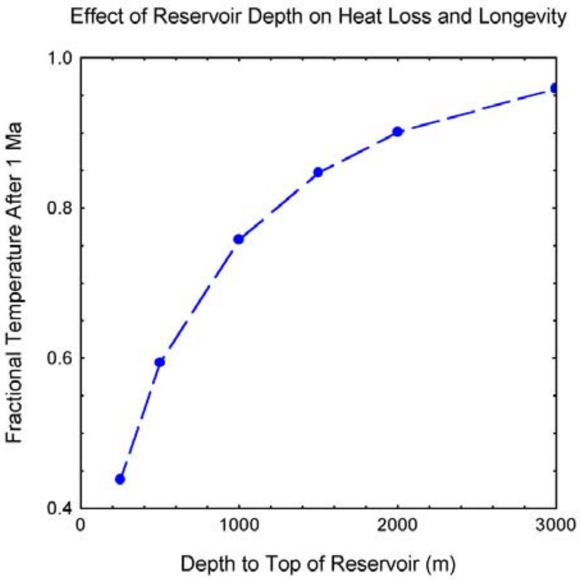

Figure 7. Plot of the ratio of reservoir temperature to initial temperature after 1 My of cooling for the rectangular block reservoir described in the text with varying depth to the top of the reservoir.

CONCLUSIONS

In summary, the simple conductive heat flow models described above indicate the following.

1. The observed relationship of thermal power and heat loss is consistent with the predictions of simple conductive reservoir models of varying geometry, size and depth.
2. Only laterally extensive reservoirs show a true proportionality between power and heat loss. For others heat flow is relatively insensitive to increasing reservoir size.
3. Existing observations are constrained by the limited exploitation depth of producing geothermal reservoirs. Deep reservoirs generate modest heat flow anomalies and are less likely to be in conductive equilibrium with the shallow crust.
4. Deep reservoirs require less additional heat to maintain high temperatures. They should be longer-lived, and if permeability conditions at depth are similar to those in the shallow crust, they should be more common. However, to the extent that production from a geothermal reservoir is in some way related to the permeability distribution that provides the “renewable” natural recharge, deep reservoirs may be poor candidates for development.
5. Heat flow is an important tool for characterizing shallow or relatively large geothermal reservoirs,

particularly in areas where magmatic heat input does not complicate interpretation of heat flow measurements. The measurement of heat loss from a geothermal reservoir provides critical information on the nature of the reservoir, and heat flow values should be derived from standard temperature gradient measurements whenever possible.

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