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THE TEMPERATURE-VOLUME RELATIONSHIP IN CONVECTIVE HYDROTHERMAL SYSTEMS

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ABSTRACT

The U. S. Geological Survey's 1978 assessment of intermediate- and high-temperature resources determined that there was a direct relationship between the volume of a geothermal system and its temperature. Since few systems had been explored at the time of that study, a number of approximations had to be used. This temperature-volume relationship has been re-evaluated using data from systems that have been extensively drilled in the last fifteen years. Only data from convective hydrothermal systems have been used. This new evaluation confirms the earlier relationship, and suggests a separate temperature-volume relationship for low- and intermediate-temperature fault-controlled systems.

INTRODUCTION

In the assessment of moderate- and high-temperature convective systems in the United States, Brook et al. (1979) noted a relationship between the characteristic temperature of a hydrothermal convective system and the volume of the system. Since few systems had been completely drilled at the time of their study, most of the information was estimated. Even so, a relationship did emerge showing higher system volume with higher temperatures.

Brook et al. considered the estimate of reservoir area to be the least certain parameter. Where the only system manifestation was one well or one hot spring, a likely area of 2 km^2 was assumed. For thickness, a uniform value over the reservoir was assumed. Also, since the assessment only included those resources above 3 km, this depth was used as a cutoff. When no information was available, a reservoir top at 1.5 km was assumed. Temperature estimates by Brook et al. were largely based on chemical geothermometers.

Since 1979, drilling has defined the size and temperature for a number of systems. I have selected several for which there was sufficient drilling, seismic, numerical simulation and other data to derive reasonable estimates of system size. There is, of course, considerable uncertainty in these estimates.

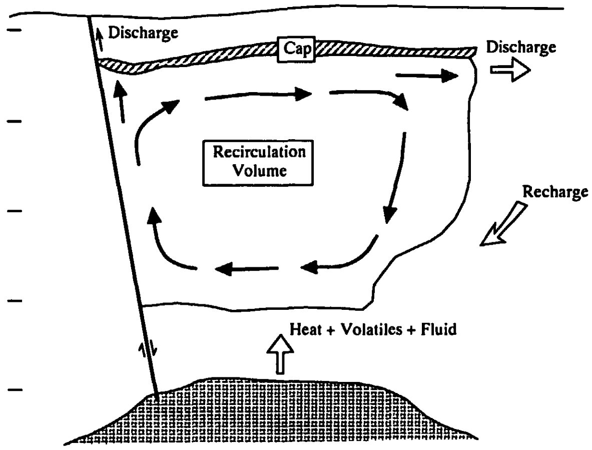

Figure 1. General model of a high-temperature hydrothermal convention system.

SYSTEM MODEL

Elder (1965) considers a hydrothermal convective system to consist of a recharge system, discharge system and recirculation volume. Figure 1 is an elementary model drawn from these concepts. The recirculation volume consists of rock and fluid residing in pores and fractures. Convection is driven by buoyancy differences and controlled by the orientation of fractures. The systems have tops that are generally conceived of as being delineated by a zone of self-sealing or as a lithologic boundary that will not support fracturing. Margins are either faults, hydrothermally sealed rocks, or a cold water interface. The bottoms of convective systems result from reduced permeability due to overburden pressure or thermally-induced plastic flow of host rocks.

Recharge systems have not been well documented; although isotopic studies can describe the sources of fluids, their pathways are often speculative. Some systems receive a large amount of recharge of fluids from magmatic heat sources (Hedenquist, 1992) while others are totally supplied by meteoric fluids.

Discharge systems are, at times, the source of production and have received somewhat greater attention than recharge components. Surface discharge is manifested by hot springs and fumaroles while subsurface discharge develops thermal outflow plumes (Goff et al., 1988).

If the volume of recharge water is equal to the volume of discharge water, the system is at steady state. If the volume of recharge is greater than the volume of discharge, the recirculation volume must increase. If the volume of recharge is less than the volume of discharge, the recirculation volume should trend towards vapor-dominated conditions.

In re-evaluating the system volumes, I have chosen to determine only the recirculation volume. Estimates of total heat flux would be concerned with the recirculation plus discharge. The recirculation volume in this evaluation consists of volume of rock + volume of fluid, the two being related by porosity.

The temperatures used represent an estimate of the average temperature of the reservoir volume. This has been determined in a number of different ways as discussed for the individual systems.

GEOTHERMAL SYSTEMS

The geothermal systems described below have sufficient data to allow reasonable estimates of recirculation volume and temperature to be made. They represent a number of different geologic environments. This evaluation is limited to discrete hydrothermal convection systems; it does not consider warm water aquifers in deep sedimentary basins or geopressured systems.

Valles Caldera, New Mexico

The Valles caldera contains two zones of fluid upwelling that are interpreted to represent the area of recirculation. These zones are Redondo Canyon that has been extensively drilled by Unocal (Hulen and Nielson, 1986), and Sulphur Springs, that has been the site of investigations by both Unocal and the Continental Scientific Drilling Program (Hulen et al.,1989). The surface area underlain by the convective volume in the Redondo Creek area was estimated at 14 km^2, and the area of the Sulfur Springs area, 4 km^2 for a total of 18 km^2. Independently, Goff et al. (1989) estimated the area underlain by the hydrothermal system as ranging from 10 to 30 km^2.

A temperature profile and hydrothermal alteration mineralogy of Baca-12 (Hulen and Nielson, 1986) shows that the hydrothermal system in Redondo Creek circulates to a depth of approximately 2500 m. At this point, circulation is apparently terminated by Permian Abo Formation that is not able to sustain open fractures. Similar relationships were documented at Sulphur Springs (Hulen et al., 1989) where an upper hydrothermal system, confined to volcanic rocks of the Valles caldera, is separated from a hydrothermal system in Precambrian granite by a sequence of Permian and Pennsylvanian sedimentary rocks.

Truesdell and Janik (1986) have analyzed fluids sampled from wells in the Redondo Creek area and calculated Na-K-Ca temperatures from five wells that average 279°C. They concluded fluid compositions could be explained by dilution of a high-salinity parent water of 335°C. On the basis of the temperature profile measured on well Baca-12 (Hulen and Nielson, 1986), equilibration of fluids at this temperature are realistic at depths of 3 to 3.5 km. Goff et al. (1989) present a model where meteoric recharge equilibrates at depths of 2-3 km and temperatures of 300°C. Truesdell and Janik's temperature of 279°C will be used as an average for the system.

The recirculation volume does extend into the underlying granitic rocks, and there is evidence of this circulation below 3 km in Baca-12. A depth estimate of 3.5 km will be used. The average water depth for wells in this field is 336 m resulting in a circulation thickness of 3.2 km, which yields a minimum estimated volume of 57.6 km^3.

Roosevelt Hot Springs, Utah

Thermal fluids of the Roosevelt Hot Springs geothermal field circulate within fractured crystalline rocks of the Mineral Mountains intrusive complex (Nielson et al., 1986). Past hot spring activity has formed areas of siliceous sinter, and the hydrothermal outflow plume is well documented (Ross et al., 1982).

Wells and geologic mapping place constraints on the area underlain by the system. The system south of Negro Mag Wash is bounded on the west by the Opal Mound fault which has served as a source of surface leakage and structural decoupling from the regional stress field (Nielson, 1989). The southern boundary of the system is located to the north of well 52-21, and on the east, the system is bounded by the Mineral Mountains. To the north, the last production well is 12-35. The area underlain by circulation to the north of the Negro Mag fault is less well constrained than in the south. The total area underlain by the recirculation system is estimated to be 9 km^2.

Fluid chemistry, seismic surveys and temperature profiles provide information for the evaluation of depth of the recirculation volume. Temperature profiles of wells 52-21 and 9-1 are plotted on Figure 2. These wells were drilled in relatively impermeable rock outside the convective volume and show gradients of 47.8 and 54.1°C/km respectively at depth. The gradients are extrapolated to a depth of 6 km. Chemical geothermometers (Capuano and Cole, 1982) show that the maximum temperature of the geothermal fluids is 288 +/- 10°C. The maximum fluid temperature recorded during initial stages of production was 268°C. Capuano and Cole also showed that most of the produced fluid was a mixture of

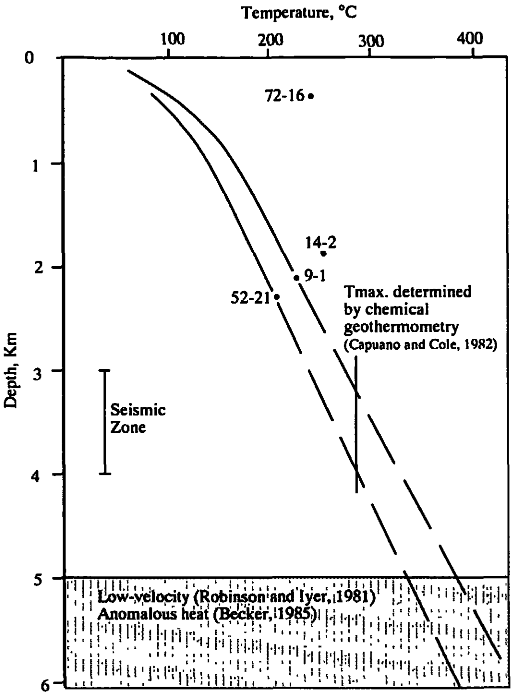

Figure 2. Temperature-depth relationship for the Roosevelt Hot Springs geothermal system, Utah.

geothermal brine with an estimated concentration of 9700 ppm and non-thermal waters. The least-mixed fluids are from well 54-3 which is along the Negro Mag fault zone. Using the estimates of temperature with depth discussed previously, the suggested depth of equilibration is 3.2 to 3.9 km. The average temperature of the recirculation volume is estimated at 250°C based on the bottom-hole temperatures of wells 14-2 and 72-16 (Fig. 2).

Pre-production seismic monitoring shows earthquake swarms located at depths of 3-4 km and 6-8 km (Nielson et al., 1988). Robinson and Iyer (1981) used teleseismic P-wave data to identify a region of low velocity extending from the mantle to a depth of 5 km beneath the geothermal area. Becker (1985) concludes that an abnormally hot zone, that may contain a small component of magma, is present at a depth of 5 km. The upper seismic zone at 3-4 km is consistent with the depth of circulation estimated by chemical geothermometry and measured temperature gradients. This will be used to estimate a maximum depth of circulation of 4 km. Since the system has, in the recent past, discharged to the surface, the total thickness of the zone is set at 4 km. This yields a recirculation volume of 36 km^3 .

The Geysers, California

The Geysers is a vapor-dominated geothermal system that is in the mature stages of production. The reservoir volume is contained within Franciscan graywacke and the underlying intrusive complex. The reservoir area can be determined from joint company maps that show the outline of the reservoir as determined by drilling. The area underlain by the reservoir encompasses 159 km^2. The thickness of the reservoir is estimated as 3 km by Bodvarsson et al. (1989) and 3.7 km by Williamson (1990). Using this range of depths, the volume of the reservoir is calculated to be in the range of 477 to 588 km^3. An estimate of 532 km^3 will be used here.

The temperature of The Geysers under pre-production, vapor-dominated conditions was 240°C. However, the system was originally developed as liquid-dominated under higher temperature conditions. Moore (1992) has determined the temperatures under liquid-dominated conditions using fluid inclusion microthermometry. Temperature conditions varied systematically with respect to distance above the felsite intrusive. Salinity also decreases away from the felsite suggesting that the intrusive complex was the source of some of the hydrothermal fluids as well as the heat for the circulation system.

Moore's data shows the maximum temperature reached 380°C for a km or more above the felsite contact. Similar temperatures were determined from samples in what is now considered the cap of the system. Thus, the temperature of the hot water circulation system is estimated to have been 380°C.

Newcastle, Utah

The geothermal system at Newcastle, Utah is moderate temperature and associated with deep circulation along a fault. There is no evidence of a magmatic heat source. Data for the system has been published by Blackett et al. (1989) and Ross et al. (1990). The system has no surface manifestations, but has been delineated by drilling and geophysics. The geothermal zone is developed along the Antelope Range fault and is approximately 100 m wide by 1800 m long. Blackett et al. (1989) suggest that the depth of circulation is 3 to 4 km. Using the above, the volume of the system is calculated 0.54 to 0.72 km^3, with a most likely value of 0.63 km^3.

The highest measured temperature in the system is 130°C. Rush (1983) estimated a temperature range of 140° to 170°C based on chemical geothermometers. A most likely temperature of 155°C is suggested.

Beowawe, Nevada

The Beowawe geothermal system in Nevada is principally controlled by range-front faulting; there is no evidence of a magmatic heat source. The system discharges to form a terrace of siliceous sinter as well as subsurface discharges to valley gravels. Olmstead and Rush (1987) estimate the system temperature at 229° +/- 8°C, based on previous publications.

The recirculation volume of the system has been estimated as follows. Olmstead and Rush show a relationship between near-surface conductive heat flow and area for the thermal anomaly. It is estimated that a heat flow of greater than 560 mW/m^2 defines the area of the recirculation volume; this is about 4 km^2. Olmstead and Rush also estimate a minimum depth of circulation of 5 km, which would result in a total volume of 20 km^3.

Salton Sea, California

The Salton Sea geothermal system is known both for its high temperatures and salinity. Newmark et al. (1988) showed that the central heat-flow anomaly underlies 30-40 km^2. For the system area, a most likely value of 35 km^2 will be used here. Newmark et al. also envision the system as extending to >2500 m with a cap at about 500 m, giving the recirculation volume a thickness of more than 2000 m. Sass et al. (1988) show, on the basis of well State 2-14, that the reservoir extends to at least 3.2 km with a temperature of at least 355°C. Their plot of temperature profiles from wells in the area suggests an average temperature of the convective volume of 325°C. A minimum depth of 3.2 km less the 500 m cap yields a minimum thickness of 2.7 km. The most likely area is estimated to be 35 km^2, and the most likely volume is calculated to be 94.5 km^3.

Heber, California

The Heber geothermal reservoir contains moderate-temperature fluids circulating through sediments in the Salton Trough. The natural state of the system has been investigated through numerical modeling based on the exploration data base (Lippmann and Bodvarsson, 1985). Their model shows a reasonable agreement with field measurements. It considers the upflow zone to be a cylinder with a radius of 1 km and a depth of 4950 m. A cap to a depth of 550 m overlies the system. Thus, the recirculation volume is 13.8 km^3. The model shows an isothermal zone of 180°C, which is again consistent with temperatures measured in wells.

Newberry, Oregon

The Newberry caldera in Oregon has a high temperature convective system that has been partially explored by drilling. However, Sammel et al. (1988) have used the available data to develop a numerical model of the system that will be used here in the absence of extensive drilling results. Based on geophysical data, they have modeled a magma body at a depth of 3 km beneath the caldera. The size the magma body is 4 km by 4 km. The depth to the top of the convective zone is 1.5 km resulting in a thickness of 1.5 km. The total convective volume is calculated to be 24 km^3.

The maximum measured temperature is 265°C measured in the bottom of USGS drill hole Newberry 2. There is no comprehensive information on the temperature of the system, therefore 265°C will be used.

Cerro Prieto, Mexico

The Cerro Prieto geothermal field is a hot water-dominated resource hosted by sedimentary rocks. Fluid circulation probably responds to a magmatic heat source which is thought to exist at 5-6 km below the surface (Elders et al., 1984). Halfman et al. (1984) have formulated a geologic model that, in association with numerical simulation, forms the basis for estimating the size of the field. Halfman et al. show that the well field covers approximately 12 km^2, but cross sections illustrate that, in the subsurface, the system may have an areal distribution of 20 km^2. Fluids flow from the east to the west rising along paths that are controlled by sedimentary lithologies. They rise to within 1 km of the surface in the west, whereas the cap in the east is more like 2 km. Wells have been drilled to 3.5 km, and Elders et al. (1984) model permeable zones to a depth of 4 km. Antunez et al. (1991) have published simulations of the system, and their diagrams give an approximate volume of the system of 72 Km^3.

Lippmann et al. (1989) indicate that the water entering the system has a temperature of about 350°C, and that numerous wells have temperatures of >300°C. The cross-sections of Antunez et al. (1991) suggest that an average temperature would be 325°C.

Fuzhou, China

The Fuzhou geothermal system in China is a moderate temperature system whose geometry is relatively well known (Hochstein et al., 1989). The fluids ascend along a 100 m wide fracture zone that has a length of 5 to 6 km, but includes a permeability barrier that divides the fault into two 2.75 km segments. Simulation suggests that the fluids circulate to a depth of 7 km where the temperatures are about 150°C. Measured temperatures at 500 m are about 100°C, for an average temperature of 125°C. The calculated volume of each segment is 1.93 km^3.

Botn, Iceland

The Botn geothermal system has been evaluated by drilling, production, electrical resistivity and numerical modeling (Axelsson and Bjornsson, 1993). The system is located along a fracture zone that the above have modeled as being 900 m high, 900 m long, and 10 m. thick, yielding a volume of .01 km^3. The fracture zone is thought to be fed by a relatively large reservoir of 105°C water from depth. Water is produced at temperatures of 84° and 96°C, and thus an average reservoir temperature of 90°C has been used in the temperature-volume relationship.

DISCUSSION

The estimated volume and temperature data for the systems discussed are plotted on Figure 3. Included are two

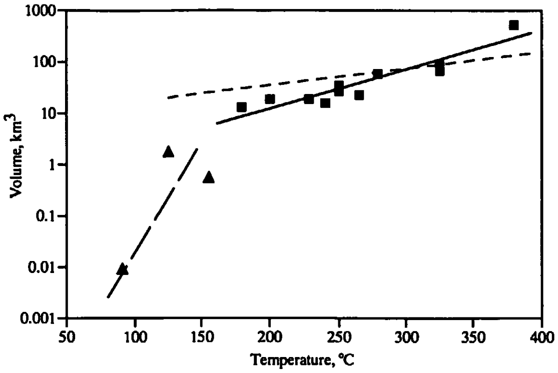

Figure 3. Temperature-volume relationship for convective hydrothermal systems. Solid line is least squares regression for the data discussed in the text. Triangles represent systems hosted by a fault or fault zone and the large-dashed curve is an approximation of that data. The small-dashed curve is from Brook et al. (1979).

additional systems for which confidential data was used in the calculation, and the volume-temperature estimate for Wairaki from Elder (1965).

Figure 3 shows a direct relationship between recirculation volume and temperature. Although there is only a limited amount of data for deep circulation along faults (essentially a two-dimensional geometry), the data show a different trend from those systems that occupy a three-dimensional volume of rock. The fault-controlled systems have lower volume and lower temperatures. Least squares regression of the three dimensional reservoirs yields the following relationship:

$$\text{Log (V)} = 7.32 \times 10^{-3}\ \text{T} - 0.336.$$

R^2 for this equation is 0.87 which is rather remarkable considering the diverse data sources used in this compilation.

The regression line determined by Brook et al. (1979) is also shown on Figure 3. It is quite similar to that calculated in this study, but it would overestimate the size of lower temperature systems and underestimate the size of systems above about 300°C. In addition, Circular 790 did not predict a separate relationship for the fault-controlled circulation systems.

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