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Geothermal Investigations of the U.S. Geological Survey in Long Valley, California, 1972–1973

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During 1972 and 1973 the U.S. Geological Survey (U.S.G.S.) conducted detailed geological, geophysical, hydrological, and geochemical investigations in Long Valley, California, as part of a new geothermal research program. The goal of these investigations was to understand a typical hot water geothermal system, thus providing a basis for extrapolation to other hot water areas and for regional exploration and assessment of geothermal resources. Although the U.S.G.S. investigations have thoroughly characterized the surface expression and geophysical signatures of the Long Valley geothermal system, our understanding of the geothermal system at depth is incomplete. The available data allow us to make only a crude estimate of 350–700 MW cent. for the electric power generation potential. Refinement of this estimate must await exploration of the area by deep drill holes.

U.S. Geological Survey Geothermal Research Program

The geothermal research program of the U.S. Geological Survey (U.S.G.S.) is a multidisciplinary earth science investigation whose goal is the understanding of the factors that control the nature and distribution of geothermal resources. A corollary objective is to provide the resource data needed to evaluate the extent to which geothermal energy can help meet the energy demands of the United States.

The U.S.G.S. has conducted modest geological and geochemical investigations of hot spring phenomena since 1945, primarily at Steamboat Springs, Nevada [*White et al.*, 1964; *White*, 1968*b*], Imperial Valley, California [*White*, 1968*a*; *Muffler and White*, 1969], and Yellowstone National Park, Wyoming [*White et al.*, 1975]. In addition, U.S.G.S. work in heat flow [*Sass et al.*, 1971], volcanology [*Smith and Bailey*, 1968], and experimental geochemistry [*Fournier and Rowe*, 1966] proved to have significance in geothermal exploration. It was not until November 1971, however, that a formal program of geothermal investigations was authorized by Congress, thus allowing a significant expansion of U.S.G.S. geothermal research [*Muffler*, 1972].

It was recognized clearly during this expansion of the geothermal research program that it was impossible to understand the distribution of geothermal resources in large regions or to make meaningful resource estimates without a detailed understanding of representative geothermal systems. Accordingly, the U.S.G.S. selected two geothermal areas in the United States for detailed study by all feasible geological, geophysical, geochemical, and hydrological methods. The first area selected was the region southwest of Clear Lake in northern California, chosen because it contains The Geysers (Figure 1), the world's largest known vapor-dominated (dry steam) geothermal system, currently producing electricity at 502 MW. The second area selected was Long Valley, California, known from shallow drilling and chemical analysis of hot spring waters to be a hot water geothermal system. The U.S.G.S. goal is to gain an understanding of the nature and extent of the geothermal resources in each of these two type areas, thus providing a basis for extrapolation and assessment of geothermal resources.

Long Valley was chosen as the type area for hot water geothermal systems because of the following factors: (1) hot spring chemistry indicating that any geothermal reservoir present would contain hot water, not steam, and would be at least 180°C; (2) a geologic setting characterized by young volcanism (<0.7 m.y.), reasonable potential of adequate reservoir rock (caldera fill), and small enough target size (the caldera is 15 km × 30 km) to be studied reasonably quickly; (3) our judgment that although Long Valley was clearly a favorable geothermal target, no systematic investigation was available to the public; (4) the prospect of extensive deep drilling by the geothermal industry in the near future (The U.S.G.S. hoped to develop cooperation with industry patterned after the situation in the Salton Sea geothermal field in the early 1960's); and (5) good accessibility and logistic feasibility.

Long Valley was not chosen as a type area because it appeared to have a greater commercial potential than other hot water geothermal areas in the United States. Indeed, data available in 1971 indicated that reservoir temperatures were perhaps only marginal for power generation under the economic conditions then prevailing.

Pertinent Information Available in 1971

Volcanology. It has been recognized since the work of *Gilbert* [1938] that the Bishop Tuff, of Pleistocene age, was most likely erupted from vents in Long Valley. *Gilbert* [1938, p. 1860] further suggested that young faults in Long Valley and perhaps even the depression itself were related to extrusion of magma from beneath the valley. The extent and depth of this volcanic depression were outlined by *Pakiser* [1961] and by *Pakiser et al.* [1964], who concluded from gravity data that an elliptical block 15 km × 30 km had subsided as much as 5.5 km. Further data on this depression were provided by *Dalrymple et al.* [1965], who used potassium-argon dating to show that the Bishop Tuff was erupted during a single igneous event about 0.7 m.y. ago.

Using these data and the geologic maps of *Rinehart and Ross*

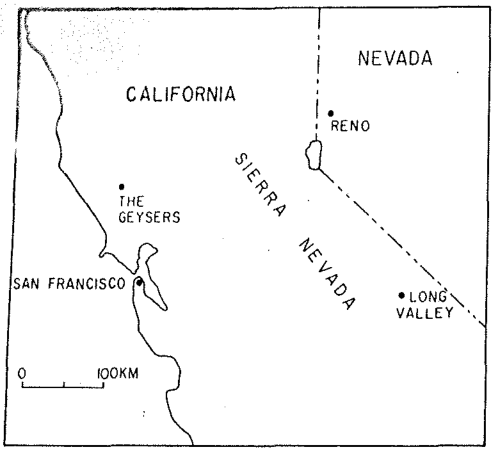

Fig. 1. Map showing location of Long Valley and The Geysers, California.

[1957, 1964] and *Huber and Rinehart* [1965], *Smith and Bailey* [1968, pp. 629-630] concluded that Long Valley was very likely a resurgent caldera and suggested that much of the volcanic rock exposed within the caldera is younger than the extrusion of the Bishop Tuff and formation of the caldera. It appeared that Long Valley had been an active volcano during the past few hundred thousand years and might still be underlain by magma or intrusive rock at temperatures approaching magmatic.

Hot springs and geothermal wells. The hot springs of Long Valley have been known since the last century [*Whiting*, 1888, p. 356]. The springs are described by *Waring* [1915, pp. 146-148, 384] and shown on Plate 1 and Figure 39 of *Rinehart and Ross* [1964]. Areas of hydrothermal alteration are also shown on Plate 1 of *Rinehart and Ross* [1964] and are discussed by *Cleveland* [1962].

Between 1959 and 1964, nine geothermal wells were drilled at Casa Diablo hot springs by Magma Power Company, and a tenth well was drilled about 4.8 km east [*McNitt*, 1963, p. 29; *California Division of Oil and Gas*, 1972]. The deepest well reached 324 m, and the maximum recorded temperature was about 180°C [*McNitt*, 1963, pp. 25-29; *California Department of Water Resources*, 1967].

Chemical analyses of waters from hot springs and geothermal wells indicated that the geothermal system was of the hot water type [*White et al.*, 1971, pp. 77-80]. Silica and Na/K geothermometry using the methods of *Fournier and Rowe* [1966] and *Ellis* [1970] suggested minimum reservoir temperatures of 180°C. *White* [1965, table 1] calculated a convective heat flow of 7×10^7 cal s^{-1} from the hydrothermal system of Long Valley by using data on total boron and the relation of boron to heat content of waters discharged from the geothermal wells at Casa Diablo hot springs.

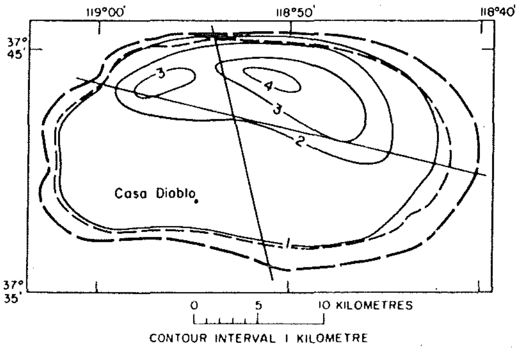

Fig. 2. Map showing depth (in kilometers) of fill in Long Valley caldera. The outer heavy dashed line marks the topographic boundary of the valley floor. The inner dashed line is the approximate location of the caldera ring fracture. The two crossing solid lines show the approximate location of seismic refraction profiles from *Hill* [1976].

U.S.G.S. INVESTIGATIONS IN LONG VALLEY, 1972–1973

The papers following in this issue of *Journal of Geophysical Research* present the data and basic interpretations derived from U.S.G.S. geothermal investigations in Long Valley during 1972 and 1973. The data accompanied by preliminary interpretations were presented at the Fall Annual Meeting of the American Geophysical Union in 1973 (*Eos Trans. AGU*, vol. 54, pp. 1211-1213, 1973) and in part amplified in U.S.G.S. open file reports [*Anderson and Johnson*, 1974; *Bailey*, 1974; *Dalrymple and Lanphere*, 1974; *Hoover et al.*, 1974; *Lewis*, 1974; *Sass et al.*, 1974; *Stanley et al.*, 1973; *Willey et al.*, 1974]. (U.S.G.S. open file reports serve to make unpublished information available to the public quickly. When a report or map is open-filed, a copy is placed in one or more depositories, and its availability is announced in the monthly periodical *New Publications of the Geological Survey* (available free from the U.S.G.S., National Center, Stop 329, Reston, Virginia 22092). This announcement lists all the depositories (U.S.G.S. offices, plus selected state agencies) and notes the location of reproducible copy if such exists. Open file reports released prior to May 1974 are listed in various U.S.G.S. circulars (1974, no. 706; 1973, no. 696; 1972, no. 668)).

A number of U.S.G.S. geothermal investigations in Long Valley are still in progress, including geologic mapping and petrology, heat flow, hydrology (supplemented by shallow drilling), magnetic, telluric, and magnetotelluric soundings, system modeling, water and gas chemistry, teleseismic analysis, and thermal infrared studies. Accordingly, the papers presented in this issue of the *Journal of Geophysical Research* should be viewed collectively as a progress report.

GEOTHERMAL ENERGY POTENTIAL

Bailey et al. [1976] suggest that Long Valley has been an active geothermal area for the past several hundred thousand years. The papers by *Lachenbruch et al.* [1976], *Sorey and Lewis* [1976], *Mariner and Willey* [1976], *Stanley et al.* [1976], *Kane et al.* [1976], and *Steeples and Iyer* [1976] reaffirm this and earlier interpretations that Long Valley is an active hot water geothermal area with high conductive and convective heat flows and is underlain at depth by a hot intrusive mass that may still contain some residual magma.

By using the results of several of these investigations it is possible to make a preliminary estimate of the geothermal energy potential of Long Valley. To do so, we must make estimates of size, temperature, and porosity of the high-temperature reservoir or reservoirs and of the efficiency of converting this high-temperature water to useful energy.

From the seismic refraction results of *Hill* [1976], the gravity interpretation of *Kane et al.* [1976], and the geologic structure of *Bailey et al.* [1976], we have constructed a model of the low-density rocks under Long Valley (Figure 2) and estimate their volume V to be 810 km^3. We interpret these low-density rocks to be primarily caldera fill (ie., the Bishop Tuff and overlying sedimentary and volcanic rocks) plus that part of the rhyolites of Glass Mountain downdropped into the caldera [*Bailey et al.*, 1976].

The bulk density ρ_b of the caldera fill can be calculated from the formula $\rho_b = (\rho_0 V - M_D)/V$, where ρ_0 is the bulk density of rocks surrounding the caldera (2.67 g/cm^3) and M_D is the mass calculated by Gauss' theorem from the integrated gravity anomaly (3.33×10^{17} g) [*Kane et al.*, 1976]. The resulting bulk density of fill ρ_b is 2.26 g/cm^3, yielding a density difference of 0.41 g/cm^3, similar to the 0.45 g/cm^3 assumed by *Kane et al.* [1976].

If we assume that all the voids and pores in the fill are full of fluid, then the porosity of the fill ϕ is $(\rho_g - \rho_b)/(\rho_g - \rho_f)$, where ρ_f is the average water or fluid density and ρ_g is the average grain density of the rocks making up the caldera fill. For ρ_g we have used the average density of 2.60 g/cm^3 from two different, carefully investigated, densely welded, and devitrified rhyolite ash flow tuffs from the Creede caldera, Colorado [*Ratté and Steven*, 1967]. This should be a reasonable estimate for the intracalcera Bishop Tuff (R. A. Bailey, personal communication, 1975), and since most of the rest of the fill is also derived from rhyolite volcanics, we used this value for the grain density of the entire caldera fill. The resulting bulk porosity of the Long Valley caldera fill is 0.19. If grain density of the fill were 2.50 g/cm^3, the porosity would be only 0.15.

Mariner and Willey [1976] and *Sorey and Lewis* [1976], using various geochemical thermometers, estimate that the temperature of the geothermal reservoir is at least 200°–210°C. *McKenzie and Truesdell* [1975], using a sulfate isotope geothermometer, calculate a reservoir temperature of 240°–250°C.

The caldera fill above the Bishop Tuff consists of a variety of rhyolitic flows and tuffs, rhyodacite flows, basalt flows, and (in the eastern half) lake, marsh, and periglacial sediments [*Bailey et al.*, 1976]. Although some of this near-surface rock is hydrothermally altered, it appears to be relatively impermeable except along faults and does not appear to contain a high-temperature geothermal reservoir [*Stanley et al.*, 1976]. Thus any significant geothermal resource in the Long Valley caldera would have to be in the Bishop Tuff and the rhyolites of Glass Mountain.

Three pieces of evidence lead us to believe that such a reservoir does exist. First, all of the hot springs appear to occur along active faults [*Stanley et al.*, 1976; *Bailey et al.*, 1976], suggesting that they are acting as conduits for hot water from some deeper zone. Second, the springs all yield approximately the same geochemically derived temperature and have almost identical chloride-boron ratios implying that they are tapping a single, well-mixed reservoir [*Sorey and Lewis*, 1976]. Finally, the Bishop Tuff extends throughout the lower part of the caldera fill and, based on the gravity data of *Kane et al.* [1976], appears to have significant porosity (> 0.15). Inclusions of Bishop Tuff found in postcaldera rhyolite tuffs exposed in the central part of the caldera are densely welded [*Bailey et al.*, 1976]. Accordingly, we infer that the porosity indicated by the gravity data is due to fractures or to local accumulations of high-porosity pumiceous material [*Kane et al.*, 1976].

Seismic data of *Hill* [1976], deep electrical data of *Stanley et al.* [1976], and shallow drilling results of *Lachenbruch et al.* [1976] allow us to construct a model showing the depth to the top of the Bishop Tuff (Figure 3). The difference in volumes calculated from Figures 2 and 3 is interpreted as the volume of Bishop Tuff and downdropped rhyolites of Glass Mountain within the caldera. This figure of 450 km^3 compares with 375 km^3 estimated for the intracaldera volume of Bishop Tuff alone [*Bailey et al.*, 1976]. What proportion of these rocks constitutes a reservoir is unknown. The reservoir could be substantially larger, including rocks outside the caldera, or a significant high-temperature reservoir may not exist at all.

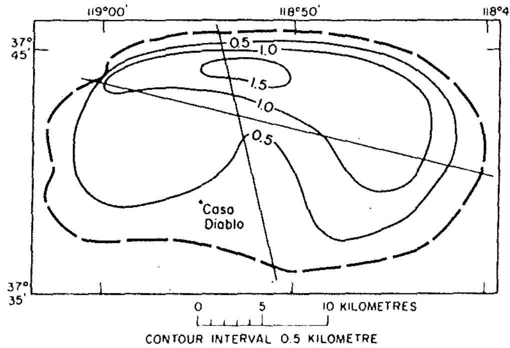

Fig. 3. Map showing depth (in kilometers) to top of Bishop Tuff in Long Valley caldera. The caldera boundary and seismic profiles are shown as in Figure 2.

Assuming that the reservoir has a volume of 450 km^3 and a porosity of 0.15, we have calculated the total heat above 0°C contained in the rock and water of the reservoir (Table 1). The geothermal resource, however, is commonly considered to be only the part of the heat that can be recovered and used under foreseeable economic conditions [*Muffler*, 1973, p. 255]. The extractable energy from Long Valley is shown in Table 1 under two assumptions [*Muffler*, 1973, p. 257]: (1) that the temperature of the reservoir will fall with time to 180°C, below which extraction will become uneconomic, and (2) that only 50% of the available energy between the reservoir temperature and 180°C will ever be extracted, owing to impermeable rock, insufficient number of drill holes, and nonoptimum drill hole spacing, etc.

Implicit in our discussion is the use of Long Valley geothermal energy for the generation of electricity. Accordingly, in Table 1 we have calculated the amount of electricity that could be generated by using conventional flashed steam techniques. We consider only the flashed steam, assume that the separation temperature is 145°C and that the thermodynamic efficiency is 14.3% (as at The Geysers [*Bruce*, 1971]), and use as a reservoir temperature the average of the initial and final conditions.

Of the many factors that affect the geothermal resource estimates for Long Valley, four are of paramount significance: (1) reservoir volume, which could range from a very small size to perhaps 1000 km^3, (2) recoverability, which could range from 0% for a completely impermeable 'reservoir' to perhaps greater than 100% for a reservoir with significant heat and fluid recharge, (3) temperature (a small change in estimated initial reservoir temperature can have a substantial effect on extractable energy estimates (e.g., Table 1)), (4) technology and economics of use (we have assumed conventional flash steam electrical generation; advanced technology or use for heating purposes obviously would increase the resource estimates of Table 1, the limiting factors being technologic, economic, and social, not geologic).

Much of the information required to refine these estimates can be obtained only in deep drill holes, but the expected deep exploration of the caldera by private industry has not yet taken

TABLE 1. Geothermal Resources of Long Valley

Reservoir Temperature, °C	Heat Above 0°C in Reservoir, J	Extractable Energy, J	Electrical Energy, MW cent.
220	24×10^{19}	2.1×10^{19}	350
250	27×10^{19}	3.6×10^{19}	700

place for a variety of reasons including the delay in leasing of federal lands. Full understanding of the Long Valley geothermal system and an accurate determination of its geothermal resource potential must await a series of deep wells coupled with a properly designed program to acquire pertinent drill hole data both during and after drilling.

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