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HEAT FLOW IN THE GEYSERS-CLEAR LAKE GEOTHERMAL AREA OF NORTHERN CALIFORNIA, U.S.A.

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ABSTRACT

From 1971 through 1984, about 620 thermal gradient/heat flow boreholes were drilled in The Geysers-Clear Lake area of northern California. The data from approximately 85 percent of these boreholes are now available in the public domain for interpretation to define the limits and magnitude of the thermal anomaly. Sixty-seven heat flow boreholes with lithologies, thermal gradients and thermal conductivities provide constraints on the quality of the data and therefore on the extent of The Geysers-Clear Lake thermal anomaly. An anomalous thermal area of about 750 square kilometers where heat flow values exceed 168 mWm^{-2} (4 HFU) surrounds the presently producing Geysers geothermal field, which has an areal extent of about 75 square kilometers with heat flow values greater than 335 mWm^{-2} (8 HFU).

INTRODUCTION

The Geysers-Clear Lake area is in the Coast Ranges physiographic province of California and is underlain by the Jurassic-Cretaceous Franciscan complex, Great Valley sequence and associated ophiolitic rocks (McLaughlin, 1977). The Franciscan complex is predominantly deformed and metamorphosed submarine fan deposits and basaltic volcanics, and the Great Valley sequence is relatively undeformed sedimentary strata. These rocks were uplifted and eroded during the Tertiary. During the Quaternary, they were partially capped by the Clear Lake volcanics and intruded by felsic equivalents of the volcanics. Regional structure is dominated by northwest-trending faults, including Mesozoic thrust faults and Quaternary high angle faults related to the San Andreas system. The region is one of high heat flow, thermal springs, active faults, historic seismicity and young (10,000 y-2 my) volcanic rocks. Heat flow in the Coast Ranges is high and averages about 84 mWm^{-2} (2 HFU), with an earlier estimate of The Geysers-Clear Lake region mean heat flow being 86.1 mWm^{-2} (Lachenbruch and Sass, 1980).

Geological, geochemical and geophysical studies of The Geysers-Clear Lake area of northern California have continued for several years with an emphasis being placed on the source of the anomalous heat and fluids of the vapor-dominated hydrothermal system manifested as The Geysers geothermal field. Presently, there is about 2,000 MW of installed electrical capacity at The Geysers, which is considerably more than from any other geothermal field. Despite the importance of this field and an exploration and development history of more than 30 years, the geophysical extent of the thermal anomaly surrounding The Geysers geothermal field has not previously been published. The exploration of The Geysers-Clear Lake area for defining the extent of the geothermal system has involved the use of numerous geophysical techniques, including gravity, magnetics, electrical resistivity, P-wave delays, seismic refraction, microearthquake monitoring, and heat flow surveys. The current state of geological, geochemical and geophysical knowledge for the region has been summarized in the collection of papers edited by McLaughlin and Donnelly-Nolan (1981).

Until recently, there had been few published heat flow measurements for The Geysers-Clear Lake area (Urban, and others, 1976, Lachenbruch and Sass, 1980) because most of the thermal gradient measurements had been obtained by industry and remained proprietary. From 1971 through 1984, at least 620 temperature gradient holes were drilled in The Geysers-Clear Lake area. These holes typically range from 75 to 150 meters in total depth, but some are completed to depths of more than 600 meters. The temperature and lithology data from these holes are submitted to the California Division of Oil and Gas (DOG), which is responsible for the regulation of drilling in the state of California. These data were initially held as confidential information by the DOG, but public law requires their eventual release to the public where certain events have occurred and specified periods of time elapse. Until 1982, very little of the temperature data in The Geysers-Clear Lake area were in the public domain. Now, data for about 85 percent of all previously drilled holes have been released to the public domain by the DOG. Consequently, it is possible to assemble data that were previously confidential and proprietary into a regional perspective. The relationships between the thermal anomaly and the Clear Lake volcanic field, The Geysers geothermal field, and a significant Bouguer gravity anomaly are discussed with the intent to demonstrate the geophysical extent of The Geysers-Clear Lake thermal anomaly.

DATA COLLECTION AND ANALYSIS

Heat flow values were determined for about 400 boreholes in The Geysers-Clear Lake area (Figure 1). The results from only 67 holes are presented because they were used to define the geophysical extent of the thermal anomaly (Figure 1 and Table 1). The units used for depths and temperature are metric although all logging depths and units of length and area in The Geysers-Clear Lake area were originally in feet and miles; consequently, the metric values are converted units. Most of the temperature measurements available for boreholes in The Geysers-Clear Lake area were originally obtained using the Fahrenheit scale; these are converted to the Celsius scale. Heat flow values are presented both in mW m^{-2} and heat flow units (HFU) where 1 HFU equals 41.87 mWm^{-2}.

Typically, temperature gradient and heat holes were completed in the following manner. To prevent collapse of the boreholes and to provide stable temperature measurements, polyvinyl chloride or galvanized steel pipe with a closure on both ends was lowered into the holes. Grout and drill cuttings were placed around the pipe and it was filled with water. Typically, two or more temperature-depth profiles were obtained for each hole to demonstrate that adequate time had been allowed for attaining thermal equilibrium from the disturbances developed during drilling.

Temperatures were measured in most of the holes at 3-m intervals with a thermistor probe. The equipment used for most of the measurements was a modified version of the "portable logging mode" described by Sass and others (1971a), with the primary difference being the replacement of the wheatstone bridge by a digital multimeter. For 57 of the 67 holes, the temperatures were measured to within about 0.01°C, with the remaining holes (Nos. 57 to 66 of Table 1) having a precision of 0.05 to 0.5°C. The least-squares geothermal gradients for each hole were calculated for the depth interval over which the rate of increase in temperature with depth was most uniform; the depth intervals and corresponding gradients are presented in Table 1. Least-squares temperature gradients in Table 1 are accurate to within 0.5°C/km except for the holes numbered 57 to 66, which have temperature gradients that are probably accurate to 2.0 to 10.0°C/km. Temperature gradients and the resulting heat-flow determinations are primarily affected by disturbances caused by thermal disequilibrium, near-surface effects, topography, groundwater movement, climatic variations and tectonic movements. Multiple measurements of the temperature-depth pairs established thermal equilibrium. Near-surface effects such as diurnal and seasonal temperature variations caused by solar radiation and seasonal climatic variations have been avoided by using only the temperature measurements taken from below about 10 meters in a borehole when calculating the geothermal gradient. The effect of groundwater movement was detected in the near-surface data for some of the boreholes presented in this study.

The Geysers-Clear Lake area is characterized by a steep-sloping mountainous terrain. Since topographic relief in the vicinity of a shallow to intermediate-depth borehole can distort the temperature field sufficiently to cause errors in heat-flow determinations, a first-order, three-dimensional, Birch-type terrain correction (Birch, 1950) was calculated for the temperature-depth data for all but two (46 and 47 in Table 1) of the boreholes. For all of the topographic corrections, the following four assumptions were made: (1) the terrain was assumed to have persisted indefinitely in its present form; (2) the data were corrected for effects of all topography outward from the borehole to 1.5 km; (3) the surface temperature was assumed to decrease at 4.7°C/km with increasing elevation; and (4) the thermal conductivity was assumed to have insignificant lateral variations. Although these simplifying assumptions can introduce significant errors in some cases, the available data on the variation of these parameters is sufficiently scant in The Geysers-Clear Lake area that these simple assumptions are the best that can be made. Corrections for past climatic effects and topographical uplift were not applied to the temperature-depth data. Application of the theoretical terrain corrections did not change the calculated heat flow values by more than 10 percent for 40 of 65 boreholes examined. Another 16 changed from 10 to 20 percent while the remaining nine had corrections greater than 20 percent, with a maximum

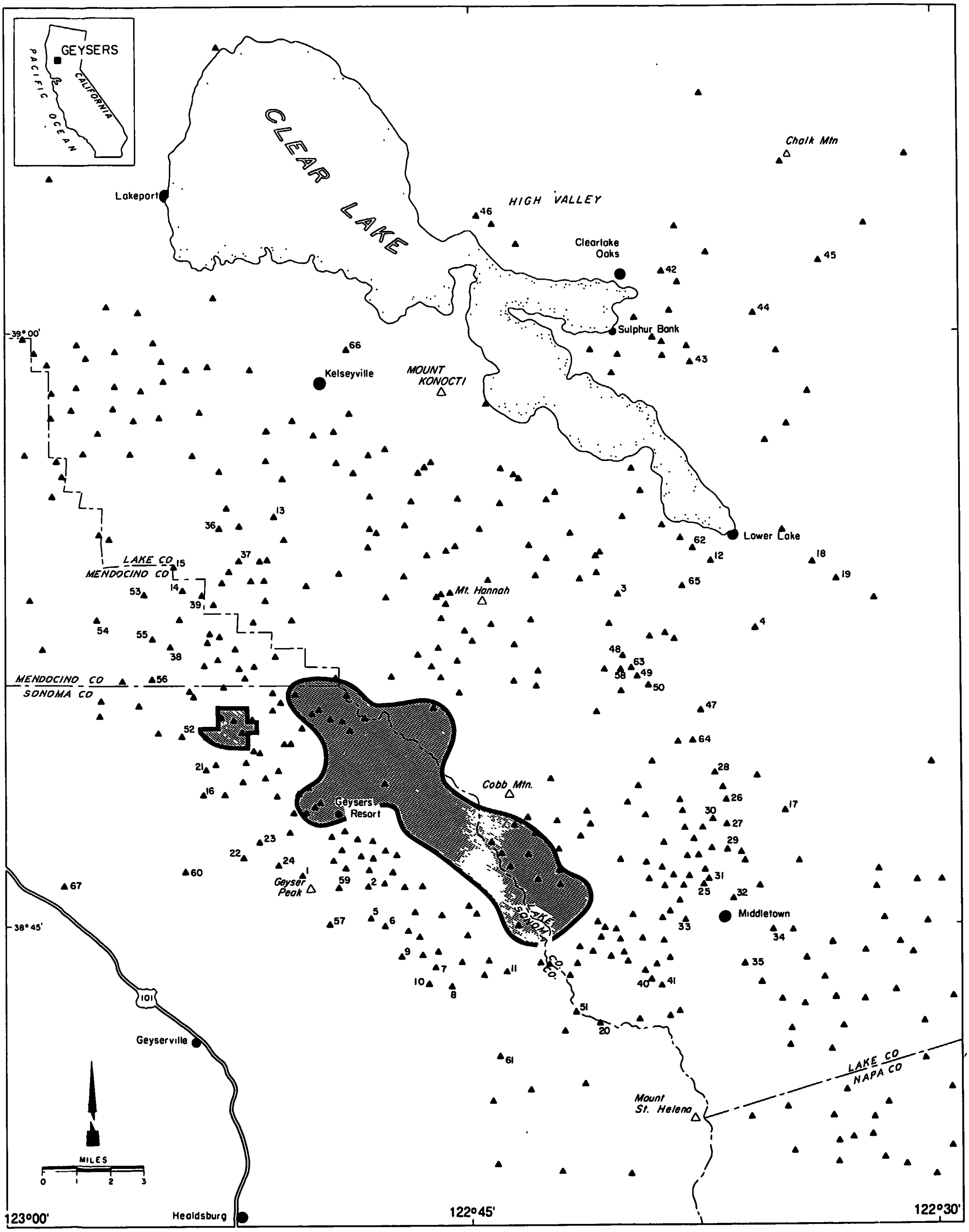

Figure 1. Heat flow hole location map. Temperature gradient and heat flow holes in The Geysers-Clear Lake area are shown as triangles. The number given for some locations refers to holes designated in Table 1. The Geysers geothermal field production area is shaded. Many holes in the region are outside the limits of this map.

Table 1. Selected heat flow data used to define The Geysers-Clear Lake thermal anomaly.

Hole No.	Operator Hole Name	Location Sec., Township, Range(M.D.B.&M.)	Depth m.	Gradient Interval m.	Temperature Gradient Uncorr. °C/km	Temperature Gradient Corrected °C/km	Thermal Conductivity (# of Samples) W/m·°K	Lithology of Gradient Interval	Calculated Heat Flow mWm^{-2}	Calculated Heat Flow HFU*
1.	A-TG-7	SE1/4 27-11N-9W	152	110-152	65.8	73.4	2.72(4)	Melange	200.	4.8
2.	A-TG-9	SE1/4 25-11N-9W	101	37-101	91.1	77.8	2.35(4)	Melange	183.	4.4
3.	A-TG-28	SE1/4 18-12N-7W	137	61-137	99.7	98.9	2.60(0)	Sandstone/Serp	257.	6.1
4.	A-TG-32	SE1/4 23-12N-7W	177	70-137	52.4	50.3	3.06(1)	Sandstone	154.	3.7
5.	A-TG-33	NW1/4 1-10N-9W	183	107-183	79.0	74.0	3.02(0)	Graywacke	223.	5.3
6.	A-TG-34	NE1/4 1-10N-9W	183	140-183	74.3	75.2	2.55(1)	Melange	192.	4.6
7.	A-TG-39	NE1/4 8-10N-8W	183	143-183	89.4	94.6	1.76(1)	Melange	166.	4.0
8.	A-TG-40	SE1/4 8-10N-8W	180	73-180	80.9	79.6	2.60(0)	Serpentinite	207.	4.9
9.	A-TG-47	SW1/4 6-10N-8W	174	73-174	80.9	79.6	2.60(0)	Serpentinite	207.	4.9
10.	A-TG-48	SW1/4 8-10N-8W	180	61-180	65.9	66.7	2.47(1)	Melange	165.	3.9
11.	A-TG-49	NE1/4 10-10N-8W	180	39-180	55.7	65.8	3.02(0)	Graywacke	199.	4.7
12.	A-TG-61	SE1/4 10-12N-7W	174	110-174	72.7	70.5	2.51(0)	Sandstone/Shale	177.	4.2
13.	A-TG-62	NW1/4 3-12N-9W	180	107-180	79.6	78.0	2.68(2)	Graywacke	209.	5.0
14.	GGC-120918-1	NW1/4 18-12N-9W	135	91-135	40.2	45.5	3.60(4)	Melange	164.	3.9
15.	GGC-BLM-1	SE1/4 12-12N-10W	152	79-122	45.5	48.8	3.14(3)	Graywacke	153.	3.7
16.	GGC-GP-11	Unsec.-11N-9W	151	49-151	32.2	50.8	3.02(0)	Graywacke	153.	3.7
17.	GGC-HS-2	Unsec.-11N-7W	91	18-91	71.2	63.9	2.26(3)	Serpentinite	144.	3.5
18.	GGC-KX-8	SE1/4 7-12N-6W	152	18-79	65.8	61.0	2.64(4)	Sandstone	161.	3.8
19.	GGC-KX-9	NW1/4 17-12N-6W	152	91-152	58.5	57.2	2.87(5)	Sandstone	164.	3.9
20.	GGC-PM-1	SW1/4 18-10N-8W	146	79-152	50.4	61.0	2.60(0)	Serpentinite	159.	3.8
21.	GEO-BR-10	NW1/4 8-11N-9W	610	536-610	62.7	62.7	2.72(3)	Argillite/Sandst.	171.	4.1
22.	GEO-GP-1	Unsec.-11N-9W	146	61-146	67.4	71.2	2.72(1)	Graywacke	194.	4.6
23.	GEO-GP-1A	Unsec.-11N-9W	146	67-146	63.7	65.2	2.76(2)	Graywacke	180.	4.3
24.	GEO-GP-3	Unsec.-11N-9W	146	61-146	50.4	61.4	3.18(2)	Graywacke	195.	4.7
25.	GEO-HS-7	Unsec.-11N-7W	146	79-146	78.5	78.3	2.26(3)	Shale/Serp.	177.	4.2
26.	GEO-HS-8	Unsec.-11N-7W	146	91-146	80.9	74.0	2.09(2)	Mudstone	155.	3.7
27.	GEO-HS-9	Unsec.-11N-7W	91	30-91	71.8	65.4	2.43(3)	Serpentinite	159.	3.8
28.	GEO-HS-13	NW1/4 15-11N-7W	152	110-152	75.2	68.7	2.60(0)	Sandstone	179.	4.3
29.	GEO-HS-19	Unsec.-11N-7W	152	134-152	73.0	70.5	2.51(2)	Serpentinite	177.	4.2
30.	GEO-HS-25	Unsec.-11N-7W	152	37-152	62.5	67.2	2.72(8)	Shale	183.	4.4
31.	GEO-HS-26	Unsec.-11N-7W	152	37-152	79.4	75.8	2.47(8)	Shale	187.	4.5
32.	GEO-HS-39	Unsec.-11N-7W	610	354-610	60.1	69.2	2.30(9)	Shale	159.	3.8
33.	GEO-LR-9	Unsec.-10N-7W	152	46-152	77.6	76.1	2.51(15)	Mudstone	191.	4.6
34.	GEO-SEG-6	NW1/4 1-10N-7W	152	122-152	61.4	60.3	2.55(4)	Siltstone	154.	3.7
35.	GEO-SEG-8	NW14 11-10N-7W	137	76-137	45.3	53.7	2.89(6)	Greenstone	155.	3.7
36.	GEO-NG-27	Center-5-12N-9W	146	104-146	70.5	71.2	2.05(1)	—	146.	3.5
37.	GEO-NG-31	NE1/4 8-12N-9W	152	91-151	88.4	76.7	2.35(2)	Melange	180.	4.3
38.	GEO-TV-2	SW1/4 19-12N-9W	151	116-151	76.1	72.1	2.81(4)	Graywacke	202.	4.8
39.	GEO-TV-8	NE1/4 18-12N-9W	603	475-603	77.4	77.2	3.10(5)	Melange	239.	5.7
40.	CH-MSH-7	SE1/4 8-10N-7W	122	30-122	97.5	80.7	2.93(0)	Graywacke/Serp.	236.	5.7
41.	CH-MSH-8	SE1/4 8-10N-7W	140	55-140	55.2	53.4	3.02(0)	Metagraywacke	161.	3.8
42.	CH-RM-5	NE1/4 32-14N-7W	75	39-75	60.7	66.3	2.81(1)	Graywacke	186.	4.4
43.	CH-RM-9	SE1/4 9-13N-7W	60	39-60	121.	91.3	2.30(1)	Greenstone	210.	5.0
44.	CH-RM-14	NE1/4 2-13N-7W	76	39-76	59.9	48.0	3.14(1)	Graywacke	151.	3.6
45.	CL-18	SE1/4 30-14N-6W	38	12-38	61.6	54.6	2.68(1)	Serpentinite	146.	3.5
46.	JL-CL-3	SE1/4 21-14N-7W	151	90-151	–	69.6	2.47(0)	Greenstone	172.	4.1
47.	RGI-B-4	SW1/4 34-12N-7W	152	7-152	71.6	75.4	2.60(0)	Sandstone	196.	4.7
48.	RGI-HU-1	NE1/4 30-12N-7W	148	18-148	113.	104.	2.22(0)	Shale/Serp.	231.	5.5
49.	RGI-HU-4	SE1/2 29-12N-7W	148	18-148	103.	104.	2.22(0)	Shale/Serp.	231.	5.5
50.	RGI-HU-5	NE1/4 32-12N-7W	140	18-140	86.9	98.8	2.22(0)	Shale	219.	5.2
51.	SH-15	Center 13-10N-8W	91	30-91	43.9	53.9	2.60(0)	Serpentinite	140.	3.3
52.	SH-40	NW1/4 6-T11N-9W	91	18-91	68.1	51.6	3.02(0)	Graywacke	156.	3.7
53.	S-23-76-2	NW1/4 13-12N-10W	127	46-127	39.9	54.1	2.89(10)	Graywacke	156.	3.7
54.	S-23-76-3	NE1/4 22-12N-10W	76	15-76	54.1	58.1	2.68(5)	Mudstone	156.	3.7
55.	S-23-76-A3	NE1/4 24-12N-10W	116	61-116	37.2	47.0	2.76(9)	Graywacke	130.	3.1
56.	S-23-76-5	SW1/4 25-12N-10W	78	46-78	70.5	85.6	2.30(4)	Greenstone	197.	4.7
57.	U-71-20	NW1/4 2-10N-9W	76	30-76	66.4	65.6	2.47(0)	Greenstone	162.	3.9
58.	U-71-35	NE1/4 30-12N-7W	76	23-76	98.4	93.9	2.22(0)	Shale	208.	5.0
59.	U-72-1	SE1/4 26-11N-9W	76	15-76	84.4	71.1	2.60(0)	Serpentinite	185.	4.4
60.	U-72-17	NE1/4 31-11N-9W	76	37-76	65.6	55.6	2.60(0)	Serpentinite	145.	3.4
61.	U-BG-73-4	SW1/4 22-10N-8W	79	15-76	66.1	56.1	2.51(0)	Melange	141.	3.4
62.	U-BG-73-13	NE1/4 9-12N-7W	76	46-76	83.8	78.9	2.26(3)	Sandstone	178.	4.3
63.	U-BG-73-22	SW1/4 29-12N-7W	73	23-73	105.	106.	2.09(3)	Shale	222.	5.3
64.	U-BG-73-25	NE1/4 9-11N-7W	66	23-66	106.	85.3	2.60(3)	Sandstone	222.	5.3
65.	U-LC-74-11	NE1/4 16-12N-7W	76	7-76	75.6	68.2	2.68(3)	Sandstone	183.	4.4
66.	U-LC-74-15C	NW1/4 12-13N-9W	75	23-69	131.	129.	1.26(8)	Sediments	163.	3.9
67.	USGS Cloverdale 1	Unsec. 11N-10W	250	130-250	63.2	–	2.70(10)	Graywacke	171.	4.1

*HFU = Heat Flow Unit = 41.87 mWm^{-2} = 1 microcal/cm^2 sec.

correction of 37 percent on values for borehole number 16 whose surface location was not available for this study.

Thermal conductivity values were measured on drill cuttings from 38 of the boreholes and from surface samples near five of the holes. Measurements were made using a steady state divided-bar cell arrangement similar to that described by Sass and others (1971b). The main uncertainty in the thermal conductivity based on drill cuttings results from the uncertainty in the estimate of the formation porosity. In order to determine the order of magnitude of this effect, thermal conductivity measurements were made on cores and drill cuttings from the same interval in 11 boreholes. Comparison of the thermal conductivity values obtained from the same holes indicates that an accuracy of better than 10 percent is achievable. Combs (1980) found that for low porosity (5 percent or less) rock types of the Coso geothermal area, a comparison of cell determinations with the values obtained on the same cores indicated that the divided-bar cell gives values which agree within 5 percent. Porosity estimates for this study were based on published values (Wolff, 1982 and Lipman and others, 1978) and the effect of porosity on in-situ thermal conductivity was used as a correction to the measured values.

Where drill cuttings or surface samples were not available, estimates of thermal conductivity were based on lithologic logs and the median values given in Table 2. The lithology for each borehole is presented in Table 1. The number of thermal conductivity measurements for each temperature-gradient interval is given in parentheses; where thermal conductivity is estimated, a zero is noted in parentheses.

The estimates of thermal conductivity are based on a study of the thermal conductivity of specific major lithologies in The Geysers-Clear Lake area. There are three major assemblages that dominate areally: The Franciscan complex, the Great Valley sequence, and the Clear Lake volcanics. Major lithologies from each of these assemblages were used as the basis of group conductivity values (Figure 2). A total of 904 thermal conductivity measurements of 10 different lithologies from more than 230 locations in The Geysers-Clear Lake area were used. The number of samples selected for each lithology are presented in Table 2 along with the statistical distribution of thermal conductivity values for each lithology. Thermal conductivity measurements for samples of only clearly identifiable, unaltered rocks with no more than 20 percent interbedded or mixed rocks of another lithology were selected for this study. Most of the conductivity samples are from depths of 30 to 150 meters. However, thermal conductivity samples from holes drilled to 600 meters and from deep (3,000 meters) geothermal wells were also used. Graywacke was the principal rock type sampled at depths of 600 meters or greater. An examination of the thermal conductivity data for graywacke as a function of depth showed no systematic variation. The present measurements were made at room temperature and therefore do not reflect the expected changes in thermal conductivity as a function of increased temperature with depth.

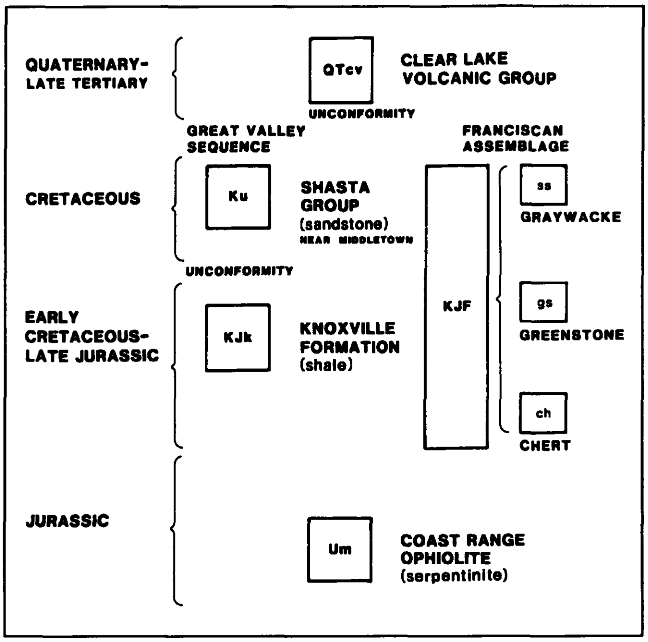

Figure 2. Stratigraphic relationships of lithologic units used in the thermal conductivity analysis.

Thomas (1986) obtained thermal conductivity values on 181 samples of drill cuttings from 16 widely spaced production wells in The Geysers. The three most commonly occurring rock types, graywacke, greenstone, and serpentinized ultramafic rocks produced arithmetic mean thermal conductivities of 3.22, 2.42, and 2.39 W/m°K for 55, 64, and 55 samples, respectively. Based on the data from Table 2 of this report, these three rock types produced arithmetic mean thermal conductivities of 2.97, 2.47, and 2.64 W/m°K for 563, 73, and 85 samples, respectively.

Table 2. Thermal conductivity of Geysers-Clear Lake area lithologic units (W/m°K)

Rock Type	No. of Samples	Range of Values	Arithmetic Mean	Median	Standard Deviation	Standard Error
QUATERNARY CLEAR LAKE VOLCANIC SERIES						
Olivine Basalt	12	1.42-2.18	1.72	1.72	0.19	0.06
Dacite	27	1.21-2.14	1.68	1.59	0.25	0.05
Andesite	6	1.59-1.80	1.68	1.68	0.07	0.03
Rhyolite	23	0.75-1.80	1.09	1.00	0.23	0.01
JURASSIC - CRETACEOUS GREAT VALLEY SEQUENCE						
Sandstone	59	2.21-3.30	2.68	2.60	0.21	0.03
Shale	35	1.92-2.68	2.22	2.22	0.17	0.03
JURASSIC OPHIOLITE						
Serpentinite	85	1.84-3.43	2.64	2.60	0.36	0.04
JURASSIC - CRETACEOUS FRANCISCAN ASSEMBLAGE						
Greenstone	73	1.88-3.14	2.47	2.47	0.33	0.04
Graywacke	563	2.43-3.77	2.97	3.02	0.29	0.01
Chert	21	3.02-4.15	3.56	3.56	0.29	0.06

Therefore, the data from these two studies confirm that an estimate of the mean thermal conductivity, based on the lithologic units in The Geysers-Clear Lake area, probably has an uncertainty of less than 10 percent.

HEAT FLOW RESULTS

The published heat flow data over the presently productive Geysers geothermal field (Thomas, 1986) indicate a predominantly conductive regime exceeding 350 mWm^{-2} (8.4 HFU) above the developed reservoir with anomalous heat flow values of 171 mWm^{-2} (4.1 HFU) extending far beyond the areal extent of the present steam production (Urban and others, 1976). Heat flow values greater than 125 mWm^{-2} require either melting within the shallow crust or convective transport by water or magmas. Values greater than 200 mWm^{-2} are representative of heat flow obtained over commercially productive geothermal fields.

The Geysers geothermal field production area is about 75 square kilometers in size and is situated in the southwestern portion of the regional thermal anomaly. Heat flow values above The Geysers producing area range from about 335 to 500 mWm^{-2} and are presented both in Figure 3 as contours adapted from Thomas (1986), and in Figure 4.

All of the holes used to define The Geysers-Clear Lake thermal anomaly are drilled in either the Franciscan complex, Great Valley sequence or associated ophiolitic rocks. Although the apparent effects of groundwater can be noted in the data from near-surface portions (0-50 meters) of the 67 holes, the linearity of the temperature-depth plots indicates that conduction is the dominant means of heat transfer in the shallow subsurface. The linearity of these temperature-depth plots is similar to those presented by Thomas (1986). Examples of temperature-depth plots for The Geysers-Clear Lake area are given in Figures 6 and 7. The logs from most holes drilled in rocks of the Quaternary Clear Lake volcanics (Figure 5) clearly indicate that the temperature-depth data are disturbed by groundwater movement. Therefore, the temperature data for holes drilled into Clear Lake volcanic rocks are not used to define the extent of the thermal anomaly.

Heat flow within the Clear Lake volcanic field was estimated using lithology and temperature logs from six deep wells which penetrated the Clear Lake volcanics. These wells were not completed or operated as temperature gradient or heat holes; however, the data were deemed useful for estimating heat flow. The basic data and assumptions for calculating heat flow values from these wells are presented in Table 3. The estimated values are anomalously high, ranging from 214 to 375 mWm^{-2}.

In the present study, a minimum heat flow value of 167 mWm^{-2} (4HFU) has been chosen to delimit the areal extent of the thermal anomaly of The Geysers-Clear Lake area. The data clearly delineate a thermal anomaly of at least 750 square kilometers (Figure 3). A Bouguer gravity anomaly of -50 milligals first described by Chapman (1975) is located at the center of the thermal anomaly and the thermal anomaly encompasses most of the Clear Lake volcanic field and its known intrusive equivalents (Figure 4).

Table 3. Heat flow values from deep geothermal wells in the Clear Lake volcanic field

Well[1]	Temperature[2] (°C)	Depth[2] (m)	Calculated[3] Temperature Gradient (°C/km)	Estimated[4] Thermal Conductivity (W/m· °K)	Calculated Heat Flow (mW/m²)	(HFU)[5]
Audrey A-1	278	1897	138.	2.72	375	9.0
Borax Lake 7-1	243	2414	94.2	2.72	256	6.1
Bouscal 1-2[6]	244	2412	94.7	2.60	246	5.9
Jorgensen 1	288	3139	86.8	2.47	214	5.1
Neasham 1	251	2756	85.4	2.72	232	5.5
Wilson 1	326	3353	92.6	2.51	232	5.5

Notes:
1) See Figure 3 for well locations.
2) Original depths and temperature measured in feet and fahrenheit, respectively.
3) Assumes 15.6 °C average mean surface temperature.
4) Thermal conductivity estimated using data from Table 2 and lithologic section for each of the wells.
5) HFU = Heat Flow Unit = 41.87 mW/m^2 = 1 $microcal/cm^2$ sec.
6) Data courtesy of Republic Geothermal Inc.

Although The Geysers geothermal field is manifested as a northwest-southeast trending thermal anomaly, the general shape of the regional thermal anomaly of The Geysers-Clear Lake area is essentially northeast-southwest. This is most likely a reflection of the regional tectonic structural framework in which both regional geologic structures and the rocks of The Geysers reservoir are northwest-southeast trending.

DISCUSSION AND CONCLUSIONS

A regional gravity study initiated in 1963 by the California Division of Mines and Geology led to the discovery of a large negative Bouguer gravity anomaly centered in the vicinity of the Clear Lake volcanic field (Chapman, 1975). The Geysers-Clear Lake geothermal system as described by McLaughlin (1977), and Goff and others (1977) has as its heat source a magma chamber situated at a depth of greater than 10 kilometers. This magma chamber, associated with the Clear Lake volcanics, is defined by a large-scale negative gravity anomaly of -50 milligals at Mt. Hannah (Figure 5) between The Geysers and Clear Lake, and is further substantiated by teleseismic P-wave delays as noted by Iyer and Hitchcock (1975). Heated water of both connate and meteoric origin reaches the surface as liquid or vapor via fractured rock. The Geysers geothermal field appears to be bounded to the southwest by the northwest-trending Mercuryville fault zone. The northwest-trending Collayomi fault zone appears to separate the southwestern vapor-dominated system from the hot water-dominated system to the northeast (Goff and others, 1977).

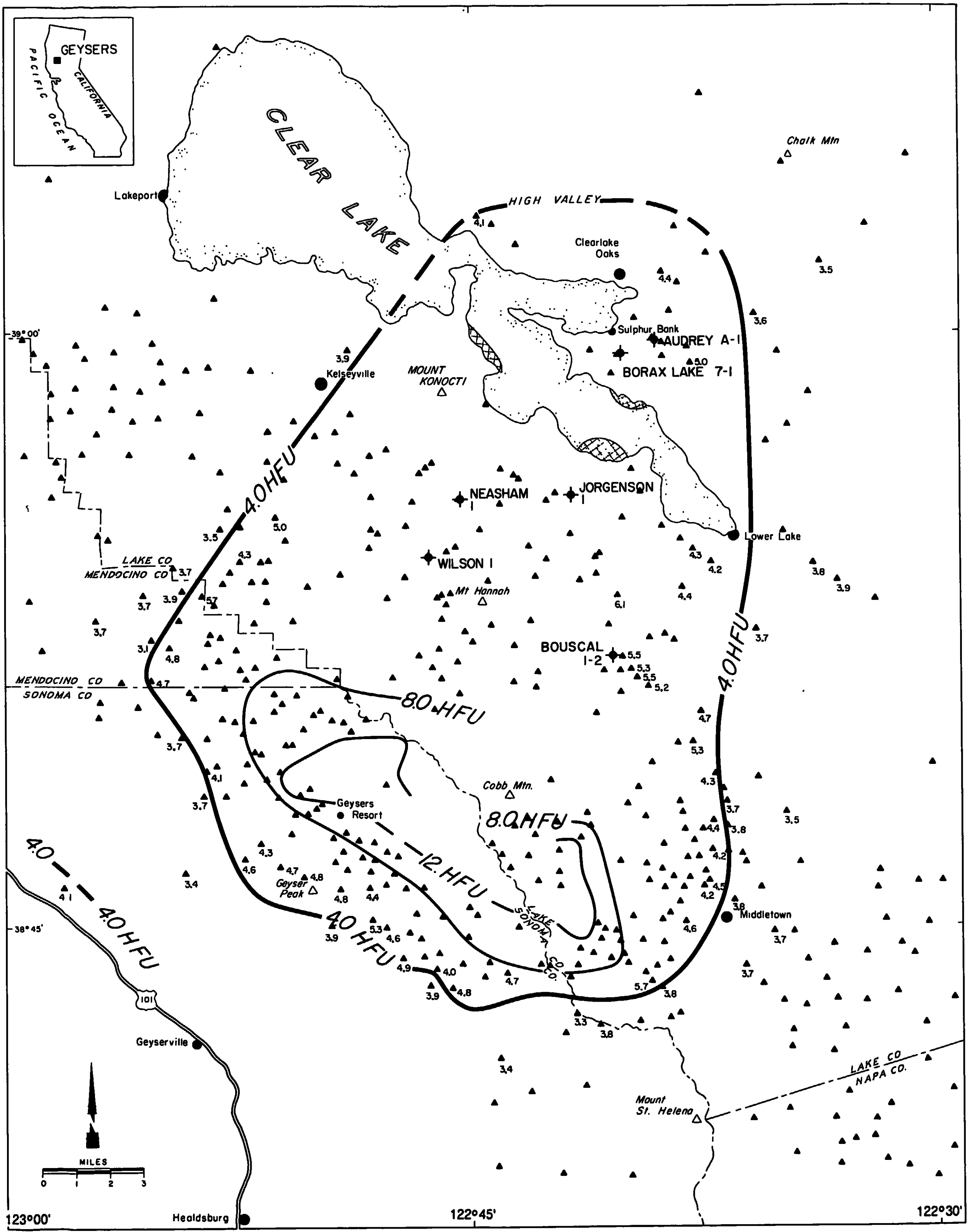

Figure 3. Heat flow anomaly map of The Geysers-Clear Lake area. The thermal anomaly is within the 4 HFU (168 mWm^{-2}) contour line. The 8 HUF (335 mWm $^{-2}$) and 12 HFU (500 mWm^{-2}) contours are adapted from Thomas (1986). Heat flow values for deep wells in the Clear Lake volcanic field are presented in Table 3. Areas in Clear Lake having anomalous lake bottom temperature (Martin, 1976) are shown by hachures. For a detailed presentation of heat flow contours above The Geysers production area, see Figure 4.

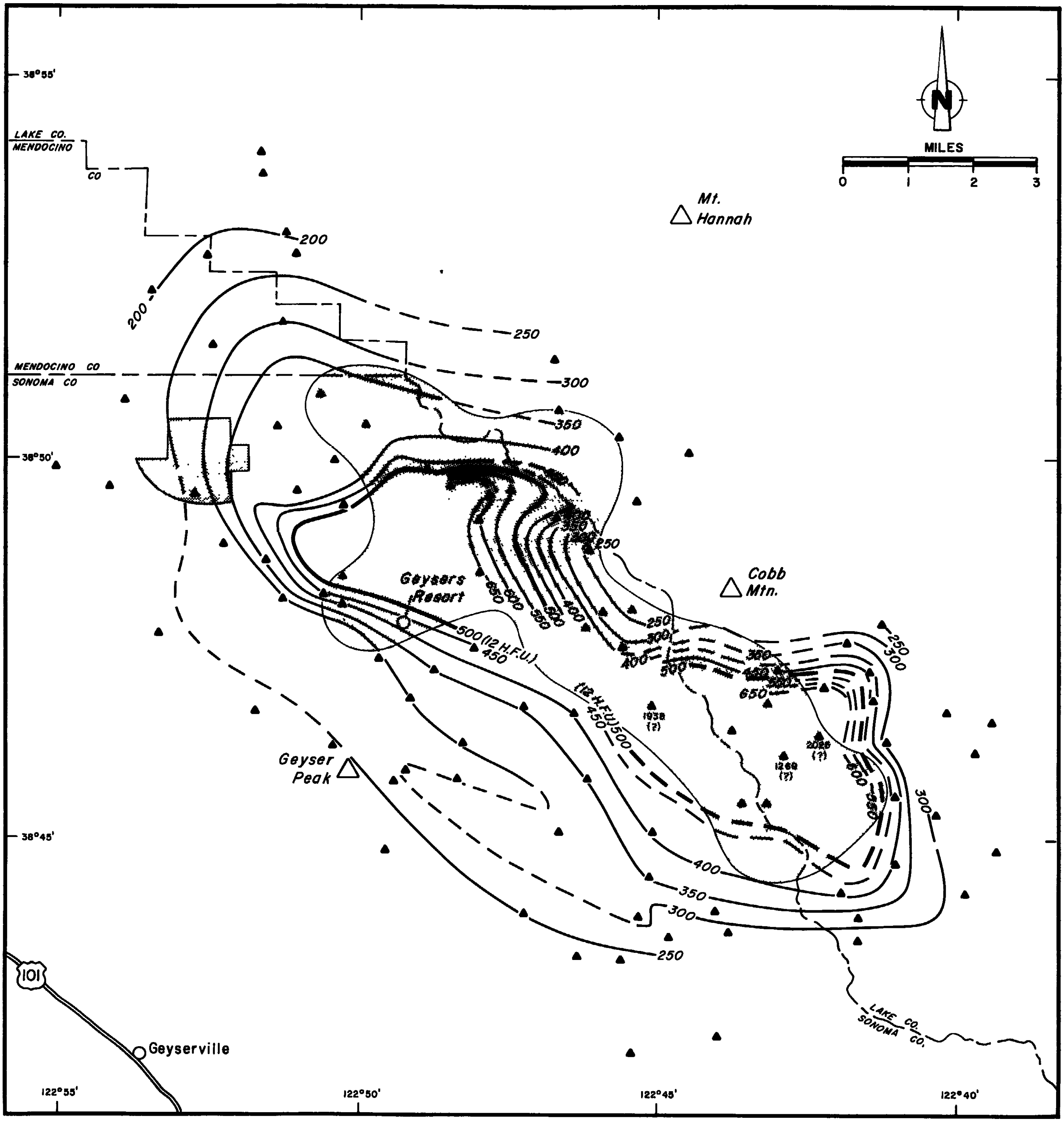

Figure 4. Heat flow map of The Geysers geothermal field. Heat flow contours shown in mWm^{-2}. Triangles are temperature gradient and heat flow hole data locations used as control points. Dashed heat flow contours are estimated from deep production well data. The 500 mWm^{-2} contour is labelled 12 HFU here for reference to Figure 3. The Geysers production area is shaded. (Adapted from Thomas, 1986).

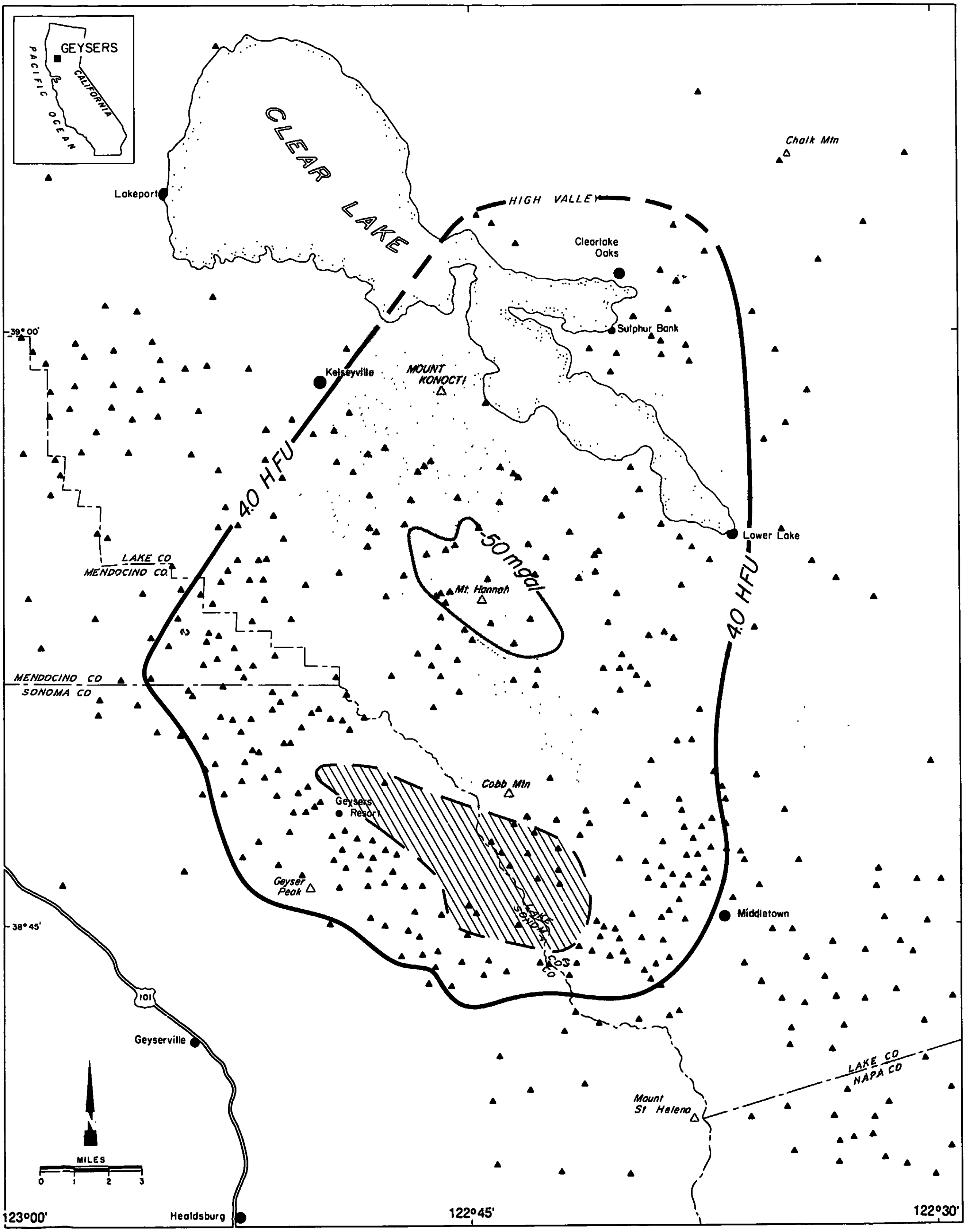

Figure 5. The Geysers-Clear Lake thermal anomaly, volcanic field and associated gravity anomaly. The extent of the thermal anomaly is outlined by the 4 HFU (168 mWm^{-2}) contour. The extrusive portion of the Clear Lake volcanic field is shown in stipples and the intrusive portion known by deep geothermal drilling is hachured. The -50 milligal Bouguer gravity anomaly associated with the volcanic field is adapted from Chapman (1975).

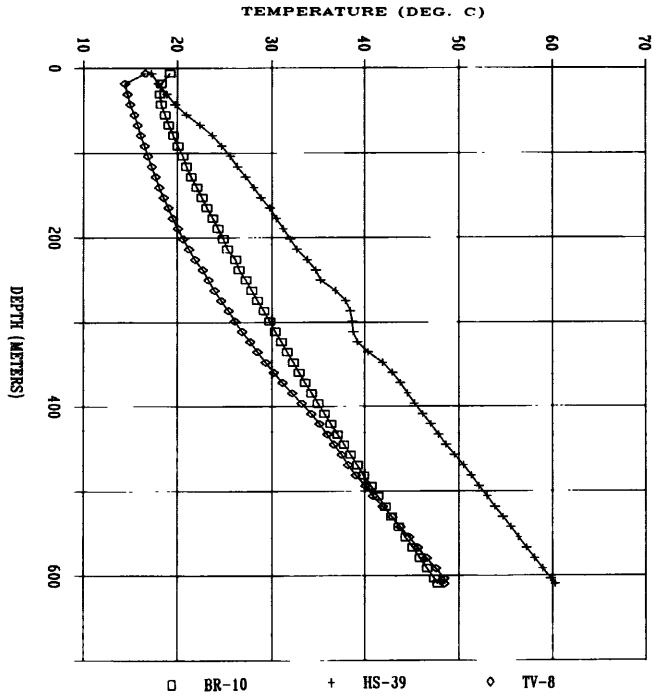

Figure 6. Temperature-depth plots. Data from intermediate-depth heat flow holes BR-10, HS-39, and TV-8 (hole numbers 21, 32 and 39 of Table 1). The measured temperatures were obtained 90 to 120 days after drilling. The temperature gradients used to derive heat flow are from the bottom portions of the holes.

Rocks in the Clear Lake volcanic field range in age from 2 million to 10,000 years. Their intrusive equivalents are known from deep drilling at The Geysers geothermal field and are dated at 1.6 million years (Schriener and Suemnicht, 1980). The age of the youngest volcanic rocks in closest proximity to both The Geysers geothermal field and negative Bouguer gravity anomaly range in age from 0.8 to 1.1 million years (Donnelly, 1977). Therefore, the measured ages of the intrusive felsic rocks beneath The Geysers geothermal field and the associated nearby erupted rocks are too old to explain the present geothermal phenomena associated with The Geysers geothermal field.

The youngest rocks in the Clear Lake volcanic field are on its northern edge near High Valley north of Clear Lake Oaks; however, the amount of surficial geothermal activity in the vicinity is small, a few hot springs near Chalk Mountain, at Sulphur Bank Mine and in Clear Lake (Figure 3). Although future volcanic activity is most likely to occur in this area (Donnelly, 1977), high heat flow values associated with these geothermal phenomena apparently are localized (Martin, 1976 and Beall, 1985).

Neither the younger nor the older volcanic rocks in The Geysers-Clear Lake area provide clues as to the source of high heat flow in the region. However, the regional perspective gained from the interpretation of all available temperature and heat flow data is the geographical coincidence of the centers of the gravity and heat flow anomalies at Mt. Hannah (Figure 5) where a magma chamber is hypothecated at about 10 km depth (Chapman, 1975 and Iyer and Hitchcock, 1975). This is the presumed heat source for the geothermal phenomena in the region.

An important issue that should be examined bears on the ultimate development of the geothermal resources in The Geysers-Clear Lake area. Why is the present geothermal development concentrated in The Geysers geothermal field at the edge of the thermal anomaly and not closer to the geographical center of the geophysical anomalies interpreted to be a magma chamber? At least six deep (2.5 to 3.0 km) exploratory geothermal wells have been drilled at widely spaced locations throughout the Clear Lake volcanic field (Figure 3). Each has encountered temperatures exceeding 240°C and four of the six have encountered small amounts of fluids. The scant geothermal development (one deep well per 50 square kilometers) within the Clear Lake volcanic field therefore is not due to a lack of anomalously high heat flow. The answer involves at least three factors:

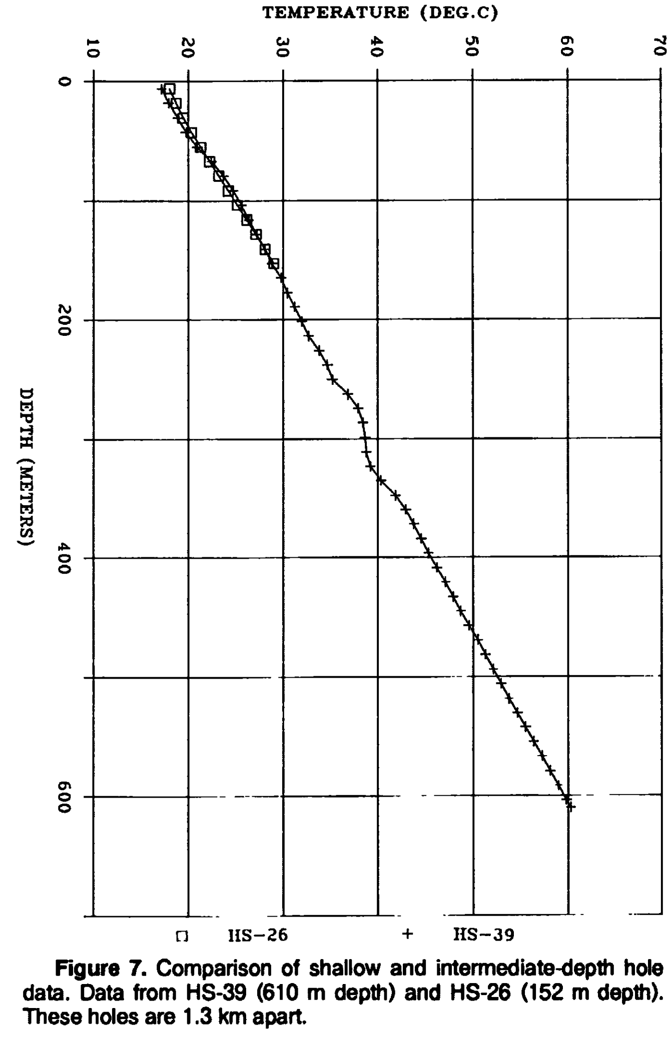

Figure 7. Comparison of shallow and intermediate-depth hole data. Data from HS-39 (610 m depth) and HS-26 (152 m depth). These holes are 1.3 km apart.

- Exploration is difficult in the Clear Lake volcanic field. Heat flow holes in this area often are not useable for determining undisturbed heat flow values unless they penetrate the volcanic cover. In the lowland areas, the volcanic rocks are 300 to 750 m thick, to a depth of about 20 meters subsea.
- Historically, it has been difficult for geothermal developers to obtain use permits in the area of the Clear Lake volcanic field because the area is more densely populated than the area of The Geysers geothermal field. This has resulted in less deep exploratory drilling.
- Most important, the geothermal wells that are closer to the center of the gravity and heat flow anomalies did not encounter at economically feasible depths the massive graywacke turbidite units associated with the steam-bearing reservoir at The Geysers geothermal field. This fact may be significant in explaining why the wells drilled in the Clear Lake volcanic field lack reservoir permeability. The rocks encountered at reservoir depths in these wells were primarily greenstone, serpentinite, melange units and argillite-rich distal turbidites. These rocks are believed to fail in a ductile mode at reservoir temperatures and therefore do not support open fracture networks. Massive graywacke turbidites as found in The Geysers geothermal field host open fracture networks with steam (Sternfeld, 1989). Until more geothermal wells are drilled within the Clear Lake volcanic field, it will not be possible to know whether massive graywacke turbidites exist below the volcanic cover.

The Geysers geothermal field development currently occupies 75 of the 750 square kilometers of the regional thermal anomaly in The Geysers-Clear Lake area. Expansion of the current geothermal resource development is not likely to be limited by anomalous heat flow. More likely, it will depend upon land ownership, politics, and the economics of deep drilling needed to determine the existence of a permeable reservoir.

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