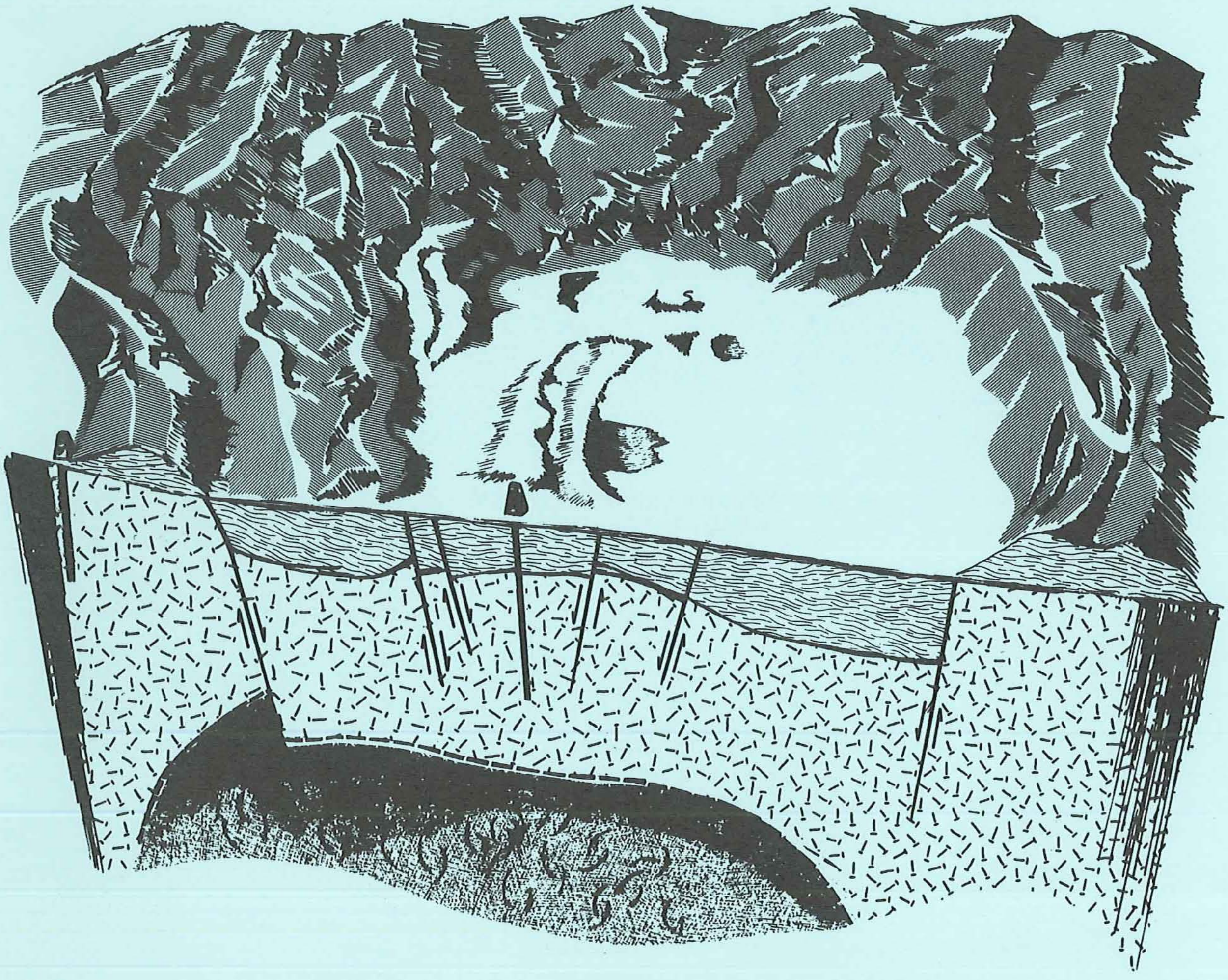
LA-8710-HDR

Preliminary Hot Dry Rock Geothermal Evaluation of Long Valley Caldera, California



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David T. Gambill

FOREWORD

In 1972 and 1973 the U.S. Geological Survey conducted a detailed investigation of Long Valley Caldera, California, for conventional geothermal resources. The investigation included structural and volcanic mapping, hot spring geochemistry, seismic refraction, teleseismic, audiomagnetotelluric, deep electrical, gravity, aeromagnetic, seismic noise, microseismics, and heat flow measurement studies of the caldera. The following evaluation is derived mainly from the work presented in a symposium devoted to these studies and from data on two deep wells recently drilled in the caldera by Union Oil.

PRELIMINARY HOT DRY ROCK GEOTHERMAL EVALUATION OF LONG VALLEY CALDERA, CALIFORNIA

by

David T. Gambill

ABSTRACT

Long Valley Caldera, formed during the catastrophic eruption of the Bishop Tuff 0.7 Myr ago, straddles the border between the Sierra Nevada and the Basin and Range tectonic provinces in eastern California. The caldera contains rhyolitic to basaltic flows, tuffs, and domes from 3.2 Myr to 450 yr old. Sierra Nevada frontal faults intersect the northwest and southeast parts of the caldera. The dominant feature within the caldera is a resurgent dome in the west-central section, which formed between about 0.7 and 0.5 Myr b.p.

Teleseismic data indicate a low P-wave velocity zone below the western part of the caldera, indicating a magma chamber between 7 and 25 km depth. This conclusion is supported by gravity data. Heat flow just west of the caldera is 3.75 HFU. Just east of the caldera, measured heat flow is about 2 HFU. However, a deep well on the eastern edge of the resurgent dome has a gradient of 38°C/km from 0.66 to 1.2 km suggesting that the magma chamber, which produced Long Valley, is largely crystallized below the resurgent dome. The high heat flow beneath the western caldera may be a manifestation of shallow silicic magma associated with the recent Inyo Craters. These data indicate a smaller magma source may lie below the western caldera.

The resurgent dome and the area just west of the caldera are cited for additional Hot Dry Rock prospection. The higher temperature gradient and lack of caldera fill beyond the west margin of the caldera combine to make this area promising for future HDR evaluation.

I. INTRODUCTION

Long Valley Caldera in east-central California (Fig. 1) lies on the border between the Sierra Nevada batholith and the Basin and Range tectonic province. West of the caldera, Mesozoic crystalline rock of the Sierra Nevada batholith crops out. The caldera is composed primarily of silicic and basaltic volcanic rocks that have erupted from about 3.2 Myr b.p. to 450 yr b.p., although the major caldera-forming event occurred 0.7 Myr b.p.

The young ages of the volcanics and seismic, gravity, and heat flow data suggest that a magma source may still be present at about 7-25 km below the western part of the caldera. The possibility of such a large heat source

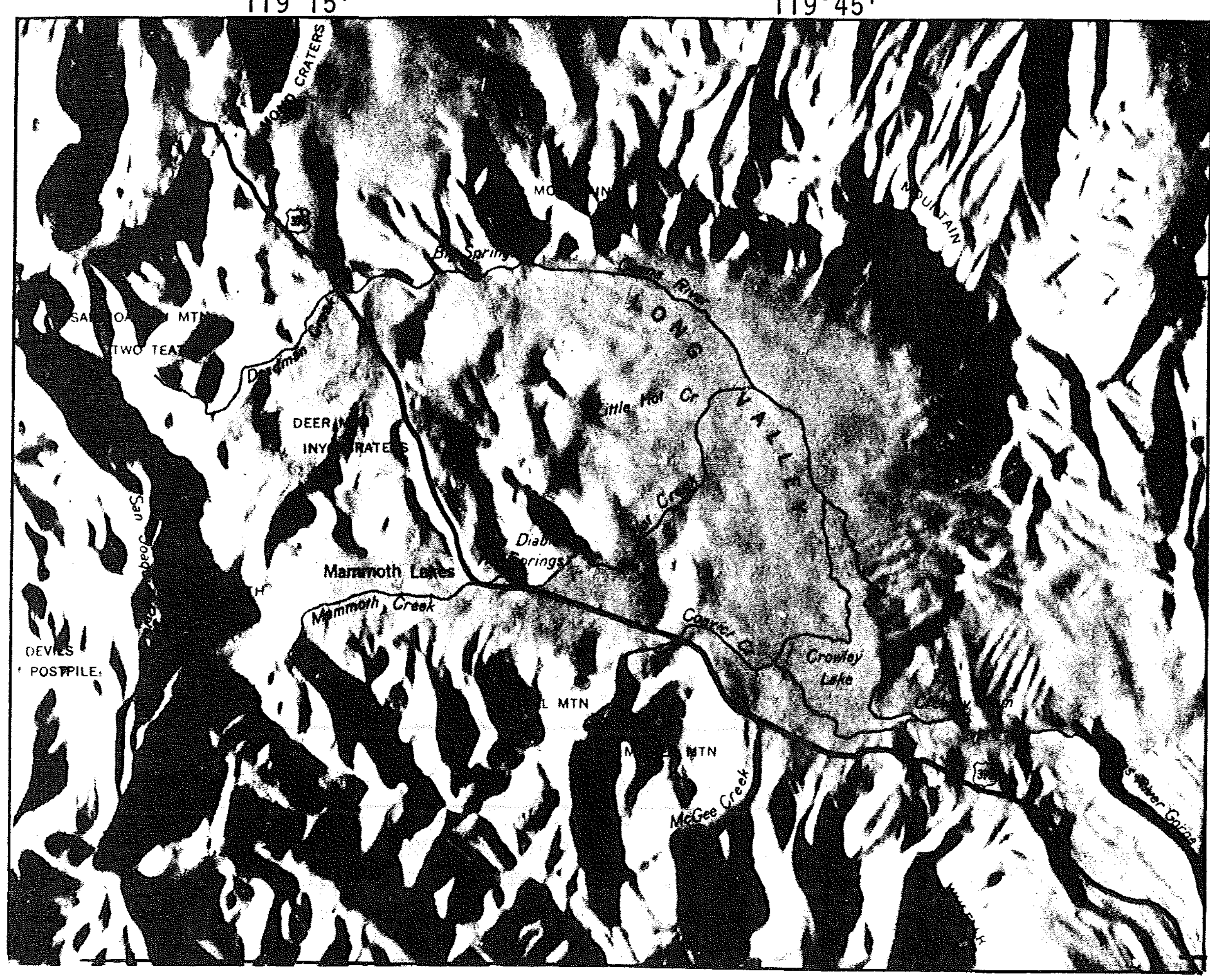

Fig. 1.
Shaded relief map of Long Valley Caldera (from Bailey et al. 1976).

under crystalline rock makes Long Valley Caldera an attractive prospect for hot dry rock (HDR) geothermal development. This report presents a preliminary evaluation of the HDR potential of Long Valley Caldera and an outline of further work necessary to more clearly define the HDR resource base of the area.

II. GEOLOGY

A. Basement Rock

North, south, and west of Long Valley Caldera, basement rocks are Jurassic and Cretaceous granodiorites and granites of the Sierra Nevada batholith with roof pendants of Paleozoic and Mesozoic metasediments and metavolcanics (Fig. 2). One deep well drilled in the west-central caldera by Union Oil (Mammoth #1) penetrated metasediments from 1378 to 1605 m; about 7 km east, the Union Oil Co. well Clay Pit #1 apparently penetrated a shallow silicic intrusive body (M. Sorey, USGS, oral communication, 1980) from 1420 to 1846 m. Gravity and seismic refraction data show that basement under the caldera dips north from a depth of about 1 to 2 km in the south to 2.5 to 3 km in the northern part of the caldera.

B. Volcanic Rocks

Precaldera rhyodacites and basalts overlie the basement in the western part of the caldera. These volcanics are about 3.2 to 2.6 Myr b.p. and do not appear genetically related to Long Valley volcanism (Bailey et al. 1976).

The principal eruptive units in Long Valley first appeared contemporaneously with the start of faulting along the eastern Sierra Nevada escarpment. Activity began with eruption of the Glass Mountain rhyolites (1.92 ± 0.05 and 0.9 ± 0.1 Myr b.p.) along incipient ring fractures as flows, ash deposits, and domes (Bailey et al. 1976). At about 0.7 Myr b.p. the second eruptive phase began with the catastrophic eruption of rhyolitic Bishop Tuff. This unit originated from vents within the caldera and spread southeast, north, northwest, and west. The Bishop Tuff does not crop out within the caldera, but inclusions of densely welded tuff are found in post-caldera units. Sesimic refraction data indicate between 1000 and 1500 m of Bishop Tuff lies buried within the caldera (Hill, 1976).

Subsidence of the caldera followed, or occurred during eruption of the Bishop Tuff. Following subsidence, eruptions within the caldera resumed, forming 'early' rhyolites (0.73 to 0.63 Myr b.p.). These units are mainly

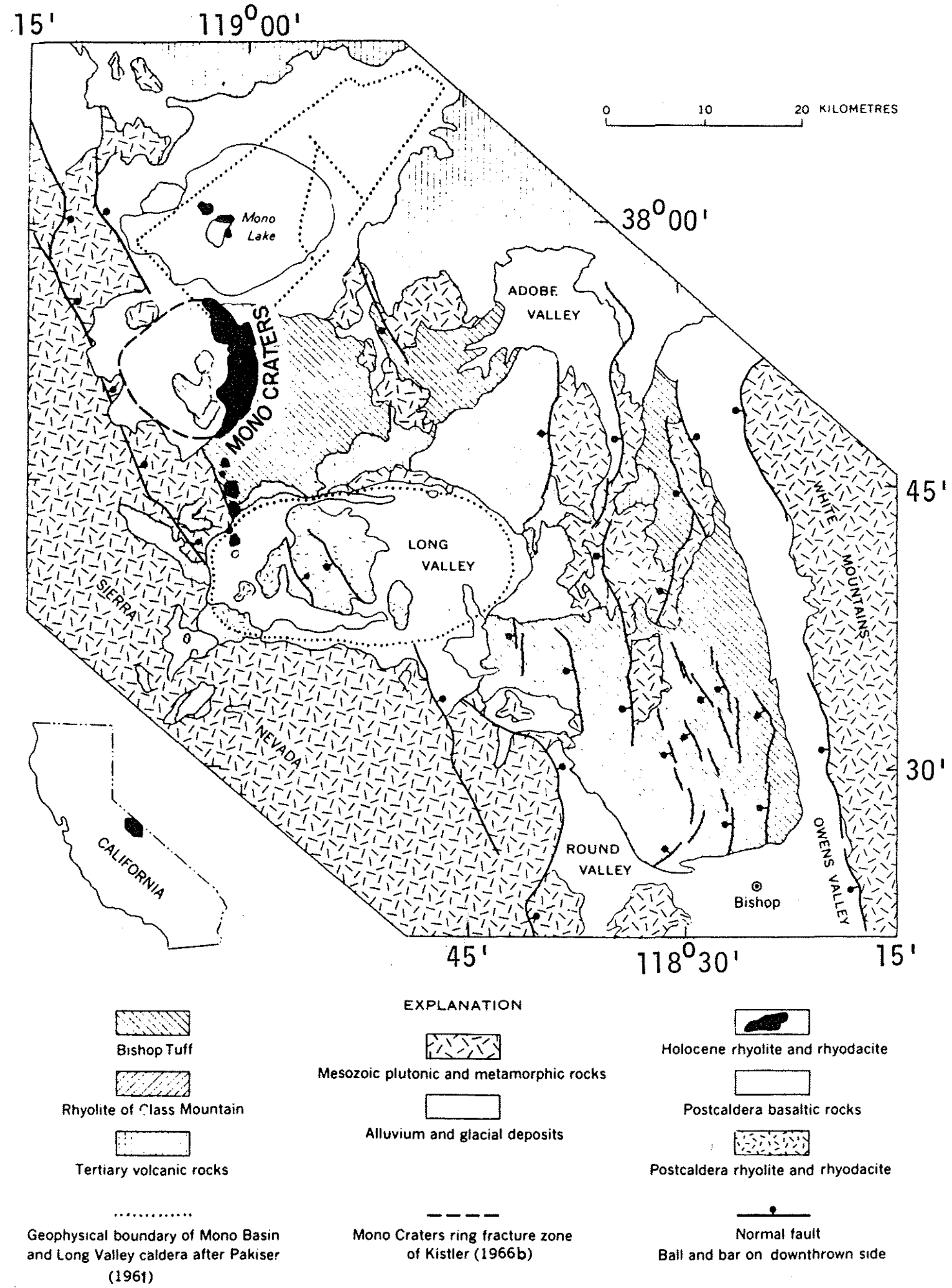

Fig. 2.
Centralized geologic map of the Long Valley-Mono Basin area, (from Bailey et al. 1976).

tuffs, domes and flows aligned along or offset by northwest-trending faults and they accumulated to a thickness of at least 500 m. Structural uplift of the west-central part of the caldera floor into a resurgent dome was contemporaneous with eruptions of early rhyolite.

After resurgence, three groups of volcanics erupted to form the 'moat' rhyolites at 0.5, 0.3, and 0.1 Myr b.p. These units are arranged in a clockwise order around the resurgent dome and appear to be controlled by the intersection of ring fractures around the dome and north-south trending faults.

The appearance of rim rhyodacites was concurrent with the last stages of formation of the moat rhyolites. Mammoth Mountain, a cumulovolcano on the southwest rim of the caldera (0.18 ± 0.09 Myr b.p.), is the largest of the rim rhyodacites. An apparent sanidine age from the summit dome is 0.05 ±0.01 Myr. Apparently Mammoth Mountain has been active for at least 0.10 Myr, partly contemporaneously with the moat rhyolites (R. Koeppen, USGS., Reston, VA, personal communication). Rim rhyodacites are also found in Deadman Creek on the northwest rim. The smallest of the rim rhyodacites is at the foot of Glass Mountain on the northeast caldera margin. These units are located along ring fractures; the largest two are at the junction of ring fractures and north-south trending faults. Possibly, the rim rhyodacites formed by mixing of contemporaneous basaltic magma, represented in the western moat of the caldera and the Long Valley rhyolitic magma (Bailey et al., 1976).

The basalts in the western moat are not directly related to the Long Valley volcanism, but are part of a 45-km-long chain of mafic volcanics extending from southwest of Mammoth Mountain north into the Mono basin (Bailey et al. 1976). These mafic volcanics erupted along a north-trending, en echelon fracture system that parallels the east front of the Sierra Nevadas.

The youngest volcanic activity in Long Valley Caldera is represented by the Inyo Craters and domes. These features are also aligned along a north-trending fracture system from the west moat to the Mono craters. They consist of five rhyolitic to rhyodacitic lava domes, the largest dated at 720 ± 90 yr b.p., and phreatic explosion craters, located on the south flank of Deer Mountain (650 ± 200 yr b.p.). Thus rhyodacitic magma was present beneath Long Valley as recently as 450 Myr b.p.

C. Structure

Long Valley Caldera is intersected on the northwest and southeast by major Sierra Nevada frontal faults. The Hartley Springs fault in the northwest wall of the caldera offsets precaldera andesites by about 450 m and offsets the Bishop Tuff by about 300 m. En echelon faults in the moat south of the Hartley Springs fault offset trachyandesites by about 15 m and offset Inyo Crater deposits by about 5 m (Bailey et al. 1976).

The Hilton Creek fault bifurcates into en echelon faults from the southeast caldera rim north into the crater. These en echelon faults offset 0.3 Myr old volcanics and lateral and outwash moraines by about 15 m.

The change in both the Hilton Creek and the Hartley Springs faults from single, continuous faults outside the caldera to en echelon, branching fractures within the caldera suggests the cauldron is less rigid than the surrounding crust and may still be underlain by magma (Bailey et al. 1976).

Within the caldera the major structural feature is the resurgent dome in the west-central caldera floor. This subcircular dome, about 10 km in diameter, is a mosaic of fault-bounded blocks that rise about 500 m above the surrounding moat. Doming probably did not continue much past 0.5 Myr b.p. (Bailey et al. 1976).

III. HYDRO-GEOCHEMISTRY

The general distribution of hydrothermal activity in the caldera is in an arcuate zone around the resurgent dome, suggesting the controlling structure at depth is caldera ring fractures. Most of the fumarole activity in the caldera is on or near north-trending faults associated with the keystone graben of the resurgent dome. Hot springs are associated with the graben and along active extensions of the Hilton Creek fault. Within hours of two earthquakes in August and October of 1973, new boiling springs and ephemeral geysers erupted along the Hilton Creek fault (the earthquake epicenters were 20 to 40 km from the Hilton Creek fault). The flow and temperature of some older springs along the Hilton Creek fault have increased since the 1973 earthquakes (Bailey et al. 1976). These effects show that the Hilton Creek fault controls the circulation of hot water from deep sources.

Most springs within the caldera are less than 63°C, the majority between 11 and 30°C, and represent mixed thermal and cool ground water (Sorey and Lewis 1976). Hot springs are most abundant in the eastern and southern part of the caldera and are found locally in the west (Fig. 3). In Hot Creek Gorge in the south-central caldera, hot springs supply about 150 ℓ/s of fluid and

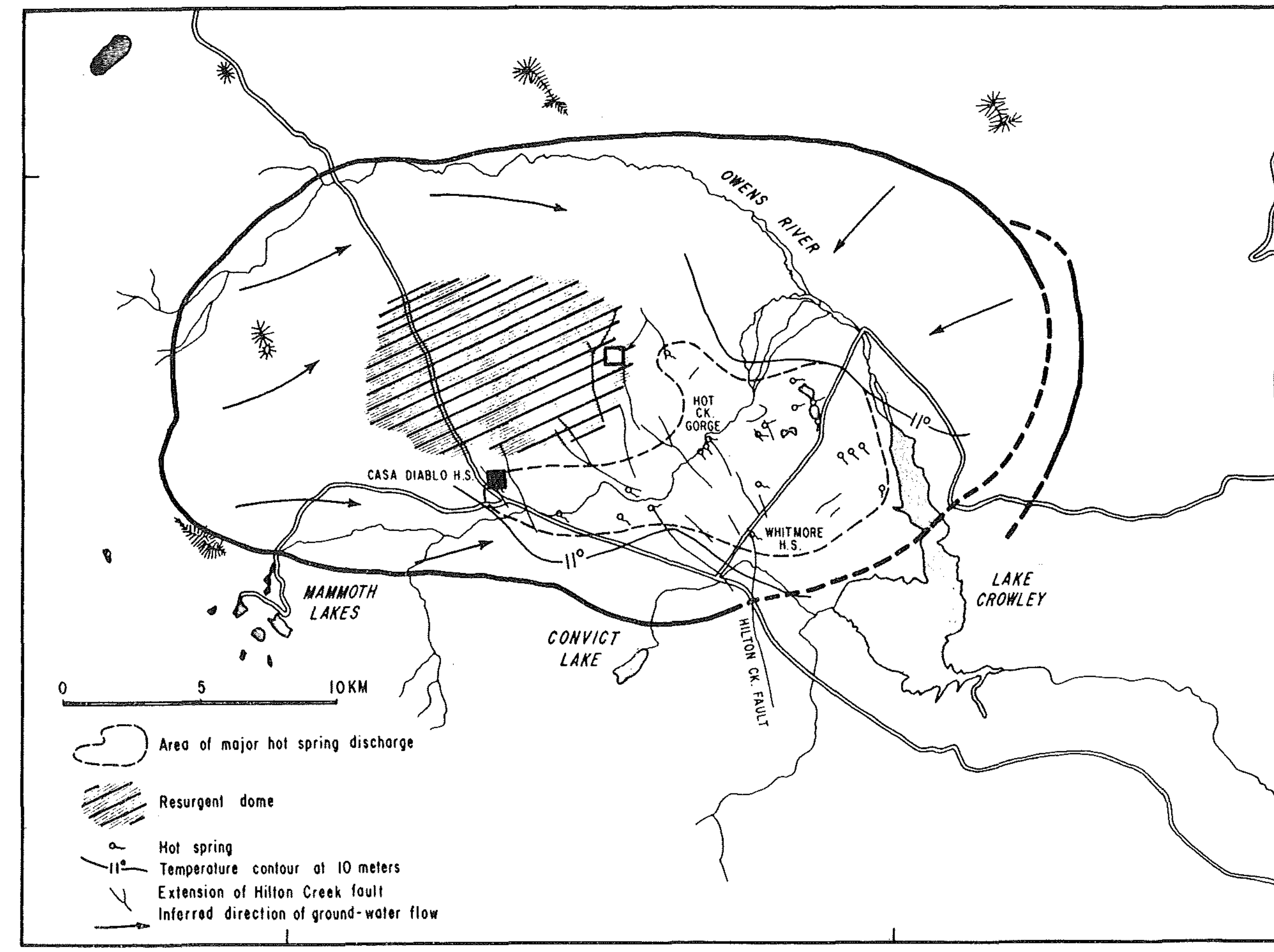

Fig. 3.
Map of Long Valley Caldera showing relations among ground water flow, hot spring discharge, 10-m temperatures, and the resurgent dome (crosshatched). Union oil wells = open square - Clay Pit #1; solid square - Mammoth #1 (Lachenbruch et al. 1976).

account for about 80% of the total hot water discharged in the caldera. Most of these springs are about 90°C and discharge below the water level of the creek. Numerous steam vents, sulfur fumaroles, and mud pots are present to the west of Hot Creek Gorge at Casa Diablo Hot Springs. The chemistry of the springs at Casa Diablo suggests these fluids are steam-heated ground water (Sorey and Lewis, 1976).

The hot springs of Long Valley are Na-HCO_3-Cl waters (Figs. 4 and 5; Table I); the fresh water springs are Na-HCO_3 with more calcium and magnesium than the thermal waters. The thermal waters of the Long Valley Caldera have high Cl/Ca and Cl/Mg ratios, possibly due to precipitation of carbonates at

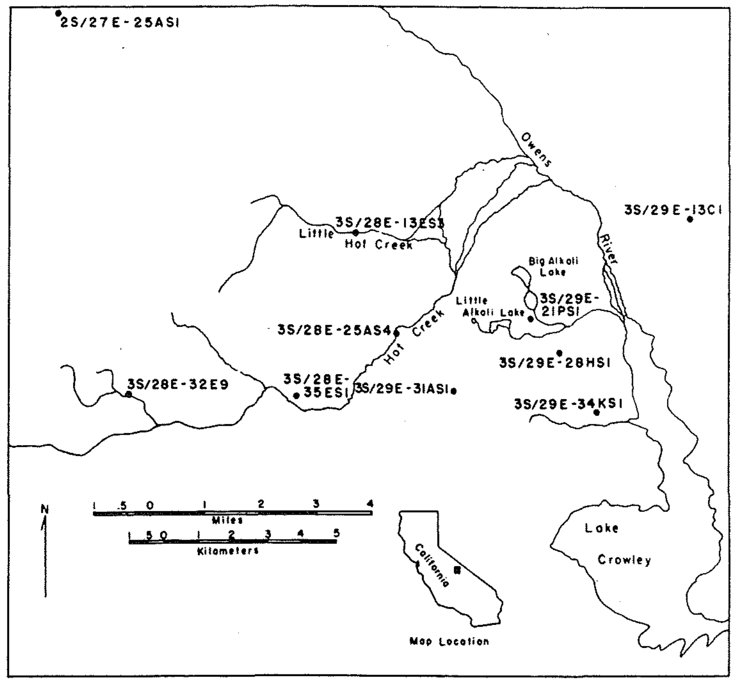

Fig. 4.
Index map showing the locations of springs and wells sampled for detailed chemical analysis, Long Valley, California. The spring issuing in Hot Creek Gorge, designated 3S/28E-25AS4, was collected during August 1973. All other samples were collected during May 1972 (from Mariner and Willey 1976). Steam Well at Casa Diablo Hot Springs is designed 3S/28E-32E9.

depth. This hypothesis is supported by a decrease in $Cl/(HCO_3 + CO_3)$ ratios of spring waters as spring temperatures decrease (Mariner and Willey, 1976).

Escaping gases in the Hot Creek Gorge are 89 to 93% CO_2 and have low methane content. The high carbon dioxide and low methane content of the gases indicates the thermal reservoir is in igneous rock, since thermal reservoirs in sedimentary rock are generally rich in methane (Mariner and Willey, 1976).

Chemical geothermometry calculations for springs in the Hot Creek Gorge yield estimated reservoir temperatures of about 225°C. Calculations on a hot spring from Little Hot Creek give a reservoir temperature of 170 to 200°C. These data suggest that the system along Hot Creek may tap a hotter and deeper? reservoir. However, a minimum estimate of the reservoir temperature for the hot springs seems to be about 200-220° (Mariner and Willey, 1976).

Shallow drill holes indicate that recharge for the hot springs is probably occurring around the rim of the caldera, causing cooling of the rock

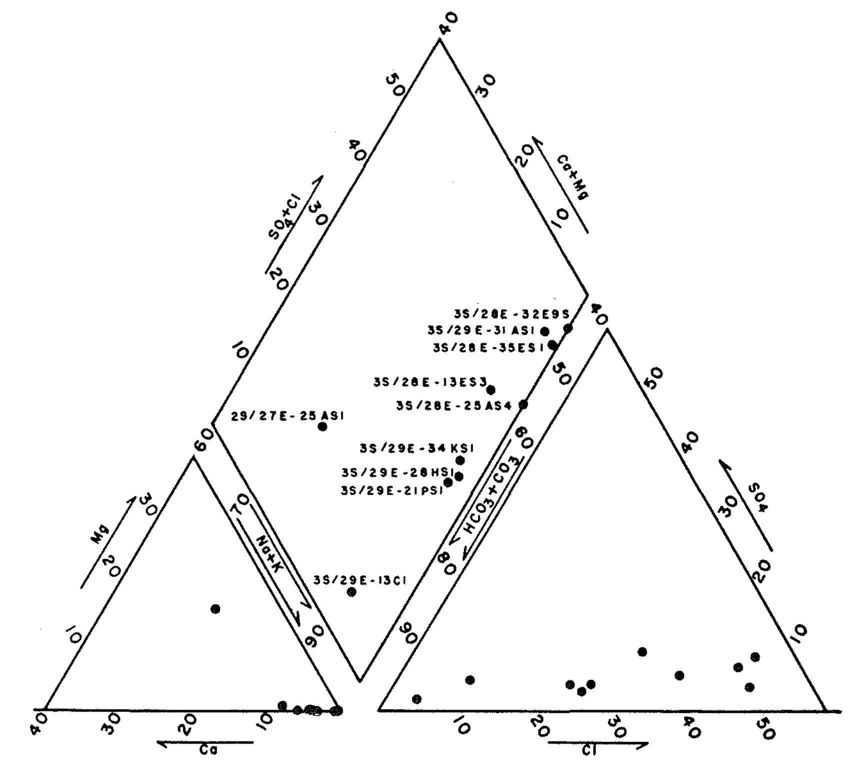

Fig. 5.
Modified trilinear plot of waters collected for detailed analysis, Long Valley, California (from Mariner and Willey 1976).

TABLE I

MAJOR CONSTITUENTS OF SELECTED THERMAL AND METEORIC WATERS FROM LONG VALLEY, CALIFORNIA

	U.S. Public Health Water Standard Limits (Drinking Water)	3S/28E-13ES3	3S/28E-32E9	3S/28E-35ES1	3S/28E-21PS1	3S/29E-28HS1	3S/29E-31AS1	3S/29E-34KS1	3S/28E-25AS4	2S/28E-25AS1	3S/29E-13C1
Sodium (Na)		410	390	380	310	400	310	320	400	23	38
Potassium (K)		30	45	25	37	43	22	28	24	4.0	1.3
Calcium (Ca)		50	0.9	3.3	25	22	15	23	1.6	5.1	5.3
Magnesium (Mg)	125	0.6	0.1	0.1	0.6	0.6	0.4	1.2	0.1	5.9	0.2
Carbonate (CO_3)*		0.3	16.6	0.7	0.3	0.3	1.9	0.3	24.0	0	2.8
Bicarbonate (HCO_3)*		735	416	466	828	845	516	695	549	90	111
Sulfate (SO_4)	250	96	130	120	68	69	81	59	100	8.1	3.7
Chloride (Cl)	250	200	280	250	150	170	170	150	225	5.7	3.0
Lithium (Li)		2.8	2.8	2.5	1.5	1.7	2.0	1.6	2.3	0.04	0.14
Boron (B)		10.6	15	13	7.7	8.8	7.9	8.1	10.5	0.37	0.18
Fluoride (F)	1.7	8.4	12	11	4.6	4.8	7.5	4.6	9.6	0.5	0.6
Silica (SiO_2)		110	340	300	250	240	150	205	150	58	64
Arsenic (As)	0.01	0.74	2.2	0.34	0.46	0.34	0.84	0.36	...	0.02	0.02
Ammonia (as N)		0.40	0.40	0.15	0.20	0.10	0.09	0.15	...	0.13	0.35
Rubidium (Rb)		0.26	0.48	0.28	0.11	0.14	0.19	0.08	...	0.01	<0.01
Sulfide, total (H_2S)		2.3	10	1.4	0.8	0.7	0.8	0.9	...	<0.1	3.8
*p*H		6.5	9.2	7.2	7.9	6.5	6.6	7.5	6.6	6.8	8.8
Temperature, °C		79	94	60	56	49	58	41	90	11	10
Specific conductance, μmho at 25°C		1950	1920	1800	1770	1790	1900	1500	1630	182	191

Analysts were L. M. Willey, J. B. Rapp, and T. S. Presser.
Concentrations are in milligrams per liter.
*Total alkalinity distributed as carbonate (CO_3) and bicarbonate (HCO_3).

to at least 200 m around the caldera edge. Limited water table elevation data and ^{18}O and D isotope chemistry indicate that the hot water feeding the springs comes from the west and mixes with cooler water coming from the east (see Fig. 3). This suggests that the heat source to warm the meteoric water is located in the western part of the caldera (Lachenbruch et al. 1976).

Two deep wells drilled by Union Oil also appear to show that the hot water is moving from west to east. Clay Pit #1 is located on the eastern edge of the resurgent dome; Mammoth #1 is at Casa Diablo to the west (Fig. 3). Thermal gradient plots for these wells are provided in Figs. 6 and 7, respectively (courtesy of W. Isherwood, USGS, Menlo Park). The well farthest to the west attains the highest temperature. The skewed shape of the gradient plots through the Bishop Tuff in both wells suggests hot water is flowing through the upper, less densely welded section of the tuff. These observations suggest hot water is cooling in the Bishop Tuff as it flows from west to east.

Fossil gas vents, sinter deposits, and acid alteration areas show the extent and intensity of hydrothermal activity has decreased in Long Valley Caldera since about 0.3 Myr b.p. This decrease in activity may have resulted from a decrease in the permeability of the sediments due to silicification, argillization, and zeolitization. Sealing of this nature has been found to depths of 300 m in cores from drill holes.

IV. GEOPHYSICS

Seismic refraction data indicate differential subsidence occurred along the Hilton Creek fault zone during caldera collapse, with the eastern section tilting west and the northern section tilting north. Displacement in the basement appears to be about 2.5 to 3 km along the north-northwest caldera bounding faults and about 1 to 2 km along the south and southeast bounding faults. About 1.5 to 2.5 km of caldera fill, including 1 to 2 km of Bishop Tuff lies within the caldera. The refraction data indicate about 2 km of basement relief within the caldera, with the basement dipping east to west and south to north (Figs. 8-10). These data also suggest a zone of low P-wave velocity at 7 to 16 km below the western caldera, possibly a magma reservoir (Hill 1976). A teleseismic survey of the Long Valley caldera identified a zone of P-wave delay below 7 km and probably shallower than 25 km under the western part of the caldera. This zone may represent an area of partial melt

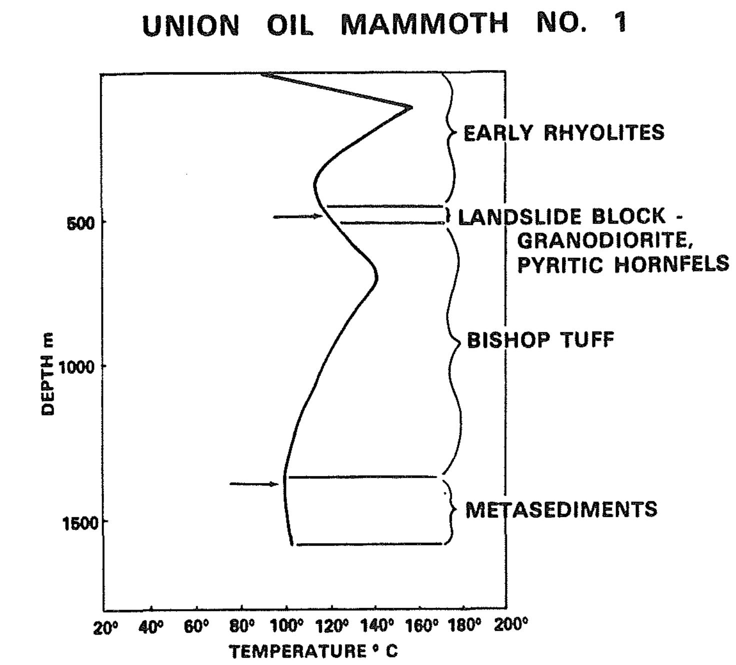

Fig. 6.
Temperature vs depth plot for Union Oil well Mammoth #1 (provided by W. Isherwood, USGS, Menlo Park, CA).

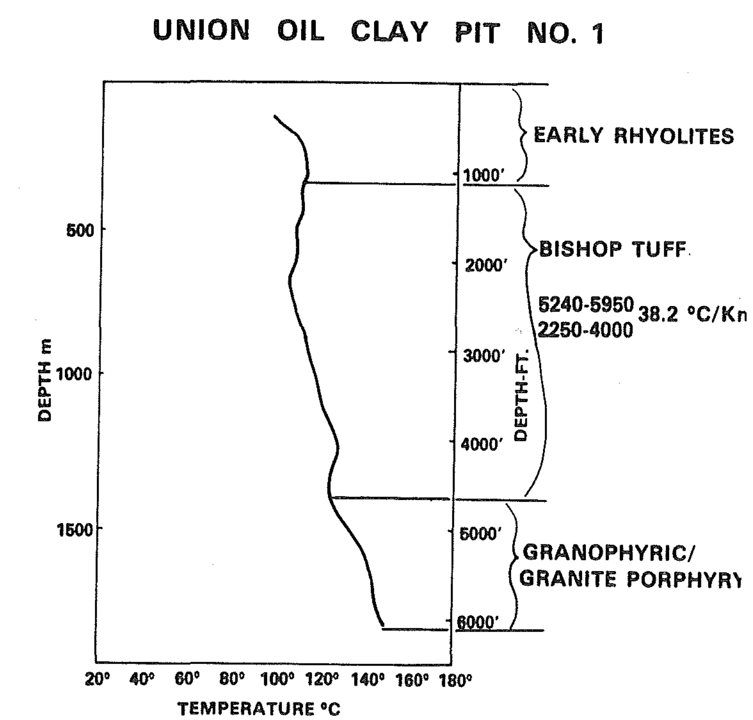

Fig. 7.
Temperature vs depth plot for Union Oil well Clay Pit #1, (provided by W. Isherwood, USGS, Menlo Park, CA).

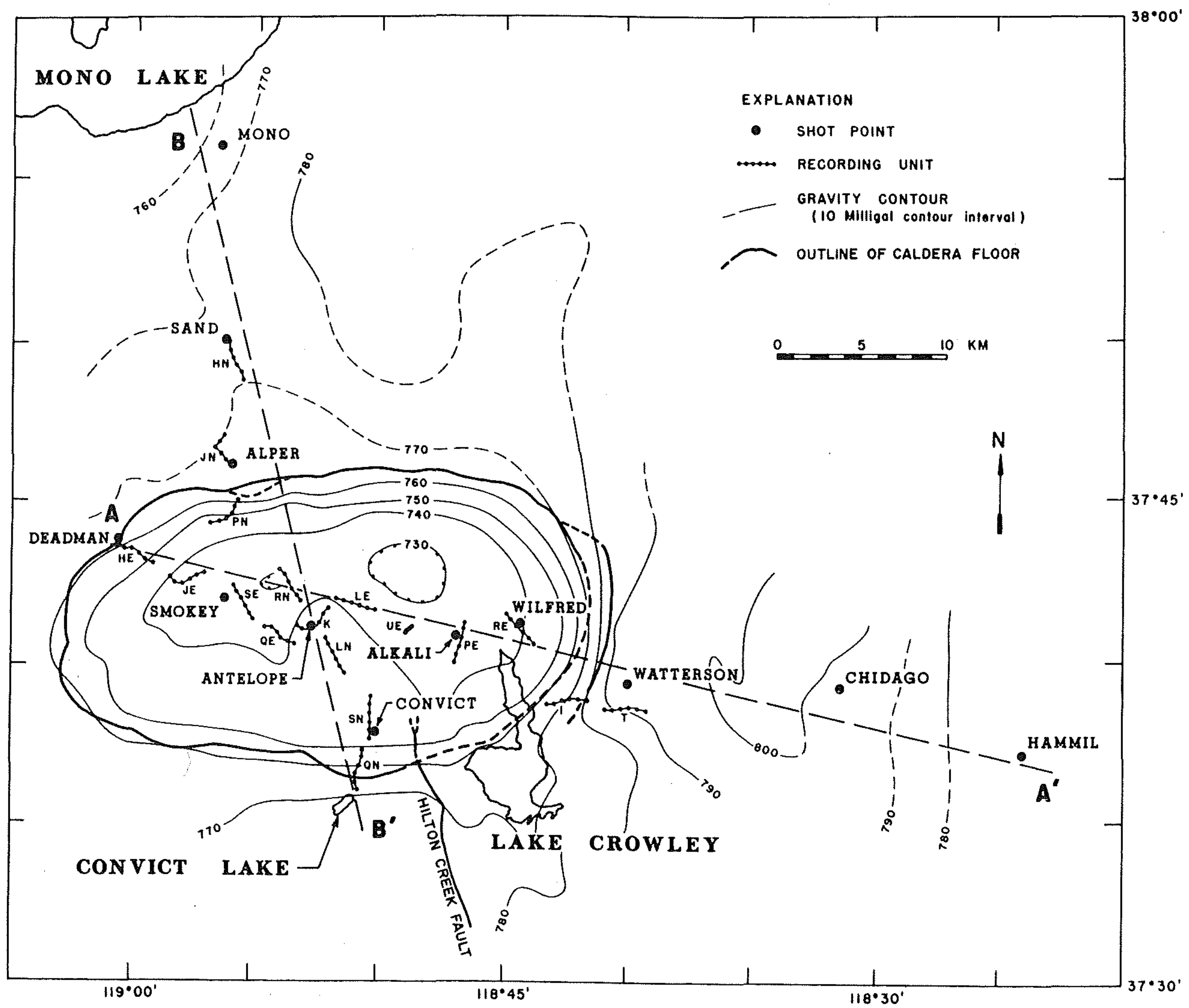

Fig. 8.
Map showing locations of shot points and recording units with respect to the outline of the caldera floor and 10-mgal gravity contours (from Hill, 1976).

less than 4 km thick or could be an area of hot rock (Steeples and Iyer 1976).

Microseismic activity was also monitored in the Long Valley area. The microseismic events are concentrated in a band from Bishop to near Mammoth with focal depths ranging from 1 to 15 km (±2 km). The only microearthquakes recorded within the caldera were at the extreme southeast corner of the caldera at about 10 km depth. These events may have been on the Hilton Creek fault and were probably associated with regional deformation (Steeples and

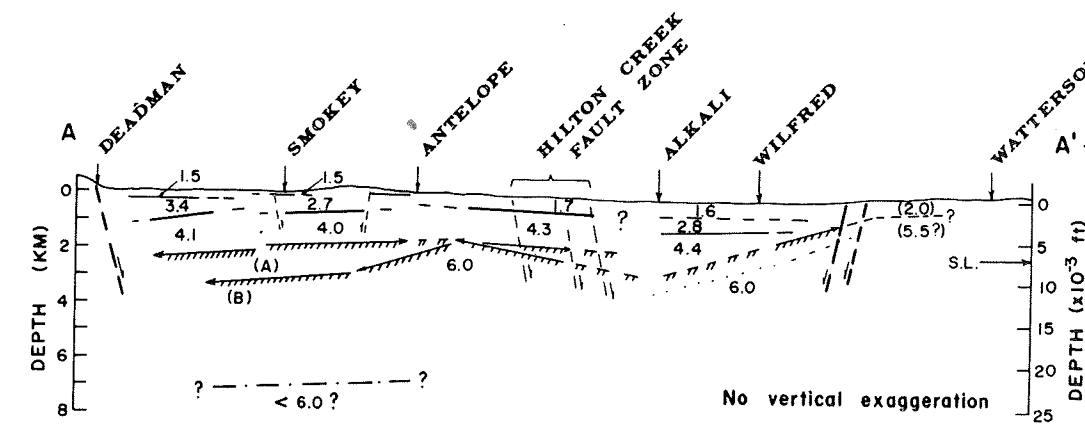

Fig. 9.
Cross section showing P wave velocity structure under profile AA'. Numbers are P wave velocities in kilometers per second. Depths are with respect to average surface elevation (2.1 km); S.L. indicates sea level. Heavy lines indicate horizons with reversed subsurface coverage. Light lines indicate horizons with one-way subsurface coverage; arrows indicate propagation direction of subsurface waves along the horizon. Dashed lines indicate horizons based on later arrivals or extrapolated horizons. Basement horizon is indicated by hachures. Faults are indicated by steeply dipping dashed lines with arrows showing sense of displacement (from Hill 1976).

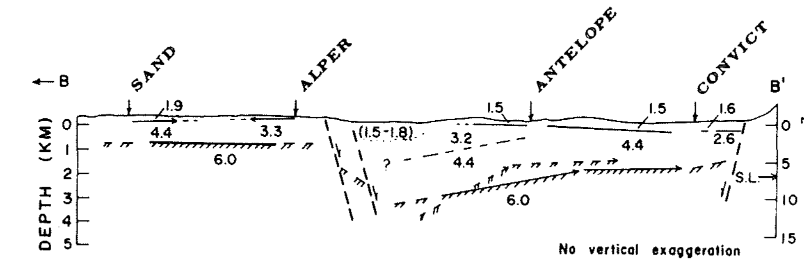

Fig. 10.
Cross section showing P wave velocity structure under profile BB'. Symbols are the same as in Fig. 9 (from Hill 1976).

Pitt, 1976). The low number of microearthquakes detected within the caldera may be due to a number of factors: (1) the microearthquakes originating within the caldera were too small to be detected by the net used, which had a minimum range of about magnitude 0 to -0.5; (2) the upper crust under the caldera is not strong enough to support the stresses necessary to create these earthquakes, as would be the case if magma or partially molten rock was present; and (3) high temperatures below the caldera could allow stable slipping rather than brittle fracturing of the crust.

A gravity survey shows Long Valley Caldera is coincident with a gravity low (Fig. 11) of more than 40 mgal. Most of this low probably corresponds to the density contrast between the caldera fill and the surrounding crystalline rock. The gravity data indicate that the caldera fill, including Bishop Tuff, is about 1500 m deep in the western part of the caldera and about 3000 m deep in three lows, one in the east and two in the north (Fig. 12)(Kane et al. 1976). However, the gravity low associated with the caldera extends too far beyond the caldera to be totally explained by the low density caldera fill. Although the data are inconclusive, it appears that a magma source between 8 and 16 km depth below the caldera can explain the regional variations that are not attributable to the caldera fill (Kane et al. 1976).

A magnetic high in the northeast part of the caldera, determined from aeromagnetic data, is interpreted as volcanic necks associated with flows. A magnetic low over the Casa Diablo Hot Springs is attributed to hydrothermal alteration of ferromagnesian minerals at the springs and to metasediments underlying the western part of the caldera at about 1 km (Kane et al. 1976).

The alteration zones and relatively saline waters associated with hot spring areas were also detected by an audiomagnetotelluric survey. The maximum depth of investigation by this method in Long Valley Caldera was about 1800 m and no structures other than alteration zones were detected.

To extend the electrical investigation of the caldera to about 2 km depth, a bipole-dipole electrical survey was performed. The lowest resistivities in the caldera are located near the Hot Creek Gorge springs, probably associated with the hot water of the springs (Fig. 13). Another resistivity low is centered just south of the Casa Diablo Hot Springs, almost exactly coincident with the Casa Diablo aeromagnetic low. The shape of this low suggests a ring fracture around the resurgent dome which may be associated with hot water or alteration products along this fracture (Stanley et al. 1976).

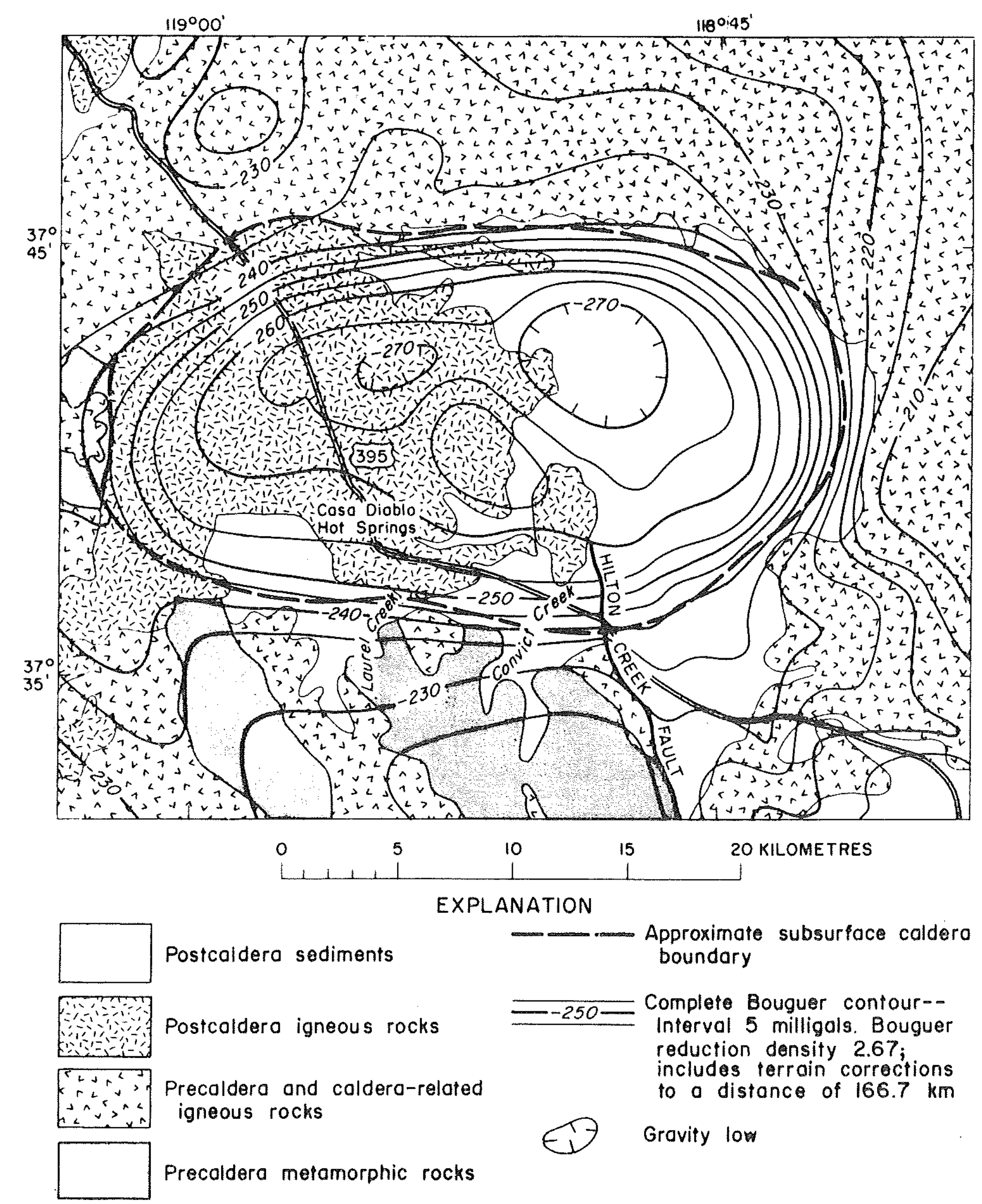

Fig. 11.
Combined generalized geology and complete Bouguer gravity map of Long Valley Caldera and vicinity (from Kane et al. 1976).

V. THERMAL GRADIENT AND HEAT FLOW

Figure 14 shows the location of heat flow holes drilled in crystalline rock in the Long Valley area. These data (Table II) reveal a high at Devil's Postpile of 3.75 HFU (site DP) which is 2.75 HFU above the expected value for the Sierra Nevada province (see Fig. 15). A possible high at Waterson Canyon

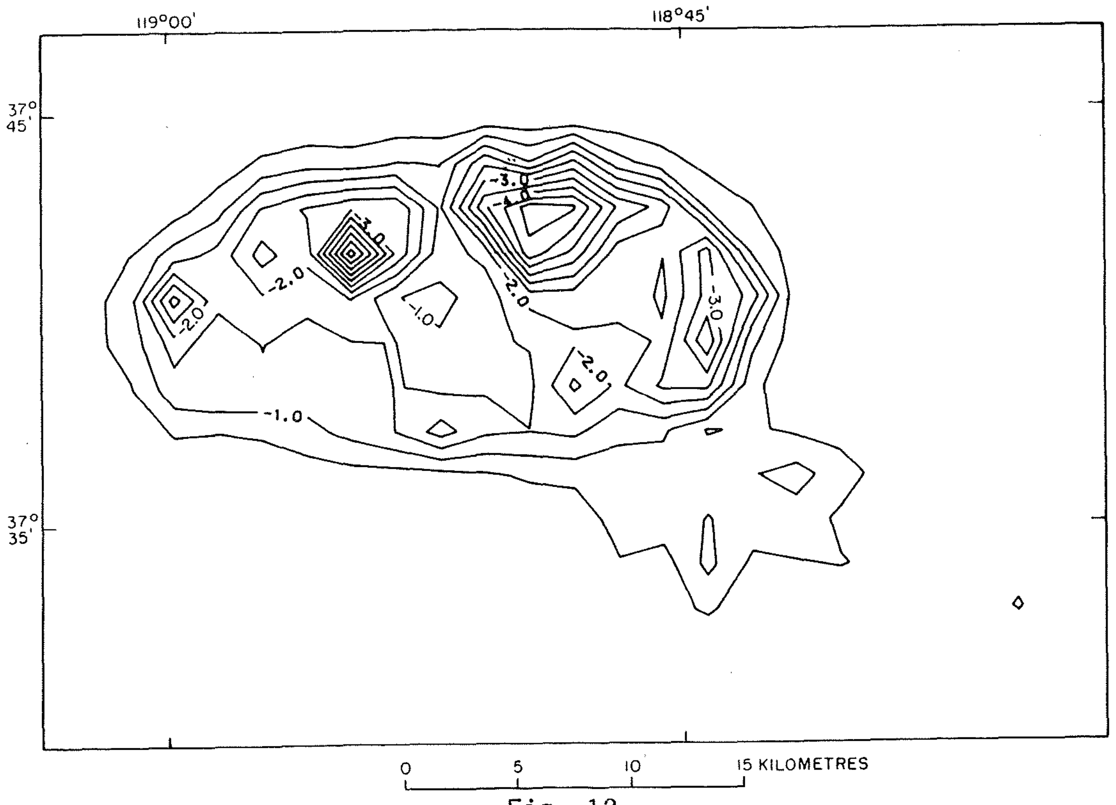

Fig. 12.
Model of caldera fill showing depth to bottom of structure, Long Valley area. Interval is 0.5 km (from Kane et al. 1976).

(WC) of 0.4 HFU above the expected value for the Basin and Range was also detected. The high at WC might be a local conductive anomaly or may be accounted for by thermal refraction or other unknowns.

Within the caldera, convective heat transfer along faults occurs near the hot springs. Thermal gradient holes drilled by Magma Power at Casa Diablo Hot Springs encountered a maximum temperature of 177°C at 120 m. Below 120 m to the maximum depth of 324 m the temperature decreased, suggesting a fault controlled influx of water at 120 m. A well drilled to 305 m about 1.6 km northeast of Hot Creek Gorge did not encounter hot water but had a gradient of 200°C/km. Other drill holes located near hot springs in the caldera have gradients of up to 187°C/km, which clearly indicate convective heat transport by fluids.

In contrast, conductive heat transfer is greatest in the western part of the caldera, as shown by the Devil's Postpile heat flow site. A simple conductive heat transfer model (Lachenbruch 1966) shows that it is unlikely that a magma reservoir chamber could have survived under western Long Valley

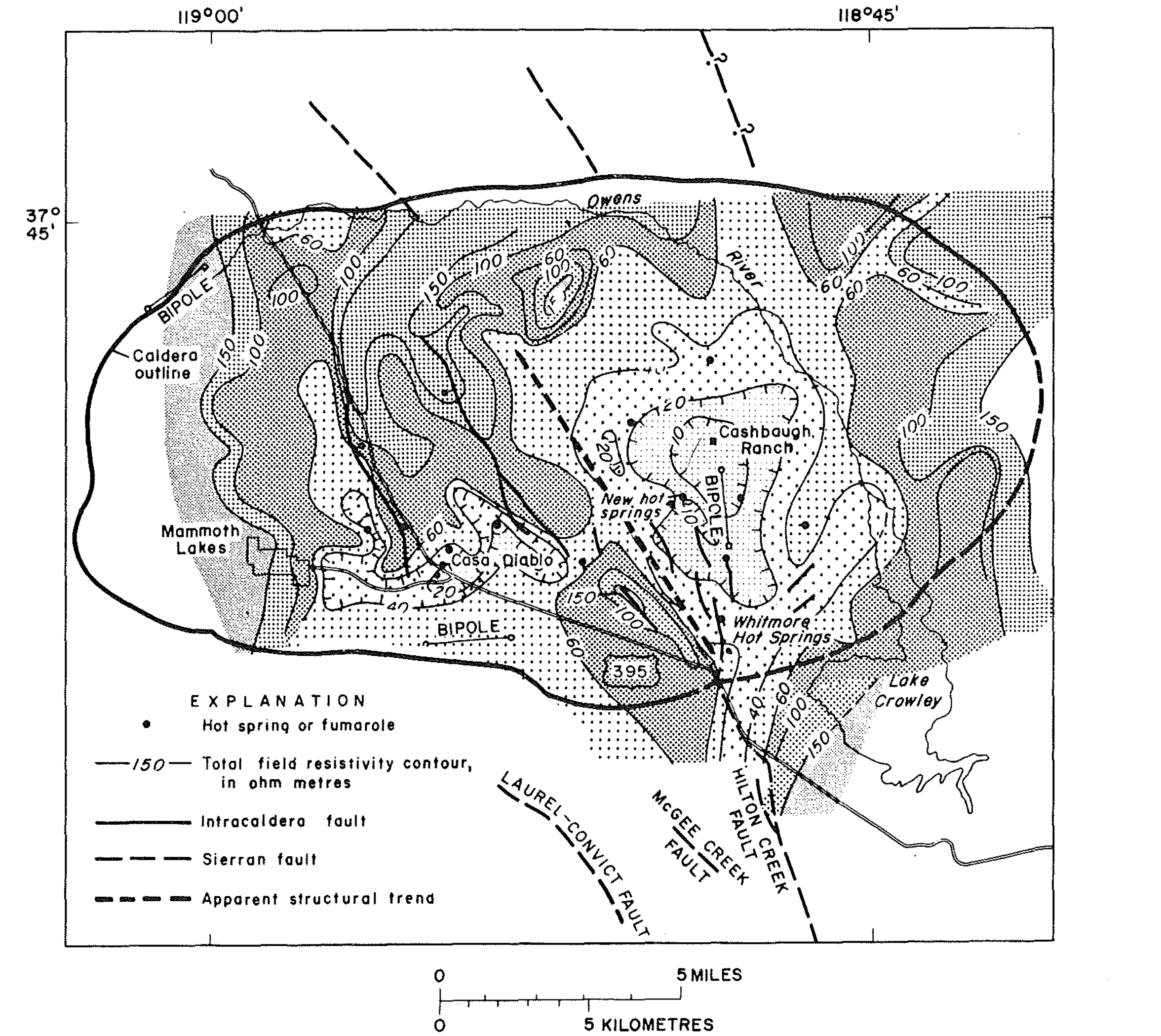

Fig. 13.
Composite total field resistivity map for Long Valley Caldera (from Stanley et al. 1976).

Caldera for the 2 Myr of activity without heat being replenished. The model also indicates that the thermal anomaly in the eastern part of the caldera is less than would be expected if magma was present beneath that part of the caldera. Thus a magma source, if present, is confined below the western part of the caldera.

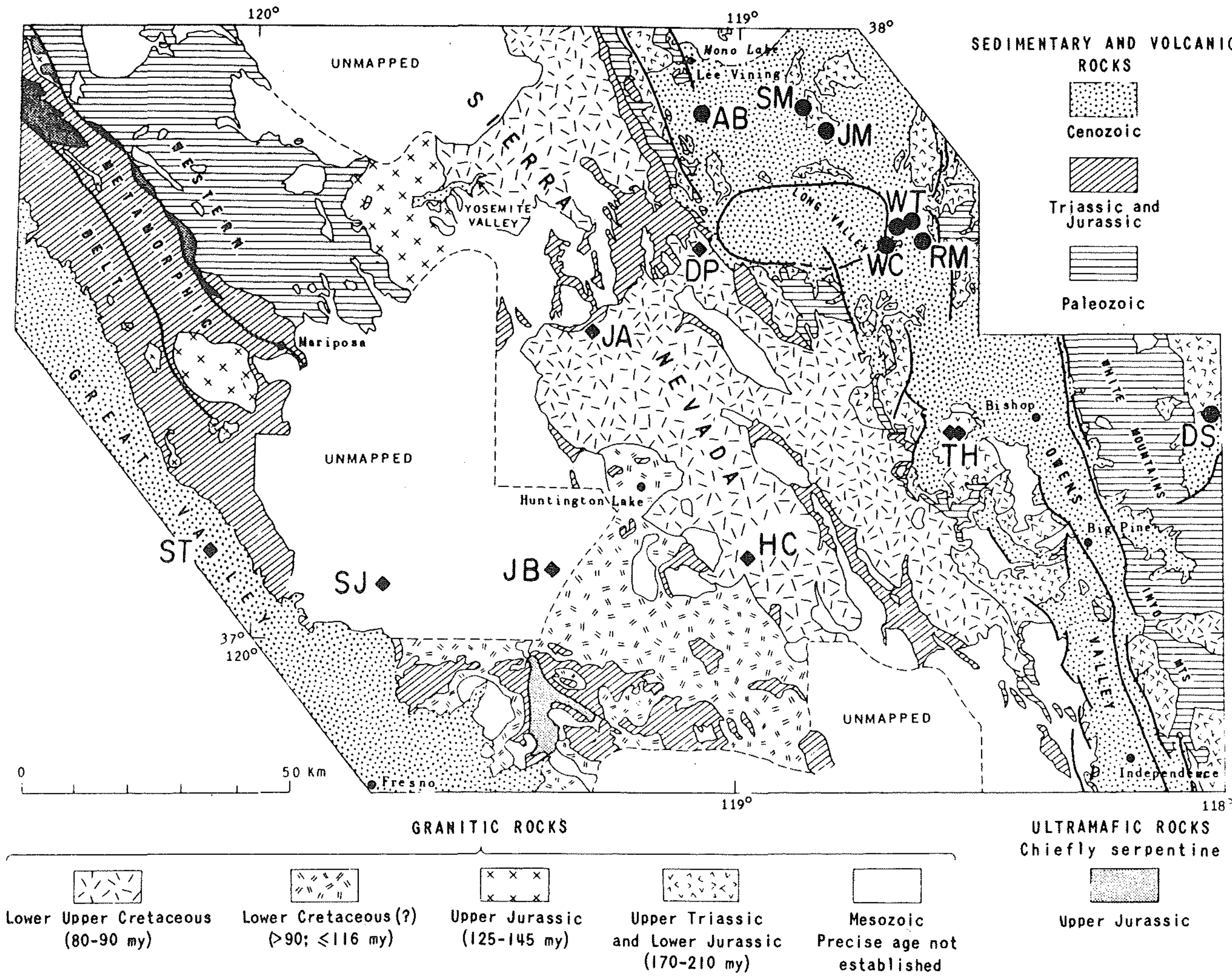

Fig. 14.
Geologic sketch map showing outline of the Long Valley Caldera and locations of heat flow stations. Square symbols are identified with the Sierra Nevada physiographic province; circles, with the Basin and Range province (from Lachenbruch et al. 1976).

VI. SUMMARY AND RECOMMENDATIONS

Volcanism has been active in the Long Valley area for the past 3 Myr with the most recent activity occurring only 450 to 650 yr b.p. Since collapse and resurgence of the caldera, activity has been concentrated mostly in the western part of the caldera. The young ages of the volcanics suggest a magma source may still be present below the western caldera.

Both seismic refraction and teleseismic data indicate a zone of low P-wave velocity beneath the western part of the caldera between 7 and 25 km

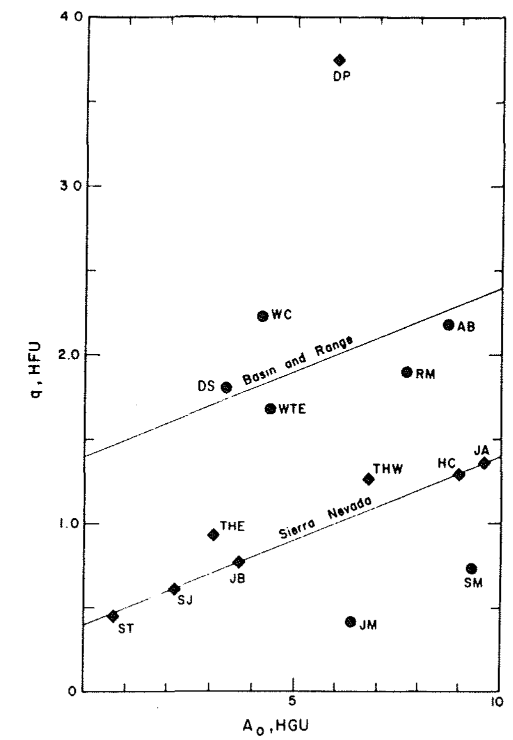

Fig. 15.
Heat flow versus heat production for granitic rocks in the region surrounding Long Valley. Square symbols are identified with the Sierra Nevada physiographic province; circles, with the Basin and Range province. The straight lines represent previously determined relationships for the two provinces (from Lachenbruch, Sass et al. 1976).

TABLE II

THERMAL GRADIENT AND HEAT FLOW VALUES FOR SITES NEAR LONG VALLEY CALDERA IN FIG. 14

Site	°C/Km	HFU
JA	17.7	1.36
DP	56.8	3.75
THE	15.1	0.93
THW	15.1	1.27
AB	31.2	2.18
WC	30.0	2.23
WTW	78.1	2.1
WTE	23.0	1.68
RM	24.0	1.90
JM	6.08	0.41
SM	9.20	0.72

indicating very hot rock or magma at depth. The gravity survey shows that, although much of the gravity low associated with the caldera can be explained by the low density of the caldera fill, the regional extent of the low must be accounted for by a much deeper source, perhaps crystallized magma. Models of the gravity data indicate a magma source may be present between 8 and 16 km depth, possibly centered under the western part of the caldera.

The geochemistry data indicate that the hot water feeding the fault-controlled springs derives its heat from the western part of the caldera. Water percolates down ring fractures all around the caldera. In the west the water is heated and flows east, possibly through the Bishop Tuff, and mixes with cooler water. The mixed water surfaces along faults, mostly around the resurgent dome.

Heat flow measurements just east of the caldera are essentially normal for the Basin and Range province in which they lie. However, at Devil's Postpile just west of the caldera the heat flow in granitic rock (3.75 HFU) is almost four times the expected value for the Sierra Nevada province. About 26 km north at site AB and 40 km southwest at site JA the measured heat flow in crystalline rock is normal for the Basin and Range and Sierra Nevada provinces, respectively. Apparently, the western part of the caldera, and the area immediately to the west, experience a much greater heat flux than the eastern caldera and the surrounding region. These geological and geophysical data strongly indicate that a significant source of heat, possibly a shallow magma body, lies beneath the western part of Long Valley Caldera.

This region of high heat flow in the Long Valley Caldera vicinity contains two prospective sites for Hot Dry Rock development. One is the area just west of the caldera; the other is the area of the resurgent dome in the west-central caldera.

Geologic and seismic refraction data show that the basement in the caldera is shallowest below the resurgent dome (Bailey et al. 1976; Hill 1976). Fumarole activity is abundant along faults associated with the keystone graben cutting the dome, which suggests a heat source below the dome. However, the nature of this heat source is not clear. The young ages of the Inyo craters and domes, heat flow considerations and teleseismic evidence indicate that magma, if present, lies below the western caldera, possibly extending just west beneath the resurgent dome area.

The precursor magma reservoir which created the caldera and caused resurgence lies closest to the surface below the resurgent dome. However, the thermal gradient in Clay Pit #1, on the east edge of the dome, is 38°C/km from .66 to 1.2 km depth, including about 200 m of basement. This is a very low gradient if magma from this earlier source is still present below the dome. Also, the youngest volcanics are located west of the dome and do not appear related to the dome structure. These data suggest no shallow magma is present below the central and eastern parts of the caldera.

Current HDR technology requires temperatures of 200°C at depths ≤ 5 km in crystalline rock for generation of electricity. Assuming the thermal gradient

in Union Oil well Clay Pit #1 persists to depth, the basement below the resurgent dome is 200°C at about 3.2 km. Thus, whether the heat source below the dome is magmatic or hot rock, the crystalline basement below the dome is sufficiently hot to provide a HDR reservoir at moderate depth. However, further drilling for exploration and development of HDR resources on the resurgent dome may be hindered by the 1.5 to 2 km of caldera fill and the large number of faults due to subsidence. Economic modeling of HDR electrical production indicates that due to future drilling costs, a geothermal gradient of 38°C/km provides a near breakeven present value for the system (Cummings and Morris, 1979). This low gradient measured in the eastern resurgent dome, combined with the problems of attaining reliable heat flow data, makes the eastern resurgent dome unattractive as a HDR prospect at this time. Future drilling to basement farther west may show the gradient below the western resurgent dome is sufficient to consider the area for HDR development. At this time the available data does not warrant further work to determine the HDR potential of the resurgent dome area.

The potential for HDR appears significant for the area immediately west of Long Valley Caldera. The highest thermal gradient and heat flow in the area were measured at Devil's Postpile west of the caldera near Mammoth Mountain, the largest and one of the youngest rhyolitic domes. Fumarole activity is associated with Mammoth Mountain. West of the caldera, crystalline rock is very near the surface and crops out in places a few kilometers west and southwest of the caldera. Assuming the thermal gradient measured at Devil's Postpile holds to depth, temperatures of over 200°C would be available in structurally intact crystalline rock at only 3.3 km depth just west of the caldera, which makes this area very promising for HDR prospecting.

A program to define the best HDR target west of the caldera must consist of additional heat flow and structural studies. Three heat flow wells should be drilled. The first two wells should be 400 to 500 m deep, one located about 8 km north of Devil's Postpile near Deadman Creek and another about 8 km southeast of Devil's Postpile near Lake Mary, both to be drilled in crystalline rock. These wells would geographically bracket the DP heat flow site and should more clearly delineate the heat flow high defined by the DP site. They should be partially cored for conductivity measurements and for petrographic work. A third well should then be drilled to 1000 m in the more clearly delineated high, with cores taken for conductivity measurements, petrographic work, and fracture studies. The depth of the third well should provide a sufficiently reliable heat flow determination to either continue with HDR development or exclude the area as a HDR prospect.

Siting of the deep well would benefit from a detailed structural analysis of the area. To insure no induced seismicity, a site for development must be located away from active faults which can be delineated by detailed airphoto work and structural survey. Structural analysis will also help define the principal directions of stress in the area. Detailed seismic reflection and refraction surveys in the area may therefore be required to define subsurface structure outside the caldera.

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