GL03166 - 8 of 8

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The Long Valley/Mono Basin Volcanic Complex in Eastern California: Status of Present Knowledge and Future Research Needs

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The Long Valley/Mono Basin volcanic complex in eastern California is one of the few major silicic systems in western North America that have exhibited volcanic activity so recently that they may still be potentially active. Such complexes are typically associated with highly developed convective hydrothermal systems and hot spring activity at the surface. Because of the ongoing interest among the scientific community in understanding the intercoupling of shallow hydrothermal reservoirs with magmatic heat sources at depth in the crust, these volcanic complexes have been studied for many years by workers interested in a variety of geological problems. Among these are metallogenesis, the mitigation of volcanic and earthquake hazards, and the development of conventional and nonconventional forms of geothermal energy. The status of some of this work, as it relates to the Long Valley/Mono Basin volcanic complex, is reviewed by way of a progress report. Although a great deal of exciting research is presently underway, much still needs to be done to adequately characterize the tectono-magmatic elements of this volcanic system. One research technique that has not been exploited is scientific drilling to intermediate depths (2–3 km). A carefully structured research program in which scientific drilling is closely integrated with surface geological and geophysical field studies would help clarify many of the present issues surrounding this volcanic complex. For example, while many workers feel that hydrothermal magma systems are prime subjects for the study of metallogenesis, there is little evidence in existing borehole data for such processes at shallow depths beneath Long Valley. This may be because volcanism is too recent (Inyo craters and domes have C^{14} ages younger than 1000 yr). Mineralization is usually associated with older, mature (solidified?) magmatic systems. We may have, in Long Valley, an opportunity for defining the initial conditions associated with the evolution of these deposits. Long Valley caldera is the only member of this class of volcanic systems for which a quantitative caldera-scale hydrothermal model has been proposed. In addition, this region offers a unique opportunity in volcanic and earthquake hazards research. Recent tectonic deformation, seismicity patterns, and the reactivation of fumarolic activity caused the USGS to issue, on May 25, 1982, a notice that a potential volcanic hazard exists for the southwestern segment of Long Valley caldera. If, as has been proposed, magma has intruded the upper crust of this area, surface geophysics and limited borehole observations may be employed to monitor tectonic and magmatic activity associated with such a phenomenon. Finally, a surprising result of commercial drilling for geothermal energy in this area is the failure to detect directly high-temperature hydrothermal reservoirs. Their presence can be inferred from other studies—particularly those using geochemical indicators in thermal fluids. In addition, present evidence supports the possibility of molten magma at depths as shallow as 6–8 km. Thus future surface geophysical and geological studies, in conjunction with intermediate depth drilling, might help understand the nature of the presently undetected (though inferred) high-temperature hydrothermal reservoir and perhaps provide some clues as to how it is coupled to the possible magma body at depth.

INTRODUCTION

The Long Valley/Mono Basin volcanic complex is one of three major silicic volcanic systems in western North America that have exhibited volcanic activity so recently that they may still be potentially active—the other two systems are Yellowstone and the Valles caldera [*Smith and Shaw*, 1975, 1978]. Each is associated with highly developed convective hydrothermal systems and hot spring activity at the surface [*White and Williams*, 1975]. Because of the ongoing interest among the scientific community in understanding the intercoupling of shallow hydrothermal systems with magmatic heat sources at depth in the crust, these three volcanic complexes have been studied for many years by workers interested in a variety of geological problems. Among the variety of topics that can be addressed through the study of these major volcanic complexes, the following are particularly germane to the Long Valley/Mono Basin area:

1. *Mechanisms of mineral migration in the crust associated with concentrations of economic ore deposits.* Hydrothermal magma systems are prime subjects for the study of metallogenesis. Although there is little evidence in existing borehole data for such processes at shallow depths beneath Long Valley, it may be because volcanism is too recent (Inyo craters and domes have C^{14} ages younger than 1000 yr). Mineralization is usually associated with older, mature (solidified?) magmatic systems. We may have, in Long Valley, an opportunity for defining the initial conditions associated with the evolution of these deposits. Compared with Yellowstone and the Valles caldera, the Long Valley complex is the only member of this class of volcanic systems for which a caldera-scale hydrothermal model has been proposed [see, for example, *Sorey et al.*, 1978]. Hence we have a reasonable starting point for unravelling the complicated interactions associated with magma-hydrothermal systems.
2. *Volcanic and earthquake hazards mitigation.* Recent tectonic deformation [*Savage and Clark*, 1982], seismicity [*Ryall and Ryall*, 1983], and the reactivation of hot spring activity caused the USGS to issue, on May 25, 1982, a Notice of Potential Hazard (3 pp., Public Affairs Office,

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USGS, Reston, Va.) for the southwestern segment of Long Valley caldera [*Miller et al.*, 1982].

3. *Conventional and nonconventional utilization of geothermal energy*. Although up to the present time commercial drilling has not directly detected high-temperature hydrothermal reservoirs, the presence of such reservoirs can be inferred from other studies. Since existing evidence supports the possibility of molten magma at depths as shallow as 6–8 km, it is tempting to consider that nonconventional energy extraction techniques might be applied, e.g., the hot-dry rock concept [*Gambill*, 1981; *Heiken et al.*, 1982] and/or energy extraction from magma itself [*Smith*, 1979; *Traeger et al.*, 1979; *Colp*, 1982].

The following discussion reviews the status of research on the Long Valley/Mono Basin volcanic complex with the above issues in mind but without further reference to them explicitly. It is our intention to describe those geological and geophysical constraints that, to our mind at least, seem to be reasonably well established for this system, and also to identify interpretations that are somewhat ambiguous or, in fact, contradictory. I hope the reader will appreciate the excellent research performed by a number of workers to date but will leave our discussion feeling that much yet needs to be done before this system is adequately characterized.

THE TECTONO-MAGMATIC CHARACTER OF THE LONG VALLEY/MONO BASIN VOLCANIC COMPLEX

Long Valley Caldera

The Long Valley volcanic system is one of several young volcanic centers occurring along the western margin of the Great Basin adjacent to the eastern front of the Sierra Nevada (Figure 1). Other such centers include Mono Craters and Mono Basin to the north and the Coso volcanic complex to the south. All occur along a particularly active marginal segment of the Basin and Range province, where seismic activity, high heat flow, and recent faulting indicate that relatively rapid east-west crustal extension dominates the tectonic regime.

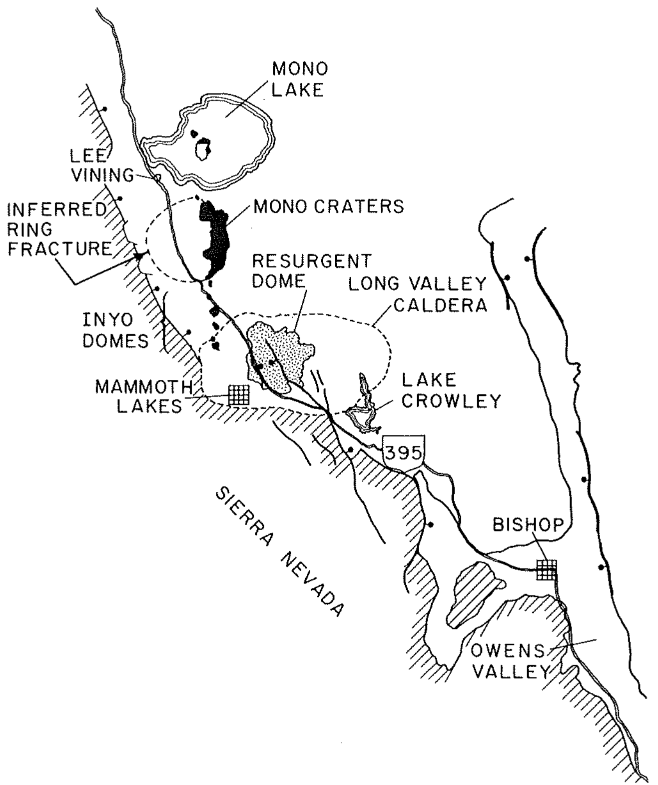


Fig. 1. Generalized map of the Long Valley/Mono Basin volcanic complex, showing its position relative to the Sierra Nevadas to the west and the Basin and Range province to the east [after *Bailey et al.*, 1976]. The darkly shaded portions of the map (Inyo Domes, Mono Craters, and the volcanic craters in Mono Lake) represent recent (Holocene) volcanism.

Although volcanism in the vicinity of Long Valley began about 3×10^6 yr ago with scattered eruption of basalt and andesite, it became localized about 2×10^6 yr ago with the eruption of the Glass Mountain rhyolite and culminated with the tremendous eruption of 600 km^3 of rhyolitic Bishop tuff 0.7×10^6 yr ago. The subsequent collapse of a shallow, zoned magma chamber produced the Long Valley caldera, 17 × 32 km in size [*Bailey et al.*, 1976].

Periodic volcanism followed the major eruption and caldera collapse. This included aphyric (a glasslike texture with few grains) rhyolite 0.68–0.64 m.y. ago during resurgent doming of the caldera floor, porphyritic (a mixture of coarse and fine grains) rhyolite from centers peripheral to the resurgent dome 0.5, 0.3, and 0.1 m.y. ago, and porphyritic hornblende-biotite rhyodacite from outer ring fractures 0.2–0.05 m.y. ago. This sequence apparently records progressive crystallization of the underlying magma chamber (Figure 2, after *Bailey et al.* [1976]).

Bailey [1980] has suggested that the volcanism responsible for forming Long Valley caldera itself has probably completed its cycle of activity, having evolved through the five stages of (1) early basalt to quartz latite effusion, (2) precaldera rhyolite ring-fracture extrusion, (3) voluminous ashflow eruption and caldera collapse, (4) post-caldera structural and magmatic resurgence, and (5) final extrusion of intracaldera rhyolite and quartz latite [*Bailey*, 1980]. In this regard, Long Valley should presently be in a stage of development similar to the Valles caldera [*Smith and Bailey*, 1968; *Smith*, 1980], although recent volcanism in Inyo Craters, as well as an increasing amount of geophysical evidence, suggests that this system may be reactivated.

Mono Craters and Mono Basin

It is important to recognize that Long Valley caldera is the southernmost and oldest member of a succession of three progressively younger volcanic complexes, each in different stages of evolution [*Bailey*, 1980]. In decreasing age, these are (see Figure 3): Long Valley (3.0–0.05 m.y.), Mono Craters (40,000–1,000 yr), and the centers in Mono Lake (<2000 yr).

According to Bailey, Mono Craters (1300 yr) may have evolved through stages 1 and 2 described for Long Valley above, and the centers in Mono Lake form the smallest and youngest complex and seem to be in stage 1. The Mono Craters are chemically homogeneous, which along with their recent age and frequency of eruption suggests that they were extruded from a single magma chamber, largely molten and perhaps still rising to the surface [*Bailey*, 1980]. The crescent-shaped trend of Mono Craters has been used to infer the outer margin of this inferred magma chamber, and its center may be beneath Pumice Valley (Figure 3).

In contrast to the chemical homogeneity of Mono Craters, the chemical heterogeneity of the underdeveloped volcanic centers in Mono Lake seems to suggest that they may have issued from small, multiple, and relatively deep magma bodies that have not yet coalesced. We therefore have available in these three volcanic complexes a set of field examples, each of which represents a different stage in the temporal evolution of their tectono-magmatic development.

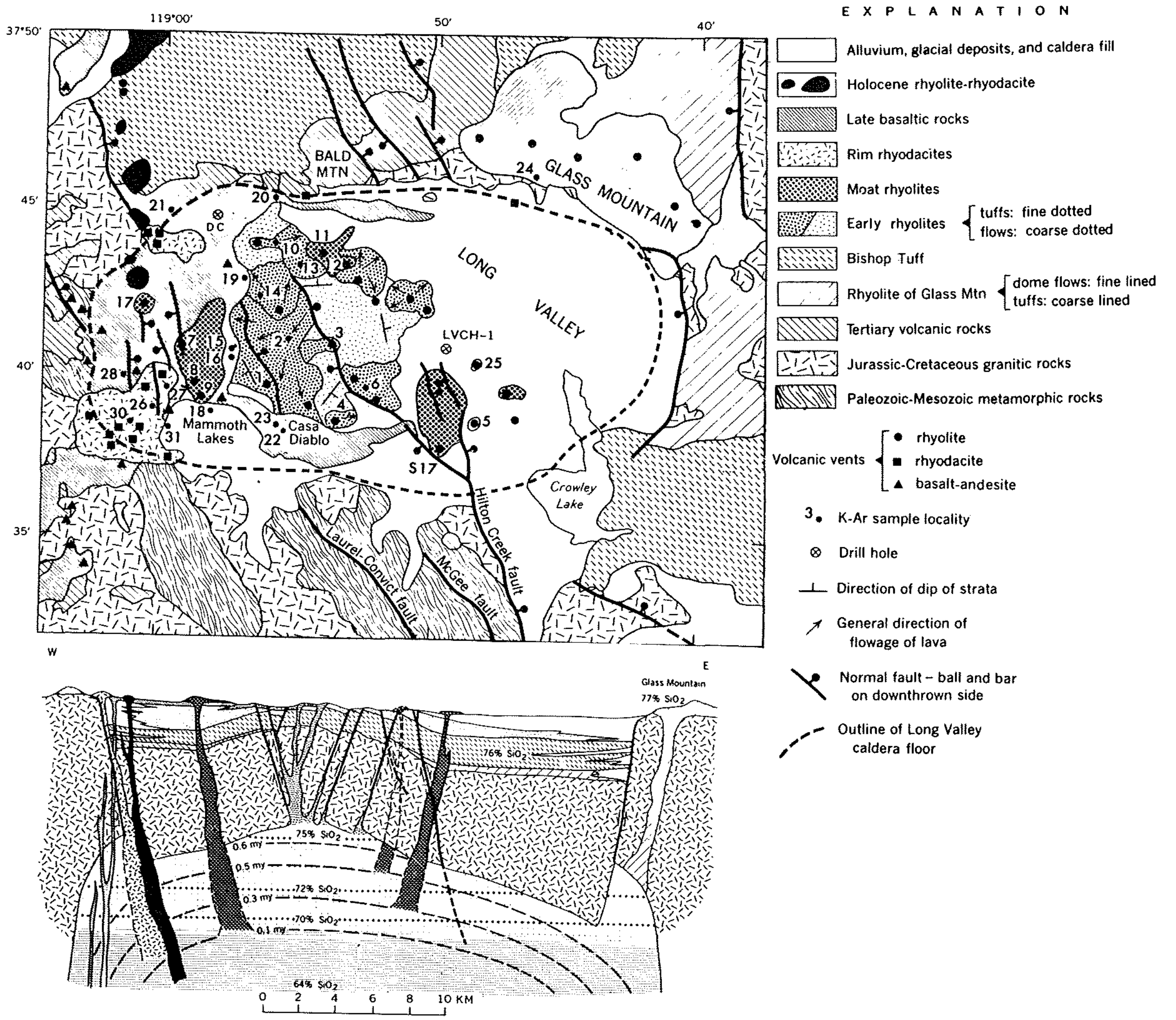


Fig. 2. Generalized geology of Long Valley caldera (top) and the east-west vertical section inferred by *Bailey et al.* [1976]. Note that the volcanic extrusives at the surface represent a progression of composition with time, which seems to relate to a cooling magma body [after *Bailey et al.*, 1976].

Inyo Domes and Craters

The youngest volcanic features in Long Valley caldera are the Inyo craters and domes (see Figure 1) which lie on a linear trend extending north from the northwest sector of the caldera, across the caldera rim, to Mono Craters [*Bailey et al.*, 1976]. The five Inyo domes are roughly rhyolitic in composition, and the three largest are less than 720 ± 90 yr old [*Wood*, 1975]. Not shown in Figure 1 are the Inyo Craters—three phreatic explosion pits on the south flank of Deer Mountain that have been dated at 650 ± 200 yr [*Rinehart and Huber*, 1965]. Early studies indicated that Inyo domes are chemically heterogeneous, which suggests that they may be a product of mixing magmas from the Long Valley chamber and the possible chamber beneath Mono Craters to the north [*Bailey et al.*, 1976]. Recently, however, R. A. Bailey (personal communication, 1982) found evidence that the Inyo volcanos may have derived from a single source associated with the Mono Craters.

In summary, present geological evidence suggests the possibility that a rather extensive magma reservoir (or system of reservoirs) may exist beneath the northwestern section of Long Valley caldera and extend 30–35 km north to Mono Lake. If, in fact, such a structure exists, it offers an inviting target for future geophysical experiments to delineate.

REGIONAL GEOPHYSICAL STUDIES

Regional Seismic Studies

There appears to be a great deal of variability in crustal parameters determined from regional seismic studies. Basement velocities along the Sierran front vary from 5.35 km/s beneath Mono Basin [*Pakiser*, 1976] to 6.4 km/s beneath Long Valley [*Hill*, 1976, p. 747]. Velocities in the basin fill itself are about 2.0 km/s (1.4–2.5 km/s) for Mono Basin [*Pakiser*, 1976] and about 4.0 km/s (1.5–4.4 km/s) for Long Valley caldera [*Hill*, 1976; *Cramer and Toppozada*, 1980]. On the average the regional velocity of *Eaton* [1966], which as shown in Table 1 indicates a depth to Moho of 50 km, appears to be adequate [*Cramer and Toppozada*, 1980], although reinterpretation of this data by *Proedehl* [1979] would indicate somewhat finer structure and would revise

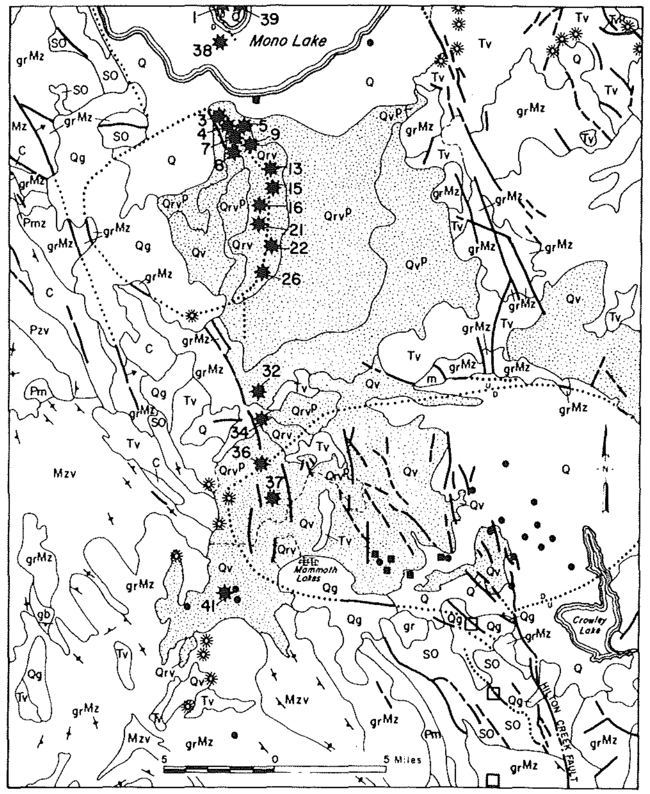


Fig. 3. Generalized geological map of the Long Valley/Mono Basin volcanic complex [after *Kilbourne et al.*, 1980, Figure 1]. Quaternary volcanic rocks are shaded, with eruptive centers younger than 2000 yr being indicated by the eight-pointed black stars.

the depth to Moho to approximately 40 km. At the present time there is little or no evidence to suggest the presence of an intracrustal low-velocity zone as seen elsewhere in the Basin and Range [*Proedehl*, 1979].

Regional electromagnetic studies. Schmucker [1970, p. 48] recognizes that anomalous concentrations of surface or subsurface electric currents must be associated with the eastern front of the Sierra Nevadas in order to explain long-period (15 min–1 hr) geomagnetic variation measurements. The interpretation of geomagnetic data from Bishop (BIS; 40 km south of Long Valley Caldera) as well as from Bridgeport (BRI; 30 km north of Mono Basin) shows anomalous vertical magnetic field fluctuations at periods of 15 min. The Bishop anomaly seems to be strongest at shorter periods (15 min). At increasing periods (30 min and 60 min) the perturbation in Z becomes minimal. At diurnal periods (24 hr) there does not seem to be any anomalous behavior at Bishop whatsoever [*Schmucker*, 1970, p. 52].

A reversal in the vertical field (Z) was detected at a 15-min period between Carson City, Nevada (adjacent to the Sierras at the scale of this study), and Fallon, Nevada (approximately 100 km to the east). Schmucker inferred the presence of an anomalous, highly conducting zone 80 km wide at a depth of approximately 40 km. It is instructive to compare Schmucker's induction analysis, which was done at only a few sites in the region, with contour maps of crustal thickness and Bouguer gravity anomalies [e.g., *Proedehl*, 1979]. One might speculate that a tortuous filament of north-south trending high conductivity in the lithosphere is adjacent to the eastern margin of the 40–50 km deep crustal root beneath the Eastern Sierras.

Additional constraints on the regional electrical structure have been provided by the studies of *Lienert and Bennett* [1977] and *Lienert* [1979], who inferred low resistivities within the crust from a large-scale controlled source experiment. Their data are compatible with a relatively resistive upper crust (d < 10 km), but the resistivity drops to values on the order of 30 ohm-m at depths of 15 km or so. Whether this crustal feature is able to explain the long-period geomagnetic variation anomalies of *Schmucker* [1970], who inferred that the conductor is at much greater depth ($d \geqq 40$ km), is not known, but clearly the answer may help us better understand tectonic features in the lithosphere that are related to crustal extension in the Basin and Range and, in turn, help us relate crustal extension to the development of the volcanic centers along the eastern front of the Sierras [e.g., as discussed by *Lachenbruch and Sass*, 1978; *Lachenbruch*, 1980].

THE LONG VALLEY MAGMA-HYDROTHERMAL SYSTEM

General

The history of hydrothermal activity in the Long Valley caldera is traceable from the present to about 0.3 m.y. ago, when it was widespread in the caldera moat [*Bailey et al.*, 1976]. It has since declined as a result of self-sealing of near-surface caldera sediments. On the basis of gravity (Figure 4, after *Pakiser* [1961]; *Kane et al.* [1976]) and seismic studies [*Hill*, 1976] the thickness of caldera fill varies from 1.5 to 4.0 km and has an average value of 2.4 km. The main hydrothermal reservoir within the caldera is assumed to be the Bishop Tuff [*Sorey et al.*, 1978], although present indications of hydrothermal activity at the surface are localized on recently reactivated northwest-trending Sierra Nevada frontal faults that tap hot water at depth [*Bailey et al.*, 1976]. Evidence is shown in Figure 5 for the presence of local subsurface hydrothermal reservoirs, which have been detected electrically by *Stanley et al.* [1976] and *Hoover et al.* [1976].

The overall pattern of present-day hydrothermal activity is complex. A number of shallow drill holes within the caldera indicate highly variable temperatures with depth (Figure 6), reflecting the high degree to which local geologic structure and hydrology control the surface thermal regime.

Several deeper holes drilled by industry within the caldera have penetrated to a maximum depth of 2.1 km but have not reached temperatures that are exploitable by present commercial standards [*Williams et al.*, 1977; *Sorey et al.*, 1978; *Gambill*, 1981; *Heiken et al.*, 1982]. The location of several examples are shown in Figure 7, and representative temperatures are shown in Figure 8.

TABLE 1. Velocity Models for the Crust along the Eastern Sierran Front

	Depth to Top, km	
Velocity, km/s	Outside Long Valley Caldera	Inside Long Valley Caldera
4.0	0.0	0.0
6.0	1.0	2.5
6.4	13.0	13.0
6.9	27.0	27.0
7.9	50.0	50.0

Data are after *Cramer and Toppozada* [1980].

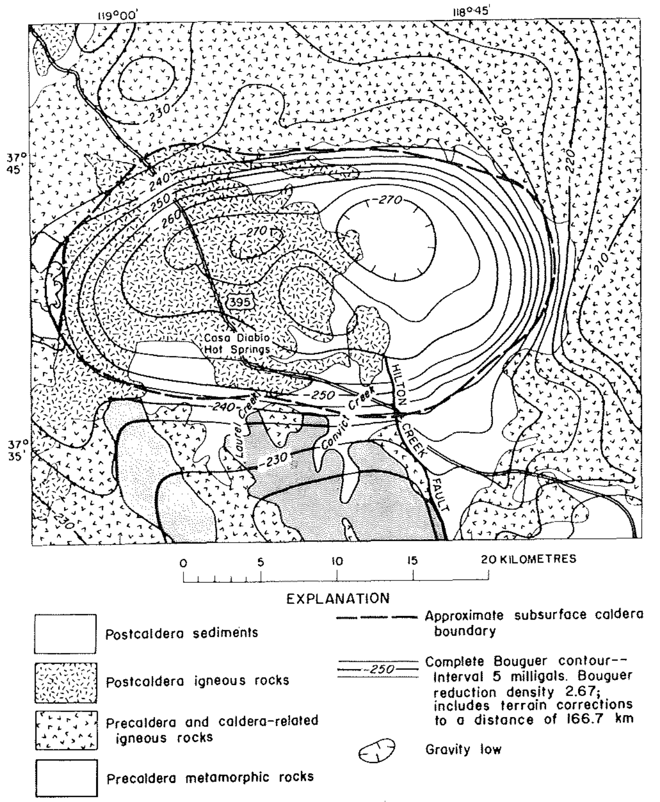


Fig. 4. Combined generalized geology and complete Bouguer gravity map of Long Valley caldera and vicinity [after *Kane et al.*, 1976, Figure 1].

Because of the low bottom-hole temperatures encountered up to the present time, industry has not been particularly active in attempting to develop the Long Valley hydrothermal system. Frankly, this is surprising, considering that geothermometry of thermal waters indicate that they derive from reservoirs with temperatures of 210–280°C [*Sorey and Lewis*, 1976; *Fournier et al.*, 1976]. The source of this high-temperature water is as yet undetected.

Moreover, there are other factors indicating that the low temperatures presently measured in shallow drill holes do not reflect conditions at depth. Figure 9 shows a zone of low seismic velocity at depths of 6–8 km and greater that was detected by using teleseismic delays [*Steeples and Iyer*, 1976]—this low-velocity body has been used to infer the presence of active magma. Also shown in this figure are seismic reflections recorded during seismic refraction experiments that also seem to suggest a relatively sharp interface in the depth range of 6–8 km beneath the central part of the caldera [*Hill*, 1976].

More recently the interpretation of data from a regional seismic network operated by the University of Nevada indicates the lack of shear waves from shallow earthquakes occurring around the southwest boundary of Long Valley caldera when observed at stations to the northwest, north, and northeast of the caldera [*Ryall and Ryall*, 1981]. This effect has been explained by the attenuation of S waves as they propagate through a magma chamber beneath the south central part of Long Valley caldera at a depth greater than 7–8 km. In addition, *Savage and Clark* [1982] have found that leveling data along Route 395, crossing the resurgent dome in Long Valley caldera, indicates an uplift of some 25 cm over the last several years. Based on the broad, domelike character of the uplift and its lateral half-width of 10 km, they suggest that it is caused by a magmatic intrusion at a depth less than 10 km.

Hence, the travel time delays of *Steeples and Iyer* [1976], the possible reflected signal recorded by *Hill* [1976], the S wave attenuation results of *Ryall and Ryall* [1981], and the recent tectonic doming described by *Savage and Clark* [1982] are all suggestive of a magma chamber that is still molten at a depth of 6–8 km. Therefore, present thinking seems to favor a model in which an active hydrothermal system (having temperatures inferred to be as high as 210–280°C) is underlain by a magma chamber at a depth of 6–8 km that may still have a partially molten core of about 10-km diameter [*Bailey et al.*, 1976; *Sorey et al.*, 1978; *Varnado and Colp*, 1978; *Bailey*, 1980].

Details on the Long Valley Hydrothermal System

Muffler and Williams [1976] argue that four major factors affect the precision of estimating the geothermal resource for Long Valley: (1) reservoir volume (which can range from 0 to 1000 km^3), (2) recoverability (0% to 100%, depending on permeability), (3) temperature (poorly known at depth), (4) technology and economics. In terms of the last factor (technology), Muffler and Williams considered only the application of conventional flash steam electrical generation. If one allows the full range of possibilities from low-temperature industrial/agricultural applications to high-temperature magma energy and hot dry rock applications [e.g., *Varnado and Colp*, 1978; *Gambill*, 1981], the upper limits on resource recoverability increase considerably and, unfortunately, the range of uncertainties is also increased, based on our present knowledge of the hydrological and deep magma regime.

The overall structure of basin fill within the caldera is shown in Figure 10 (after *Sorey et al.*, [1978], Figure 3). Much of this information is based on reasonably dense gravity coverage [*Pakiser et al.*, 1961; *Kane et al.*, 1976] in conjunction with several seismic refraction profiles along the two lines shown in the figure [*Hill*, 1976].

It is generally agreed that knowledge of the hydrothermal system beneath Long Valley caldera suffers from the lack of sufficient deep drill hole data, which could potentially provide much better constraints on modeling the physical and structural properties of the assumed reservoir [*Muffler and Williams*, 1976; *Sorey et al.*, 1978]. Nevertheless, attempts to simulate the broad-scale hydrothermal regime of the caldera have been quite productive, albeit primitive [*Lachenbruch et al.*, 1976*a*; *Sorey et al.*, 1978]. In fact, Long Valley caldera is the only major silicic center for which this has been attempted. The conceptual framework for these modeling efforts is illustrated in Figure 11.

Sorey et al. [1978] contend that it is sufficient to assume that thermal water discharges only through springs in Hot Creek gorge and through the southeast rim of the caldera; apparently this accounts for 80% of the surface discharge from the thermal reservoir. An east-west vertical section through the model is shown in Figure 12 (after *Sorey et al.* [1976], Figure 24), which shows the steady state conduction-only isotherms without the effects of fluid flow. This model served as the initial condition in simulations of flow in the hydrothermal system. The stippled region represents the inferred reservoir as well as the vertical flow channels; it is assumed that two thirds of the recharge occurs through vertical flow along the west (northwest) rim and one third of

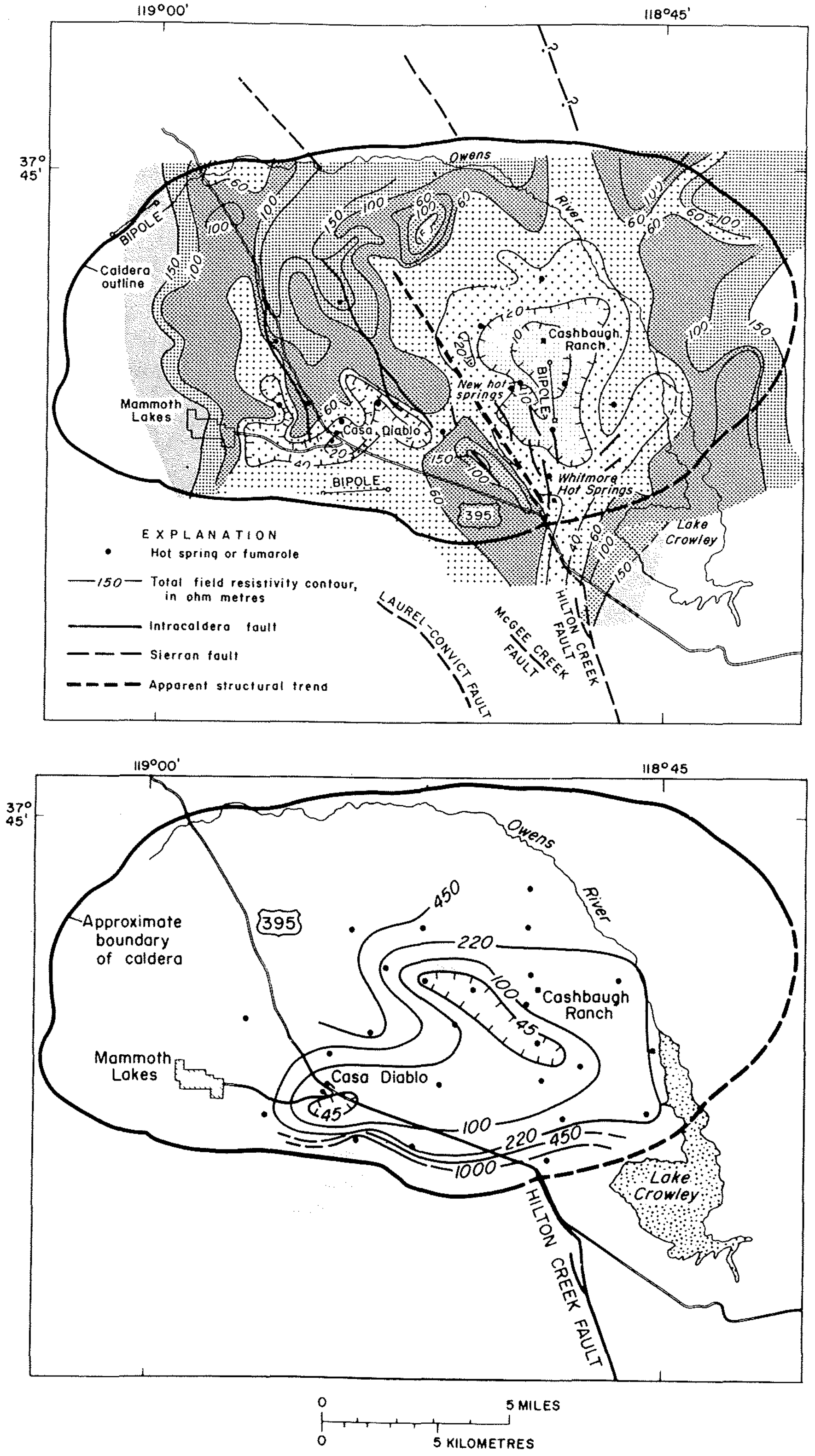


Fig. 5. (Top) Composite total field resistivity map (shaded contours) for Long Valley caldera [after *Stanley et al.*, 1976]. (Bottom) Audio magnetotelluric scalar apparent resistivities at 26 Hz (electric line east-west). Contours are in ohm-m [after *Hoover et al.*, 1976]. Note, for both figures the association of low resistivity values with areas of surface hot springs.

the recharge occurs through vertical flow along the east (northeast) rim. Discharge occurs along Hot Creek Gorge.

In terms of characterizing mechanisms for the transfer of thermal energy between hydrothermal and magma systems, it is important to note that the boundary condition Sorey et al. apply at a depth of 6 km (i.e., 800°C under the western half of the caldera) is intended to simulate magma at a depth of 6 km! On the basis of available geophysical data we do not know if, in fact, that is the case.

The present-day surface thermal regime is dominated by a total heat discharge of 6.9×10^7 cal/s and an average reservoir temperature of 210–280°C beneath the discharge areas. When the above model allows for appropriate fluid flow (i.e., circulation to depths in a reservoir of 1.5 to 2.5 km), this heat discharge may have been sustained for a period of 35,000 years by magma at a depth of 6 km under the western three fifths of the caldera. There are other indications, however, that the reservoir may have been active for a much longer period of time (350,000 yr?) and/or that the reservoir might have a larger areal extent. If such was (were) the case(s), fluid circulation to depths of 4 to 5 km might be required. One needs to ascertain whether permeable channels extend downward to these depths. This is not presently known, but the question could be addressed through drilling, sampling, and appropriate down-hole geophysical experiments.

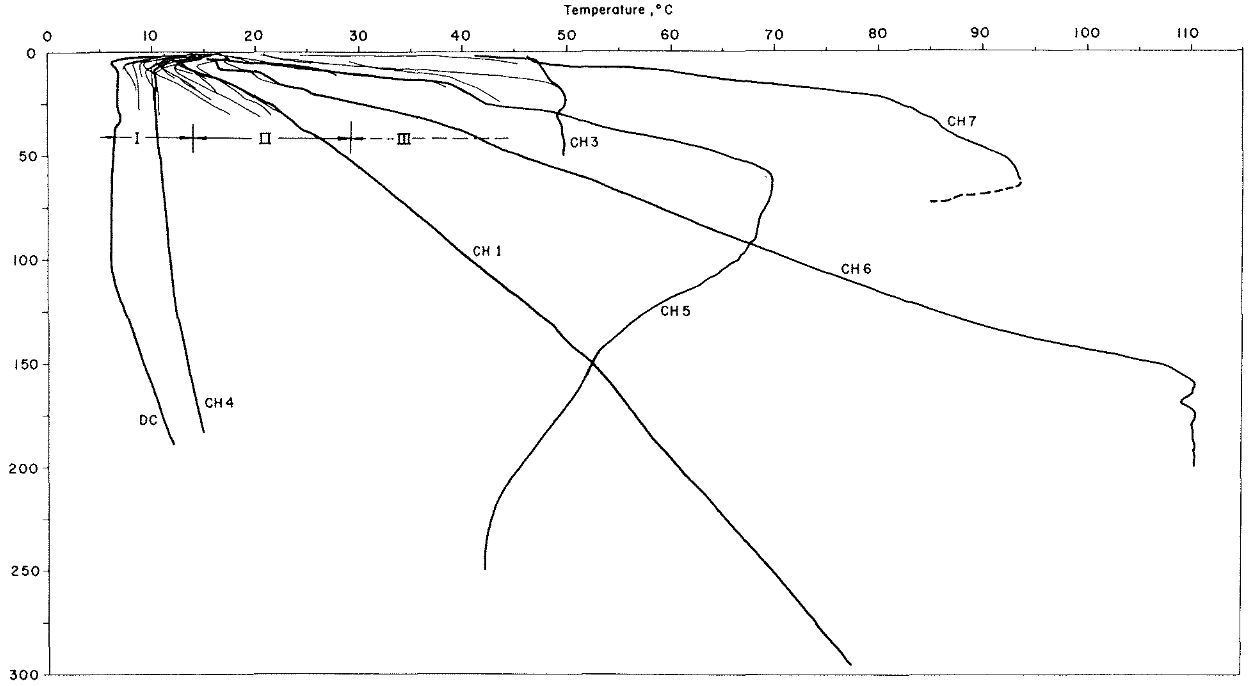


Fig. 6. Temperatures in shallow drill-holes from Long Valley caldera [after *Lachenbruch et al.*, 1976].

Under the eastern two fifths of the caldera, Sorey et al. feel that temperatures in a 2.1-km test hole, along with their model simulations, indicate that temperatures are sufficiently low to preclude the possibility of electrical energy development east of Hot Creek. Although there is little incentive to study this latter area from the viewpoint of energy extraction, important questions emerge if the east side of the caldera is considered for possible reinjection of residual geothermal fluids [*Sorey et al.*, 1978]. If, in the future, large-scale production of hot fluids occurs from the present hot spring area, with a concomitant reinjection of residual waters into the eastern caldera, there could be a resultant

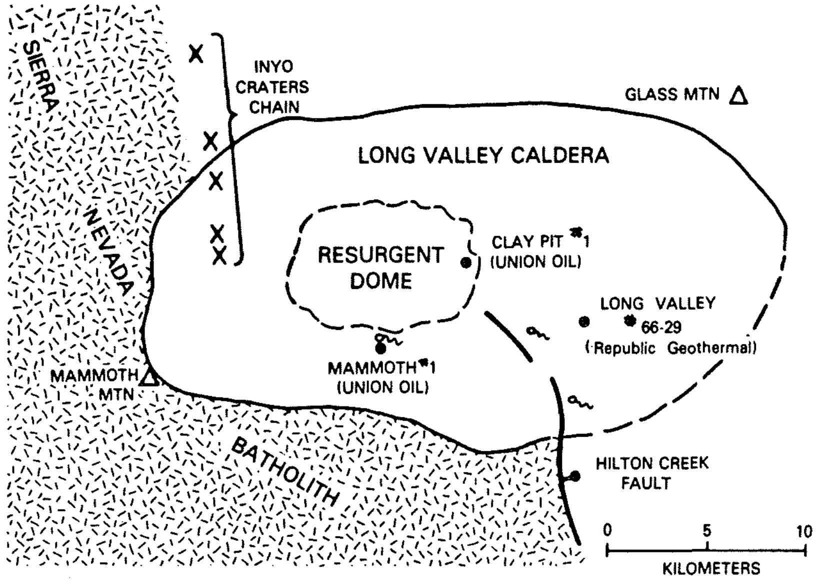
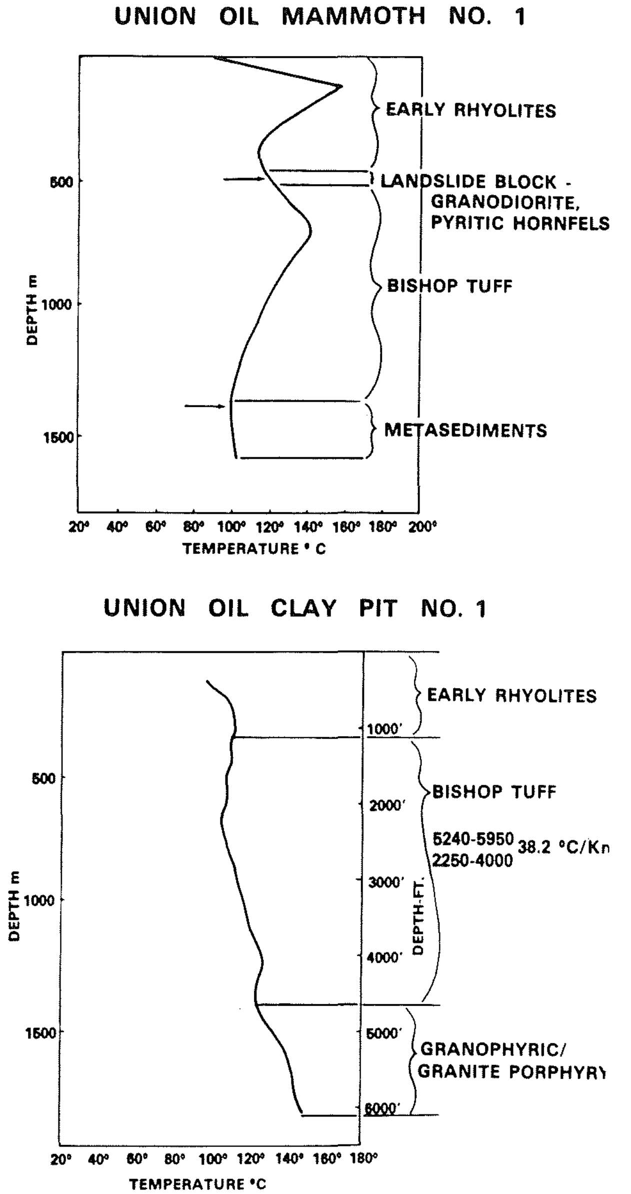


Fig. 7. Location of intermediate depth wells (approximately 2 km) drilled by industry in Long Valley caldera [after *Heiken et al.*, 1982, Figure 5].



UNION OIL MAMMOTH NO. 1

UNION OIL CLAY PIT NO. 1

Fig. 8. Temperature observed in two wells drilled by Union Oil in Long Valley caldera [after *Gambill*, 1981].

westward migration of this cool water toward the production area. It is important therefore to determine the existence or nonexistence of a permeability barrier between the high temperature and low-temperature hydrothermal regimes within the reservoir.

Clearly, a well-planned drilling effort to intermediate depths (1.5–2.5 km) at a number of sites, along with several holes to greater depth (>2.5 km), would immeasurably improve our ability to reconstruct the temporal and spatial evolution of such systems [*Muffler and Williams*, 1976; *Sorey et al.*, 1978; *Inter-Union Commission on the Lithosphere*, 1981].

Pending Problems in the Long Valley/Mono Basin Volcanic Complex

Problems in Basin Structure

Depth to basement. Seismic refraction studies in Mono Basin and Long Valley caldera have been used to place constraints on subsurface basement structures often buried beneath several kilometers of sedimentary fill. One must recognize that basic inconsistencies persist between gravity interpretations and seismic interpretations of depth to basement beneath these basins. In order to obtain reasonable agreement between depths determined from seismic refraction measurements and those inferred from gravity studies in Mono Basin, *Pakiser* [1976] assumed an average density contrast of −0.8 gm/cc. On the other hand, studies in Long Valley caldera by *Hill* [1976] indicate good agreement between seismic and gravity interpretations when one assumes a density contrast of −0.45 gm/cc. The question is, are there fundamental differences in the average density of sediments in these two areas or has the interpretation been overly simplified in some manner?

If, for example, a density contrast of −0.45 gm/cc is too small for the fill in Long Valley caldera, then the depth to bedrock ($d < 4$ km) may be overestimated, and the thickness of aquifers assumed by *Sorey et al.* [1978] might be optimistic, especially where seismic and drilling controls are lacking, as in the northeastern and northwestern portion of the valley (see Figure 10). If the assumed density contrast is too large, then the converse may be true. It is important, therefore, to calibrate gravity interpretations against depth to basement as inferred from seismic and other geophysical studies as well as from drilling results. In principle this would allow one to use gravity data more reliably to interpolate between selected seismic lines (either refraction or reflection lines) or between drill holes where they are now available or as they become available in the future.

Major boundary faults in Long Valley Caldera. This point is illustrated in Figure 13 by comparing three models (based on essentially the same gravity data) as interpreted by *Muffler and Williams* [1976], *Kane et al.* [1976], and *Sorey et al.* [1978]. Although there are gross similarities in these three models, there are significant differences in detail that affect the overall characterization of the hydrothermal reservoir.

The degree to which seismic refraction measurements complement the gravity data is illustrated in Figures 14 and 15. In Figure 14 we compare the interpretation of gravity data by *Pakiser* [1961] with the interpretation of seismic refraction data by *Hill* [1976] for a north-south line crossing Long Valley caldera. Although the two profiles are displaced somewhat, there is clear agreement for the presence of both a northern and southern boundary fault. In Figure 15, however, we see a conflict between the two interpretations for east-west profiles. The gravity interpretation shows a modest boundary fault in the west and a profound vertical offset along the eastern margin of the caldera. On the other hand, the seismic refraction interpretation suggests just the opposite relationship, with the greater vertical offset being in the west. We are not aware of any attempt to quantitatively reconcile the gravity data with the seismic refraction interpretation, but present models seem to favor the seismic interpretation.

It is clear from the limited data available, however, that the concept of caldera collapse occurring as a gigantic, structurally coherent piston withdraws from the surface along a single ring fault is not generally supported by field evidence from geologic exposures in Long Valley caldera nor, unequivocally, by past geophysical studies. The east wall of the caldera has a distinct outer ring fault which can be traced a distance of 12 km. However, its maximum vertical

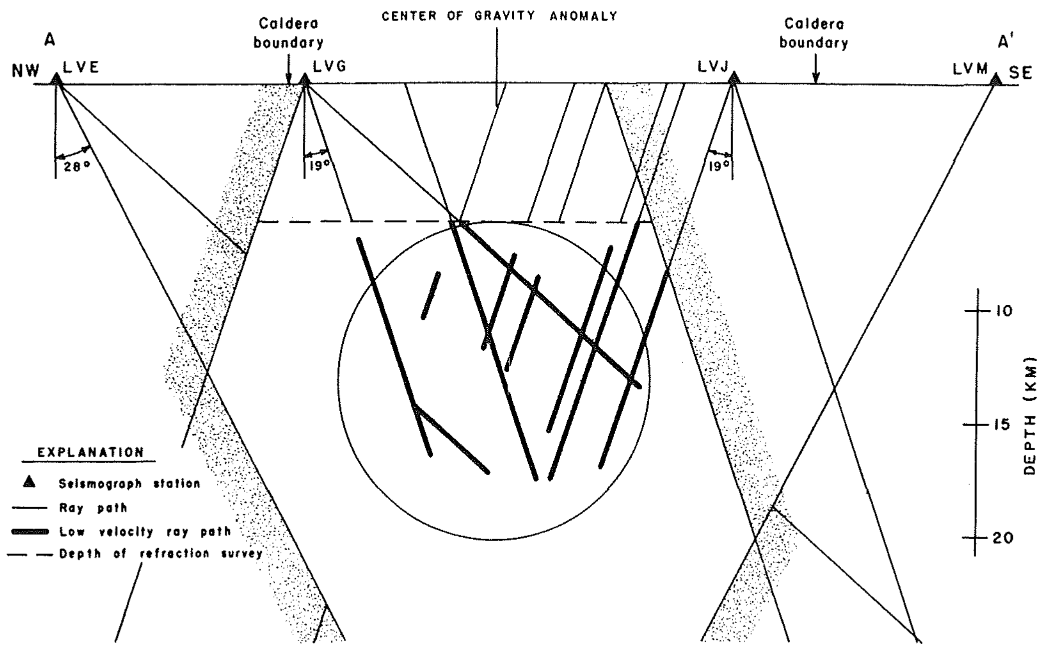


Fig. 9. Low-velocity body beneath the Long Valley resurgent dome, used to infer the presence of a magma accumulation. The model shown here represents a 15% velocity decrease along the heavy ray paths. The circle is a sectional view of a sphere centered at a depth of 12.5 km and having a radius of 7 km. Velocities outside the stippled area are normal (6.0 km/s). After *Steeples and Iyer* [1976, Figure 5].

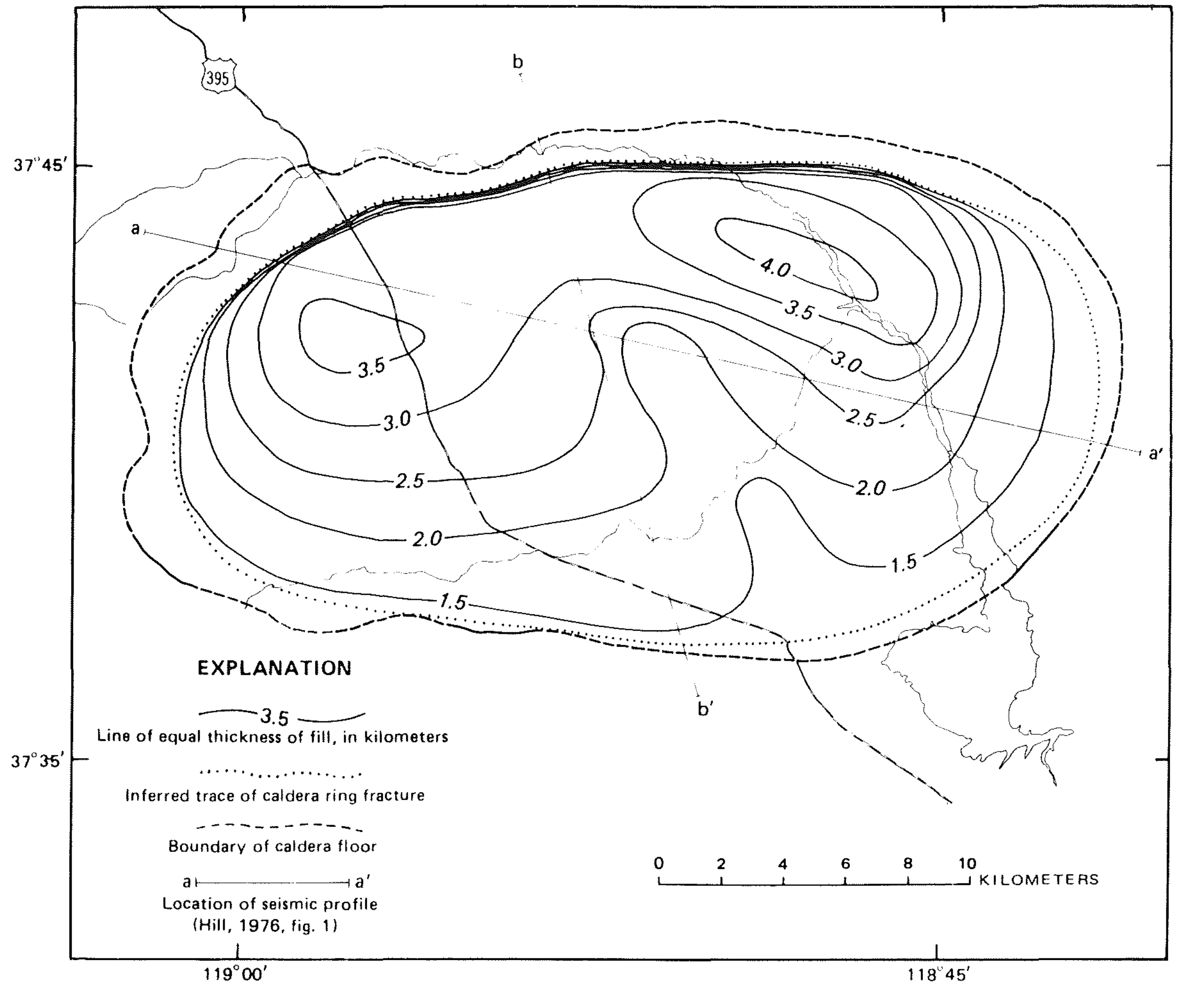


Fig. 10. Contours showing the thickness (km) of basin fill in Long Valley caldera, based on areal gravity coverage and seismic refraction profiles along the lines shown (a–a', b–b'). After *Sorey et al.* [1978, Figure 3].

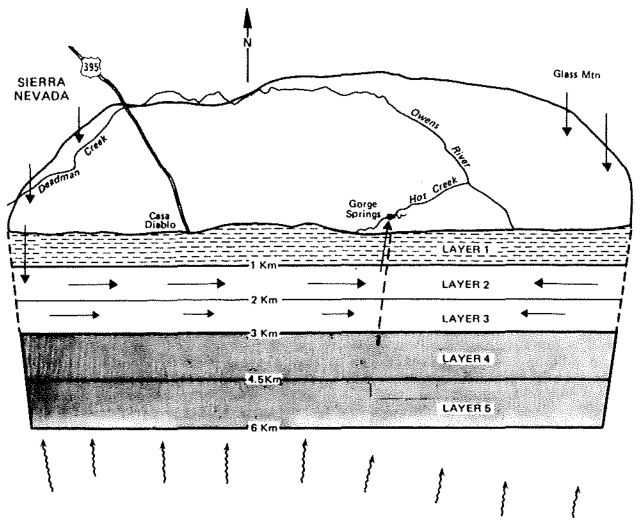


Fig. 11. Conceptual model of Long Valley caldera, representing the regional hydrologic regime. Meteoric water enters the system along the boundary faults near Deadman Creek in the west and Glass Mountain in the east. As the water moves laterally through an aquifer extending over the depth range of 1 to 3 km, it is heated from a residual heat source below the caldera. The heated water leaves the system along vertical fractures in the vicinity of Hot Creek Gorge [after *Sorey et al.*, 1978, Figure 18].

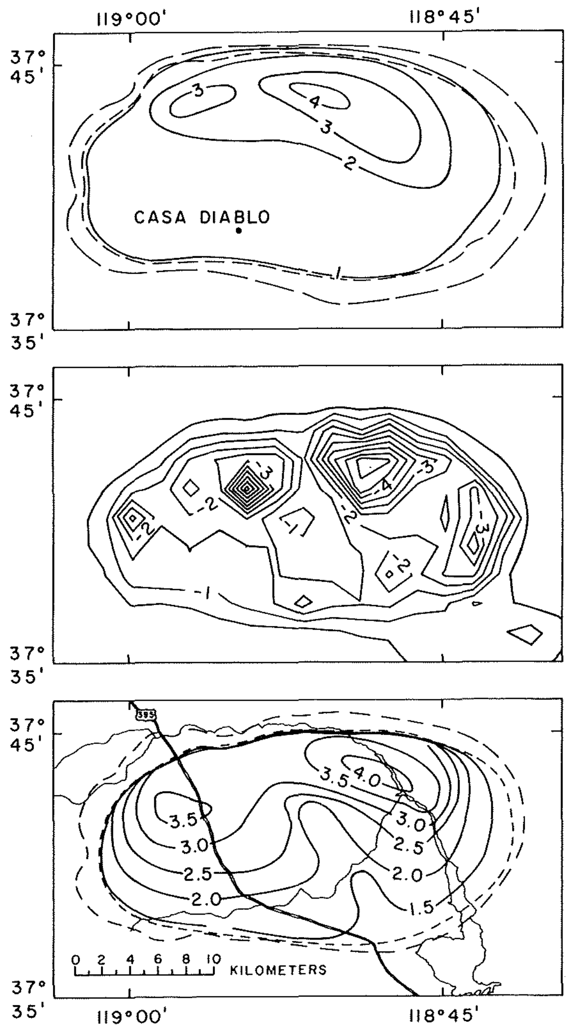


Fig. 13. Three interpretations of the thickness (km) of basin fill in Long Valley caldera, based primarily on gravity data. (Top, after *Muffler and Williams* [1976]). In the top and bottom diagrams the outer long-dashed line represents the topographic boundary of the caldera floor, the inner short-dashed line represents the approximate location of the inferred ring fracture. (Middle, after *Kane et al.* [1976]). The fine structure may actually represent changes in the depth to basement or may be artifacts introduced by lateral variations in the density of the caldera fill. (Bottom, after *Sorey et al.* [1978]). Note the slight displacement of the deepest troughs when intercomparing these figures.

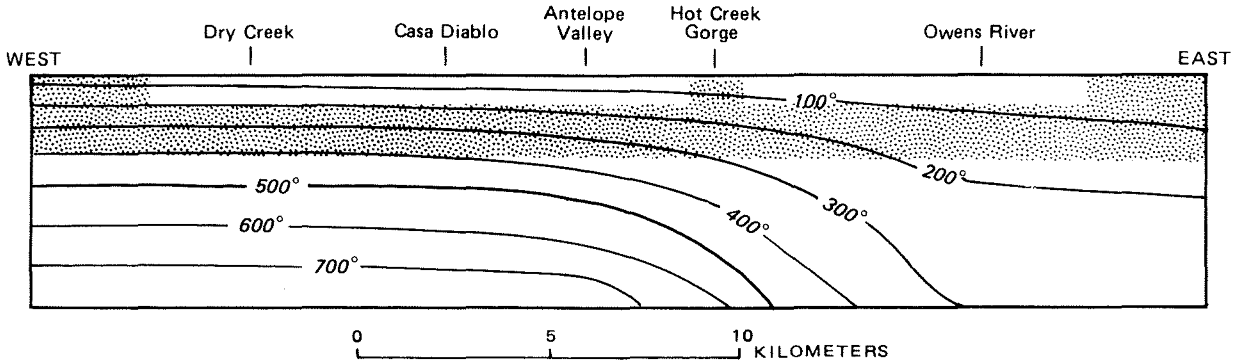


Fig. 12. East-west vertical section through the hydrologic model of Long Valley caldera, schematically showing steady state, conduction-only isotherms (°C) without fluid flow. The dotted patterns represents the simulated reservoir (fractured Bishop Tuff) and the vertical flow channels through which meteoric water enters and leaves the system [after *Sorey et al.*, 1978].

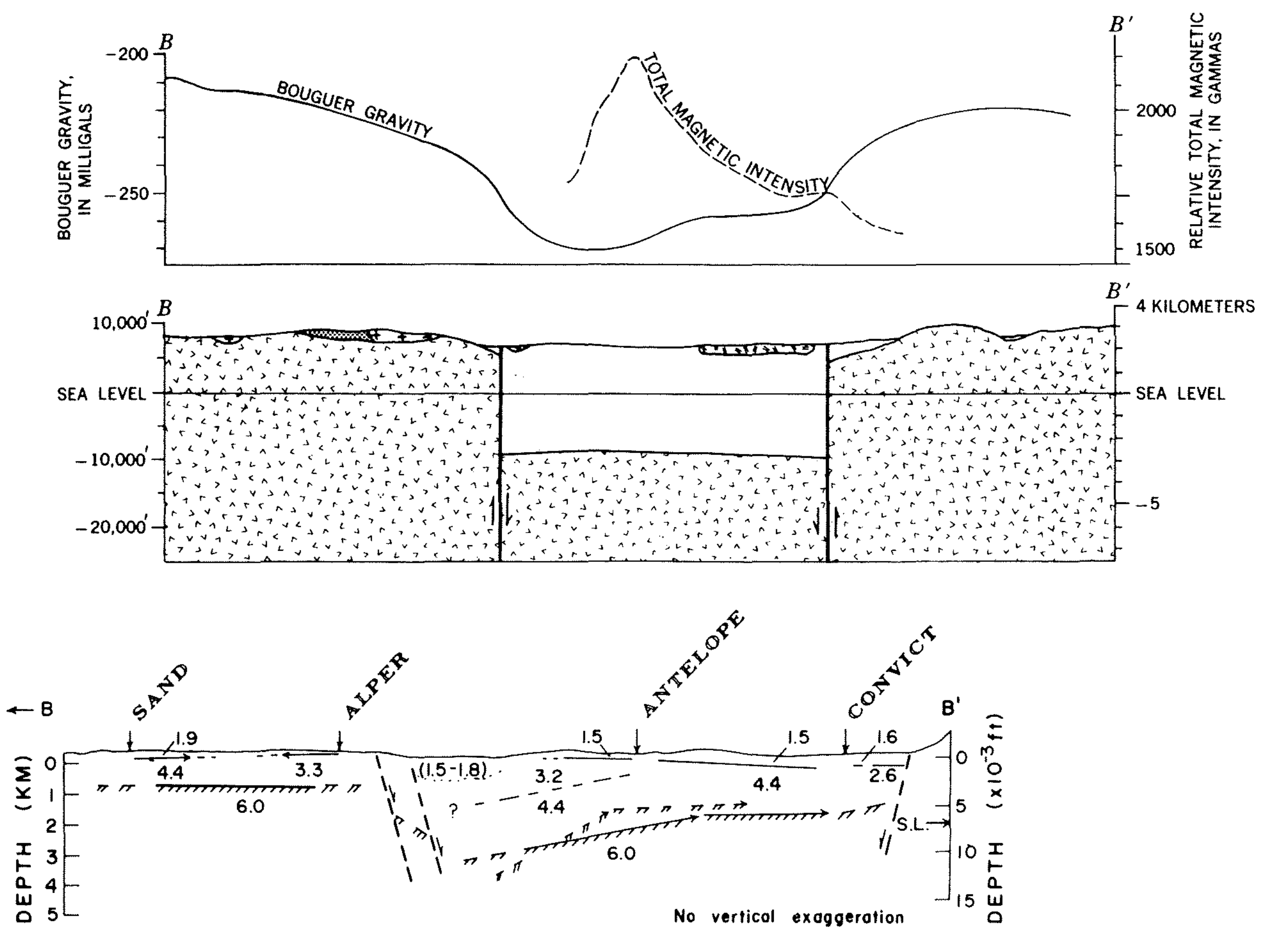


Fig. 14. North-south vertical sections through Long Valley caldera comparing the original gravity interpretation of *Pakiser* [1961] (top diagram) with the seismic refraction interpretation of *Hill* [1976] (bottom diagram). Note that the scales are different for either diagram. The qualitative agreement between these two diagrams is quite reasonable.

displacement is only 250 m, whereas the gravity requires a much greater displacement, perhaps several thousand meters [*Bailey et al.*, 1976]. For example, *Pakiser* [1961] interpreted gravity data to imply a vertical downdrop of the caldera floor in the east of over 5000 m (Figure 15). As mentioned above, however, subsequent seismic refraction experiments by *Hill* [1976] failed to detect the main boundary fault in this area, although if one is present it probably lies well within the caldera moat [*Bailey et al.*, 1976].

An alternative possibility is that there is no single boundary fault in the east but that subsidence has been distributed over a wide zone of parallel faults and flexures [*Hill*, 1976]. The implications of this latter possibility are significant for reconstructing the dynamics of caldera collapse, such as for constraining estimates of the total volume of material erupted from the primeval magma chamber as well as for establishing structural constraints on the migration of hydrothermal fluids within the caldera.

Much of the fine structure inferred from the gravity data (e.g., shown in the middle panel in Figure 13) is absent in the seismic refraction interpretation. One must recognize that seismic refraction techniques are not ideally suited for detecting the existence and defining the geometry of flexure, boundary faults, or en echelon parallel faults. Frequently, the faults produce backscattered reflections which confuse refracted arrivals [e.g., *Vaughn and Ward*, 1983]. Clearly more refined seismic studies are called for in the area.

Long Valley caldera fill. The Bishop Tuff is felt to extend throughout the lower part of the caldera fill. Based on the gravity data of *Kane et al.* [1976], *Muffler and Williams* [1976] argued that it appears to have a significant bulk porosity (up to 20%). However, *Bailey et al.* [1976] report that samples of Bishop Tuff found as inclusions in post-caldera eruptives exposed in the central part of the caldera are densely welded, implying that the deeper, unexposed Bishop Tuff may have low porosity and high density. Based on these two conflicting sets of evidence for the character of the caldera fill, Muffler and Williams inferred that the porosity indicated by the gravity data is due either to widespread fracturing or to local accumulations of high-porosity pumiceous material. Which (if either) of these suggestions is correct has enormous implications for the nature of the hydrothermal reservoir and the manner in which it is coupled to a possible magma source deep in the crust. If widespread fracturing is present, then one might expect a relatively high effective permeability over large regions at depth. In terms of the geothermal potential this could be beneficial in that the reservoir may be large and open or it could be detrimental in that cold, meteoric waters can flush through the system too quickly, carrying the heat away. On the other hand if the basin fill is characterized by local pods of highly porous material (see for example the middle panel in Figure 13), certain of these pods may be able to achieve relatively high temperature and, if sufficiently porous and sufficiently numerous, may cumulatively represent economic hydrothermal reservoirs, in spite of their small dimensions. These questions are unresolved at present but need to be addressed by future research, particularly by refined surface geophysics in conjunction with drilling to intermediate depths.

Subsurface features in the Long Valley caldera fill. The map of residual magnetic intensities from an aeromagnetic survey flown at an altitude of 4000 m is shown in Figure 16. The magnetic field is dominated by a well-developed trend of magnetic highs over the eastern half of the caldera and by an equally well-developed low over the western half [*Kane et al.*, 1976; *Williams et al.*, 1977]. Of particular importance are the two magnetic maxima that appear to be superimposed on a broader, but smaller, positive anomaly in the northeastern segment of the caldera. Kane et al. concur with the suggestion of *Pakiser et al.* [1964] that the higher-amplitude, short-wavelength anomalies probably represent volcanic necks that may have been sources of a sequence of lava flows

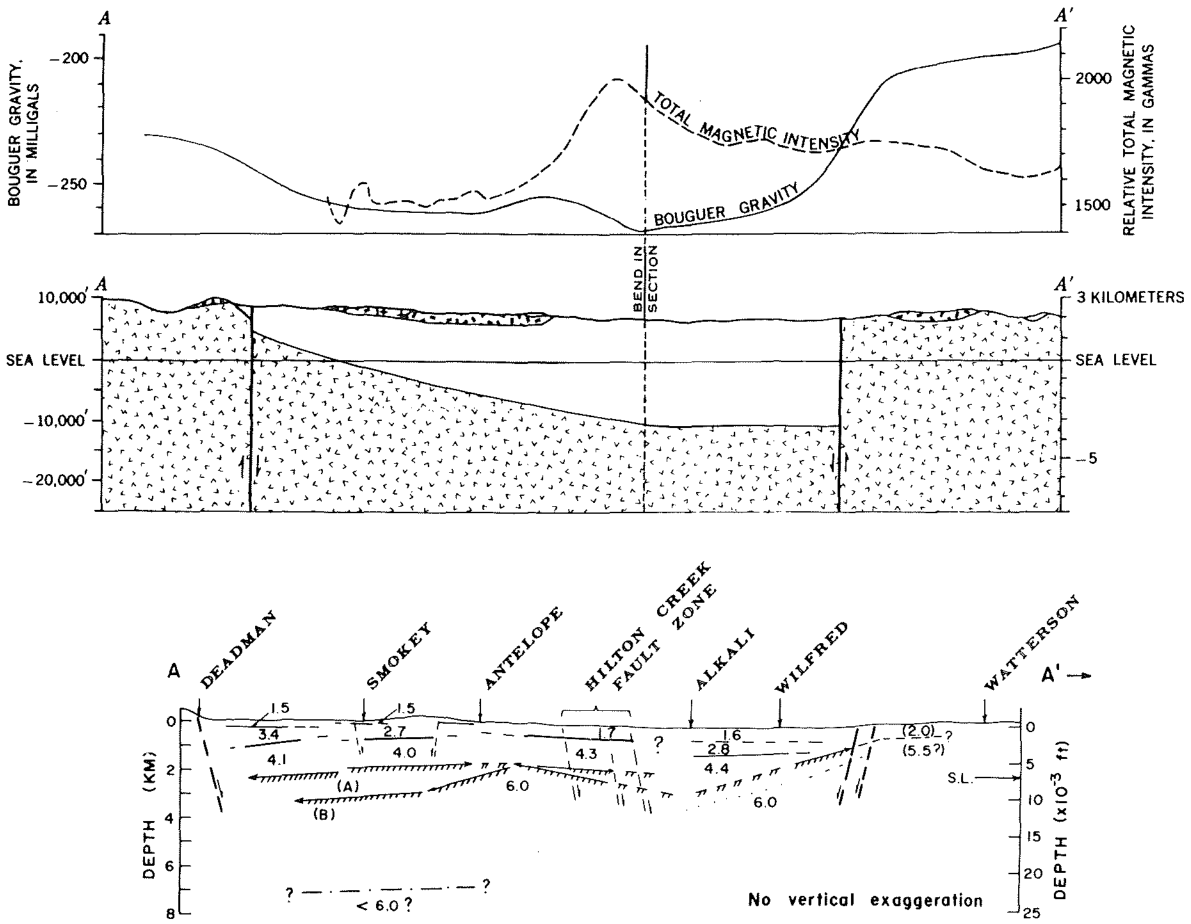


Fig. 15. East-west vertical sections through Long Valley caldera comparing the original gravity interpretation of *Pakiser* [1961] (top diagram) with the seismic refraction interpretation of *Hill* [1976] (bottom diagram). Note that the top figure depicts a large vertical displacement in the east, whereas the bottom figure depicts a larger displacement in the west.

causing the broader lower-amplitude features. In addition, Kane et al. feel that the magnetic mass is bounded on the west by the projected Hilton Creek fault and is genetically related to it. Neither the hypothetical volcanic necks nor the broader lava flows have geologic surface expressions in this area, although *Pakiser* [1976] has inferred the presence of an analogous feature beneath Paoha Island in Mono Basin, based not only on magnetic data but on positive gravity anomalies and higher-than-normal seismic velocities as well.

As an alternative interpretation of the magnetic field data, *Williams et al.* [1977] feel that a major factor in magnetic anomalies within the caldera is due to the variation of magnetization within the Bishop Tuff itself, and they discount the presence of the hypothesized volcanic necks and lava flows proposed by *Pakiser et al. [1964]* and *Kane et al.* [1976].

While not discussing the merits or problems associated with either point of view at present, we emphasize the importance of resolving this controversy in future studies, since it concerns such a major feature in the magnetic and, perhaps, the tectonic fabric of the caldera. One cannot discount the volcanic neck hypothesis offhand. These necks, for example, could be sources of basaltic lava flows similar to those seen elsewhere within the caldera and which have occurred since its formation; some as recently as 60,000 yr ago [*Bailey et al.*, 1976]. The important point to recognize is that deciding which of these two alternative models applies has important implications for evaluating the hydrothermal regime of Long Valley caldera. The suggestion of Williams et al. would imply that the magnetic highs are zones of relatively undisturbed Bishop Tuff. On the other hand, *Pakiser et al.* [1964] and Kane et al. [1976] imply quite the opposite: the magnetic highs are underlain by anomalous features within the caldera. If in fact, these features are volcanic necks associated with lava flows interbedded with the caldera sediments, then either the volcanic necks themselves could be associated with enhanced hydrothermal activity (probably the result of structural control on the upward migration of thermal fluids heated at great depth rather than direct local heating by the intrusion), or the interbedded lava flows may act as cap rocks on a deeper hydrothermal system. Therefore, determining which of these alternative models is correct, either through surface geophysics or through exploration drilling, is important for developing refined models of the hydrothermal system of Long Valley caldera.

Problems in the Thermal Regime

The locations and temperatures of two exploration wells drilled by Union Oil were referred to in Figures 7 and 8. Clearly the temperatures in both wells are showing the effects of hydrothermal convection. Temperatures in Mammoth No. 1 appear to be perturbed by two-cell convection; one cell above the granodiorite landslide block, the other below.

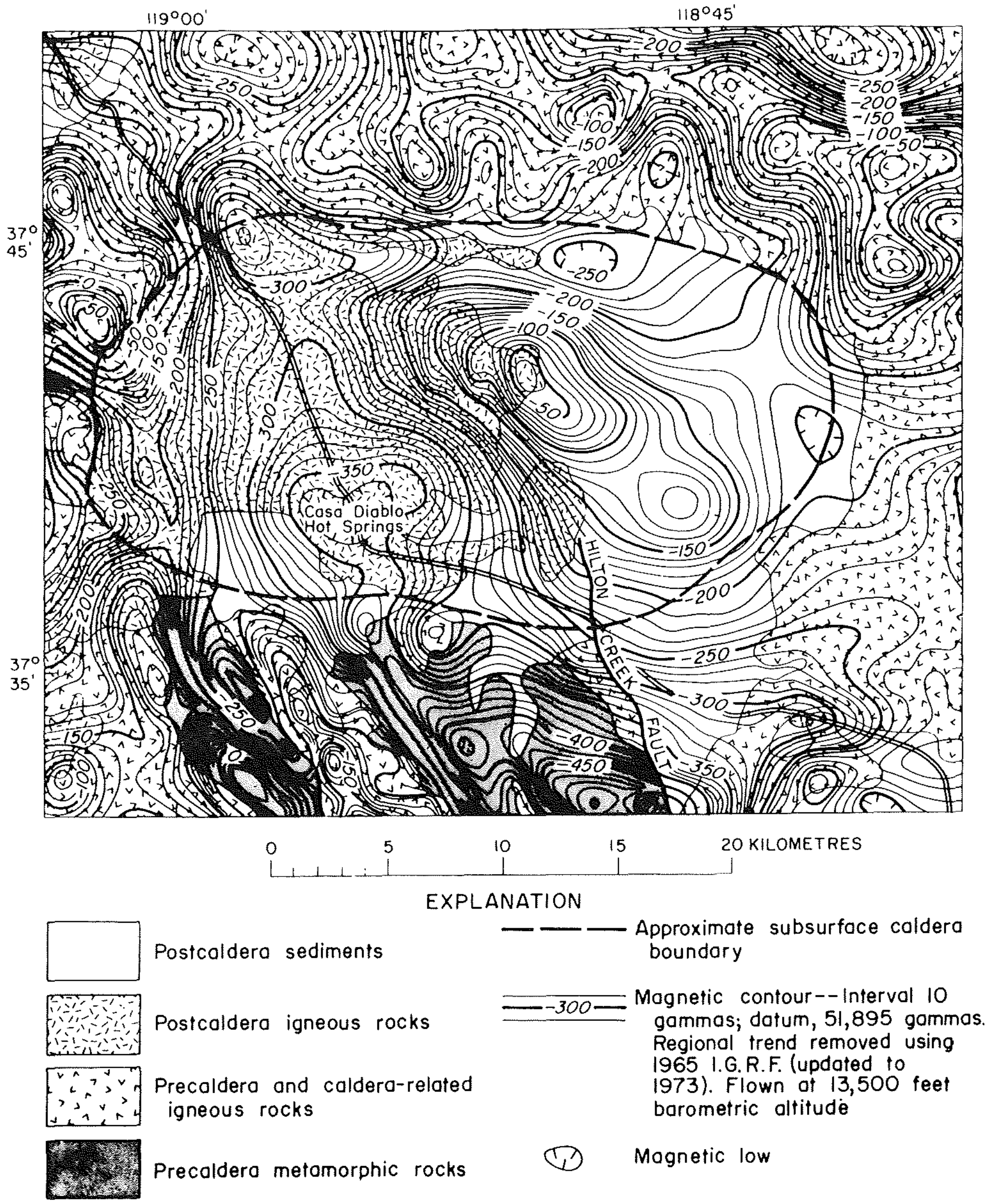


Fig. 16. Contours of high-level residual magnetic intensity combined with generalized geology for Long Valley caldera [after *Kane et al.*, 1976, Figure 7].

Such patterns of temperature are compatible with simple models of convective transport as described, for example, by *Elder* [1965]. In Figure 17 we show, on the left, a simple conceptual model representing temperatures in a hydrothermal plume driven by some deep heat source. On the right we show a vertical temperature profile in a drill hole off the axis of the plume.

This temperature distribution is not unlike those indicated in the actual borehole temperatures in Mammoth No. 1. If these temperatures represent steady state convective conditions, then the two maxima at 150-m and 700-m depth, respectively, probably represent high-temperature flow away from a convective thermal plume, whereas the minima at 400 m and 1350 m represent the return flow of cool water. It is interesting to note that the flow seems to permeate the entire section of Bishop Tuff above the metasedimentary basement.

Temperatures in Clay Pit No. 1 are significantly different. However, they also seem to reflect fluid convection, though perhaps to a lesser degree than in Mammoth No. 1. We note two aspects of the temperature in this well. First, bottom-hole temperatures are higher at Clay Pit No. 1 than at Mammoth No. 1, indicating that deep waters are heated as they flow eastward in the caldera. This is compatible with the models of *Lachenbruch et al.* [1976*b*] and *Sorey et al.* [1978] reviewed above. This seems to be a significant constraint on characterizing the regional hydrothermal system. *Gambill* [1981], on the other hand, observed that temperatures at shallow depth show a cooling trend from west to east—opposite to the trend of bottom-hole temperatures. Which of these trends is more important for determining the characteristics of a regional hydrothermal system is not certain at present. The observation that bottom-hole temperatures increase from west to east may simply reflect the transition from Sierra Nevadan tectonics to Basin and Range tectonics.

A second aspect of temperatures in Clay Pit No. 1 is that the temperature gradient in the bottom of the well (i.e.,

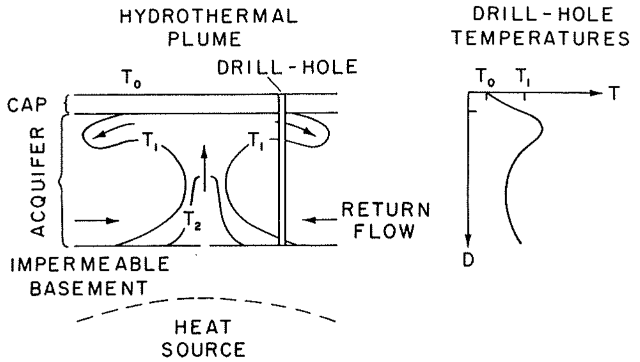


Fig. 17. (Left) A conceptual model of a hydrothermal plume in an aquifer heated by a source at depth in the impermeable basement [after *Elder*, 1965]. (Right) Hydrothermal temperatures in a drillhole located off the central axis of the plume.

below 1500 m) is on the order of 50°C/km, which is somewhat larger than the 38°C/km described by *Heiken et al.* [1982] and may indicate an atypically large value of heat flow when compared with average gradients in the Basin and Range nearby [*Lachenbruch et al.*, 1976*a*; *Lachenbruch and Sass*, 1978]. There is some question as to whether this hole actually encountered basement and/or whether the temperature gradient is disturbed by the movement of water below (R. Bailey, personal communication, 1983). For the present, however, we will treat the observed gradient as the best estimate we have. By averaging the thermal conductivity of 10 samples described by *Lachenbruch et al.* [1976*a*], obtained from as many boreholes in the area, an average conductivity for granite appears to be 7.3 CU (where 1 CU = 10^{-3}cal/cm/s/°C = 0.418 W/m/°K). Combining this conductivity with a thermal gradient of 50°C/km leads to an estimated heat flow of 3.5 HFU (where 1 HFU = 10^{-6}cal/cm^2/s = 41.8 mW/m^2). This value can be compared with an average regional value of 1.9 HFU determined from five nearby measurements in basement reported by *Lachenbruch et al.* [1976*a*]. Hence if the bottom-hole temperature gradient is reliable in the Clay Pit No. 1 well, then heat flow in Long Valley caldera exceeds the regional average by 1.6 HFU and seems to be a further manifestation of recent volcanism in the area.

Clearly, the question of deciding which factors are dominant in characterizing the regional hydrothermal regime of Long Valley caldera will only be resolved after intensive borehole studies in a number of intermediate depth and deep drill holes into crystalline basement within and outside the caldera. Reliable conductive thermal gradients need to be determined at depths where low permeabilities preclude the advection of heat.

Mono Craters

Very little is known about the subsurface structure of Mono Craters, although this may be one of the most dramatic elements evolving in the tectonic fabric of the region. Basically, volcanism is too recent for surface geologists to reconstruct a model of temporal evolution.

In one of the earliest reconnaissance studies of the area, *Russell* [1889] concluded that the Mono Craters were located along faults associated with the east scarp of the Sierra Nevada. *Mayo et al.* [1936] described the relation of Mono Craters to an embayment in the east front of the Sierra Nevadas, which in turn is controlled by a pattern of oblique jointing in the basement. They contended that the trend of Mono Craters is associated with one (or several?) of these zones. *Kistler* [1966] has argued, from field observations on the few available outcrops, that the zone of weakness controlling the pattern of volcanic extrusion in this area defines a roughly circular pattern of faulting that contains Pumice Valley and may represent the development of an incipient ring fracture system. Within this ringlike feature, basement rocks indicate the effects of metamorphic reaction with a fossil granodiorite pluton of Late Cretaceous age (to form hornblende-bearing quartz monzonite).

In any event, whether the volcanics are being extruded along a regional jointing pattern or along a fossil metamorphic zone, present-day volcanism at the surface is, to a marked degree, structurally controlled. *Bailey et al.* [1976] and *Bailey* [1980] have argued that the inferred ring fracture outlines what may be an incipient magma chamber in the crust. The depth to such a magma body, if it exists, is not clear, however Bailey has drawn on *Carmichael*'s [1967] petrologic study of samples from Inyo Domes, to the south, to suggest a source depth of less than 22 km. Temperatures at the time of extrusion averaged 825°C [*Carmichael*, 1967].

Little geophysics has been done in the area of Mono Craters. Regional gravity studies do not indicate the type of strong anomaly patterns associated with low-density basin fill beneath Long Valley caldera and Mono Basin proper (i.e., in the vicinity of Mono Lake). Seismic refraction studies show essentially that the overburden in Pumice Valley is quite thin [*Pakiser et al*, 1960; *Pakiser*, 1976]. The surface geology confirms this with crystalline basement outcropping in several places over the floor of the valley. Hence although the setting is ideal for using gravity to detect a shallow low-density magma body, the data do not indicate that one is present.

Lachenbruch et al. [1976*a*] reported a preliminary heat flow estimate of 2.2 HFU from a drill hole into Mesozoic granite rocks at Aeolian Buttes, within the inferred Mono ring fracture. A. Lachenbruch (Heat flow at Aeolian Butte—Constraints on a magma chamber beneath the Mono ring fracture, Contributions to Field Trip Notes: Mono Craters/Long Valley Field Trip, May 5, 1982), noting that this value is not atypical for the Basin and Range province, argued that there may be no detectable heat flow anomaly over this feature. He concluded that if the background heat flow is, in fact, typical of the Basin and Range, then any magma body must be deeper than 10 km if older than 0.7–1 m.y., 8 km if older than 3 × 10^5 yr, and 6 km if less than 1.5 × 10^5 yr. On the other hand, he pointed out that if the background heat flow is more characteristic of the Sierra Nevada province (which is about 1.2 HFU), then the observed heat flow is indeed anomalous by approximately 1 HFU. This could be caused by a magma chamber at 8 km emplaced 5 × 10^5 yr ago or a chamber at 6 km emplaced 2 × 10^5 yr ago. Clearly, additional heat flow observations are needed to separate the regional contribution from the contribution of any localized magma body.

Problems in the Regional Geophysical Setting

As described above, seismic refraction measurements from Mono Basin to China Lake suggest crustal thicknesses of approximately 40–50 km. The crust therefore appears to be anomalously thick in relation to the typical Basin and Range (which is 25–30 km). If this is true, it serves to raise important questions about *Lachenbruch*'s [1980] suggestion regarding the development of volcanic centers along the Eastern Sierran front (Mono Basin, Long Valley, Coso, etc.,). He suggested that these centers may be related to locally high rates of extension associated with dramatic crustal attenuation (i.e., crustal thinning or necking). The seismic evidence does not support the possibility of crustal thinning; in fact there appears to be an anomalously thick crustal root beneath this region. The present seismic constraints on the crust beneath Mono Basin and Long Valley, if taken quite literally, require a mechanism for transporting magma from the mantle through 40–50 km of crust (hot or cold?) into reservoirs at intermediate levels in the crust.

One may note however the previous electromagnetic studies indicate that these techniques can place useful constraints on magma genesis: (1) *Schmucker*'s [1970] data suggest a width of a few tens of kilometers for an anomalous lithospheric conductor along the eastern margin of the Sierras. (2) *Lienert*'s [1979] data suggest a depth to this conductor (if both workers are seeing the same feature) of 15–20 km and that it has a resistivity of 30 ohm-m (or somewhat less). Thus it appears (qualitatively at least, considering the limited precision of the data) that the crust may, in some way, be dynamically involved over a relatively broad region (tens of kilometers) in the development of volcanism in this area.

In other words the major volcanic centers need not be connected by narrow ducts through a cold lithosphere to magmatic sources at great depth, which would be implied if one took the interpretation of seismic refraction experiments quite literally. The low resistivities in the deeper crust may be an indication of some thermally activated process, perhaps the presence of detectable concentrations of magma within the crust. Hence this interpretation of previous electromagnetic studies suggests that the crust itself may be involved in magma genesis over a large region in a way not yet resolved by using conventional seismic techniques and not accounted for in present thermal transport models, which require dramatic crustal thinning.

Evidence for Magma Intruding Long Valley Caldera

A number of reports have recently appeared regarding the possibility of renewed volcanism in Long Valley caldera [*Savage and Clark*, 1982; *Ryall and Ryall*, 1983; *Miller et al.*, 1982; *Geotimes*, 1982*a*, *b*]. In particular, the evidence was sufficiently persuasive to cause the U.S. Geological Survey to issue a notice of potential volcanic hazard for the area on May 25, 1982 [*Miller et al*, 1982].

In terms of recent studies that might bear on this issue we begin with consideration of Figure 18, which depicts the pattern of seismicity for the region represented in a study by *Ryall and Ryall* [1980]. This region is a transition zone between the Eastern Front of the Sierra Nevadas and crustal extension in the Great Basin. Seismicity is distributed along two broad east-west belts, one passing to the northeast of Mono Basin, the other southeast of Long Valley caldera. Little seismicity is reported in the region between these two belts (see Figure 18). In particular, *Steeples and Pitt* [1976] reported from a month-long survey of microearthquakes in 1973 that little activity was noted within the central region of the Long Valley caldera and was conspicuously absent beneath the resurgent dome. They noted that the only microearthquakes recorded within the caldera were at its extreme southeastern edge, at a depth of about 10 km. They ventured a suggestion that if magma or partial melt were present in the upper 15 km of the crust beneath Long Valley (see, for example, Figure 9), then this area might have a sufficiently low rigidity as to be effectively isolated from the regional stress field responsible for the seismicity outside the caldera. From a pair of almost identical seismic events close to the village of Mammoth Lakes, but 2–3 km south of the rim of the caldera, Steeples and Pitt observed a significant decrease in the amplitude of *S* waves observed at certain sites. Although at first they were prompted to explain this as being due to the attenuation of shear wave energy upon passing through one or more magma chambers, upon careful analysis of their data they found that the phenomenon was more likely due to the seismic radiation pattern itself. In fact they found little evidence for attenuation along ray paths passing through, and penetrating to depths of 3–4 km beneath, the central caldera.

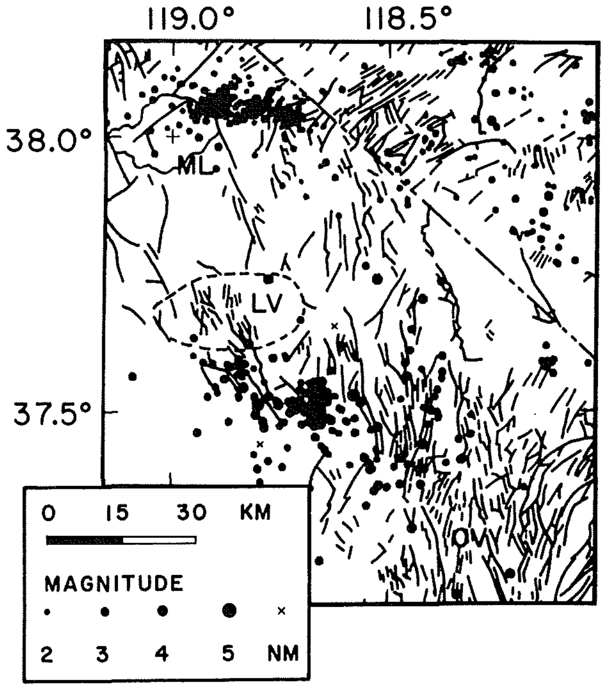


Fig. 18. Pattern of regional seismicity in the Long Valley/Mono Basin area for the period 1970 to 1978 [after *Ryall and Ryall*, 1980, Figure 2]. Earthquake epicenters are indicated by dots, mapped faults by sinuous lines; ML-Mono Lake, LV-Long Valley.

In late 1977 an unusual lull in the seismicity between Bishop and Mammoth Lakes caused concern among some seismologists for an impending large earthquake in this area [*Ryall and Ryall*, 1980]. Then, beginning in October of 1978, a sequence of moderate earthquakes occurred northwest of Bishop (Figure 19). The first, on October 4, 1978, was a magnitude 5.8 and was followed 20 months later by what is now called the Mammoth Lakes earthquake sequence, of which 11 events had magnitudes close to 5 or larger and four had magnitudes between 6 and 6.3. The four major earthquakes, as well as their aftershock sequences, had fault plane solutions compatible with strike-slip motion along steeply dipping fault planes [*Cramer and Toppozada*, 1980; *Archuleta et al.*, 1982], although considerable debate has revolved around whether the sense of motion was left lateral

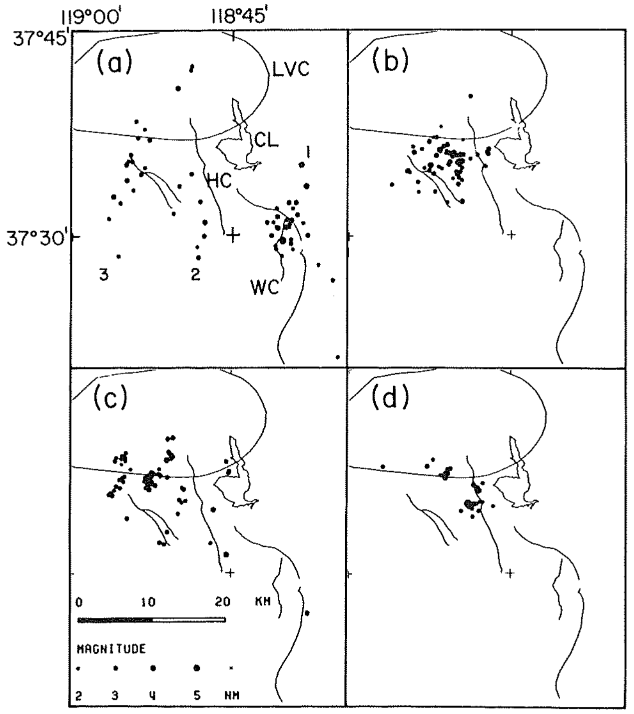


Fig. 19. The evolving pattern of earthquake epicenters in the Bishop-Long Valley area for the period of September 1, 1978, to May 25, 1980 [after *Ryall and Ryall*, 1980, Figure 8]. (*a*) September 1, 1978–November 6, 1979; The subgroups indicated by numbers are (1) October 4–December 13, 1978; (2) February 7–March 26, 1979; (3) April 10–November 6, 1979. (*b*) November 7, 1979–December 18, 1979. (*c*) November 19, 1979–April 17, 1980. (*d*) April 18–May 25, 1980. Also indicated are Long Valley caldera (LVC), Crowley Lake (CL), Hilton Creek fault (HC), and Wheeler Crest fault (WC).

along north-south faults or right lateral along east-west faults. Patterns of first motions are the same for either case. From the distribution pattern of epicenters (Figure 20), Archuleta et al. favor right-lateral motion along east-west faults. *Savage and Clark* [1982], on the other hand, favor left-lateral motion along north-south striking faults.

The unusual nature of seismic activity which followed the Bishop earthquake on October 4, 1978, and which has continued to the present time, is described by *Ryall and Ryall* [1980], *Savage and Clark* [1982], and *Ryall and Ryall* [1983]. Following the Bishop earthquake, seismicity began to migrate through a series of earthquake swarms to the west-northwest, away from the Bishop aftershock area to the west of the Hilton creek fault (Figure 19). The location of almost 1500 earthquakes reported by *Ryall and Ryall* [1983] that occurred in this area from 1978–82 are shown in Figure 21. Some of these events were used by *Ryall and Ryall* [1981] to infer the presence of the anomalous zone of shear wave attenuation described above.

Following the main shocks in May 1980, intensive swarms of small earthquakes occurred in a small area beneath the southwest moat of the caldera [*Ryall and Ryall*, 1983]. Typical swarms lasted several hours and had the appearance of spasmodic tremor. Nine such swarms have been reported, all within a 3-km radius circle centered on 37.63°N, 118.94°W, just to the east of the town limits of Mammoth Lakes (Figure 21). Swarms occurring elsewhere in the region during this time did not have the appearance of spasmodic tremor. Moreover, *Ryall and Ryall* [1983] have suggested that there seems to be a tendency for the more recent earthquakes to occur at shallower depths—a swarm that occurred on May 7–8, 1982, was in the depth range 4–9 km.

Renewal of fumarolic activity at Casa Diablo hot springs to the northeast, but outside, of this 3-km radius area was reported in January 1982. This in itself is not particularly remarkable, since modification of hot spring activity is typical after moderate earthquakes in the Mammoth Lakes-Bishop area. Following the October 4, 1978, Bishop earthquake (magnitude 3.8), a 10–15 m geyser of hot water was observed for a day or so at Hot Creek [*Cramer and Toppozada*, 1980]. Again, following the May 25, 1980, earthquake, three geysers (one 10 m high) suddenly erupted in the Hot Creek area. Moreover, in some places, new boiling pools appeared, and public swimming areas had to be closed because of the high water temperature [*Cramer and Toppozada*, 1980; *Rinehart and Smith*, 1982]. However, the appearance of fumarolic activity in January 1982, along with the localization of spasmodic tremor, which *Ryall and Ryall* [1983] argued is usually associated elsewhere with volcanic activity, led many workers to become apprehensive about the potential volcanic hazard of this region.

Contemporaneous with these latter observations, Savage and Clark circulated a manuscript during the December 1981 AGU meeting in which they reported geodetic leveling data that suggested a dramatic doming of the central part of Long Valley caldera and which apparently occurred between surveys in 1975 and 1980. Even after accounting for a possible displacement of 15 cm along the Hilton Creek fault, following the May 1980 earthquakes [*Clark and Yount*, 1981], one is left with at least 10 cm of uplift to account for. The total doming could of course exceed 25 cm, which, while a remarkable figure, is the value actually preferred by *Savage and Clark* [1982].

This and other manifestations of contemporary tectonic activity are illustrated in the composite diagram of Figure 22. The inferred uplift predicted theoretically by the magma injection model of Savage and Clark is shown as dashed contours centered on the Long Valley resurgent dome. Also shown, as dashed arrows, are the horizontal strains predicted by this model along with the strains actually observed by *Savage et al.* [1980], shown as solid arrows. Although the theoretically predicted and the observed horizontal strains agree at many sites far from the caldera, the results are contradictory for the site just south of the caldera rim (actually the site closest to the resurgent dome). It is not clear whether this is due to the model being inappropriate or whether motions on active faults associated with earthquakes have superimposed local disturbances on an otherwise simple regional pattern.

Also shown in the composite diagram of Figure 22 are the locations [after *Archuleta et al.*, 1982] and the generalized fault plane solutions [after *Cramer and Toppozada*, 1980] of the four major earthquakes in May 1980. The shear wave shadow zone reported by *Ryall and Ryall* [1981] is shown as the hatched area, and the location of the anomalous 1982 earthquake swarm activity is shown as a circle immediately to the east of Mammoth village.

The lack of geometric coincidence of some of these features may in some part be due to an artifact of the geophysical technique used to delineate them. On the other hand this may be suggesting that certain of these phenomena are not, in fact, directly related to one another.

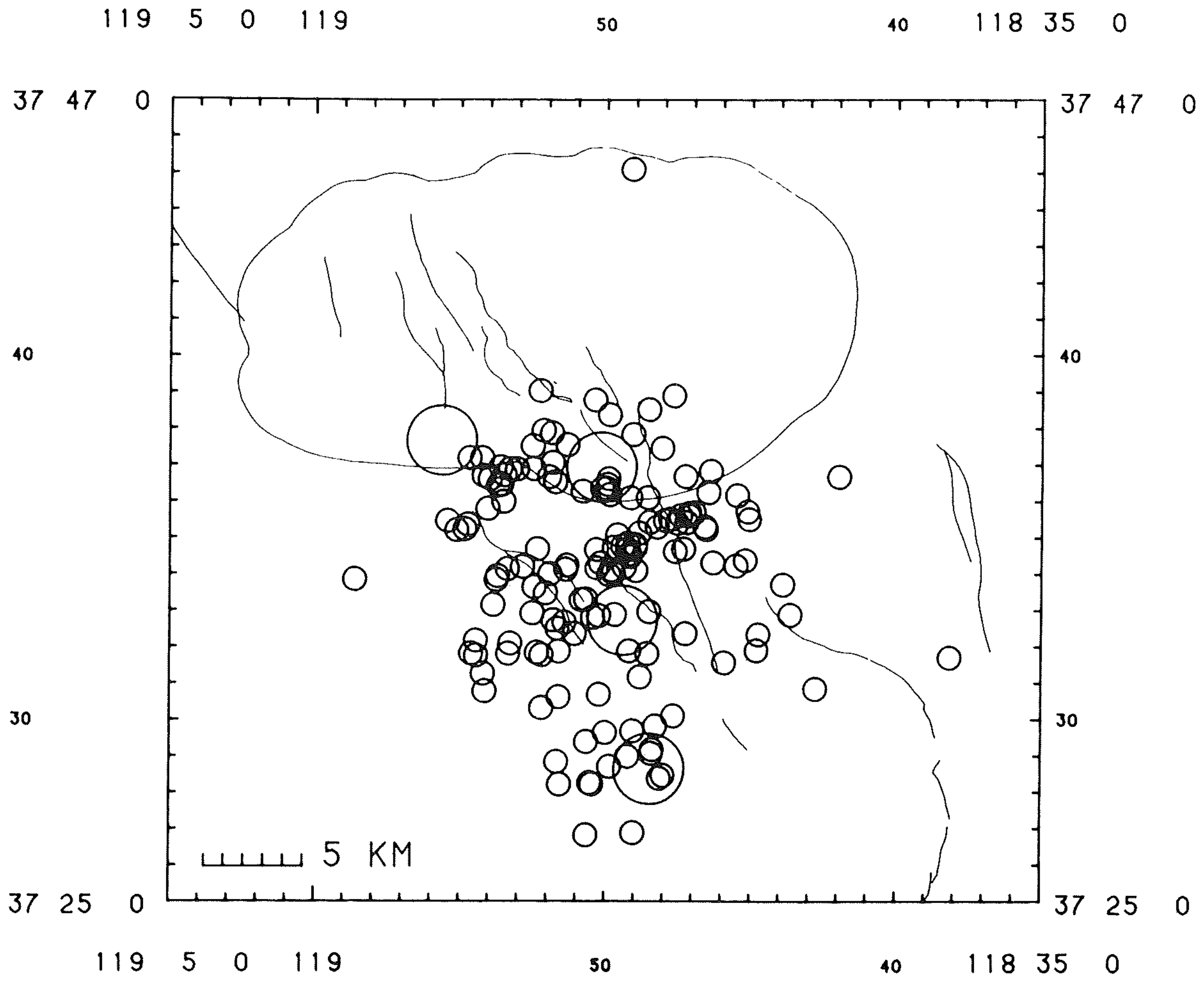


Fig. 20. The epicenters of the four major 1980 Mammoth Lake earthquakes ($M \geq 6.0$, large circles) and 150 aftershocks (small circles). The aftershocks are shown for the period May 26 to June 13, 1980 [after *Archuleta et al.*, 1982, Figure 2].

One must recognize the abnormal nature of the uplift centered on the resurgent dome. The rate of uplift that has been suggested (perhaps exceeding 10 cm/yr) is larger by several orders of magnitude than uplift rates observed in the central and eastern U.S. (which are on the order of 1 mm/yr; *Brown and Oliver* [1976]). The only comparable phenomenon in the western U.S., except in active volcanic areas, is the Palmdale 'bulge,' which was originally described as an uplift of 15–25 cm occurring during the period between 1960–1974 [*Castle et al.*, 1976; *Thatcher*, 1976; *Vanicek et al.*, 1979; *Stein et al.*, 1979]. Castle et al. argue that Palmdale rose by as much as 20 cm between 1961 and 1962. Although some workers have discounted these results on the basis of possible systematic measuring errors [e.g., *Jackson and Lee*, 1979], others have maintained that the magnitude of the uplift far exceeds any possible measuring error [e.g., *Stein*, 1979]. The issue is clearly unresolved [*Rundle and McNutt*, 1981], but there is increasing evidence that aseismic uplifts of the order of 10 cm/yr are not as exceptional as one might expect in tectonic areas. An interesting aspect of the Palmdale bulge, which was largely aseismic, was the occurrence of an earthquake swarm over the interval 1976–77, in which most events were tightly clustered in a 3-km diameter region on the margin of the uplift [*McNally et al.*, 1978]. The similarity between this activity and present seismicity and uplift in Long Valley caldera is worth noting, though it may be superficial. Drawing such an analogy between phenomena in Long Valley caldera and that associated with the Palmdale bulge, one must first be wary that perhaps the leveling surveys themselves may not be free from systematic errors, e.g., uncompensated optical refraction effects and rod miscalibrations [see *Rundle and McNutt*, 1981]. Given, however, that the uplift is real, then the contribution of reginal tectonic strain accumulation may not be inconsequential.

Savage and Clark do not consider tectonic strain as the primary cause of uplift in Long Valley caldera. Instead, they argue that the uplift is associated with resurgent doming caused by magmatic intrusion beneath Long Valley caldera. If so, the second remarkable feature of this phenomenon is its aseismic nature. Most episodes of volcanic intrusion are accompanied by at least some type of seismicity. However, inspection of the composite diagram in Figure 22 shows that the earthquake epicenters are displaced well to the southwest of the zone of greatest uplift. Moreover, the zone of anomalous *S* wave attenuation delineated by *Ryall and Ryall* [1981] is centered to the south of the maximum uplift postulated by Savage and Clark.

Nevertheless, there is a persuasive (but perhaps not compelling) set of evidence to support the hypothesis of renewed volcanic activity in Long Valley caldera: the cen-

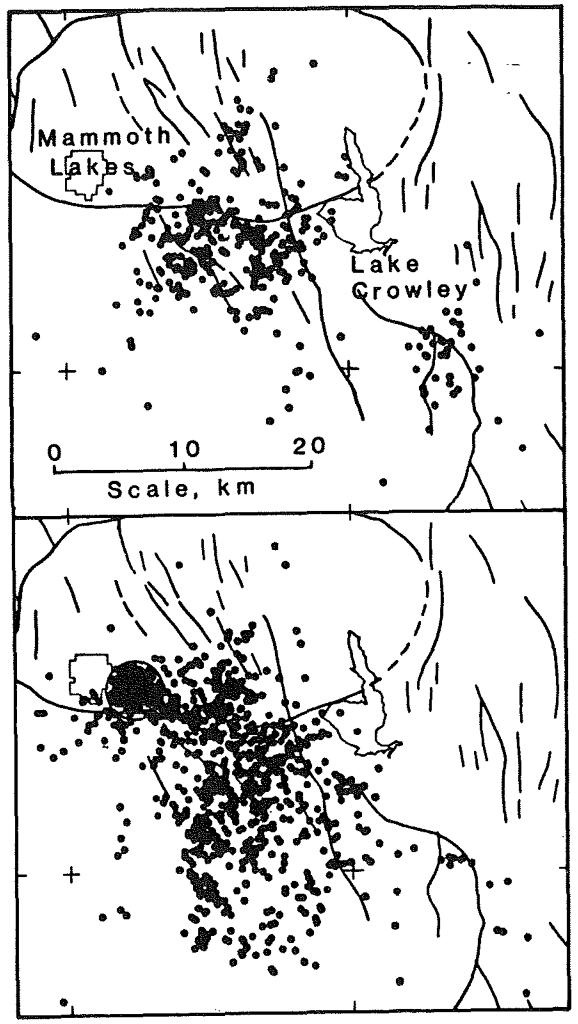


Fig. 21. The evolution of recent seismicity in the region of Long Valley caldera (after *Ryall and Ryall*, 1983, Figure 1]. The outline of Long Valley caldera and prominent faults are shown by the heavy lines. (Top) 386 earthquakes for the period October 4, 1978, to May 24, 1980 (see Figure 19 for the spatial evolution of activity during this time). (Bottom) 1088 earthquakes for the period May 25, 1980, to October 1, 1982; swarms with the appearance of spasmodic tremor were located in the circle just east of the town of Mammoth Lakes.

tralization of spasmodic tremor, the renewal of fumarolic activity, and the resurgence of doming. Based on this the USGS inferred that 'magma at depth beneath the Long Valley caldera was forced upward at about the time of the May 25 to 27, 1980, swarm of magnitude 6 earthquakes, causing bulging in the central part of the caldera and opening of fractures at depth in the southern part of the caldera, thereby allowing a tongue of magma beneath the epicentral site near Mammoth Lakes to begin moving toward the surface.' The potential for a volcanic eruption is not clear at present, nor is it certain that the scenario inferred above is at all appropriate. However in view of the uncertainties of our present knowledge of how these volcanic systems evolve, the issuance of a volcanic hazards notice on May 25, 1982, seems to be well advised [*Miller et al.*, 1982].

Conclusions

The Long Valley/Mono Basin volcanic complex is one of several young volcanic centers along the eastern front of the Sierra Nevadas. It is also one of the three major silicic centers in western North American that are likely to be still active. One of the most intriguing aspects of the Long Valley/Mono Basin complex is that it consists of a number of subsystems that are apparently in different stages of temporal evolution while being geographically displaced from each other. Hence future studies of this volcanic complex offer unique opportunities for piecing together parts of a puzzle that have been obliterated through overprinting in other silicic centers such as Yellowstone and the Valles caldera.

Present geological evidence suggests the possibility that an extensive magma reservoir (or system of reservoirs) may extend from the western portion of Long Valley caldera 30–35 km north to Mono Lake—a feature which, if it exists, has not yet been delineated geophysically. It is well-known, of course, that on a broad scale a distinct transition occurs in the nature of the lithosphere between the Basin and Range and the Sierra Nevada batholith. This is reflected in seismic and electrical data as well as in regional heat flow studies. On the other hand, geophysical experiments have not been sufficiently refined to address this transition in terms of its relation to volcanism along the Sierran front.

We do not know, for example, if the crust directly below the volcanic centers is as thick as suggested by large-scale refraction surveys (50 km) or whether it is locally thinned, as suggested theoretically by certain thermal transport models. We do not know the exact position of the transition between the electrically conducting Basin and Range and the resistive Sierran block. Nor do we know what the background, or so-called 'normal,' heat flow is for this local area. Is the background heat flux typically Basin and Range, as might be assumed from surface geomorphology, or is it typically Sierran, as might be assumed from the presence of what is currently believed to be a thick crustal root (d = 50 km)? Clearly these questions are important to ascertaining the heat flow that the volcanic centers themselves are contributing to values actually observed in boreholes. In fact, it is not clear as to what degree heat flow in boreholes is distorted by the movement of water in the basement.

The thermal regime beneath Long Valley caldera is particularly challenging, both because of the complicated pattern of thermal gradients in shallow, exploratory holes as well as the conflicting observations in deeper holes. Up to the present time, industry has encountered surprisingly low bottom-hole temperatures during drilling to depths of 1.5–2.5 km. This is puzzling, considering that geochemical thermometers indicate that these thermal waters derived from reservoirs having temperatures of 210°–280°C. The source of this high-temperature water is as yet undetected. In fact there is some question as to whether this high-temperature water is present or whether the observations are biased as a result of an artifact of reequilibration with surface waters (R. Rex, personal communication, 1983). The most reliable estimate of the deep heat flow beneath Long Valley caldera is remarkably high (3.5 HFU), but there is some question as to whether basement was actually encountered by the borehole and/or whether the thermal gradients are unperturbed by groundwater movement.

Clearly, characterizing the vertical transport of heat from one or more deep magma sources will only be resolved after intensive studies in a number of intermediate-depth holes into crystalline basement within and outside the caldera. Reliable conductive thermal gradients need to be determined at depths where low permeabilities preclude the advection of heat.

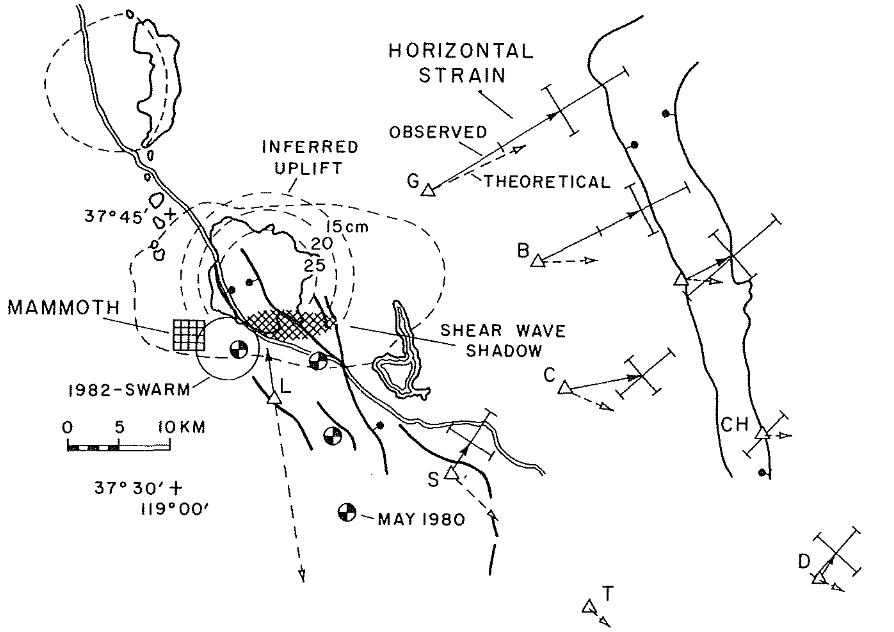


Fig. 22. Composite diagrams showing the interrelationships of various types of recent tectonic activity in the region of the Long Valley/Mono Basin volcanic complex. Long Valley caldera and the incipient Pumice Valley 'caldera' are indicated by dashed lines. Mono Craters and the Long Valley resurgent dome are indicated by solid lines. Owens Valley is shown to the east, and major faults are shown by heavy lines. This figure illustrates horizontal strain, the locations and general fault plane solutions for the major earthquake sequence in May 1980, the shear wave shadow zone, and the theoretical contours of the uplift inferred from recent releveling. The circle to the east of Mammoth village outlines the area of 1982 earthquake activity. The relative magnitude of the horizontal strain at each site can be estimated, noting that approximately a 40-mm strain was observed at site C.

A primitive hydrothermal transport model has proven to be quite useful in providing insight into the major factors affecting the advection of heat in acquifers in Long Valley caldera. However, the model essentially neglects lateral variations in the permeability and thickness of the reservoirs—variations which surface gravity and seismic and limited drill hole data suggest are profound.

In addition the exact manner in which meteoric water enters the system is poorly known. It is commonly postulated that water enters the regional acquifer primarily along the major boundary faults in the western portion of the caldera. However, it is difficult to assess this hypothesis because subsurface structures in this area have not been well studied. It is conceivable that a significant amount of water enters the system from the west by flowing laterally from outside the caldera through cracks and joints in the basement.

In addition, it is possible that a freshwater acquifer of considerable thickness (3–4 km) may exist beneath the northern and western moats. Whether or not such a feature is present has important implications for evaluating the degree to which fresh groundwater resources can be developed in the region. In some sense, surface geophysical studies can address this question, but the ultimate test is drilling.

It has been argued for many years that our knowledge of the hydrothermal system, in fact the general hydrology, of Long Valley caldera suffers from the lack of comprehensive deep drill hole data. We can only reaffirm this position.

Basic inconsistencies persist between gravity and seismic interpretations, not only regarding depth to basement but also regarding lateral variations in the character of basin fill. Not surprisingly, much of the fine structure inferred from gravity is absent in seismic refraction interpretations. It is not clear whether this is due to superficial lateral variations in density (e.g., changes in porosity) or whether the gravity is actually reflecting first-order structures in the basement that seismic refraction studies are smoothing out. Refined geophysical studies, calibrated against actual drilling results, would go a long way toward improving these interpretations.

Popular notions view the basement beneath Long Valley caldera as an impermeable layer across which heat is vertically transported by solid conduction from a deep magma reservoir into an advecting hydrothermal acquifer within the basement fill. Our knowledge of actual basement characteristics (hydrological, petrological and geophysical) is limited at best and totally absent at worst. Since vertical heat transport is controlled by the nature of basement materials, and since most of the recent tectonic activity occurs in the basement (at a depth of 4–10 km), our ignorance of this regime is a significant impediment to developing a comprehensive understanding of the total system.

Over the last few years a significant increase of tectonic activity in Long Valley caldera has lead some workers to infer that magma has intruded the upper crust, and there has been rising concern about the possible renewal of volcanic activity at the surface. The three most compelling pieces of evidence for this are the recency of volcanism along Inyo Domes (perhaps as young as 200 yr b.p.), the localization of spasmodic tremor in the southwest moat, and the recent uplift of the resurgent dome. Few would argue that geological dating and stratigraphic mapping should be intensified to better understand the prehistoric development of Inyo Domes, Mono Craters, and the volcanic centers in Mono Lake.

In addition, an understanding of the mechanism of spasmodic tremor needs to be developed to a point where workers can confidently say that, in fact, this phenomenon is directly caused by magmatic injection—at present, several other causes are possible, some of which have no direct relation to volcanic intrusions.

Finally, the magnitude of recent uplift of the resurgent dome has to be established beyond any question of leveling errors of the type associated with the so-called Palmdale 'bulge.' Having done so, it is still imperative to separate the effects of tectonic strain from the effects of a possible magmatic intrusion. Up to 10 cm of the presently reported 25-cm uplift can be accounted for by coseismic displacement during the May 1980 earthquakes. How much of the rest can be accounted for by tectonic deformation rather than magmatic injection? Many episodes of magmatic inflation are spatially associated with intensive seismic swarming. Why are the seismic swarms in Long Valley caldera significantly displaced from the zone of maximum uplift?

In short, recent manifestations of tectonic activity in Long Valley caldera highlight the importance of understanding the dynamics of this region, but in no way should future science be driven totally by what is presently happening beneath the southwest moat. The entire complex is rich in research problems that have only begun to be addressed.

The case I have tried to present here concerns the wide variety of unanswered questions still associated with the Long Valley/Mono Basin volcanic complex. Clearly, a well-planned drilling effort to intermediate depths (1.5–2.5 km) at a number of sites, closely coordinated with surface geophysical studies, would immeasurably improve our ability to model subsurface structure and stratigraphy. This in conjunction with refined petrologic studies would, in the long term, provide the necessary constraints needed to quantitatively reconstruct the temporal and spatial evolution of these volcanic systems.

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