

What's New at Long Valley

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At few places in the conterminous United States does magma, the raw material of the Earth's crust and mantle, appear as tantalizingly close to the surface as at Long Valley caldera in eastern California. Here the search for a site to drill into a magma chamber for the purpose of geothermal energy development coincides with a separate scientific imperative, the need to monitor the caldera for potential hazards due to earthquakes and volcanic eruptions. The region has a proven potential for these hazards; five $M \geq 6$ earthquakes have struck since 1978, and phreatic, ash and steam, eruptions have occurred as recently as 550-600 years ago [Miller, 1985]. As we assess the results of additional intermediate depth holes and the results from a widening spectrum of divining tools, the magma seems farther from the surface and less abundant than it did just a few years ago. We have also begun to discern the profound imprint of structures which predate the formation of the caldera 0.73 Ma and which now appear to control its eruptive behavior and hydrothermal system.

To help plan future drilling of the caldera, a symposium was held at Lawrence Berkeley Laboratory in California in 1987; a volume of extended abstracts [Goldstein, 1987] and a meeting report in *Eos* [Goldstein, 1988] followed. Most of the papers which appear in this issue were born at the Berkeley conference. Special sections of the *Journal of Geophysical Research* devoted in part or in total to the caldera appeared in 1976, 1984, and 1985 [Muffler and Williams, 1976; Lipman et al., 1984; Hill et al., 1985]. The Geothermal Technologies Division of the Department of Energy plans to begin drilling the first phase of a deep hole in 1988, which is hoped to reach conditions close to the solidus temperature of a silicic melt at a depth of 6 km.

MAGMA CHAMBER CHARACTERISTICS

The most persuasive evidence for contemporary magmatic injection is the past decade of measured surface deformation [Savage and Clark, 1982; Savage, this issue; Vasco et al., 1988; Wu and Wang, this issue]. Since 1975, geodetic leveling and electronic distance measurement have discerned a dome-shaped uplift, now about 0.5 m, and areal extension centered on the resurgent dome (Figure 1).

Uplift has been contemporaneous with widespread seismicity at depths of 4-8 km. Some of these earthquakes exhibited characteristics of dike-like injections of magma [Julian, 1983; Julian and Sipkin, 1985]. Resurveys of leveling and trilateration networks began in 1980 following the sequence of four

magnitude 6 or larger earthquakes that year. The networks were expanded in 1982 and 1983, and the more complete geodetic control has better defined the cumulative deformation during the 1982-1987 interval. The deformation, believed mainly due to reinflation of a magma chamber [Savage and Clark, 1982; Savage et al., 1987; Savage, this issue; etc.], has been described in terms of three major components: (1) roughly symmetric uplift centered on the southern part of the resurgent dome, (2) down-to-the-east normal slip along the north end of the Hilton Creek fault (Figure 1), and (3) right-lateral slip on the south-moat fault, which is also defined by an east-southeast trending zone of earthquake epicenters [Savage et al., 1987; Savage, this issue].

Savage [this issue] shows from principal component analysis of trilateration and leveling data that the deformation can be accounted for by a single coherent source; higher-order components are either insignificant or can be explained as systematic measurement errors. The temporal components of the analyses show a clear correlation between uplift and horizontal strain and show that a uniform rate of deformation has persisted during the 1984-1987 interval following a more rapid rate in 1983-1984.

The deformation gives an accurate indication of the location of the source of inflation and a reasonable measure of its depth. However, as McTigue [1987] explained, analysis of deformation data gives a poor indication of the geometry of the region undergoing expansion. As a consequence, one of the most important parameters for both drilling and volcanic hazards monitoring, the depth to the roof of the magma chamber, is the least certain. Assuming an ellipsoidal expansion volume, Wu and Wang [this issue] conclude that the center of inflation is at 9.5 km depth, which agrees with many earlier estimates for point sources of 8-10 km depth. The dimensions of the body are not resolved, although a spherically shaped zone of inflation satisfies the horizontal displacement data better than a prolate ellipsoid. Making no a priori assumption of the expansion zone geometry, other than that needed for discretization, Vasco et al. [1988] find that L^2 norm minimization of the differences between predicted and observed uplift, subject to the condition that only expansion occurs, places most of the expansion in 4- to 8-km depth interval and beneath the resurgent dome for the 1985-1982 interval. Although this depth interval is among the shallowest reported by various workers, the depth of expansion depends on the discretization. Regardless of chamber model or time interval studied since 1975, results to date indicate that the amount of magma chamber inflation or magma intrusion is small, probably of the order of 0.20-0.25 km³ between 1975 and 1985. Assuming that the entire expansion resulted from

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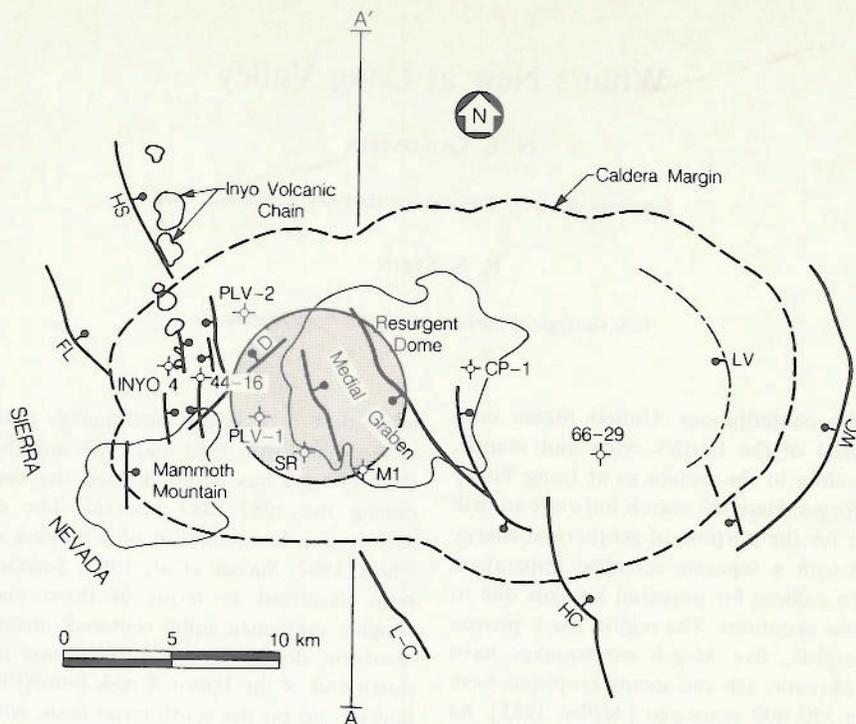


Fig. 1. Map of the Long Valley caldera showing some of the major faults within or near the caldera (HS for Hartley Springs, FL for Fern Lake, D for Discovery, L-C for Laurel-Convict, HC for Hilton Creek, LV for Long Valley, and WC for Watterson Canyon). Also shown are some of the holes drilled for geothermal exploration or scientific studies within the caldera. The shaded area is the approximate location of a midcrustal P wave velocity low (2–5% less than the mean velocity for 9- to 20-km-deep layer) [Dawson *et al.*, 1988]. A-A' is a north-south line of section (longitude $118^{\circ}54.5'W$) through well M-1 at Casa Diablo Hot Springs (See Figure 2).

the movement of magma from a deeper chamber to midcrustal depths, the uplift would correspond to the intrusion of, for the sake of numerical example, 8–10 dikes each 1 m thick and 5 by 5 km in extent.

While there seems to be incontrovertible evidence for recent magmatic activity, opinions have varied on the geometry and condition of the melt zone. A model drawn mainly from seismic results [Hill *et al.*, 1985] indicated that the present-day magma chamber could be between 500 and 1000 km³. Magma that has coalesced to this volume would pose a serious potential volcanic hazard for an eruption, one several orders of magnitude greater than the Mount St. Helens eruption. However, the absence of both a conspicuous thermal anomaly [Lachenbruch *et al.*, 1976] and a deep conductor caused Hermance [1982] to question whether a large, well-connected melt exists at the depths indicated by the seismic and deformation anomalies.

The model that is emerging, and which is supported by a number of papers in this special section, is an anomalous midcrustal zone beneath the western part of the caldera that hosts separate small batches of melt. The zone was first recognized by Steeples and Iyer [1976], who imaged a midcrustal low-velocity anomaly using P wave delays of teleseisms. Using additional data, Dawson *et al.* [1988] refined the velocity interpretation, and they estimate a 200 km³ region containing partial silicic melt (Figure 1 and 2). Carle [this issue] carried out a detailed three-dimensional inversion of the isostatic residual gravity anomaly and found two low-density zones in the midcrust that cannot be explained by low-density caldera fill or other causes. The larger of the two correlates very well with the source of the P wave travel time anomaly (Figure 2)

and thus supports the contention that the midcrustal velocity anomaly represents a root zone that may yet contain an appreciable percentage of melt.

As yet there is no clear indication of an electrical conductivity anomaly associated with the velocity and density anomalies. With the benefit of data from 77 magnetotelluric stations, Park and Torres-Verdin [this issue] completed the first detailed three-dimensional resistivity interpretation of the entire caldera. Within the uncertainty of the data, all of the conductivity inhomogeneities needed to account for the phase spectra are confined to the caldera fill, i.e., to layers no deeper than 1.6 km. At greater depths the crust appears layered and resistive. On the basis of sensitivity analyses the authors rule out the possibility of a large, conductive melt centered at 8 km. However, they do not rule out the presence of smaller melt zones, each of the order of 30–40 km³, at depths greater than 5 km, and with the resistivity of a wet, granitic magma (5 ohm m).

Evidence for a small cupola or upward extending finger of magma beneath the southern end of the resurgent dome has been based on shear wave attenuation [Sanders, 1984] and delays in P wave arrivals [Elbring and Rundle, 1986]. A detailed reexamination of high-quality borehole seismograms and surface seismograms by Hauksson [this issue], however, shows that the compressional-to-shear wave velocity ratio is in fact constant with depth. This means that a magma chamber need not be present, although a small melt zone, one with a diameter less than 3 km, cannot be resolved from the data.

New studies of the Inyo volcanic chain, the most recent of whose 15 rhyolitic domes and explosion craters have been

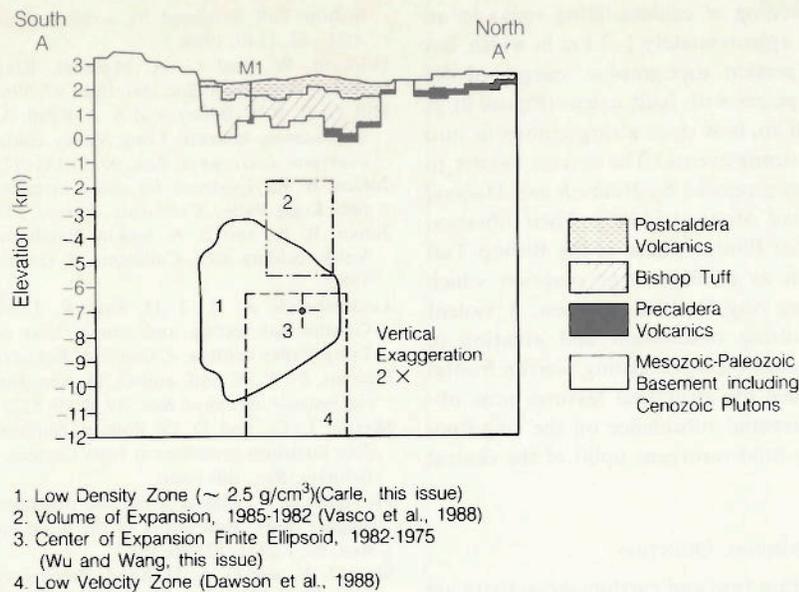


Fig. 2. A north-south cross section through the Long Valley caldera at longitude $118^\circ 54.5' \text{W}$ showing geophysical anomalies discussed in this paper and in the following papers of this special section. The low-velocity zone from teleseismic P wave delays is also shown for reference [Dawson et al., 1988]. M-1 is the Mammoth 1 hole at Casa Diablo Hot Springs. The vertical exaggeration is 2 times.

carbon dated at only 550–600 years [Miller, 1985], reveal several surprises. Eichelberger et al. [this issue] report that a slant corehole (Inyo 4 in Figure 1) designed to intersect the rhyolitic feeder dike directly below the South Inyo Crater intersected three rhyolitic breccia zones, the largest of which contains basalt clasts and was probably a feeder for the earlier basaltic eruptions as well. Although the vesicular rhyolite in the breccia matches fresh-appearing pyroclasts in the crater ejecta, the rhyolite is chemically different from the rhyolites associated with the Inyo Domes farther to the north along the chain. These results not only support the hypothesis of multiple feeder dikes for the Inyo volcanic chain [Fink, 1985; Mastin and Pollard, this issue; Suemnicht and Varga, this issue], but they also support the argument that the Inyo volcanic chain erupted from at least two different batches of melt [Sampson and Cameron, 1987].

If the multimagma model for the Inyo volcanic chain is correct, can it be extrapolated to the present-day condition of the caldera? If it can, then what could explain the multiplicity of seismic reflectors and attenuation zones beneath the caldera [Hill et al., 1985; Goldstein, 1987]?

Detailed surface mapping around the South Inyo craters and numerical and scale model experiments to simulate the Inyo dike intrusion by Mastin and Pollard [this issue] lead to new insights about the physics and deformation associated with dike emplacement. They point out the importance of inelastic processes at the dike tip and that these processes are the least understood facet of dike advance and termination. The dike thickness predicted from scale model experiments to explain the surface deformation is an order of magnitude larger than found by drilling [Eichelberger et al., this issue]. While there are several possible explanations for this large difference, Eichelberger et al. suggest that the surface deformation may not solely be the result of magmatic intrusion. Fault displacement and compaction of caldera fill may have contributed to the surface deformation. If so, might the eruptions be related to, possibly triggered by, a major earthquake

along the Hartly Springs fault? This mechanism would explain the coeval eruption of magma from separated chambers beneath the 11-km extent of the Inyo volcanic chain.

CALDERA EVOLUTION AND STRUCTURE

Three recently completed drill holes in the west moat area provide new and surprising information on caldera structure, the thermal regime, and the hydrothermal system for that part of the caldera. The locations of the Shady Rest (SR) corehole [Wollenberg et al., 1987], the Unocal 44-16 geothermal exploration hole [Suemnicht and Varga, this issue] and the Inyo 4 slant corehole [Eichelberger et al., this issue] are shown in Figure 1. Holes SR and 44-16 encountered the highest subsurface temperatures yet measured in the caldera ($200^\circ\text{--}220^\circ\text{C}$), reinforcing the view that the present-day heat source driving the hydrothermal system must underlie the rhyolite-basalt domes and flows in the western part of the caldera. Hole Inyo 4, on the other hand, reveals that the 600-year-old Inyo eruptions had no more than a trivial thermal effect on the hydrothermal system.

A yet unanswered question is what faults presently control the hydrothermal system beneath the west moat. It has been generally assumed that north-south and north-northwest striking normal faults, such as the precaldern Sierran range-bounding faults, are the most numerous and important. However, Suemnicht and Varga [this issue] argue for a system of northeast trending faults. One of these, the Discovery fault, appears to have been a conduit for meteoric-hydrothermal circulation within the last 0.1 m.y., and its intersection with the north-south trending faults might be an important geothermal target.

Suemnicht and Varga [this issue] present a simplified cross-section view of caldera structure based on a compilation of drilling results. Constraining parameters in his gravity inversion by the same drill hole data, Carle [this issue] also presents a number of geological cross sections based on the gravity data. An unsuspected feature revealed by these structural

cross sections is the thickening of caldera-filling rocks in an annular zone. The zone is approximately 1–2 km in width, lies 2–3 km inboard of the present topographic margin of the caldera, and correlates in places with fault scarps (Figure 2). Is this zone a ring graben? If so, how does a ring graben fit into the sequence of caldera-forming events? The correct answer to this may have already been proposed by Hildreth and Mahood [1984, 1986] and Metz and Mahood [1985]. Their observations suggest that the initial Plinian phase of the Bishop Tuff eruption may have begun as a single vent eruption which evolved into a propagating ring fracture eruption. A violent ring fracture eruption causing brecciation and ablation of basement rocks, superimposed on a preexisting Sierran frontal fault pattern, might produce the structural features now observed, particularly if differential subsidence on the ring fracture zone was followed by mild resurgent uplift of the central part of cauldron.

THE REGIONAL QUESTION

Although the current strain rate and earthquake activity are much less than during the 1980–1984 period, Long Valley continues to be a very active area, and our desire to understand the dynamics of this unique volcanic system continues unabated. On a regional scale we still grapple with the causes for the episodic nature of the recent major seismicity and the relation of that seismicity to Sierran front tectonics and with what may be the stirrings of possible related magmatic complexes to the north at Mono Craters and to the south, deep within the Sierra batholith. Processes and conditions at Long Valley may hold the key to understanding the present-day tectonics and volcanism in the transition zone between the Basin and Range and Sierra Nevada.

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