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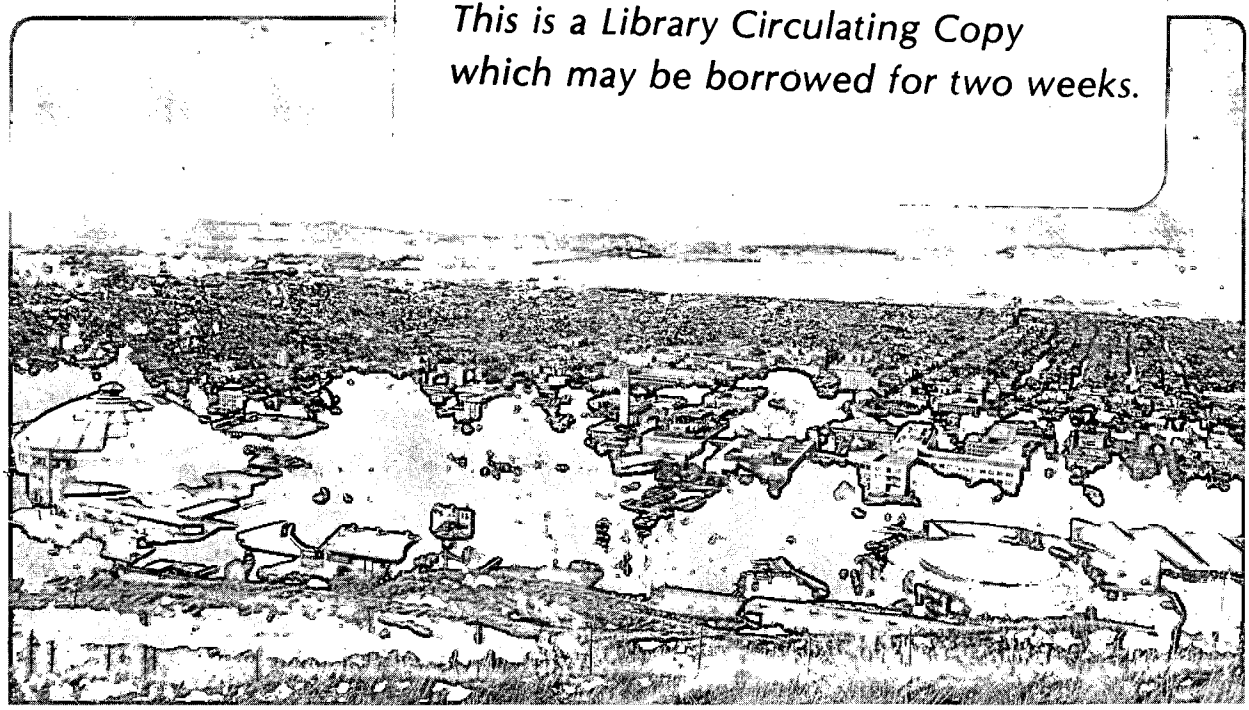

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Using Surface Displacement to Constrain Deformation at Long Valley Caldera, CA

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During the ten-year interval 1975–1985 up to 47 cm of vertical displacement has been measured within Long Valley caldera (Savage and Clark, 1982; Castle et al., 1984). Four surveys from this period, those made in 1982, 1983, 1984 and 1985, are examined relative to a survey from 1975. Because leveling prior to 1975 detected little or no displacement, this survey may serve as a base for subsequent measurements. The magnitude of the uplift from 1975 to the present and the occurrence of strong earthquake activity within the caldera has led to the suggestion that magma intrusion has taken place (Savage and Clark, 1982; Savage and Cockerham, 1984; Rundle and Whitcomb, 1984; Castle et al., 1984). Besides the observed deformation, the hypothesis of resurgent magmatic activity is supported by many lines of geophysical evidence, such as *P*-wave teleseismic delays (Steeples and Iyer, 1976; Ryall and Ryall, 1981), *S*-wave attenuation (Sanders, 1984; Sanders and Ryall, 1983), *P*-wave tomography (Kissling et al., 1984) and focal mechanisms (Julian, 1983).

To derive constraints on the possible magma intrusion in the region we assume that the uplift is only due to volume expansion. The effects of local faulting and regional tectonic forces were accounted for through modeling and the addition of error terms. Using the uplift data, we examined (a) the bounds on the depth to the top of any intrusion satisfying the data, (b) the total volume change associated with the intrusion satisfying the data, and (c) the incremental volume changes associated with the intrusion for the years 1982, 1983, 1984,and 1985. It was found that magma intrusion occurred above a depth of

13 km. Line 1 is the long northwest to southeast line of leveling stations that follows Highway 395 across Long Valley and over the western edge of the resurgent dome.

A generalized inverse was constructed. No assumptions of positivity were made in deriving this model. The noticeable elements in this solution are concentration of expansion in the second layer (4–8 km) and the lack of significant expansion below 12 km. The expansion is distributed within the second layer with little apparent concentration. The lowest region, below 12 km, contains contracting elements. This feature is attributed to elevation decreases outside the caldera and the discretized region of the model.

The result of minimizing the l^1 norm of the residuals, subject to the constraint that only expansion occur in the region, is presented. In detail this model differs from the generalized inverse, but both results share common elements. Again the bulk of the volume expansion, .20 km^3, occurs in the second layer. This time the changes are concentrated in the center block. No changes are found below this layer, and only diffuse expansion is found above it; most are less than .06 km^3.

We calculated a temporal estimate of the constraints on the possible intrusion at Long Valley caldera. No significant changes have occurred in the constraints on the depth of any magma body satisfying the data. Hence there is no suggestion that significant magma movement has occurred following the initial activity in the interval 1982–1975. Two models of volume change between 1983 and 1985 were derived, each using different assumptions. The models have certain features in common, such as predominant expansion between 4 and 8 km and very little expansion below 12 km. These features agree with the results from other inversions of displacement data, as shown in Table 1. They also support recent tomographic inversions (Kissling et al., 1984; Kissling, personal communication, 1986) in which the significant low *P*-velocity lies above 8 km.

TABLE 1

Model Comparisons				
Reference	Interval	Chamber Model	Depth to Center	Volume Change
Savage & Clark, 1982	1980-1975	point source	11	0.15
Savage & Cockerham, 1984	1983-1982	dipping dike	10	0.03
Rundle & Whitcomb, 1984	1983-1975	two spheres	5,8	0.0045,0.05
Castle et al., 1984	1983-1975	sphere	10	0.19
Denlinger & Riley, 1984	1982-1975	sill,sphere	7-8,<7	0.019,0.004
Wu & Wang, 1987	1983-1975	ellipsoid	10	0.18
This paper	1985-1982	l^1 inversion	4-8	0.20

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Summary of Discussions

At the conclusion of the prepared talks, several scientists were asked to give their views regarding the scientific results presented at the symposium and in particular how these results are influencing the choice of drilling targets for the DOE programs such as Magma Energy Development and Thermal Regimes CSDP. The speakers were Roy Bailey (USGS), Jack Hermance (Brown University), Dave Hill (USGS), Gail Mahood (Stanford University), John Rundle (SNL), Ross Stein (USGS), and Gene Suemnicht (Unocal). Overall, their feeling was that significant progress seems to have been made in imaging the caldera structure and that we also have a much improved model for the hydrothermal system within the post-caldera rocks. However, there was no consensus among the speakers on the best place to drill to intersect a magma body. Gene Suemnicht, representing the interests of the Geology-Geohydrology-Geochemistry Study Group, favored a drilling program in the western moat area. John Rundle, on the other hand, showed that a plot of overlapping geophysical anomalies would dictate a deep drill hole on the resurgent dome. Jack Hermance made a strong argument for beginning a drilling program as soon as possible so as not to lose the momentum of the program and the interest of the scientific community, which has invested so much time and energy in the planning of a thermal regimes drilling program in Long Valley. He stated that we may never have enough information to pick the best site. Gail Mahood argued that it may be impossible to pick a best site in Long Valley because magma probably occurs in too small a volume to be clearly resolved by means of geophysics. She felt that if DOE were truly interested in a drillhole to magma, the only logical site is Yellowstone.

The results of drilling, geophysical studies, and geochemical analyses of soil gases and waters strongly support the long-held notion that the active upflow zone of the hydrothermal system and the heat sources driving the system are located in the west-southwest portion of the caldera. The following picture of the hydrothermal system has emerged. The principal recharge is from the west and northwest rims of the caldera; the cold waters invade selected volcanic units within the caldera fill or, guided by major Sierran frontal faults, penetrate the Paleozoic metasedimentary roof pendant rocks to depths of over 2 km, where they are heated to 220–230°C . The hot waters then ascend along a series of northwest-trending intra-caldera faults in the west and south moats and spread laterally into permeable units of the Bishop Tuff and Early Rhyolites. Most of the flow is west to east; a tongue may flow northeasterly through the resurgent dome. The cooled, mixed waters discharge at permeable fault zones on the south and east sides of the resurgent dome. Small ^{18}O shifts in the discharge waters indicate either a large water/rock ratio or rocks depleted in ^{18}O as a result of prolonged hydrochemical reactions. The increase in the $^{3}He/^{4}He$ ratio from west to east suggests the incremental addition of magmatic ^{3}He. The episodes of high seismicity in the period 1980–1983, when there was major swarm activity in the south moat, seemed to have a temporary effect on the hydrothermal system. The most notable changes were an increase in the temperature of thermal water discharges and co-seismic peaks in Rn, H, and other gases.

Electrical methods, mainly magnetotellurics and time-domain EM, essentially support the hydrogeological model and have aided in its development. Conductivity anomalies in the first 2 km are complex and are believed to be due mainly to an

increased concentration of hydrothermal clay minerals (smectites) but perhaps in part to increased temperature, matrix porosity, and fracturing.

Opinions varied on the nature of the heat sources driving the hydrothermal system. Although several geophysical papers presented at the symposium made specific reference to the possible effects of magma on the data, much of what was presented argued against the notion that a large, continuous magma chamber measuring 500 to 1000 km^3 exists today. Individual melt zones are likely to be small. Such zones would present both a challenge to detection by geophysics and to intersection by drilling.

The present limits of resolution using electromagnetic and seismic geotomography are not good enough to resolve individual bodies less than 2 km in linear dimension and deeper than 4 or 5 km. It is a real challenge to geophysicists to design experiments to improve on this. On the positive side, however, Roy Bailey was encouraged by the coincidence of the *P*-wave anomalies beneath the western part of the caldera and, in particular, their proximity to the extension of the Hartely Springs Fault, which has been a focus of magma eruption in post-caldera times. These anomalies may reflect the residual part of the main Long Valley chamber, now mostly crystallized but kept hot by continued injections of basaltic magma. Gail Mahood also pointed out that we cannot ignore the possible heating of waters by relatively shallow intrusives beneath the west moat and the composite rhyodacitic volcano known as Mammoth Mountain.

There also remain strong arguments, as expressed by Jack Hermance, John Rundle, and Ross Stein, for a major source of heat beneath the resurgent dome. Although holes in this area have encountered generally low temperatures, the resurgent dome area is roughly the center of many overlapping geophysical anomalies. Besides the seismic anomalies that several workers have reported, the main evidence for a deep heat source comes from the uplift data and an unexplained but possibly interesting SP anomaly. Ross Stein argued that even though the estimated 0.1 to 0.2 km^3 of magma injected beneath the resurgent dome is a small amount, the deformation and related seismicity in the south moat are among the strongest geophysical anomalies detected in the caldera. Therefore, they are among the best pieces of evidence that a major heat source exists beneath the affected areas.

John Hermance and John Rundle felt strongly about the need to formulate a drilling and science plan as quickly as possible and to begin drilling despite our current uncertainties. They argued that we already have enough testable geophysical targets so that a hole drilled from almost any location in the west-southwest part of the caldera or from the resurgent dome would prove to be not only of scientific value but would also provide a focus for future Long Valley activities. A hole intelligently located would serve several objectives: (1) a study of the deep parts of the hydrothermal system, (2) a means to calibrate present interpretations and models, and (3) an opportunity to conduct deep geophysical observations and experiments.

With regard to better defining the hydrothermal system, Mike Sorey, Gail Mahood, and Gene Suemnicht clearly favored a hole in the west moat, somewhere near the Shady Rest hole or toward Mammoth Mountain. Their principal objectives

are to drill and test the hottest part of the present-day hydrothermal system, to test for the contribution of heat from post-caldera intrusives, to study in detail the temperature-age relationships of multiple episodes of hydrothermal alteration, and to intersect fault zones that strongly influence fluid flow.

Seismologists at the symposium had the most divided views on the significant seismic anomalies and on the question of whether to drill a deep hole and what its target should be. The need for better and more carefully planned seismic experiments was evident in the opinions expressed by a few. Among the large number of unexplained phenomena the seismologists want to investigate in future experiments are the following: (1) the nature, distribution, and cause(s) of *P*- and *S*- wave attenuation, (2) the causes of site-dependent late *P*- phases, (3) the cause of the low-frequency earthquakes around Mammoth Mountain, and (4) the cause of the deep reflections and their relations to melt zones. Answers to all these questions might be obtained from a well-designed experiment involving long-term monitoring using a downhole array of 3-component geophones. The high-quality data possible from this array would allow seismologists to study local microseisms originating from within the caldera, larger regional earthquakes, and teleseisms.

On a regional scale, seismologists and geologists are still grappling with the causes for the recent episodic nature of major seismicity in relation to Sierran front tectonics and in relation to what may be the stirrings of possible related magmatic complexes near Long Valley, such as to the north at Mono Craters. Understanding the causes of the geophysical anomalies associated with the Long Valley caldera may hold the key to understanding the present-day tectonic and volcanic processes along the eastern front of the central Sierra Nevada.

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