GL03165-9 of 12

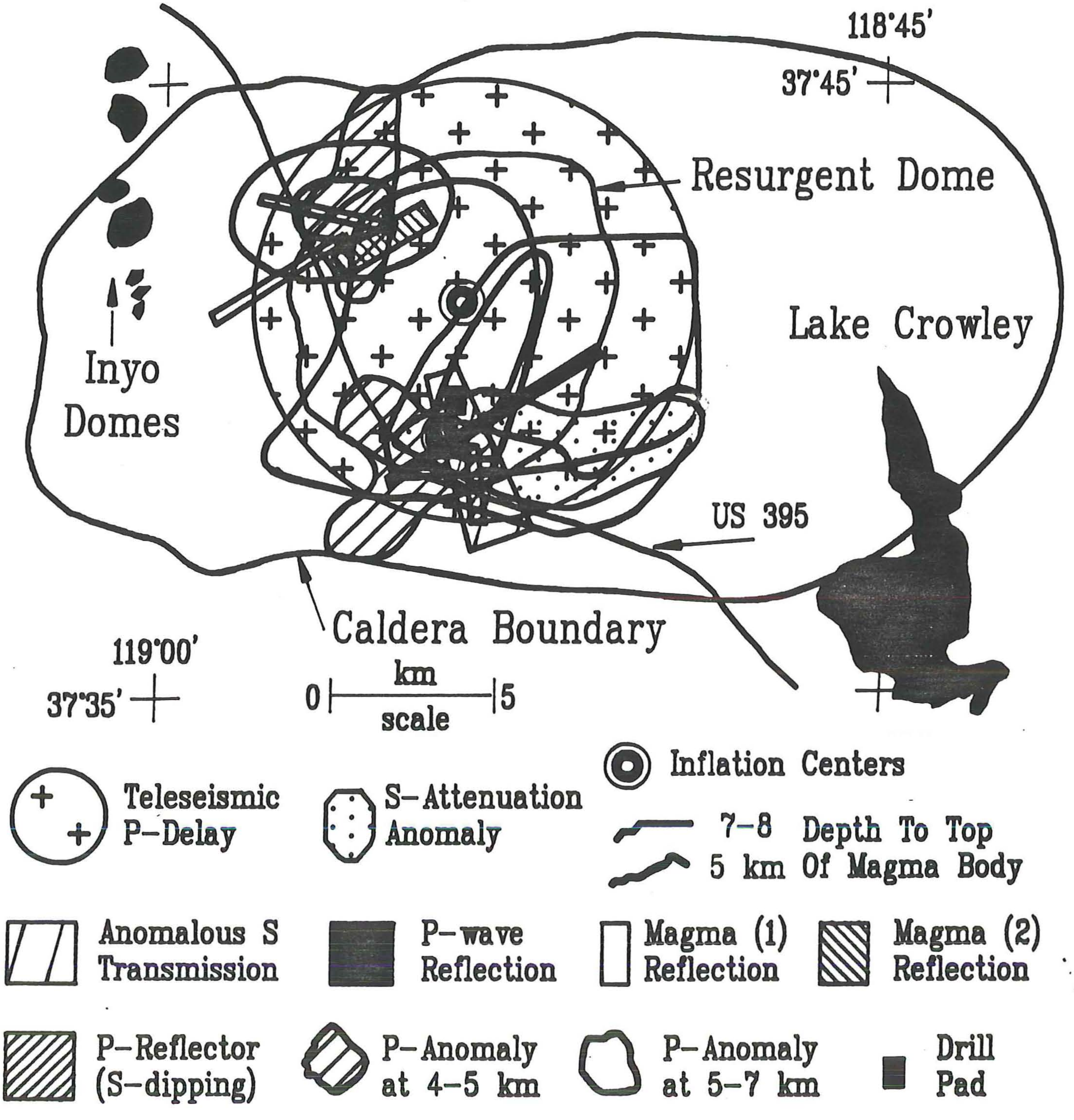
#8

EOS

Transactions, American Geophysical Union
Vol. 67 No. 21 May 27, 1986

Geophysical Evidence For Magma:

Long Valley Caldera, California



Eos, Vol. 67, no. 21, Pages 490, 491, May 27, 1986

Deep Drilling to the Magmatic Environment in Long Valley Caldera

John B. Rundle,
Charles R. Carrigan,
Harry C. Hardee,
and William C. Luth
Geoscience Department, Sandia National Laboratories,
Albuquerque, N.M.

Earthquakes, ground uplift, and increased hydrothermal activity are only the most recent examples of the intense tectonic and volcanic activity that has occurred at Long Valley caldera, Calif., over the last 3 million years. A large number of geophysical experiments, conducted by several hundred investigators over the past few years, clearly indicate that a major body of magma exists within the central part of the caldera at drillable depths of 4–5 km. Plans are underway to drill toward and eventually into this magma body.

Introduction

Long Valley caldera in eastern California has been the focus of intense scientific interest in the past 5 years, largely because of considerable deformation, seismic, and hydrothermal activity since 1980 [for example, *Rundle et al.,* 1985*a*; *Hill et al.,* 1985*a*]. Long Valley, which was formed in the great Bishop Tuff eruption some 0.7 m.y. B.P., has been the site of considerable eruptive activity ever since, with the most recent extrusion event being the Inyo Domes and flows of 500 years ago. Beginning in 1980, renewed activity within the caldera, including intense seismic swarms with peak magnitudes $M_L > 6$, uplift in excess of 0.5 m, horizontal extension across the caldera of 2–4 ppm/yr, and visible changes in the surficial hydrothermal system herald the onset of a new cycle of tectonism. Analysis of the deformation data has in fact revealed that as much 2×10^8 m^3 of new magma has been injected into the magmatic "plumbing system" beneath the caldera during the past 5 years.

Cover. Locations within the Long Valley caldera for the results of recent seismic experiments. The legends for the various studies are given in the figure, which illustrates the dense coverage of the entire resurgent dome. The studies show that minimum depths to all the anomalies illustrated agree very well: about 4–5 km underneath the southern end of the dome and about 6–8 km underneath the northern end of the dome. The Long Valley caldera has been the site of intense volcanic and tectonic activity for 3 million years. Plans are now underway to drill a well toward and eventually into the magma body indicated by the anomalies. For more details, see "Deep Drilling to the Magmatic Environment in Long Valley Caldera," by John B. Rundle et al., p. 490

Geophysical data collected by hundreds of investigators during the past 15 years indicate that a major body of magma, with essentially the same volumetric capacity (600 km^3) as that responsible for the Bishop Tuff eruption, presently exists within the confines of the caldera. Both the current activity and extent of the subsurface parental magma body have led a variety of agencies and programs to focus upon Long Valley as a primary site for further, more detailed, scientific investigations [*Rundle et al.,* 1985*b*]. Chief among these investigations is the possibility of drilling a well as deep as 6 km into the magmatic environment. This endeavor is of interest to two programs: the Continental Scientific Drilling Program (CSDP), a cooperative venture among the National Science Foundation, the U.S. Department of Energy, and the U.S. Geological Survey (USGS); and the Department of Energy's Magma Energy Technology Program, which seeks to use new technology to eventually demonstrate the feasibility of extracting heat energy directly from the magma itself.

Of greatest importance to these future investigations has been the very recent discovery that all of the considerable body of data developed to date concurs on the location and extent of magma within the caldera. Moreover, these studies indicate that at 5 km depth, the top of the magma body is sufficiently shallow in the south central part of the caldera to permit drilling to reach into the immediate, near-magmatic environment. Hence sampling of rocks and fluids, together with seismic, electromagnetic, geodetic, thermal, and in situ stress observations, would reveal for the first time the nature of conditions and physical processes associated with a major crustal magma body. In addition, in situ validation of surficial techniques used to locate magma bodies within the crust would contribute substantially to the success of the Magma Energy Technology Program.

In the following sections, we provide a brief summary of the scientific results that have led us to the conclusion that Long Valley is the prime site for investigations into the near-magmatic environment (further details can be found in our earlier work [*Rundle et al.,* 1985*b*]). Most important is the evident self-consistency of the data, which has led us to select the southern end of the old resurgent dome as the site most favorable for drilling activities. At the present time the Magma Energy Technology Program is making plans to begin drilling a deep exploratory well on this site to depths as great as 20,000 ft (6 km). With the cooperation of Santa Fe Geothermal, Inc., a large drill pad and its associated permits have been transferred to Sandia National Laboratories (Albuquerque, N.M.). The location of the pad is optimally placed over the shallowest seismic anomalies (see cover). It is expected that drilling will commence in 1987 and will occur in a series of stages over a period of 3–5 years to allow ample time for scientific investigations at each depth stage.

Geophysical Anomalies

Table 1 summarizes some of the existing seismic work that deals specifically with location of and depth to magma within the caldera. The cover figure shows a location key for the north end of the resurgent dome, the south end of the resurgent dome, and other points of interest within the caldera, as well as the spatial locations of the anomalies listed in Table 1. As a point of reference, the depths to magma determined by *Sanders* [1984] in a detailed study of shear waves from earthquakes within and to the south of the caldera are superposed on the figure. Some of the work summarized in Table 1 is in preparation, while other papers have already appeared in the open literature. For example, G. J. Elbring and J. B. Rundle (unpublished manuscript, 1986) have collected shear wave data from earthquakes in the Sierra Nevada mountains to the south of the caldera. Energy from these events passed through the central part of the caldera and was recorded in a 900-m drill hole on the northern end of the central resurgent dome. Thus the shear energy was most sensitive to the effects of structure beneath the resurgent dome. The results clearly show that the shear wave energy is attenuated and delayed in passing beneath the dome. Surface effects cannot be responsible, since both well and earthquakes are substantially below the surface. Another example is recent work by J. Luetgert (U.S. Geological Survey, Menlo Park, Calif.; personal communciation, 1985), in which USGS refraction data was replotted by using a simple reduced time (normal moveout) correction. In a shot from the southeast part of the caldera into a fan of geophones laid out NE-SW in the northwest part of the caldera, a clear reflection was seen corresponding to a depth of about 7 km. Again, these ray paths would be most sensitive to structure beneath the southern end of the resurgent dome. Finally, while reflection data from the summers of 1984 and 1985 are still

0096-3941/86/6720/0478$01.00

TABLE 1. Seismic Imaging: Partial List

Project	Location	Depth to Top, km
Refraction [*Hill*, 1976]	north dome	7–8
Teleseismic *P* delay [*Steeples and Iyer*, 1976]	central caldera	6–7
Shear wave shadowing [*Ryall and Ryall*, 1981]	south moat	7–8
Refraction		
[*Hill et al.*, 1984]	north dome	6–7
(J. Luetgert, unpublished data, 1985)	south dome	7–8
Shear wave shadowing [*Sanders and Ryall*, 1983; *Sanders*, 1984]	north dome, south dome	5–6 4–5
P wave tomography [*Kissling et al.*, 1984]	central caldera–south dome–south moat	5–7
Borehole shear waves (G. J. Elbring and J. G. Rundle, unpublished manuscript, 1986)	south dome, north dome	4–5 5–6
P wave reflection		
[*Rundle et al.*, 1985*a*]	north dome	6–7
[*Murphy et al.*, 1985]	south dome	4–5

being processed, preliminary results indicate that a shallow reflector does exist beneath the southern end of the resurgent dome and out into the south moat [*Murphy et al.*, 1985].

Table 1 summarizes the results of these and other studies by a variety of investigators. Most impressive is the consistency of location and depth to magma. Beneath the northern end of the resurgent dome, inferred depth to magma is about 6–7 km, while beneath the southern end of the dome, depth is of the order of 4–5 km. It is important to emphasize that these results do not depend upon any one investigation but are instead the virtually unanimous result of all of the work done to date. It is unlikely that additional surface geophysics will add significant new information to our current picture of magma location and depth, especially since the most recent seismic reflection and shear wave transmission data already are confirming the previous results.

By their nature, models of potential field (geodetic) data can only provide information on the subsurface volume change and on the location of the "center" of inflation. This is quite analogous to the problem of determining a mass distribution from observations of the gravity field, a problem that is well known to be nonunique. Hence geodetic data cannot yield much useful information on the depth to the top of the magma chamber, since the size of chamber can be traded off against volumetric strain within the chamber. However, the model of *Rundle and Whitcomb* [1984] had point sources of inflation located at 5 km depth beneath the southern end of the resurgent dome and at 8 km depth beneath the northern end of the dome. The roofs of both chambers must therefore be less than 5 and 8 km, respectively, a result that is generally consistent with those in Table 1.

Thermal Investigations

Evidence for the thermal signature of crustal magma has been sought in studies of the Long Valley hydrothermal regime. Simple thermal conduction models indicate that a magma body intruded at a depth of 5 km would give rise to detectable surface heat flow within 100,000 yr after emplacement. While significant geothermal activity exists within the Long Valley Caldera, the observed surface heat flows cannot readily be used to locate magma using thermal conduction models: the presence of an active hydrothermal system in the caldera obscures any thermal signature that might define the depth and state of a crustal magma chamber. Studies of the subsurface thermal regime by *Lachenbruch et al.* [1976*a*,*b*], *Sorey* [1984], and *Blackwell* [1984] have contributed to a better understanding of this hydrothermal system, but almost all temperature and heat flow observations have been limited to the permeable caldera fill and Bishop tuff lying above the Sierran basement. Evidently, these layers support a complicated hydrologic flow regime that involves both forced and free convection. Temperature measurements obtained within the upper 300 m of sedimentary fill indicate purely conductive heat flows of 4 HFU near the western rim and center of the caldera and only 2 HFU near the eastern rim [*Lachenbruch et al.*, 1976*a*], where 1 HFU = 1 μcal cm^{-2} s^{-1}. The regional background heat flow was estimated by the same authors to be 1.5 to 2 HFU. However, conductive heat flow represents the least important mechanism for removing heat from the caldera. If the heat loss associated with groundwater flow into creeks and springs is included in the estimates, the total loss rate climbs to an average over the caldera of 10–16 HFU [*Lachenbruch et al.*, 1976*a*; *Sorey and Lewis*, 1976]. Interpreted in the context of the simplest steady state model of *Lachenbruch and Sass* [1977], this large heat loss rate implies a depth to magma of about 5 km, which is consistent with recent seismic modeling. It has been argued that a significant fraction of the total heat flow of 10–16 HFU might be associated with very shallow sources in the caldera [*Blackwell*, 1984]. In this case, the contribution from any large body of underlying magma would necessarily be somewhat less than the total value, implying depths somewhat greater than 5 km in a time-independent system.

In reality, there is little reason to expect that either a magmatic heat source or the overlying hydrothermal zone behaves in a time-independent fashion. A more realistic model of the heat source would involve periods of injection of new magma into the chamber, interspersed between periods of repose during which the magma is cooling down. Thus, for example, the temperature of the magma source might be approximated by a "saw tooth" periodic function. For such a periodic source the heat flow can be significantly less than for a time independent heat source located at the same depth. Figure 1 illustrates the time-dependent variation of temperature with depth when a saw tooth cycle of 2×10^5 years is assumed. Initially, magma injection occurs at the beginning of the cycle, causing the source temperature to increase linearly with time. The dashed curve in Figure 1 is indicative of the temperature in the conductive layers above the magma source when it has reached its maximum temperature (850°C) at the end of the injection period. During the cooling phase of the cycle (here, the last 90%), the source temperature slowly decreases to a minimum of 500°C. The solid curve in the figure illustrates the temperature profile at the time when the source has cooled to its minimum temperature. (For comparison, a plot of the geothermal gradient, 35°C/km, which corresponds to about 1 HFU, is provided.) The average heat flow reaching the surface is only about 6 HFU, just one third to one half of the total rate of heat loss from the caldera. For a given heat flow, the depth of the heat source will be determined by the ratio of the heating time to the cooling time in a cycle, as well as by the total temperature variation over one cycle. The thermal model presented here is a reasonable one that supports the concept of reasonably shallow magma characterized by a moderate heat flow. Of course, the model is not unique, and the final test of this and other models will be found by observing the thermal gradient in a deep well drilled into the Sierran basement.

Drilling and Downhole Experiments

A possible drilling program and anticipated lithologies are shown on the left and center portions of Figure 1. Tentative plans call for drilling to 6000 ft (~1829 m) in fiscal year (FY) 1987; to 12,000 ft (~3658 m) in FY 1988; to 15,000 ft (4572 m) in FY 1989; and as much deeper as makes sense until FY 1991. Casing would be set at each step-down point during the first 3 years. Initial diameter would be about 30 in. (76 cm), and bottom hole diameter would be perhaps 6 in. (15 cm). Immediately at the end of each phase of drilling, a small core drilling rig would be brought on site, and approximately 200–300 ft of slim core would be returned (size PQ: core diameter = 3.3 in. (8.4 cm); hole diameter = 4.8 in (12.2 cm)). This part of the well would then be left uncased for a year, until the next phase of drilling, for scientific experiments. Perforation of the casing at various levels would be considered for fluid sampling. Cuttings from the drilling operations would also be retrieved. While the staged approach is more expensive in total than drilling the entire well at once, budgetary constraints make a one-shot drilling operation impossible. Moreover, the staged approach makes the systematic collection of data at ever-increasing depths possible, as well as providing time for the construction of preliminary hypotheses to be tested in the succeeding stages of drilling. In addition, experiments can be planned more carefully as depths increase, allowing more flexibility and time to solve unanticipated problems. As dis-

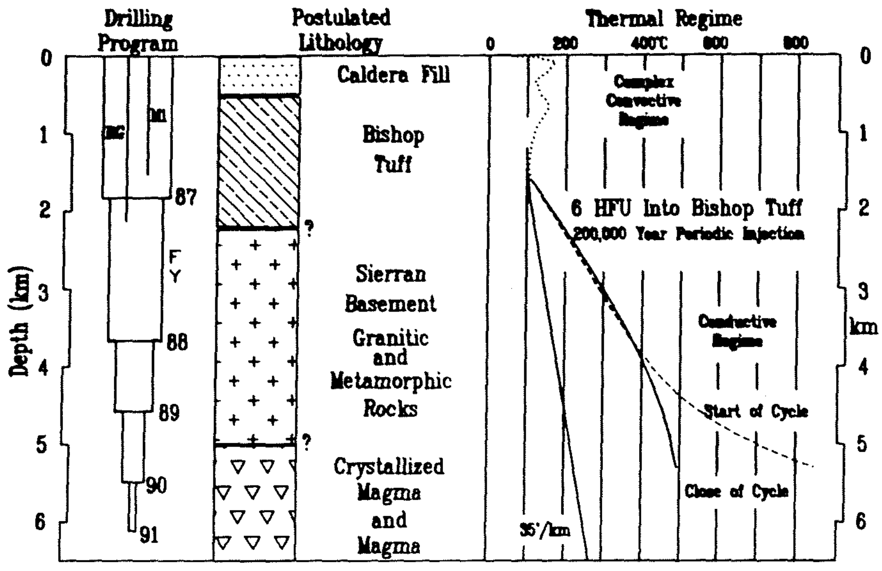


Fig. 1. Proposed drilling program, anticipated lithologies, and possible deep temperature profiles. On the left part of the figure is shown a possible drilling and (schematic) casing program for the well with a total depth of 20,000 ft (~6 km). Depth is shown in kilometers on the left axis, and time is shown down the right side of the well profile. The two deepest wells to date within the caldera (Mammoth 1 or M1, near the Casa Diablo Hot Springs, and the Republic Geothermal well or RG, in the southeast moat) are shown as the lines in the upper central part of the casing diagram. In the middle part of the figure is shown a possible lithology that the well could encounter. On the right side of the figure, at the top, is the temperature profile observed in well Mammoth 1; attached to it are several possible temperature profiles, as described in the text.

cussed in the introduction, it is very clear that a deep borehole is needed in the near future to validate the analyses based on surficial data and to provide answers to fundamental questions on the nature of physical processes in the magmatic environment. It is clear from the current work that the 2-km-deep caldera fill substantially obscures the basement structure and prevents the detection and analysis of the more subtle structural, physical, and chemical contrasts within the basement. Experiments in the first well will include

- Deep borehole seismic observations, with either the source or the receiver (or both) below the obscuring effects of the caldera fill, to establish accurately the location and extent of nearby magma;
- Thermal and heat flow measurements deep into basement to detect the thermal signature of the magma;
- Fluid and gas sampling at depth to establish chemical conditions in the magmatic environment;
- Electromagnetic and hydrologic observations deep within the basement to establish the location and extent of magma;
- Measurement of in situ stress to establish the physical condition of the magma and its environment.

With these data, it will be possible to site precisely other deep wells, which may, in the future, actually penetrate into the magma for sampling purposes. Data obtained from the near magmatic environment, without the complications related to the overlying caldera fill and hydrothermal system, are the only data that can provide an accurate definition of the magma body and its surrounding environment.

References

Blackwell, D. D., A transient model of the geothermal system of the Long Valley caldera, California, in Proceedings of Workshop XIX, Active Tectonic and Magmatic Processes Beneath Long Valley Caldera, Eastern California, *U.S. Geol. Surv. Prof. Pap. 84–939,* 1984.

Hill, D. P., Structure of Long Valley caldera, California, from a seismic refraction experiment, *J. Geophys. Res., 81,* 745, 1976.

Hill, D. P., R. E. Wallace, and R. S. Cockerham, Review of evidence on the potential for major earthquakes and volcanism in the Long Valley-Mono Craters-White Mountains regions of eastern California, *Earthquake Pred. Res., 3,* 571, 1985*a*.

Hill, D. P., E. Kissling, J. H. Luetgert, and V. Kradolfer, Constraints on the upper crustal structure of the Long Valley–Mono Craters Volcanic complex eastern California, from seismic refraction measurements, *J. Geophys. Res., 90,* 11135, 1985*b*.

Kissling, E., W. Ellsworth, and R. S. Cockerham, Three-dimensional structure of the Long Valley caldera, California, region by geotomography, 188–220, *U.S. Geol. Surv. Open File Rep. 84–939,* 1984.

Lachenbruch, A. H., and J. H. Sass, *Heat Flow in the United States and the Thermal Regime of the Crust, Geophys. Monogr. Ser.,* vol. 20, pp. 626–675, AGU, Washington, D.C., 1977.

Lachenbruch, A. H., M. L. Sorey, R. E. Lewis, and J. H. Sass, The near-surface hydrothermal regime of Long Valley caldera, *J. Geophys. Res., 81,* 763, 1976*a*.

Lachenbruch, A. H., J. H. Sass, R. J. Munroe, and T. H. Moses, Jr., Geothermal setting and simple heat conduction models for the Long Valley caldera, *J. Geophys. Res., 81,* 769, 1976*b*.

Murphy, W. J., E. Renaker, M. Robertson, A. Martin, and P. E. Malin, The 1985 Mammoth wide-angle reflection survey, *Eos Trans. AGU, 66,* 960, 1985.

Rundle, J. B., and J. H. Whitcomb, A model for deformation in Long Valley, California, 1980–1983, *J. Geophys. Res., 89,* 9371, 1984.

Rundle, J. B., et al., Seismic imaging in Long Valley, California, by surface and borehole techniques: An investigation of active tectonics, *Eos Trans. AGU, 66,* 194, 1985*a*.

Rundle, J. B., C. R. Carrigan, H. C. Hardee, and W. C. Luth, Assessment of Long Valley as a site for drilling to the magmatic environment, *Rep. SAND 85–2356J,* Sandia Natl. Labs., Albuquerque, N.M., 1985*b*.

Ryall, F., and A. Ryall, Attenuation of *P* and *S* waves in a magma chamber in Long Valley caldera, California, *Geophys. Res Lett., 8,* 557, 1981.

Sanders, C. O., Location and configuration of magma bodies beneath Long Valley, California, determined from anomalous earthquake signals, *J. Geophys. Res., 89,* 8287, 1984.

Sanders, C. O., and F. Ryall, Geometry of magma bodies beneath Long Valley, California, determined from anomalous earthquake signals, *Geophys. Res. Lett., 10,* 690, 1983.

Sorey, M. L., Evolution and present state of the hydrothermal system in Long Valley caldera, Proceeding of Workshop XIX, Active Tectonic and Magmatic Processes Beneath Long Valley Caldera, eastern California, *U.S. Geol. Surv. Prof. Pap. 84–939,* 1984.

Sorey, M. L., and R. E. Lewis, Convective heat flow in the Long Valley Caldera, Mono County, California, *J. Geophys. Res., 81,* 785, 1976.

Steeples, D. W., and H. M. Iyer, Low-velocity zone under Long Valley as determined from teleseismic events, *J. Geophys. Res., 81,* 849, 1976.