30
3-14-86 JS(1)

(7)

I-25318

DR-1599-7

SANDIA REPORT SAND85-2356 • Unlimited Release • UC-66
Printed January 1986

Assessment of Long Valley as a Site for Drilling to the Magmatic Environment

John B. Rundle, Charles R. Carrigan, Harry C. Hardee,
William C. Luth

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof or any of their contractors or subcontractors.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A03
Microfiche copy: A01

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

MASTER

CONTENTS

	Page
1. Introduction	2
2. Literature Summary	5
2.1 Seismology	5
2.2 Geodetic Data	7
2.3 Electromagnetic Methods	8
2.4 Thermal Investigations	9
3. Drilling and Downhole Experiments	13
4. Recommendations	15
5. Appendix A	19
6. References	21
7. Table Captions	28
8. Figure Captions	29

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

EB

This page intentionally left blank.

DO NOT MICROFILM
THIS PAGE

SAND85-2356
Unlimited Release
Printed January 1986

Distribution
UC-66

ASSESSMENT OF LONG VALLEY AS A SITE FOR
DRILLING TO THE MAGMATIC ENVIRONMENT

by

John B. Rundle
Charles R. Carrigan
Harry C. Hardee
William C. Luth

Geoscience Department 1540
Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

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

*This work was supported by the U.S. Department of Energy under contract number DE-AC04-76DP00789.

1. Introduction

Since 1980, the Long Valley caldera, California, has been the site of intense swarms of earthquakes, some in excess of magnitude 6; ground uplift in excess of 0.5 meter; horizontal rates of strain in excess of 4 ppm/a; and extensive changes in the surface hydrothermal system (Cramer and Topozada, 1980; Savage and Clark, 1982; Ryall and Ryall, 1983; Hermance, 1983; Savage and Cockerham, 1984; Castle et al., 1984; Rundle and Whitcomb, 1984; Hill et al., 1984). This activity is only the most recent example of intense tectonic and volcanic activity over the last 3 million years (Bailey et al., 1976), which includes the Inyo Domes extrusion event of 500 years ago (Miller, 1984); the Mono Craters eruptions of the last 50,000 years (Miller, 1984); the caldera-forming Bishop Tuff eruption of 700,000 years B.P. (Bailey et al., 1976); and numerous other extrusive and intrusive events throughout that time. A variety of investigations during the past five years has led to the conclusion that the activity within the caldera is related to the recent injection of 150 to 200 million m^3 of magma beneath the central part of the caldera.

In the following, we briefly summarize the results of numerous experiments performed during the past 10 years that have delineated the location and boundaries of the magma body which currently exists within the caldera. We conclude that further surface geophysical and geochemical studies will not lead to substantive new results, but that observations in deep boreholes can. We recommend that deep drilling commence in the very near future.

2. Literature Summary

Comprehensive reviews of the literature and compendia of papers include Steeples (1975); a special issue of Journal of Geophysical Research (see, e.g., Muffler and Williams, 1976); Lipshie (1976); Strojan and Romney (1979); Sherburne (1980); Hermance (1983); Iyer (1984); Goldstein (1984); and Hill et al. (1984). The latter volume is in fact the proceedings of the U.S. Geological Survey workshop on Active Tectonic and Magmatic Processes Beneath Long Valley Caldera, eastern California, and as such, summarizes much of the knowledge existing to date. Rather than recapitulate all of this work in the present document, we shall excerpt and synthesize parts of selected papers that pertain specifically to the location and depth of large bodies of magma within the caldera.

2.1 Seismology

In Table 1 and Figures 1 we summarize some of the existing seismic work which deals specifically with location and depth to magma within the caldera. Figure 1 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 spatial location 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 Figures 1. Some of the work summarized in Table 1 is in preparation

while other papers have already appeared in the open literature. For example, Elbring and Rundle (1985) 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 meter drill hole on the northern end of the central resurgent dome. Thus, the shear energy was most sensitive to the effects of structure on the southern end of the resurgent dome. These data clearly show that the shear wave energy is attenuated and delayed in passing beneath the southern end of the dome. Surface effects cannot be responsible since both well and earthquake are substantially below the surface. Another example is recent work by Luetgert (personal communication, 1985), in which USGS refraction data was replotted using a simple normal moveout correction. In a shot from the southeast part of the caldera into a fan 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 raypaths would be most sensitive to structure beneath the southern end of the resurgent dome. Last, some of the reflection data from the summer of 1984 is still being processed, due to the problems encountered with correcting for surficial caldera fill. In addition, more data from summer 1985 is being processed, and this will be complete in due course. 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., personal communication, 1985).

Thus, Table 1 shows the results of these and other studies by a variety of investigators. The most impressive result of the work 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 on 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. Additional surface geophysics will not add significantly 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.

2.2 Geodetic Data

The major work in this area has been done by Savage and Clark (1982), Savage and Cockerham (1984), Castle et al. (1984), Rundle and Whitcomb (1984), Whitcomb and Rundle (1985), Savage et al. (1985), Denlinger et al. (1985), Gross and Savage (1985). All of this work generally agrees that the total amount of magma injected between 1980 and 1985 is on the order of 150 to 200 million m^3 . By their very nature, however, 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. This latter problem is well known to be non-unique: for example, both a point mass and a spherical shell give the identical gravity field external to the shell. Hence, geodetic data cannot yield much useful

information on the depth to the top of the magma chamber, since size of chamber can be traded off against volumetric strain within the chamber.

However, the model of Rundle and Whitcomb (1984) had a point source of inflation located at 5 km depth beneath the southern end of the resurgent dome. Thus the roof of this shallower chamber must be less than 5 km depth, again giving partial support to the results listed in Table 1. Depths to the point sources under the northern or central part of the resurgent dome are all in excess of 8 km, thus neither agreeing with nor contradicting the results given in Table 1. Further work on these data will almost certainly not yield any new information on minimum depth to magma: for example, the most recent paper, by Denlinger et al. (1985), simply assumes the configuration proposed by Sanders (1984) and proceeds to find the volume expansion needed to satisfy the data.

2.3 Electromagnetic Methods

Results of the electromagnetic methods (Magnetotelluric (MT), Controlled Source Electromagnetic (CSEM), Audiomagnetotelluric (AMT), Total Field Resistivity Measurements (TFR), and D.C. Vertical Electric Soundings (VES)) are summarized in Hoover et al. (1976), Stanley et al. (1976), Hermance (1983), Hermance et al. (1984), and Goldstein (1984). The principle result of all this work has been delineation of the hydrothermal system configuration, with little or no information forthcoming on the location and extent of deeper conductors (magma). It appears that the highly conducting hydrothermal waters coursing through

the caldera very effectively mask the underlying magmatic conductor. Hence, no significant progress can be made until sensors can be placed below the caldera fill, in basement, at depths of 2-3 km.

2.4 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 1000,000 years after emplacement. While significant geothermal activity exists within the Long Valley Caldera, the observed surface heat flows cannot be readily used to locate magma using thermal conduction models. This is because the presence of an active hydrothermal system in the caldera obscures any definitive thermal signature that might provide clues to the depth and state of a crustal magma chamber. Studies of the subsurface thermal regime by Lachenbruch et al. (1976a), Lachenbruch et al. (1976b), Sorey (1984), Blackwell (1984) and others have contributed to a better understanding of this hydrothermal system. However, virtually all temperature and heat flow observations have been limited to the permeable caldera fill and Bishop tuff lying above the Sierran basement. It is the consensus that these layers support a complicated hydrologic flow regime involving 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., 1976a). The regional background heat flow was estimated by the same authors to be 1.5 to 2 HFU. However, conductive heat flow represents only the least important mechanism for removing heat from the caldera. If the heat loss associated with ground water 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., 1976a; 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 that is consistent with recent seismic modeling.

Unfortunately, there is little reason to expect that either a magmatic heat source or the overlying hydrothermal system behaves in steady-state fashion. Further, any attempt at pinning down the present time frame in an evolutionary model of the magma-hydrothermal system will be subject to the high degree of nonuniqueness that characterizes such relatively unconstrained models. Other models have been proposed to account for the total heat flow without invoking the need for a significant magmatic heat source beneath the Sierran basement.

To make matters even worse, the problem of extracting information about present-day magma from current thermal observations is further compounded by the slow propagation rate of thermal signals through the magma-hydrothermal system. Thus, even if a magma-hydrothermal model was somehow adequately constrained by thermal observations in the caldera fill or Bishop tuff layers, it could only be expected to yield an accurate picture of the magmatic heat source at a time no later than about 30,000 years before the present.

While any model presented here is subject to the criticisms outlined above, it can be instructive to show how introducing a time-dependent heat source can affect estimates of the depth to magma when they are subject to constraints on the heat flow through the hydrothermal system. Figure 2a illustrates the variation of temperature with depth assuming a steady-state conduction model for the flow of heat from the magma source to the surface. The value selected for the rate of heat loss is taken to be nominally 4 HFU rather than the 10-16 HFU that is indicative of the average heat flow over the caldera. In this case temperature increases linearly with depth reaching magmatic temperatures at a depth of about 10 km. In Figure 2b, the heat source is periodic. One cycle represents an injection of fresh magma beneath the Sierran basement followed by a period of cooling. To produce approximately the same heat flow as the steady source, a periodic magma heat source must be emplaced at a somewhat shallower depth. The depth will be determined by the ratio of the heating time to the cooling time in a cycle as well as the total temperature variation over one cycle. To produce a heat flow comparable to a steady-state body emplaced at 10 km, the periodic source considered here must be emplaced at only 5 km depth. Again, we wish to emphasize that the rate of heat loss would be only 4 HFU at this shallow depth and not the 10-15 HFU which has been measured.

From all this, we conclude that while the above mentioned studies might elucidate the present nature of the hydrothermal regime in the caldera fill and in the Bishop tuff, they provide nothing definitive about the state and depth to a magma chamber beneath the Sierran

basement. Downhole temperature estimates well within the Sierran basement are required for determining the depth to magma. Such information would also place a much needed boundary condition on models of the Long Valley hydrothermal system that does not presently exist.

3. Drilling and Downhole Experiments

As an integral part of the assessment of Long Valley as a site for drilling to magma, it is very clear that a deep borehole is needed in the very near future, near the magma target. Observations in the well can then be used to precisely define the location and extent of the magma, so that the larger diameter, and more expensive, magma energy feasibility well can be accurately sited. 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 well into basement, to establish the location and extent of magma
- * Measurement of in situ stress, to establish physical condition of the magma and environs

With these data and others, it will be possible to precisely site the magma energy feasibility well. Data obtained from the near magmatic environment, without the complications relating to the overlying caldera fill and hydrothermal system, are the only data that can provide the unique definition of the magma body we are seeking.

4. Recommendations

The U.S. DOE Long Valley database (Luth, in preparation, 1985) contains more than 1000 references pertaining to surface geology, geophysics, and geochemistry. Many more papers appear each year. If one assumes that 3-6 man months of effort goes into each paper, then it can be calculated that 250-500 man years of effort has been expended upon understanding the caldera and its environs. At current rates, this translates to about \$30-\$40 million or more of money spent on science related to the caldera and its tectonic setting. All of this work has involved surface, or near surface studies, with the exception of the three 1.5-2 km wells mentioned above, which were drilled by industry for hydrothermal resource assessment, did not penetrate significantly into basement, and whose only useful data is typically a temperature log and some lithologic information. None of these wells can currently be accessed for scientific use, and none of them is located over the most interesting shallow anomaly under the southern end of the resurgent dome.

Moreover, experience under the Magma Energy Program funded by the Office of Basic Energy Sciences from 1975 to 1982 indicates that drilling into a high temperature regime is a necessary early step in such an engineering and scientific development program. Neel et al. (1979), Colp and Traeger (1978), and Colp (1979) document cases in which tools were designed to withstand anticipated physical conditions which were unfortunately never encountered in the field. Moreover, given the masking effect of the caldera fill on the physical data originating in

and passing through the basement rocks, it is clear that such physical data needs to be observed deep within the basement (Hardee et al., 1982). Both of these points require a deep hole, drilled early in the program, into or near the physical environment around the target magma body.

Based upon the work outlined above, we have come to the following conclusions:

1. Comprehensive surface geophysical data already exists for Long Valley relating to magma location and definition.
2. We have reached a point of diminishing returns with respect to further surface geophysical data in Long Valley.
3. Qualitatively new data on the deep structure beneath Long Valley can only be gained by drilling and in situ observations.
4. In light of the amount of money expended to date (> \$30 million), a deep observation well to 15,000'-20,000', costing about \$5 million, is the most cost effective way to get the data.
5. At the present time, we have more than sufficient information to site a deep hole near the shallowest magma target, under the southern edge of the resurgent dome.

6. It is time to begin work on a series of ever-deeper observations in a deep (15,000'-20,000') drillhole. This effort will involve:

- A. Permitting the well.
- B. Designing and drilling the well, probably in stages, to a total depth of 15,000'-20,000'.
- C. Planning and implementing a series of key experiments to accurately define magma location, extent, and near-magmatic physical conditions

Now is a particularly fortuitous time to begin work on drilling the well. We have recently been offered a drill pad, valued at over \$400,000, by Santa Fe Geothermal, Inc., which is located just over the shallowest anomaly, on the southern end of the resurgent dome (see Figure 1abc). The pad includes two 10,000 Bbl mud pits, a 20,000 Bbl sump, a working water well with downhole pump, and surface conduit already in place. Of great importance is the fact that the permits and environmental clearances are already in place, and can be readily transferred. We emphasize that the pad is already in place over the shallowest part of the anomaly. Since the goal of the well is to reach the near magmatic environment, but not necessarily to drill into magma, it is difficult to see how the well could be any better sited, given the existing surface data. Moreover, we have been advised by knowledgeable sources that the various permitting agencies will require a deep observation well to be drilled into the near magmatic environment, for baseline monitoring purposes, before a well into magma can be

permitted. Thus we conclude that a deep well should be drilled from the Santa Fe pad as expeditiously as possible.

Finally, a workshop to discuss geophysical needs in Long Valley, convened at the Lawrence Berkeley Laboratory on October 2, 1985, produced strong, widespread support among the attending scientists, for the concept of drilling a deep well. We therefore recommend that planning for the well commence immediately, and that drilling begin on the Santa Fe pad by fall 1986 at the latest.

5. Appendix A

In applying the approach of Lachenbruch and Sass (1977), we invoke the simplest possible model that explains the observed rate of heat loss (10-15 HFU). It is assumed that an underlying magma body loses heat through conduction into the base of the hydrothermal zone above the Sierran basement. All processes occurring in the magma-hydrothermal system are assumed to be steady state. More recent papers by Blackwell (1984) and Sorey (1984) suggest that much of the heat supplied to the hydrothermal system may not be associated with cooling of magma by conduction through the Sierran basement. Observations of temperature inversions occurring in the topmost part of the hydrothermal system suggest that a heat source in the hydrothermally dominated layers could produce the observed temperature versus depth distribution as well as temporarily supplying the heat needed to produce the observed rate of heat loss. The two most likely sources of this shallow heating of the hydrothermal zone are thought to be hydrothermal upwelling associated with the caldera ring fracture system and/or the "flash" heating of runoff groundwater from the Sierra Nevada range as it flows past the geologically recent Inyo domes, associated feeder dikes and conduits at the western end of the caldera (Blackwell, 1984). However, logging of two recent scientific boreholes at the Inyo domes (Eichelberger, 1985) has yielded temperatures which are far below values required to explain the observed temperature inversions in the hydrologic flow. It now seems most likely that thermal waters from a deep magmatic source flow

upward along high permeability paths in the west moat ring fracture and fault system to create the observed temperature inversion.

Weak temperature variations in deep boreholes penetrating well into the Bishop tuff have also been used as evidence for the lack of significant heat flow emanating from the Sierran basement. It has already been shown that a time-dependent injection of magma beneath the Sierran basement need not lead to large conductive heat flows across that zone. The lack of a large conductive component at the top of the basement would only rule out shallow magma in a steady-state system. Further, we want to point out that it is not apparent from existing borehole data that a significant heat flow from the Sierran basement is ruled out. Temperature variations in deep wells can only yield accurate estimates of the heat flow if the variations are associated with conductively dominated regimes or thermal boundary layers of convecting hydrothermal systems. Boreholes which are well into the caldera fill certainly pass through the upper conductive thermal boundary layer of the hydrothermal system permitting estimates of the rate of heat loss from the system to be determined. On the other hand, boreholes penetrating well into the Bishop tuff may not pass through the lower thermal boundary layer that may lie deeper still. In this case, the temperature variations sampled will be characteristic of the more or less isothermal core of the convecting system. Basing bottom heat flow on such measurements would lead to an extreme lower bound on the heat transfer from the Sierran basement.

6. References

Bailey, R.A., Dalrymple, G.B. and M.A. Lanphere, Volcanism, structure, and geochronolgy of Long Valley caldera, Mono County, California, J. Geophys. Res., 81, 725-744, 1976.

Blackwell, D.D., A transient model of the geothermal system of the Long Valley caldera, California, Proc. Workshop XIX, Active Tectonic and Magmatic Processes Beneath Long Valley Caldera, eastern California, U.S. Geological Survey Professional Paper 84-939, 1984.

Castle, R.O., Estrem, J.E. and J.C. Savage, Uplift across Long Valley caldera, California, J. Geophys. Res., 89, 11507-11516, 1984.

Colp, J.L., FY79 Lava Lake Drilling Program - Geoscience Studies: Plans and Results, SAND79-1361, Sandia National Laboratories, 1979.

Colp, J.L. and R.K. Traeger, Magma Energy Research Project State-of-the-Project Report - October 1, 1978, SAND78-2288, Sandia National Laboratories, 1978.

Cramer, C. and T. Toppozada, A seismological study of the May 1980 and earlier earthquake activity near Mammoth Lakes, California, in Mammoth Lakes, California Earthquakes of May 1980, Spec. Rep. Calif. Div Mines Geol., 150, 91-136, 1980.

Denlinger, R.P., Riley, F.S., Carpenter, M.C. and J. Boling, Deformation of Long Valley caldera between August 1982 and August 1983, J. Geophys. Res., in press, 1985.

Eichelberger, J.C., Lysne, P.C., Miller, C.D. and L.W. Younger, Research Drilling at Inyo Domes, California: 1984 Results, EOS Trans. AGU, 66, 186-187, 1985.

Elbring, G. J. and J. B. Rundle, Analysis of borehole seismograms from Long Valley Caldera: Implications for caldera structure, submitted to J. Geophys. Res., 1985.

Goldstein, N.E., ed., Proceedings of the Workshop on Geophysical Modeling of the Long Valley Caldera, LBL-18106, pub. Lawrence Berkeley Laboratory, 1984.

Gross, W.K. and J.C. Savage, Deformation near the epicenter of the 1984 Round Valley, California, earthquake, Bull. Seism. Soc. Am., 75, 1339-1348, 1985.

Hardee, H.C., Dunn, J.C., and J.L. Colp, Magma Source Location Survey, SAND 82-0219, Sandia National Laboratories, 1982.

Hermance, J.F., The Long Valley-Mono basin volcanic complex in eastern California: Status of present knowledge and future research needs, Rev. Geophys. Space Phys., 21, 1545, 1983.

Hermance, J.F., Slocum, W. and G.A. Neumann, The Long Valley/Mono Craters volcanic complex; a preliminary interpretation based on telluric field patterns, Proc. Workshop XIX, Active Tectonic and Magmatic Processes Beneath Long Valley Caldera, eastern California, U.S. Geological Survey Open File Rept. 84-939, 1984.

Hill, D. P., Structure of Long Valley Caldera, California, from a seismic refraction experiment, J. Geophys. Res., 81, 745-753, 1976.

Hill, D. P., Kissling, E., Luetgert, J. H. and V. Kradolfer, Constraints on the upper crustal structure of Long Valley-Mono Craters volcanic complex in eastern California from seismic refraction measurements, J. Geophys. Res., 90, 11135-11150, 1985.

Hill, D.P., Bailey, R.A. and A.S. Ryall, eds., Proceedings of the Workshop on Active Tectonic and Magmatic Processes Beneath Long Valley Caldera, eastern California, U.S. Geological Survey Open File Rept., 84-939, 1984.

Hoover, D.B., Frischknecht, F.C. and C.L. Tipples, Audiomagnetotelluric sounding as a reconnaissance exploration technique in Long Valley, California, J. Geophys. Res., 81, 801-809, 1976.

Iyer, H.M., Geophysical evidence for the locations, shapes and sizes, and internal structures of magma chambers beneath regions of Quaternary volcanism, Phil. Trans. R. Soc. Lond., A 310, 473-510, 1984.

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

Lachenbruch, A. H. and J. H. Sass, Heat Flow in the United States and the Thermal Regime of the Crust, AGU Geophysical Monograph, 20, 626-675, 1977.

Lachenbruch, A.H., Sorey, M.L., Lewis, R.E., and J.H. Sass, The near surface hydrothermal regime of Long Valley caldera, J. Geophys. Res., 81, 763-768, 1976.

Lachenbruch, A.H., Sass, J.H., Munroe, R.J. and T.H. Moses, Jr., Geothermal setting and simple heat conduction models for the Long Valley caldera, J. Geophys. Res., 81, 769-784, 1976.

Lipshie, S.R., Geologic Guidebook to the Long Valley-Mono Craters Region of eastern California, GSUCLA Field Guide No. 5, University of California at Los Angeles, Los Angeles, 1976.

Miller, C.D., Holocene eruptions at the Inyo volcanic chain, California -- Implications for possible eruptions in Long Valley caldera, Proc. Workshop XIX, Active Tectonic and Magmatic Processes Beneath Long Valley Caldera, eastern California, U.S. Geological Survey Open File Rept. 84-939, 1984.

Muffler, L.J.P. and D.L. Williams, Geothermal investigations of the U.S. Geological Survey in Long Valley, California, 1972-1973, J. Geophys. Res., 81, 721-724, 1976.

Murphy, W. J., Renaker, E., Robertson, M., Martin, A., and P. E. Malin, The 1985 Mammoth wide-angle reflection survey, Trans. Am. Geophys. Un. EOS, 66, 960, 1985.

Neel, R.R., Striker, R.P. and R.M. Curlee, FY79 Lava Lake Drilling Program: Results of Drilling Experiments, SAND79-1360, Sandia National Laboratories, 1979.

Rundle, J.B. and J.H. Whitcomb, A model for deformation in Long Valley, California, 1980-1983, J. Geophys. Res., 89, 9371-9380, 1984.

Rundle, J.B., Elbring, G.J., Striker, R.P., Finger, J.T., Carson, C.C., Walck, M.C., Ellsworth, W.L., Hill, D.P., Malin, P., Tono, E., Robertson, M., Kuhlman, S., McEvilly, T., Clymer, R., Smithson, S.B., Deemer, S., Johnson, R., Henyey, T., Hauksson, E., Leary, P., McCraney, J., and E. Kissling, Seismic imaging in Long Valley, California, by surface and borehole techniques: An investigation of active tectonics, Trans. Am. Geophys. Un. EOS, 66, 194-200, 1985.

Ryall, F., and A. Ryall, Attenuation of p and s waves in a magma chamber in Long Valley caldera, California, Geophys. Res Lett., 8, 557-560, 1981.

Ryall, A. and F. Ryall, Spasmodic tremor and possible magma injection in Long Valley caldera, eastern California,, Science, 219, 1432-1433, 1983.

Sanders, C.O., Location and configuration of magma bodies beneath Long Valley, California, determined from anomalous earthquake signals, J. Geophys. Res., 89, 8287-8302, 1984.

Sanders, C. O. and F. Rayll, Geometry of magma bodies beneath Long Valley, California, determined from anomalous earthquake signals, Geophys. Res. Lett., 10, 690-692, 1983.

Savage, J.C., Lisowski, M., Estrem, J.E., and R.O. Castle, Deformation of Long Valley caldera, eastern California, 1983-1984, U.S. Geological Survey Open File Rept., 85-41, 1985.

Savage, J.C. and R.S. Cockerham, Earthquake swarm in Long Valley caldera, California, January 1983: Evidence for dike inflation, J. Geophys. Res., 89, 8315-8324, 1984.

Savage, J.C. and M.M. Clark, Magmatic resurgence in Long Valley caldera, California: Possible cause of the 1980 Mammoth Lakes earthquakes, Science, 217, 531-533, 1982.

Sorey, M. L. and R. E. Lewis, Convective Heat Flow in the Long Valley Caldera, Mono County, California, J. Geophys. Res., 81, 785-791, 1976.

Sorey, M.L., Evolution and present state of the hydrothermal system in Long Valley caldera, Proc. Workshop XIX, Active Tectonic and Magmatic Processes Beneath Long Valley Caldera, eastern California, U.S. Geological Survey Prof. Paper 84-939, 1984.

Sherburne, R.W., ed., Mammoth Lakes, California Earthquakes of May 1980, Special Rept. 150, Calif. Div. Mines Geol., Sacramento, CA.

Stanley, W.D., Jackson, D.B. and A.A.R. Zohdy, Deep electrical investigations in the Long Valley geothermal area, California, J. Geophys. Res., 81, 810-820, 1976.

Steeple, D.W., Teleseismic P-Delays in Geothermal Exploration with Application to Long Valley, California, PhD Dissertation, Stanford University, 1975.

Steeple, D. W. and H. M. Iyer, Low-velocity zone under Long Valley as determined from teleseismic events, J. Geophys. Res., 81, 849-860, 1976.

Strojan, C.L. and E.M. Romney, An Environmental Overview of Geothermal Development: The Mono-Long Valley KGRA, pub. by Laboratory of Nuclear Medicine and Radiation Biology, University of California at Los Angeles, 1979.

Whitcomb, J.H. and J. B. Rundle, Vertical distortion in Long Valley, California, associated with the January 1983 earthquake swarm, Geophys. Res. Lett., 12, 522-525, 1985.

7. Table Captions

Table 1. Compilation of minimum depth to magma in the locations shown in Figure 1. Authors are listed in column 1; general location is listed in column 2; and minimum depth is listed in column 3.

Table 1.
Seismic Imaging - Partial List

<u>Project</u>	<u>Location</u>	<u>Depth to Top (km)</u>
Refraction (Hill, 1976)	N. Dome	7-8
Teleseismic P-delay (Steeple and Iyer, 1976)	Central Caldera	6-7
Shear Wave Shadowing (Ryall and Ryall, 1981)	S. Moat	7-8
Refraction (Hill, et al., 1984) (Luetgert, 1985)	N. Dome S. Dome	6-7
Shear Wave Shadowing (Sanders & Ryall, 1983; Sanders, 1984)	N. Dome S. Dome	5-6 4-5
P-wave Tomography (Kissling et al., 1985)	Central Caldera- S. Dome-S. Moat	5-7
Borehole Shear Waves (Elbring & Rundle, 1985)	S. Dome N. Dome	4-5 5-6
P-wave reflection (Rundle et al., 1984) (Murphy et al., 1985)	N. Dome S. Dome	6-7 4-5

8. Figure Captions

Figure 1. Locations within the caldera for the results of the seismic experiments summarized in the text and in Table 1. The long dashed line is the caldera boundary, the heavy black line is highway 395, and the little blobs in the northwest corner of the figure are the Inyo Domes. The legend for the various studies are given in the figure. The figure illustrates the dense coverage of the southern end of the resurgent dome; Table 1 indicates that minimum depths to all the anomalies shown agree very well, at about 4-5 km underneath the southern end of the dome.

Figure 2. Comparison between steady-state and periodic magma heating models. Steady-state model (a) emplaced at 10 km depth produces 4 HFU heat flow signature at surface. Square wave periodic model (b) with 30,000 year cycle simulates heating that results from injection of magma at 5 km level corresponding to the bottom of the Sierran basement. Owing to its periodicity, the much shallower body also produces only a 4 HFU heat flow at the surface.

This page intentionally left blank.

DO NOT MICROFILM
THIS PAGE

Fig. 1

This page intentionally left blank.

DO NOT MICROFILM
THIS PAGE

Fig. 1

This page intentionally left blank.

DO NOT MICROFILM
THIS PAGE

Fig. 1

This page intentionally left blank.

**DO NOT MICROFILM
THIS PAGE**

COMPARISON BETWEEN TIME DEPENDENT AND STEADY STATE MODELS

a) STEADY STATE MODEL

b) PERIODIC INJECTION
MODEL

Fig. 2

DO NOT MICROFILM
THIS PAGE

This page intentionally left blank.

DISTRIBUTION:

U.S. Department of Energy (3)
Office of Basic Energy Sciences
Engineering and Geosciences
Washington, DC 20545

ATTN: J. S. Coleman, Director, ER-15
G. A. Kolstad, ER-15
E. Schreiber, ER-15

U.S. Department of Energy (2)
Geothermal Technology Division
1000 Independence Avenue SW
Washington, DC 20585

ATTN: J. C. Bresee
M. Reed

Arizona State University (2)
Department of Geology
Tempe, AZ 85287

ATTN: Jonathan H. Fink
Michael F. Sheridan

Boise State University
Department of Geology
Boise, ID 83702

ATTN: Spencer H. Wood

Brown University
Department of Geological Sciences
Providence, RI 02912

ATTN: John F. Hermance

CalTech (5)
Pasadena, CA 91125

ATTN: Thomas J. Ahrens, 252-21
Hiroo A. Kanamori, 252-21
Christopher O. Sanders, 252-21
Kerry E. Sieh, 170-25
Jim Westphal, 170-25

CalTech
Seismology Laboratory
Pasadena, CA 91103

ATTN: Don V. Helmberger,

CalTech (3)
4800 Oak Grove Drive
Pasadena, CA 91109

ATTN: Gregory A. Lyzenga, JPL
Carl Thiele, JPL
Donald Trask, Aries Program Manager, JPL

Cascade Volcano Observatory
5400 MacArthur Boulevard
Vancouver, WA 98661
ATTN: Roger P. Denlinger

California Division of Mines and Geology (3)
2815 O. Street
Sacramento, CA 95816
ATTN: Chris H. Cramer
Roger C. Martin
Stephen R. McNutt

California Division of Mines and Geology
610 Bercut Drive
Sacramento, CA 95814
ATTN: Steve Bezore

Carnegie Institute of Washington
5241 Broad Branch Road NW
Washington, DC 20015
ATTN: Natalie Valette-Silver

Dartmouth College
Department of Sciences
Hanover, NH 03755
ATTN: Stanley N. Williams

Geothermal Resources Council
P. O. Box 1350
Davis, CA 95617
ATTN: David N. Anderson

Geothermal Research International
545 Middlefield Road
Menlo Park, CA 94025
ATTN: Chandler A. Swanberg

ISTAC, Inc.
444 North Altadena, Suite 101
Pasadena, CA 91107
ATTN: Dr. James H. Whitcomb

Michigan State University (2)
Department of Geological Sciences
East Lansing, MI 48824
ATTN: Benjamin C. Schurayt
Thomas A. Vogel

Occidental Geothermal
5000 Stockdale Hwy.
Bakersfield, CA 93309
ATTN: Doug Goodwin

Pacific Geoscience Center
Box 6000, Sidney, B.C.
CANADA V8L 4B2
ATTN: Trevor Lewis

Scripps Institute of Oceanography (2)
La Jolla, CA 92093
ATTN: Bill Rison
Mark Zumberge

Smithsonian Institute
Museum of Natural History
Washington, DC 20560
ATTN: Thomas Simkin

Sohio Petroleum Company
5400 LBJ Freeway, Suite 1200
Dallas, TX 75240
ATTN: Joseph M. Mills, Jr.

Southern Methodist University
Department of Geological Sciences
Dallas, TX 75275
ATTN: David D. Blackwell

State University of New York
Department of Earth and Space Sciences
Stony Brook, NY 11794
ATTN: Clifford H. Thurber

Stanford University (2)
Department of Geology
Stanford, CA 94305
ATTN: G. A. Mahodd
Jenny Metz

Stanford, University
Department of Applied Earth Sciences
Stanford, CA 94305
ATTN: David Pollard

Virginia Polytechnic Institute
4052 Derring Hall, V.P.I.
Blacksburg, VA 24061
ATTN: Roy E. Chaudet

Woodward-Clyde Consultants
566 Eldorado Street
Pasadena, CA 91101
ATTN: Jeffrey S. Barker

Woodward-Clyde Consultants
P. O. Box 93245
Pasadena, CA 91109
ATTN: Lawrence J. Burdick

University of Arizona
Department of Geoscience, Bldg. 11
Tucson, AZ 85721
ATTN: Terry C. Wallace, Jr.

University of California (3)
Earth Sciences
Santa Cruz, CA 95064
ATTN: Kenneth L. Cameron
Karen C. McNally
Daniel E. Sampson

University of California (2)
Berkeley, CA 94720
ATTN: Burton Kennedy
Huntley F. Morrison

University of California (2)
Department of Geological Sciences
Santa Barbara, CA 93106
ATTN: Arthur G. Sylvester
Peter E. Malin

University of Chicago
5734 South Ellis Avenue
Chicago, IL 60637
ATTN: Stanley N. William

University of Nevada (5)
Seismological Laboratory
Reno, NV 89557
ATTN: Ed Corbett
William A. Peppin
Ute R. Vetter
Alan S. Ryall, MS M
Flori Ryall, MS M

University of Nevada
Mackay School of Mines
Reno, NV 89557
ATTN: Keith F. Priestly

University of Southern California (3)
Department of Geological Sciences
Los Angeles, CA 90089
ATTN: Keiiti Aki
Thomas L. Henyey
Egill Hauksson

University of Florence
Via Lapira 4
50121 Florence
ITALY 05-288-194
ATTN: Marino Martini

University of Tokyo
Earthquake Research Institute
Tokyo
JAPAN 00113
ATTN: Kazuaki Nakamura

U.S. Forest Service
P. O. Box 148
Mammoth Lakes, CA 93546
ATTN: Mark D. Clark

U.S. Geological Survey (7)
Denver Federal Center
Denver, CO 80225
ATTN: William H. Diment, MS 966
Richard P. Hoblitt, MS 903
Peter W. Lipman, MS 913
C. Dan Miller, MS 903
Michael Reimer, MS 963
William D. Stanley, MS 964
David L. Williams, MS 964

U.S. Geological Survey (2)
2255 North Gemini Drive
Flagstaff, AZ 86001
ATTN: Paul T. Delaney
John H. Sass

U.S. Geological Survey
Hawaiian Volcano Observatory
Hawaiian Volcanoes National Park
Hawaii National Park, HI 96718
ATTN: Dallas B. Jackson

U.S. Geological Survey
P. O. Box 25046, Bldg. 25
Lakewood, CO 80225
ATTN: Frank Riley

U.S. Geological Survey
906 Tigertail Road
Los Angeles, CA 90049
ATTN: Jon Linker

U.S. Geological Survey (31)
345 Middlefield Road
Menlo Park, CA 94025

ATTN: Charlie Bacon, MS 90C
Roy A. Bailey, MS 910
Bernard A. Chouet, MS 977
Malcolm M. Clark, MS 77
Robert S. cockerham, MS 977
G. Brent Dalrymple, MS 937
James A. Davis, MS 65
William L. Ellsworth, MS 77
Ed Harp, MS 998
Wes Hildreth, MS 90C
David P. Hill, MS 977
H. Mahadeva Iyer, MS 977
Robert C. Jachens, MS 18
Cathy Janik, MS 910
Malcolm J. Johnston, MS 77
Bruce R. Julian, MS77
Chi Yu King, MS 77
Ronald W. Kistler, MS 937
Arthur H. Lachenbruch, MS 923
Kenneth R. Lajoie, MS 977
John O. Langbein, MS 977
James H. Luetgert, MS 77
Bob Mariner, MS 434
Arthur F. McGarr, MS 977
Walter D. Mooney, MS 77
Carl Mortensen, MS 77
Patrick Muffler, MS 910
James C. Savage, MS 77
Michael L. Sorey, MS 439
Mark Wheeler, MS 910
Mark D. Zoback, MS 77

U.S. Geological Survey
2246 Harvard Street
Palo Alto, CA 94306
ATTN: Stuart A. Rojstaczer

U.S. Geological Survey
745 La Para Avenue
Palo Alto, CA 94306
ATTN: Gary S. Fuis

U.S. Geological Survey
1838 Woodside Road
Redwood City, CA 94062
ATTN: Douglas A. Stauber

U.S. Geological Survey (2)
National Center
Reston, VA 22092
ATTN: Robert P. Koeppen, MS 954
Motoaki Sato, MS 959

U.S. Geological Survey
P. O. Box 4, Jakarta
APO San Francisco, CA 96356
ATTN: Tom Casadevall

U.S. Geological Survey
190 Los Palms Drive
San Francisco, CA 94127
ATTN: William H. Prescott

U.S. Geological Survey
P. O. Box 1298, WRD
Santa Rosa, CA 95402
ATTN: Chris Farrar

U.S. Geological Survey (4)
5400 MacArthur Boulevard
Vancouver, WA 98661
ATTN: Daniel Dzurisin
Kenneth A. McGee
Christopher G. Newhall
Jeff Sutton

Lawrence Berkeley Laboratory (6)
University of California
Berkeley, CA 94720
ATTN: Norman E. Goldstein
Ernest L. Majer
Thomas V. McEvilly
Art F. White
Mike Wilt
Harold A. Wollenberg

Lawrence Livermore National Laboratory (6)
P. O. Box 808
Livermore, CA 94550
ATTN: Norman R. Burkhard, L-206
Donald O. Emerson, L-279
Paul W. Kasameyer, L-207
Robert N. Schock, L-203
Albert T. Smith, L-205
Leland W. Younker, L-224

Los Alamos National Laboratory (6)
P. O. Box 1663
Los Alamos, NM 87545
ATTN: James N. Albright, J-979
Fraser E. Goff, D-462
Robert H. Hendron, J-979
H. William Laughlin, D-462
Hugh D. Murphy, J-981
Kenneth H. Wohletz, D-462

Dwight R. Crandell
7101 West Ninth Place
Lakewood, CO 80215

Michael C. Fehler
1029 Big Rock Loop
Los Alamos, NM 87544

Steve Flexer
5422 Shafter, #3
Oakland, CA 94618

Don R. Mabey
P. O. Box 678
Bountiful, UT 84010

Louis C. Pakiser, Jr.
2710 South Sandy Ridge Road
Perry Pines, Sedalia, CO 80135

Carter W. Roberts
5 Highgate Court
Berkeley, CA 94707

William U. Savage
1035 Stratford Avenue
South Pasadena, CA 91030

Don W. Steeples
3026 Ranger Drive
Lawrence, KS 66044

Bruce E. Taylor
209 Irving Place
Ottawa, Ontario, K1Y1Z7
CANADA

1510 J. W. Nunziato
1520 D. J. McCloskey
1530 L. W. Davison
1540 W. C. Luth
1541 H. C. Hardee
1541 C. R. Carrigan
1541 G. J. Elbring
1541 J. B. Rundle (20)
1541 M. C. Walck
1542 B. M. Butcher
1543 T. M. Gerlach
1543 W. H. Casey
1543 R. T. Cygan
1543 J. C. Eichelberger
1543 J. L. Krumhansl
1543 H. W. Stockman
1543 H. R. Westrich
6240 R. K. Traeger
6240A L. C. Bartel
6240A P. C. Lysne
6240A R. Meyer
6241 J. R. Kelsey
6242 J. C. Dunn
3141 S. A. Landenberger (5)
3151 W. L. Garner (3)
3154-3 C. H. Daline (28) for DOE/OSTI
8024 P. W. Dean