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Science Guide for the Long Valley Caldera Deep Hole

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SCIENCE GUIDE FOR THE
LONG VALLEY CALDERA
DEEP HOLE

Science Advisory Panel
Magma Energy Technology Project
Sandia National Laboratories
Albuquerque, New Mexico 87185

Edited by
John B. Rundle
John C. Eichelberger

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SUMMARY*

The Magma Energy Program of the U.S. Department of Energy, Geothermal Technology Division, is planning to begin drilling a deep (6 km) exploration well in Long Valley Caldera, California, in September 1988. The location of the well is in the central part of the caldera, coincident with a large number of shallow (5-7 km) geophysical anomalies identified through many independent investigations. Results from the hole will permit the following:

1. Direct investigation of the geophysical anomalies interpreted to be magma.
2. Investigation of the patterns and conditions of deep fluid circulation and heat transport below the caldera floor.
3. Determination of the amount of collapse and subsequent resurgence of the central portion of Long Valley caldera.
4. Determination of the intrusion history of the central plutonic complex beneath the caldera, and establishment of the relationship of intrusive to eruptive events.

The hole will thus provide a stringent test of the hypothesis that magma is still present within the central plutonic complex. If the interpretation of geophysical anomalies is confirmed, the hole will provide the first observations of the environment near a large silicic magma chamber.

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I. INTRODUCTION

A. Present Tectonic Unrest

Based on recency of volcanism, the Long Valley/Mono Craters Volcanic Complex in eastern California might well be the most active major silicic system within the conterminous United States (the other active systems being the Valles and the Yellowstone calderas). The last, well-documented episode in the Long Valley/Mono Craters complex which resulted in a significant surface eruption occurred only 550 years ago, whereas the most recent volcanism in the Valles caldera and the Yellowstone caldera occurred approximately 50,000 and 70,000 years ago, respectively. In fact there are newspaper accounts of a possible eruption beneath Mono Lake in 1890.

A series of tectonic events began in October 1978 which may be a consequence of major intrusions beneath the Long Valley caldera. A sequence of moderate earthquakes occurred northwest of Bishop, California, migrating toward the southwest moat of Long Valley caldera, and culminating in the May 1980 Mammoth Lakes earthquake sequence. Eleven of these events had magnitudes close to 5 or larger; four had magnitudes larger than 6. Since 1980, Long Valley caldera has been the site of intense earthquake swarms and localized spasmodic tremor, ground uplift in excess of 0.5 meter, horizontal strain rates in excess of 1 ppm/year (significantly larger than the rates along the San Andreas fault zone in Southern California); and extensive changes in the surficial hydrothermal system (Cramer and Toppozada, 1980; Savage and Clark, 1982; Ryall and Ryall, 1983; Hermance, 1983; Savage and Cockerham, 1984; Rundle and Hill, 1988; Spec. Vol. J. Geophys. Res., 90, No. B13, 1984).

This activity is only the most recent example of intense tectonic and volcanic activity extending over the last 3 million years (Bailey et al., 1976). The regional history includes the caldera-forming Bishop Tuff eruption of 700,000 years B.P. (Bailey et al., 1976), the Mono Craters eruptions of the last 50,000 years (Wood, 1977), the Inyo Domes extrusion event of 550 years ago (Miller, 1985), and numerous other extrusive and intrusive events throughout that time. A variety of recent investigations have led to the conclusion that present activity within the caldera is a result of the injection of 150 to 200 million m³ of magma beneath the central part of the caldera since 1980. In fact, because of the tectonic unrest, Long Valley caldera is the only one of the three active calderas for which the USGS has issued a Volcanic Hazards Notice. In effect for several years following its issuance in May 1982, the hazard has since been downgraded, but Long Valley caldera continues to be among areas at the highest risk for seismic unrest within the conterminous US.

Long Valley caldera is thus one of the prime targets for a broad multidisciplinary study of magma-hydrothermal systems as envisioned by the Thermal Regimes Panel of the continental Scientific Drilling Committee (NRC, 1984) because of: (1) the strong possibility for the presence of active magma at relatively shallow depth beneath Long Valley; (2) a large-scale hydrothermal system in the caldera fill which can be readily mapped using geophysics; (3) an extensive data base developed over the last 5 years as a result of broad collaborative effort among DOE/OBES, NSF and USGS scientists; (4) strong commercial interests in developing the geothermal reservoir for electric power production with the implicit potential for additional scientific experiments; (5) access throughout the caldera for drilling

and geophysical experiments (unlike Yellowstone, for example, where drilling is not likely to be allowed anywhere near the most likely magma target) and; (6) a very real possibility for add-on scientific experiments in an engineering borehole to be drilled by the Magma Energy Technology Program of the U. S. Department of Energy/Geothermal Technology Division.

This Science Plan has been developed with this last consideration in mind.

B. The Long Valley Magma Energy Borehole

The Magma Energy Program of the U.S. Department of Energy, Geothermal Technology Division, has selected Long Valley Caldera, California, (Fig. 1A), as a site for testing the concept of extracting energy from magma. To assure the success of the Magma Energy project, it is critical to first ascertain whether geophysical anomalies in the caldera (Fig. 1B) indeed represent a large body of magma in the upper crust, as has been proposed. Hence, plans have been formed to drill a 6 km well into the environment of the anomalies.

Although the ultimate goal of the program is to drill into magma and to emplace and operate a heat exchanger there, a systematic engineering approach demands caution. Because conditions within the magma chamber are not well known, this first exploratory well is designed to avoid potential problems to the fullest extent possible, while at the same time providing the maximum return of data. The objective for the well is thus to reach a temperature of 500°C, or a depth of 6 km, whichever comes first. If it is verified that a major body of crustal magma exists near this depth, a subsequent production well would be drilled to meet the engineering objectives of the program.

Figure 1A: Regional geologic and tectonic setting of Long Valley caldera, and location key. Dots indicate the boundary of the caldera. Cross section A-A' refers to that shown in Figure 1B. HCF = Hilton Creek fault, HC = Hot Creek, LCF = Laurel Canyon fault, MLF = Mono Lake fault (also known as Lee Vining fault). WCF = Wheeler Crest fault, HSF = Hartly Springs fault, SLF = Silver Lake fault, CD = Casa Diablo, LM = Lookout Mountain, TP = Tom's Place, VC = Crestview. Numbers refer to following dates and magnitudes of earthquakes: (1) 4 October 1978, M = 5.7; (2) 25 May 1980, M = 6.1; (3) 25 May 1980, M = 6.0; (4) 25 May 1980, M = 6.1; (5) 27 May 1980, M = 6.2; (6) 30 Sept. 1981, M = 5.7; and (7) 23 November 1984, M = 5.8. From Rundle and Hill (1988).

Figure 1B: Vertical section through Long Valley caldera along profile A-A' in Figure 1A. Shallow caldera structure based on seismic-refraction results of Hill et al. (1985). deeper structure beneath caldera shows the location and geometry of inflation (dislocation) sources used to model deformation observed during the years indicated (e.g., 79-80), seismic P-wave reflecting boundaries, and volumes that produce anomalous S-wave attenuation. Parenthetic numbers give references: (1) Hill 1976, (2) Savage & Clark 1982, (3) Rundle & Whitcomb 1984, (4) Sanders 1984, (5) Savage & Cockerham 1984, (6) Castle et al. 1984, (7) Denlinger & Riley 1984, (8) Denlinger et al. 1985, (9) Hill et al. 1985, (10) Luetgert & Mooney 1985, (11) Savage et al. 1987, (12) Langbein et al. 1987. From Rundle and Hill, 1988.

As the well is the principal activity for the project during the immediate future, the timing and priorities of the applied research and supporting scientific studies will be set by the drilling objectives. It is anticipated that the well will be drilled in stages over a 3-5 year period (Fig.2), with ample time between stages for a variety of scientific observations.

Supporting scientific and technological research is of value to the project if it serves to answer questions concerning the existence and character of the magmatic heat source and the engineering problems of energy extraction. More general scientific work will also be possible. However, additional experiments should not interfere with programmatic objectives, nor should they impact the integrity of the well. These conditions nonetheless allow a broad range of investigations to be considered.

The hole will by far be the deepest hole ever drilled into the center of a large, young caldera. It will therefore provide important new information concerning the collapse, resurgence, and subsequent magmatic history of silicic calderas, as well as a stringent test of the hypothesis that a large body of magma is still present beneath Long Valley. The purpose of this document is to identify the key scientific issues and corresponding research opportunities that the scientific community (as represented by workshop participants) believes should be addressed as drilling progresses. This document is intended to aid potential investigators in focusing their research objectives. The goal is to encourage the maximum scientific return from an unusual research opportunity.

II. PROJECT HISTORY

The Magma Energy project of the U.S. Department of Energy began in the summer of 1973 with a proposal to the Atomic Energy Commission that the magma energy concept be studied as an alternative energy technology (Colp, 1982). Active investigations started during the fall of that year and led to a program of laboratory experiments and thermal calculations that demonstrated promise. Beginning in 1975, and continuing until 1982, the Energy Research and Development Agency's Division of Physical Research funded the Magma Energy Research Project. Management and funding activities were later taken over by the Office of Basic Energy Sciences of the U.S. Department of Energy. Total funds expended over these years amounted to \$4.9 million, with about \$1 million of the funds going to universities.

Among the project tasks were location and definition of magma and characterization of its physical and chemical properties. A variety of laboratory rock mechanics studies were also performed to determine whether a wellbore could remain stable and open during drilling and heat extraction operations. In addition, field investigations were pursued in and around the Kilauea Iki lava lake, a pit crater filled with lava from the 1959 eruption of Kilauea Volcano, Hawaii. These investigations included seismic and electrical experiments to detect the presence of melt, temperature measurements, and petrologic analysis of cores recovered from small-scale drilling experiments (Colp, 1982). The 1981 drilling operation was particularly noteworthy, in that drilling penetrated 40 m into molten rock, at temperatures that exceeded 1100°C. Drilling under these conditions was made possible by means of specially designed high-velocity water jet bits that cooled the molten rock in advance of drilling. A continuous column of

core was retrieved from the molten zone. Moreover, engineering experiments were successfully performed in the molten zone. These involved placing both open and closed heat exchangers in lava at temperatures in excess of 1000°C. The experiments demonstrated that high rates of energy extraction could be achieved and that the effective heat transfer area in the magma zone could be increased with time as the zone solidified and thermally fractured (Dunn, 1981; Hardee et al., 1981).

Following the successful completion of the scientific feasibility studies of the 1975-1982 period, the Magma Energy Technology Project was initiated in the year 1983. Funded by the Division of Geothermal Technology of the Department of Energy, its goal is to develop the technological base to allow commercial implementation of the concept. Engineering activities are focused on developing the technology to drill a deep well into a continental magma body and then conducting a one-year energy extraction experiment. A review of 23 potential U.S. sites (Hardee, 1984; Carson, 1985) led to the choice of Long Valley as the primary site for drilling and energy extraction experiments. After further careful study (Rundle et al., 1985; Rundle et al., 1986), a site in the central part of the caldera, on the resurgent dome, was selected as most promising. The first well to be drilled will be designed to understand the nature of the seismic and other geophysical anomalies, to investigate the central plutonic complex and deep hydrothermal conditions, and to evaluate the present state of magma beneath the caldera. If this phase of the program is successful in confirming the existence of crustal magma, a second well would be drilled to evaluate energy extraction and production techniques.

III. PROGRAMMATIC GOALS

A. General Objectives

Drilling for an energy production well to penetrate into magma represents a profound technical challenge. The well will be large in diameter, hot, deep, and expensive. The preliminary exploratory well is both an exploration tool and a medium for engineering design and definition studies. With lesser requirements on diameter, depth, and service life, the exploratory well is considerably cheaper than a production well. However, we anticipate that a great deal of data will be obtained, permitting considerable cost-savings in drilling a production well. These data will allow:

1. Confirmation of the existence of magma at drillable depths. If no such source can be found in Long Valley, a new field area would have to be identified. Moreover, magma location and definition represents one of the major activities in the program. The geophysical methods used to define the target need to be critically tested at an early stage in the project by direct observation of the target region.

2. Prediction of drilling problems. Historically, much of the cost of big wells is a direct result of unexpected events: lost circulation, unstable formation, sudden changes in lithology requiring a different bit, or zones of unusually high or low pressure. It is possible that these problems might be extremely severe and very expensive to solve for the large production well. However, they can be mitigated by experience gained in drilling the exploratory well because that hole will encounter the same conditions, formations, and problems as the production well.

3. Materials compatibility assessment. The high temperature and likelihood of encountering corrosive gases or liquids make the selection of

tubular and heat exchanger materials a crucial part of the production well design. If no data were available on conditions at depth, uncertainty about the local geochemistry would force the experiment hardware to be capable of resisting a very broad range of corrosives. Clearly, data from the exploratory hole would allow materials selection to be precisely targeted at the local conditions, and would lead to considerable cost savings during the purchase of drillpipe, casing, and heat exchanger parts.

B. Specific Experiments

Some of the most fruitful experiments to answer these questions 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.
- Measurements of in situ stress, to establish the physical condition of the magma and its environment.

With these data and others, it will be possible to precisely site the actual energy extraction well to be drilled as part of the second phase of this study. Data obtained from near the 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 to be drilled for energy extraction. Clearly, surface geophysical and geological studies are reaching the point of diminishing returns if not supported in the near future by borehole measurements into basement. Conversely, performing deep borehole experiments in close coordination surface studies will dramatically increase our ability to constrain models of the fundamental physio-chemical processes involved.

C. Site Location for the Exploratory Well

As a result of these investigations, a site just south of the center of the resurgent dome has been selected for the exploratory well (Fig. 1, 3). The precise designation and location of the well is Long Valley Federal Unit 51-20, Section 20 , Township 3S, Range 28E. At the present time, the plan is to begin drilling in a series of staged episodes, at one year intervals, each episode being approximately two months long, and each episode covering a depth range of 3000' to 6000' (Fig. 2). Because of budgetary restrictions, the well will, for the most part, be rotary drilled, with limited spot coring. Additional coring may be considered if money can be found from other sources.

Figure 2: Design for the Long Valley deep exploratory magma well. For Phases II through IV, approximately 70 m of slim core hole will be drilled and left open after each phase's final cementing.

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Figure 3: Comparison of the major structural features of Long Valley and Valles calderas. See Table 1 for further comparisons. Data from Bailey and Koeppen, 1977, and R. A. Bailey, personal comm., 1988; and Smith et al., 1970.

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Table 1: Comparison of Valles and Long Valley Calderas

	Valles	Long Valley		
	<u>Comments/Ref.</u>	<u>Date</u>	<u>Date</u>	<u>Comments/Ref.</u>
<u>Diameter:</u> topographic	nearly circular Smith et al., 1970	18 x 21 km	16 x 30 km	elongate E-W Bailey et al., 1976
ring fault	well-constrained by postcaldera vents	13 x 17	12 x 16	poorly constrained Bailey and Koepfen, 1977
resurgent dome	asymmetrical - to W	13	10	asymmetrical - to W
<u>Caldera eruption:</u> age	second cycle Doell et al., 1968	1.1 ma	0.7 ma	single cycle Bailey et al., 1976
volume	Smith, 1979	>300 km ³	600-750 km	Bailey et al., 1976; Hildreth & Mahood, 1986
eruption	central to ring Self et al. 1986	~10% into eruption	~20% into eruption	single vent on ring to ring Hildreth & Mahood, 1986
<u>Structure:</u> maximum known thickness of intra-cald. tuff	Nielson & Hulen 1984	1.2 km	>1.2 km	Smith & Rex, 1977
relief on resurg. dome	Smith et al., 1970	800 m	300-500 m	Bailey & Koepfen, 1977
max. known relief on intra-cald. tuff (under dome)	Nielson & Hulen, 1984 Smith et al., 1970	900 m	500 m	west and east most to flank of dome, Suemnicht, 1987
relief on precalders substrate (under dome)	top of lower Bandelier; Nielson & Hulen, 1984	-0 m	-0 m	Top of basement Hill et al., 1984, 1985, 1987
<u>Drilling:</u> number of deep (>1.5 km) holes	Nielson & Hulen, 1984	17	4	Suemnicht, 1987
total depth drilled below intra-cald. tuff	" " " "	17 km	1.4 km	" "
Intrusions encountered as portion of above	" " " "	0%	38%	Most central of deep holes bottomed in large 300-500 ky intrusion; Suemnicht, 1987

IV. SCIENTIFIC OPPORTUNITIES IN THE PROJECT

A. Rationale for Downhole Geophysical Experiments

A three-dimensional understanding of the dynamics of magma-hydrothermal systems in the earth's crust is essential for addressing questions regarding geothermal energy, chemical transport of minerals in the crust, emplacement of economic ore deposits, as well as the mitigation of earthquake and volcanic hazards (NRC, 1984). Our knowledge of such systems, however, has been limited, up to the present time, by our inability to sample more than the upper, cooler parts of active hydrothermal systems. Although geothermal wells have been drilled to depths greater than 4 km and to temperatures greater than 400°C, meaningful measurements are presently restricted to temperatures less than 250°C. Ideally, one would like to drill and carry out observations in the entire magma-hydrothermal system, to magmatic temperatures and to depths well within the crust. The ways in which information from a deep drillhole could help us understand the "roots" of magma-driven hydrothermal systems can be categorized according to four broad purposes:

- Characterization of the Natural Hydrothermal System to the Depth Penetrated

Without direct determination of the in situ physical properties of an active hydrothermal system, both conceptual and mathematical models of the system are only speculative. A variety of parameters need to be known in three-dimensions: temperature, fluid pressure, and transport properties (thermal conductivity, porosity, permeability, and fracture geometry).

- Constraints on Conceptual Models of the Overall Magma - Hydrothermal System in Space and Time

Many experiments or observations that might be made in drillholes are not only necessary to constrain the hydrothermal model to that depth, but also to provide important constraints on the model of the overall magma-hydrothermal system at depths much greater than the actual depth penetrated. For this, we need geophysical measurements in the borehole that are capable of probing to considerable depth below and to the sides of the well.

- Validation and Refinement of Interpretative Methods for Surface Geophysics

A variety of in-hole experiments are essential to evaluate and calibrate surface geophysical techniques. Direct in-situ determination of density, magnetic susceptibility and remanence, electrical conductivity, and seismic velocity and their comparison with surface gravity, magnetic, electromagnetic, and seismic surveys offer a much greater ability to infer structures and properties at depths greater than those penetrated by the drillholes. They also allow one to extrapolate information laterally from the drillhole into the adjacent environment. Furthermore, the increased precision of geophysical interpretations will allow the various surface geophysical techniques to be used much more effectively and confidently at the sites of other magma-hydrothermal systems where drilling information may not be readily available, or obtainable.

- Determining Parameters that Bear on the Regional Tectonic Setting

Deep drillholes in a hydrothermal system also provide information that bears critically on the regional tectonic setting. Stratigraphic data are essential for determining the geological history of the system. The

hydrothermal mineral zonation patterns and the characteristics of fission tracks elucidate the history of the thermal anomaly. And finally, drillholes provide a unique environment for deterring the in situ association of various seismic and electrical properties with such things as the variation of tensor stress, fluid pressure and rock strength with depth, and allows for intercomparing these parameters with their counterparts in nearby holes that are not thermally anomalous.

B. Interaction of External Investigators with the Project

Procurement of funding for the non-programmatic investigations will be the responsibility of the individual investigator groups, via peer reviewable proposals to funding agencies. Copies of these proposals should be sent, at the same time, to the chief scientist of the project (J. B. Rundle, Division 6231, Sandia National Laboratories). Proposed activities which affect the integrity of the well, or incur additional costs to the project, will generally not be approved. However, certain facilities, such as cable, draw-works, and some logging tools, may be provided by the project. Add-on experiments will be constrained by the primary engineering objectives and drilling plan for the project, and those experiments that involve the emplacement of tools in the well will require project approval. Current copies of the drilling and engineering plans may be obtained from the project manager (J. C. Dunn, Division 6252, Sandia National Laboratories).

C. The Geophysical Setting

Recent experiments have delineated the locations and boundaries of geophysical anomalies which are likely to be manifestations of magma accumulations beneath the caldera proper. Comprehensive reviews include

Sherburne (1980), Hermance (1983), Goldstein and Stern (1988), Hill et al. (1985), and Rundle and Hill (1988). Data summarized in these studies suggest a large anomalous region under the caldera shot through with small patchy blobs of magma. In other words, rather than a large volume of molten rock some 10 kms in diameter, refined seismic studies, particularly seismic tomography and S-wave attenuation studies, suggest that such a volume is a heterogeneous assemblage of small melt pockets. This, in fact, may be a typical characteristic of this class of volcanic centers. If so, the only way to test such a model is by drilling coupled with high-resolution surface geophysics.

Thus, while recent studies differ in detail, a consistent picture is emerging which indicates that beneath the northern end of the resurgent dome, the inferred depth to the zone containing magma is about 6-7 km, while beneath the southern end of the resurgent dome the depth is possibly as shallow as 4-5 km. It is important to emphasize that these results do not depend upon any one single investigation, but represent the synthesis of virtually all the work done to date. These seismic studies along with recent vertical uplift accompanied by intense seismic swarms of spasmodic tremor, provide evidence for magma beneath Long Valley that is every bit as convincing as that for magma beneath Yellowstone -- perhaps more so because of the recency of volcanism.

The Symposium on Long Valley Caldera held at Lawrence Berkeley Laboratory on March 17-18, 1987, reviewed much of our current knowledge regarding this active volcanic center (see the recent special volume of the J. Geophys. Res., B11, 93, 1988). It was clear to those attending that there is considerable synergistic value in mobilizing a long-term study

which, from the outset, combines both drilling and refined surface investigations. In this context, drilling becomes as viable a tool for characterizing the third dimension as surface geophysics.

Even now, drilling could help enormously in supplementing the information being returned from surface studies. Many of the surface studies probing to depths of 6-10 km are heavily contaminated by geologic noise at depths of only 0-2 km. Thus, several drillholes penetrating beneath this "surface nose" would go a long way toward calibrating geophysical studies probing to even greater depth. Moreover, as we embark on a new generation of field studies, deep drilling becomes the only tool to test and verify the conceptual models that are proposed by these studies. There is no doubt that more refined geophysical studies on the surface and downhole will go a long way toward optimizing the sites of progressively deeper drillholes in the future. In addition, the results of the Berkeley Symposium suggest that any drilling which is done in the near term will contribute substantially toward calibrating the next generation of refined surface geophysical studies.

1. Geodetic Measurements

Geodetic measurements of uplift and horizontal strain have been reported 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), Wu and Wang (1988), Savage (1988). 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 are non-unique and can only provide information on the

subsurface volume change and on the location of the "center" of inflation. Geodetic data alone cannot yield unique bounds on the depth to the top of the magma chamber, since the size of the 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. If their model is correct, then the roof of this shallower chamber appears to be at a depth of less than 5 km.

2. Electromagnetic Studies

Results of electromagnetic studies -- magnetotelluric (MT), controlled source electromagnetic (CSEM), audiomagnetotelluric (AMT), total field resistivity measurements (TFR), and D.C. vertical electric soundings (VES) -- are summarized by Hoover et al. (1976), Stanley et al. (1976), Hermance (1983), Hermance et al. (1984), Goldstein (1984), Hermance and Karlsdottir (1986), Park and Torres-Verdin (1988), Hermance et al (1988a,b). Such studies have contributed substantially to characterizing the tectonic style of shallow structures in the caldera.

The geologic boundaries of Long Valley caldera are sharply delineated by steeply dipping normal faults which, for the most part, are buried and obscured by recent volcanic and sedimentary cover. Detailed MT work in the northwest moat has delineated a parallel set of buried high angle normal faults which have virtually no expression at the surface. The first has a throw of approximately 500 m, while the second has throw of approximately 2 km; neither has an expression in the surface morphology. Moreover, based on a relatively low resistivity contrast between the basement and the basin fill, a relatively high fracture porosity is inferred

for the Sierran basement, which therefore appears to be open to the lateral and vertical migration of meteoric water; a result which has considerable significance for understanding the regional hydrology.

Whereas the results of regional electromagnetic studies have been substantial in delineating the hydrothermal system and the major boundary faults, few constraints have been placed on the location and extent of deeper (magma) conductors. It appears that the highly conducting hydrothermal waters within the caldera fill effectively mask any underlying magmatic conductor(s). Hence, little significant progress can be made in delineating a deeper target until sensors can be placed in the basement below the caldera fill at depths of 2-3 km.

3. The Geothermal Reservoir

An extensive geothermal reservoir exists within the Long Valley caldera, with a commercial geothermal power plant already in operation. Detailed studies of the subsurface thermal regime include those of Lachenbruch et al. (1976a), Lachenbruch et al. (1976b), Sorey (1984), Blackwell (1984), and Suemnick and Varga (1988). Up to the present time, 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. The regional background heat flow is estimated 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, which 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 a steady-state fashion. Clearly, the effect of the hydrothermal system is to obscure any thermal signature associated with a deep magma source beneath the Sierran basement. Constraints on understanding the hydrothermal system and the nature of a magmatic heat source will remain elusive until deep drilling into basement permits a good estimate of the depth to magma.

V. GEOLOGY OF THE SITE

Resurgent cauldrons such as Long Valley are complex structures that reflect the stopping of a large body of magma to the surface. Although by definition they share certain structural and volcanological features, they show great variation. Presumably, these variations result from widely differing crustal and structural settings, differences in precaldern volcanic histories, and a large range in volumes and properties of magmas responsible for caldera-forming events. As a consequence of this variation, the lithologic units and physical conditions to be encountered by a single borehole cannot be reliably predicted, even in a caldera as well-studied as Long Valley. Conversely, many of the results from a single deep hole cannot be readily applied to the overall structure of such complex features. Nevertheless, the scientific opportunity afforded by a very deep hole, centrally located within a major caldera, is an outstanding one. There is evidence from current geophysical anomalies, from surface geological observations, and by analogy to comparable eroded systems that the hole will penetrate a central pluton, likely still cooling or recently rejuvenated, thereby providing the first direct link between large young calderas and their intrusive roots. While the structures to be encountered cannot be accurately predicted, we can consider results to date at Long Valley and other comparable systems in order to prepare scientifically for key observations.

In considering what the hole will encounter, it is important to locate the well in relation to the main structural features of the caldera: the initial Plinian vent, the ring fracture system, and the resurgent dome (Fig. 3 and Table 1). It is helpful to use the Valles Caldera for

comparison because it is of comparable size and age and because it has been more extensively explored by drilling than Long Valley.

A. Models for Caldera Structure

Current concepts about calderas are based primarily upon the surface structure and eruption history of young calderas such as the Valles and Long Valley (Fig. 3; Smith and Bailey, 1966; Self et al., 1986; Bailey et al., 1976) combined with geophysical evidence (e.g., Hill et al., 1984, 1985), drilling constraints on their deep structure (Fig. 4; Suemnicht, 1987), field geologic observations of moderately eroded tertiary systems such those of the San Juan (Fig. 5; Steven and Lipman, 1976) and Mogollon-Datil fields (e.g., Elston, 1984), and deeply exposed ancient calderas such as represented by the Mesozoic-age ring dike complexes of New Hampshire (Fig. 6, Kingsley, 1931). Lipman (1984) has provided a recent review. Considerable uncertainty exists as to the interpretation of this large but disparate body of evidence, and probably different calderas develop in different ways. End member models (Fig. 7) are: (1) eruption from a ring fault with largely intact collapse of the encircled block (Smith and Bailey, 1968) and (2) eruption of a central vent with development of a large depression through a combination of explosive excavation, slumping and piece-meal stopping into the subjacent chamber (Aramaki, 1984). The former may best describe large calderas while the latter probably applies to most small ones. However, even for large calderas, activity may begin at a central vent and progress to ring-fracture venting (evidence for which is indirect) and large-scale, intact subsidence after substantial withdrawal of magma has occurred (Self et al., 1986).

A basic problem with applying observations of ancient eroded systems to modern calderas concerns the deep intrusive regime, which is of special

interest here. Caldera systems are the products of many igneous events. While this results in a complex but interpretable volcanic stratigraphy at the surface, at depth the emplacement of large intrusive bodies obliterates the record of previous intrusive events. Thus, the intrusive record is incomplete and biased toward late events. One of the important aspects of the Long Valley hole is that it will sample the intrusive system at a central location less than a million years after a major caldera-forming event. Since Long Valley is still evolving, the hole will view an earlier stage in evolution than the view afforded by fossil systems.

Figure 4: Generalized cross sections through Long Valley caldera, showing position and depth of the major drill holes in relation to the caldera fill. Note that the planned hole (51-20) will be almost three times deeper than 66-29 and almost four times deeper than M-1. For a more detailed east-west section, see Suemnicht and Varga, 1988.

Caldera fill: dominantly early rhyolite and Bishop Tuff
post-caldera rhyolite intrusion 300-500 ka

* projected > 2 km to section

Figure 5: Lake City caldera, a moderately eroded Tertiary cauldron in the San Juan Volcanic Field, Colorado (Lipman, 1976 and 1984). The ring fracture zone is almost completely exposed, but does not contain significant intrusions at this level of dissection. Post-caldera intrusion occupy less than 10% of the intra-ring fault region.

Figure 6: The Ossipee Mountains, a deeply eroded inferred caldera of Mesozoic age in northern New Hampshire (Kingsley, 1931). The ring fracture is everywhere intruded by granitic magma and the central pluton occupies about 50% of the intra-ring region.

Figure 7: Conceptual end members (I and II) and an intermediate case for large silicic calderas: I - Eruption from ring fractures with intact collapse of the encircled block (Smith and Bailey, 1968); II - Eruption from a central vent with piecemeal collapse of the surrounding region (Aramaki, 1984); III - Onset of eruption at a central vent with later venting and subsidence along ring fractures (Self et al., 1986).

B. Initial Plinian Vent

Like many major ash-flow tuff sheets, the Bishop Tuff is underlain by a Plinian air-fall deposit representing the opening phase of the caldera-forming eruption. Such deposits are interpreted as a more energetic phase, since they involve a very high velocity jet feeding a convective column, whereas ash-flows develop from low vent fountains or collapsing columns (Wilson et al., 1980). The progression from Plinian to ash-flow activity could be accomplished by decreasing magmatic volatile content or by a broadening vent orifice (resulting in lower exit velocities at constant mass flux). Broadening may occur either by erosive reaming of the vent walls or by progression from venting at a central vent to a ring-fracture vent. The latter has been suggested for both Long Valley (Hildreth and Mahood, 1986) and the Valles (Self et al., 1986). The location of the initial Plinian vent is of interest because it represents the point at which the main magma body first approached the surface and because it represents a major structural feature that may lie in the vicinity of the planned drill hole.

Surface structural evidence for an early central vent is never preserved in large calderas because large ash-flow eruptions immediately follow the initial Plinian events. Lacking surface expression for the vent, the next most direct means of establishing its location is by measuring the thickness of the Plinian deposit at a large and well-distributed number of points and thereby delineating isopachs. Intersecting thickness axes of layers within the Plinian deposit were used at the Valles to suggest a central location for the Plinian event (Fig. 3; Self et al., 1986). Such an approach is not possible at Long Valley because of the restricted distribution of exposures of the Plinian deposits. Instead, Hildreth and

Mahood (1986) used their identification of a unique assemblage of lithic fragments in the Plinian deposit, which matches units of limited distribution exposed on the south wall of Long valley caldera, to suggest a south-central location for the Plinian vent (Fig. 3). They argued that the vent could not lie very far north-northeast into the caldera along the strike of this rock unit assemblage because the Plinian deposit does not contain fragments of the precaldern Tertiary basaltic and Pleistocene Glass Mountain rhyolitic volcanic piles, which are known to be present to the north. However, since the actual distribution of these units in the caldera floor is unknown, it remains possible that the Plinian vent does have a more central, rather than ring-fault position and may therefore be near the planned hole. Hildreth and Mahood (1986) estimate that 150 km³ of magma (50 km³ in the Plinian eruption and 100 km³ as early ash flows) erupted from the central vent before ring-fracture venting began (Table 1), so the initial vent must be a very large structure.

C. Ring Fracture System

The existence of ring faults along which magma has reached the surface and much or most of caldera subsidence has occurred is indicated in young calderas by arcuate fault structures and vent systems, by geophysical evidence, and, to a lesser extent, by drilling results (Smith et al., 1970; Bailey et al., 1976; Hill et al., 1985, 1987; Suemnicht, 1987; Eichelberger et al., 1988), in moderately eroded systems by actual exposure (Lipman, 1976), and in ancient deeply eroded systems by ring dikes enclosing downdropped volcanic rocks (Kingsley, 1931). Ring fractures lie well inboard of the topographic expression of the caldera because the rim retreats first by catastrophic landsliding and later by normal erosion and

slumping (Lipman, 1984). At the Valles caldera it is unusually well delineated by a necklace of postcaldera rhyolite domes (Smith et al., 1970). No such clearly arcuate vent system exists in Long Valley. However, the geologic requirement that the ring fracture zone lie beneath the caldera moat, between the topographic rim and the resurgent dome, is supported by geophysical results and the limited drilling. Beyond that, the location can be suggested from vent and fault positions as shown in Figure 3. Probably the greatest uncertainty is in the eastern part of the caldera where the moat is broadest and there are relatively few vents. However, this is not a concern for purposes of the hole considered here. Hildreth and Mahood (1986) argued that about 600 km³ of magma erupted from the ring fracture, and that the fracture opened counterclockwise from the inferred initial vent location on the south side of the caldera. This inference, and the evidence provided by ring dikes in deeply exposed systems, suggests that major intrusive bodies should be present at depth in the ring fracture.

A mechanical requirement for collapse is that the ring fractures along which collapse is accommodated cannot be shallowly inclined inward. At the particularly well-exposed ring fracture of Lake City caldera, Lipman (1976) determined a range of dips from vertical to 80° inward. The location of the planned hole is such that it would not reach the ring fracture zone at the total depth of 6 km unless the fracture dips inward at 50° or less (Fig. 4). Hence, it is unlikely that the hole will intersect the ring fracture. Rather, the position of the hole relative to the ring fracture indicates that the hole is centrally located with respect to the main caldera magma chamber because the ring fracture marks the boundary of

subsidence due to magma withdrawal. Based upon drilling and geophysical results, the average collapse of the caldera block within this fracture zone is 2 km (Hill et al., 1985; Suemnicht, 1987).

These considerations suggest that if intrusions matching the Bishop eruption in composition and age are encountered in drilling, they will represent the feeder for the early central vent or the roof of the main magma reservoir, rather than invasions of the ring fault system. Because of the well-defined chemical stratigraphy of the Bishop eruption (Hildreth, 1979), it may be possible to tie any Bishop-related intrusions to a particular stage of the climactic eruption.

D. Resurgence

Resurgence of the central caldera floor, involving structural uplift - not merely rebuilding of the volcanic pile - is unequivocally required by surface observations at many large calderas. The evidence includes the distribution of faults indicative of extension and doming, development of radially outward dips on tephra and lava units, and occurrence of caldera lake terraces and deposits at elevations above those for comparable deposits on the caldera walls and above plausible lake outlet elevations (Smith and Bailey, 1968). All of these features occur on the resurgent dome of Long Valley caldera (Bailey et al., 1976; R. A. Bailey, personal comm., 1988) and require a minimum uplift of 200 m. The more topographically dramatic resurgent dome of the Valles caldera, the type resurgent cauldron, exposes the intracaldera portion of the upper Bandelier Tuff at its core, whereas units no earlier than early postcaldera rhyolites crop out on the Long Valley resurgent dome. In both cases, however, the evidence suggests that

most of the resurgence occurred within 100,000 years of collapse (it could be considered as continuing in the present period of unrest at Long Valley).

Although the interpretation of surface deformation in resurgent cauldrons presented by Smith and Bailey (1968) still stands, aspects of the subsurface configuration they proposed require modification in light of drilling results. At the Valles, and based on seismic data and limited drilling data at Long Valley, the precaldra substrate does not rise broadly under the resurgent dome. It appears to be fairly flat or irregular. In view of the strength of the surface evidence for uplift, this cannot be taken as evidence against resurgence. Rather, it indicates that collapse was greater under what became the dome and that resurgence gradually returned this area to the level of the caldera floor beyond the dome. The higher elevation of the dome then expresses the greater thickness of the tuff under the dome. Because ash flows that comprise the Bishop Tuff were fluid and formed gentle surfaces, the top of the Bishop Tuff (provided it is uneroded, the top of the Bandelier Tuff is eroded under Redondo Dome; Nielson and Hulen, 1984) should provide the best marker of the structure of the resurgent dome. The Bishop Tuff is nowhere exposed within the caldera, so reliable delineation of its surface depends on drilling results. The limited available data show 500 m of relief on the Bishop surface between the resurgent dome and the west and east moats (Suemnicht and Varga, 19887). The data further show that the dome extends farther west than its surface expression (Wollenberg et al., 1987), its west flank buried by late lavas. This is a lower limit to the actual structural uplift because none of the holes are centrally located on the dome, as the planned hole will be. The elevation of the top of the Bishop Tuff and the thickness of the tuff will

therefore be key observations in interpreting the history of collapse and resurgence in the center of the caldera. A complication at Long Valley (and probably at most large calderas) is that there is considerable relief on the surface on which the caldera tuff was deposited, reflecting precaldera basement structures. Geophysical results indicate a depression in the basement surface under the north flank of the dome and a northwest-trending horst under the southeast flank (Hill et al., 1987; Hermance et al., 1987).

E. Central Intrusions

Because of its timing, central position, and spatial coincidence with many early postcaldera vents, resurgence is presumed to be related to high-level intrusion of magma associated with the caldera event (Lipman, 1984). Most cartoons of resurgent cauldrons show large plutons at least as wide as the ring faults at depths of a few to several kilometers. This is based on the general observation that the deeper the level of erosion of this class of systems, the larger the proportion of the intra-ring fracture area is occupied by caldera-related intrusions (Fig. 5 and 6). In many cases, the central intrusions(s) reach up into the volcanic pile and sometimes into the intracaldera tuff. It is surprising, therefore, that none of the several holes that penetrated below the volcanic section in the Valles caldera encountered young intrusions. A general conclusion cannot be drawn from this, however, because the deepest holes are restricted to a relatively small area of the caldera. In contrast, one of only four deep (≥ 1.5 km) holes in Long Valley penetrated 500 m into and bottomed in a granitic body that was intrusive into the Bishop Tuff. The intrusion appears to belong to the moat rhyolite group and the hole CP-1 is on line with seven moat rhyolite vents (the closest is 1 km) of 500,000 to 300,000 year age

(Suemnicht, 1987; Suemnicht and Varga, 1988; Bailey and Koeppen, 1977; Bailey, personal comm., 1988). Since this hole is on the resurgent dome and the most centrally located of any of the holes drilled to date (Fig. 4), we must consider it possible that a large central intrusion(s) underlies much of the resurgent dome at relatively shallow depth. Hence, the planned hole could pass directly from Bishop Tuff into an intrusive complex at depths as shallow as 1-2 km. Seismic reflection data, which suggests basement at 1-2 km under the resurgent dome (but does not pass through its center), cannot distinguish between Mesozoic granitic basement and Quaternary granitic intrusion. However, this distinction can be readily made from drill cuttings and core.

F. Basement and Magma

If the hole does not encounter young intrusions, it will penetrate Sierran basement. The Hilton Creek Fault forms the eastern boundary between the Mt. Morrison roof pendant and granitic plutonic rocks. This fault trends into the caldera along the east flank of the resurgent dome and it dips steeply eastward. Hence, the planned hole should penetrate roof pendant material. Geophysical evidence (Oliver, 1977) indicates that the roof pendants are relatively thin flakes, so the hole should pass downward into Sierran granitic plutonic material well before its planned final depth. Of interest will be whether the cauldron block was substantially fractured and deformed during its ~2 km of subsidence.

There has not been an eruption on the resurgent dome in 300,000 years, so there is little basis for speculation concerning the composition and conditions of magma storage that may be present now. It is possible, however, that recent eruptions in the west moat came from deep beneath the

resurgent dome, guided by steeply east-dipping faults such as the Hartley Springs. All eruptions during the past 100,000 years within the caldera have been rhyodacitic to rhyolitic. Volumes of eruptive events have declined in volume by 3-4 orders of magnitude from the Bishop event, so it is reasonable to expect that the current magmatic system is silicic and exists within a crystallized carapace of its predecessor chambers, as depicted by Bailey (1976, 1984). The hole is planned to stop at 500°C, and so it will not encounter melt. The solidus, at which interstitial melt should appear, would be expected to be about 700°C at 6 km depth (1.5 kb; Tuttle and Bowen, 1958; Naney, 1983). The hole may well encounter the crystallized margin of the current body and possibly recently crystallized offshoots from that body.

VI. WORKSHOP TO IDENTIFY CRITICAL ISSUES

In order to aid in defining the critical scientific problems which need to be solved to ensure success of the technological program, it will be necessary to utilize the expertise of a wide variety of scientists. Hence, a workshop was held in June 8-9, 1988, in Albuquerque, NM, to better understand the nature of these scientific issues. About 60 participants (Table 2) from a variety of institutions were divided into four groups: "Geophysics," "Geology," "Hydrothermal Systems," and "Stress and Mechanics". These groups discussed the important questions in each area, and how best to address them within the context of the drilling program mandated by the engineering constraints. The following five sections summarize the results of these discussions.

Table 2

MAGMA ENERGY SCIENCE WORKSHOP ATTENDEES

June 8-9, 1988

NAME	AFFILIATION	TELEPHONE
Ken Wohletz	LANL	505-667-9202
Earl Hoskins	Texas A&M	409-845-1171
Mark Ziegenbein	BLM	619-872-4881
Mike Sorey	USGS	415-329-4420
Herb Wang	U. of Wisconsin	608-262-5932
Mingdong Wu	U. of Wisconsin	608-262-4885
Ron Jacobson	Sandia	505-844-0938
Doug Drumheller	Sandia	505-844-4181
Virgil L. Dugan	Sandia	505-844-8735
Paul Kasameyer	UNL	415-422-6487
Dick Dondanville	UNOCAL	707-545-7600
Bob Smith	Exlog/Smith	707-411-1700
Bill Luth	Sandia	505-844-3690
Ken Cameron	UCSC	408-429-2795
Malcolm Johnson	USGS	415-329-4812
Norman Goldstein	LBL	415-486-5961
Lee Silver	Cal Tech	818-356-6490
John Eichelberger	Sandia	505-846-0398
Lee Younker	LLNL	415-422-0720
Mike Mayhev	NSF	202-357-7355
Chris Sanders	USGS	415-329-4750
Steve Flexser	LBL	415-486-4816
Terry Gerlach	Sandia	505-844-5929
Philip Johnson	NRINT	505-835-1612
Peter Lyane	Sandia	505-846-6328
Dan Lyster	Mono County	619-934-6704
Charles Q. Grigaby	LANL	805-667-3605
Jim Dunn	Sandia	505-844-4715

Gladys Hooper	DOE	202-586-1146
John Arestad	Santa Fe Geo	214-701-7773
David Blackwell	SMU	214-692-2745
Chip Shearer	S.D. School of Mines	605-394-2495
David C. Gosselin	Battelle - PNL	509-946-4262
Schon Levy	LANL	505-667-9504
Larry Newman	Nova Mud	801-266-6682
H. M. Iyer	USGS	415-329-4756
Henry Westrich	Sandia	505-846-9613
Bill Olsson	Sandia	505-844-7344
Colleen Barton	Stanford	415-723-2751
Al Tripp	ESL/UURI	801-524-3431
John Evans	USGS	415-329-4753
Philip Candela	U. of Maryland	301-454-3548
George Tennyson	USDOE/AL	505-846-3219
Kerry Burns	LANL	505-667-4318
Bob Christiansen	USGS	415-329-5228
Roy Bailey	USGS	415-329-5240
Harold Wollenberg	LBL	415-486-5344
John F. Hermance	Brown U.	401-863-3830
Marianne Walck	Sandia	505-846-0146
Dennis Nielson	UURI	801-943-5113
Jonathan Fink	ASU	602-965-3195
Lewis C. Bartel	Sandia	505-844-6902
Charles Carrigan	Sandia	505-846-3463
Sanford Ballard	Sandia	505-846-6984
Bill Livesay	Livesay Cons.	619-587-9731
Tom Blenkinsop	UCSB	805-961-8421
R. K. Traeger	Sandia	505-844-2155
R. P. Wemple	Sandia	505-844-2230
John Rundie	Sandia	505-844-8158
Tom Henyey	USC	213-743-6123
Jim Rannels	DOE HDQTRS	202-896-8070
Grant Heiken	LANL	505-667-8477
Alan Jelacic	DOE HDQTRS	202-252-9152

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VII. BOREHOLE GEOPHYSICAL TECHNIQUES (Group Chairman: J. F. Hermance,
Brown University)

A number of borehole geophysical techniques, divided broadly into two classes of methods, well logging and far field geophysical sensing, can contribute to characterizing the subsurface environment of an active magma system. The basic differences are that well logging is a conventional, high precision method for characterizing the immediate vicinity of the borehole (typically within a radius of a few meters), whereas far field sensing techniques are useful for probing the environment at hundreds, or even thousands, of meters away from the borehole.

These far field methods are still highly experimental and are in a rapid stage of development. Nevertheless they appear to be very promising for exploring the subsurface magma-hydrothermal environment. This latter application offers unique challenges to established approaches, not only from the higher temperatures at which we expect these instruments to operate, but also by requiring that a maximum amount of information be acquired from each borehole. The geothermal industry, and particularly, a scientific drilling program, will tend to drill fewer exploration holes than the petroleum industry, so that the information from each hole drilled must be optimized.

The critical scientific questions identified in this group were:

- a. What is the local crustal structure to depths of 10 km?
- b. What is driving the seismicity and deformation, and can current models be tested through the use of borehole data?
- c. How are pore pressure changes related to observed seismicity, deformation, and temperature changes?

- d. Is the brittle-ductile transition responsible for variations in seismicity with depth in the caldera?

Answering these questions will demand a program consisting of several elements.

A. Structure from Seismic Methods

Structural models of Long Valley constructed in the past have been for the most part constrained by poor transmission of energy through the near-surface caldera fill. Thus, important experiments to resolve these issues include Vertical Seismic Profiling (VSP), and passive recording of local, regional, and teleseismic earthquakes. Other possibilities include borehole-tomographic measurements using active sources.

1. Vertical Seismic Profiling

VSP is used to extend information about geologic structures and rock properties, inferred from drill cuttings, core and geophysical logs, away from the borehole. The extent to which the borehole information can be carried into the surrounding rock mass depends on the distribution and density of surface source locations and downhole receiver (geophone) positions.

Reflected wavefields are used to map fracture zones, faults and contacts, intersected by the bit, and to "look ahead" of the bit to the as-yet-undrilled interval. These data can then be used to plan drilling and coring strategy. Reflected wavefields can also be used to explore below the total depth (TD) of the hole to an effective depth on the order of twice TD. Reflector mapping includes both the elements of continuity and orientation of interfaces in the subsurface. Major interfaces at Long Valley include the top and bottom of the welded Bishop Tuff, the top of the

Sierran basement, and the top of any magma body. Lesser interfaces would include faults, fracture zones, and erosion surfaces. Source walk-aways from the wellhead can be used to trace key reflectors to distance.

Transmitted wavefields are used to study rock properties including fracture and petrologic anisotropy, seismic velocity, intrinsic attenuation, and scattering. Splitting of shear waves into SH and SV components (generated either at the source or by mode conversion) are particularly useful for exploring fracture density and orientation. Fracture orientation may be related to present day paleo stress fields. The extent to which the basement and overlying volcanic pile has been fractured by subsequent intrusion, doming, and regional tectonics is particularly pertinent to questions of hydrothermal circulation.

2. Passive Seismic Experiments.

A second seismic method of major interest is passive recording of local, regional, and teleseismic earthquakes. Passive source seismic experiments using either local or teleseismic earthquake sources are a principal means of imaging the Long Valley caldera crustal structure. The local earthquake tomography problem utilizes small earthquakes located in and near Long Valley and recorded at seismic stations in the same area. The recorded signals contain information about the compressional and shear wave velocity and attenuation structure in the upper 10 to 50 km of the caldera and can be used to determine the structure, including magma bodies, potentially to a resolution of 1-2 km. The currently available (from a 3-component, wide-aperture, surface array, 1984) and proposed (from a 3-component, narrow-aperture, borehole array, 1989+) seismic data can provide particularly good structure resolution in the local area of the

borehole. Thus, the structure and other data obtained in the deep borehole will provide a direct test of the results of this geophysical technique. Also, since the crustal structure can be imaged to greater depth and to considerable distance laterally from the borehole, data trends observed in the borehole may be extrapolated to the sides and down. In this local tomography experiment the deep borehole is not needed for instrument installation, and the drilling schedule does not affect the experiment.

3. Tomography Using Borehole Receivers

Another local source tomography experiment would utilize a string of seismic recorders in the borehole. This in-hole array can be used to:

- a. Record local seismic noise in hole array related to fluid movement or rapid strain;
- b. Record local earthquakes similar to the above experiment except without the distorting effects of the near surface materials;
- c. Record clean teleseismic signals below the surface.

This string of seismometers would be in-place for times measured in months and would be shared by all seismic experiments, both passive and active. Careful instrument development will probably be required to withstand the borehole environment. This experiment would occur after drilling had ceased for the year and would probably restrict other experiments during the deployment period.

The teleseismic crustal conversion problem uses teleseismic earthquakes recorded on 3-component seismic arrays located around and in the borehole. The technique utilizes direct P-wave arrivals and arrivals immediately following which can be identified as conversion from major

structural discontinuities in the crust, such as magma bodies and the crust-mantle boundary. Triangulation of the arrival time differences allows the discontinuities to be located. In the upper crust, bodies of sizes about 2 km or greater can be located. In addition, other analyses can provide S-wave velocity structure of the entire crustal column at the borehole site. This allows comparison of the deep crustal structure to the shallow structure and may potentially yield evidence of the deeper crustal processes related to the caldera. The experiment would use several small arrays of 3-component seismometers placed on the surface and within 5 km of the drill site, and operated for several months in an event-detection mode. A linear borehole array would contribute additional high-quality teleseismic data to this experiment.

B. Structure from Electrical Methods

Electrical geophysical methods have been used in Long Valley to map electrical conductivity variations related to geothermal activity. Specific objectives have included mapping hydrothermal attenuation, mapping resistivity variations associated with structure and stratigraphy, and the detection of magma at depth. Borehole electrical and electromagnetic measurements in the magma exploratory well can be of great value in increasing the resolution of conductive structure as well as increasing the depth of electrical investigation. In these ways, the electrical measurements would effectively increase the volume and depth of rock investigated by the well.

Two types of experiments are envisaged. The first experiment would attempt to resolve the lateral conductivity variations around the drillhole. In this experiment, a transmitter array would be deployed on the earth's

surface at some distance from the drilling and receiver electrodes would be lowered into the drillhole. Electrical field magnitude and phase at discrete intervals would be made, before casing at the end of each drilling phase. The data would be valuable in modeling the lateral conductivity structure between the borehole and the surface transmitters.

The second type of experiment would attempt to sense conductivity to the side or ahead of the drillhole. The borehole receiver in this case would be magnetometer or an array of magnetometers. In one variation of the experiment, the magnetometers would measure three-components of the magnetic field. The source of electromagnetic energy could be either the natural earth fields or an active source. One possible result of these measurements would be the estimation of the in-situ resistivity of magma itself.

Since the two data sets would be complementary, they could both be used to constrain extensive surface measurements made previously. In this way, the conductivity structure around the borehole can be further resolved.

Laboratory studies of the electrical conductivity of core at borehole temperatures would also be valuable in interpreting all borehole electrical data. A standard log suite, including an induction log, will be very useful for data interpretation.

C. Structure from Borehole Gravity Measurements

The elevation and thickness of the Bishop Tuff are key observations in interpreting the history of collapse and resurgence in the caldera. Unfortunately, the position of contacts observed in 51-20 may be influenced by local topography on the pre-Bishop Tuff surface, erosion of the top of the Bishop Tuff, or horst-graben structures associated with resurgence. Because of the density contrasts among the Bishop Tuff, the post-caldera

volcanics, and the basement, borehole gravity measurements in 51-20 will allow us to assess the average elevation of the contacts in a ~500 m circle about 51-20.

Commercially available borehole gravimeters are dewatered and can be run to ~250°C in 6" casing; or to at least 7500' in the expected hole environment. By comparing gravimetric estimates of density with density log values, we can learn how the structure around the well deviates from flat-lying layers. These measurements would require about two and one-half days of well access, and may require an oversized lubricator and gate valve. If the well can be cooled, then the depth range could be extended by collecting the deepest data with the rig over the hole. The borehole gravity would be interpreted jointly with the surface gravity data to improve density models in the area of the borehole.

If the borehole gravity measurements can be repeated after several years, it may be possible to detect density changes around and beneath the hole caused by changes in the hydrothermal system or migration of the magma bodies.

D. Investigation of Changes in Crustal Strain

Of particular interest is the study of currently active processes within the caldera. The objective is to learn about the physical processes associated with magma injection. In addition to measurement of in situ stress, which is discussed in a later section, it would also be of interest to observe changes in pore pressure, tilt, and strain.

During the periods between drilling activity, water level and/or pore-pressure can be monitored in the well as a direct indicator of the state of crustal strain. These measurements would be coordinated with other

experiments related to continuous monitoring (seismic, etc.). All instrumentation would be battery operated with solar charging. Data would be transmitted through a digital satellite link to remote sites for recording. If insufficient open hole exists, pore-pressure rather than level can be measured by emplacing a packer just below the water table.

In addition, at least three borehole strainmeters/tiltmeters within 5 km of the proposed hole could be used, first, to monitor changes in the subsurface hydrothermal and pore-pressure system associated with drilling, and second, to constrain the location and size of any shallow magmatic injection source. Changes in wellbottom pressure associated with drilling and hydrofracturing would provide information on medium-scale (~a few kilometers) permeability and porosity. Data can be transmitted through a digital satellite system to remote sites for recording.

E. The Brittle - Ductile Transition

A 6-km deep drillhole will probably penetrate the base of the seismogenic zone beneath the resurgent dome, and will thus afford a rare opportunity to study, in situ, conditions associated with the temperature-dependent transition from brittle to ductile deformation within the crust. Because of the relatively sparse seismicity beneath the south-central resurgent dome, the base of the seismogenic zone is not as sharply defined as it is beneath the south moat region of the caldera. Nevertheless, based on the 1982-1987 US Geological Survey seismicity catalog for the Long Valley region, seismicity terminates at a depth of between 5 and 6 km. Measurements in the well at these depths, should allow characterization of temperatures, pore pressures, rock composition, and rock fabric. These data

will also allow calibration of the laboratory-based flow law parameters for quasi-ductile deformation of rocks beneath the base of the seismogenic, brittle zone.

VIII. GEOLOGY (Group Chairman: Roy A. Bailey, USGS)

The most important scientific questions identified by the geology group are:

- a. What are the mechanics of caldera collapse and resurgence?
- b. How extensive are the precaldern volcanic sequences and what is the character and physical state of the basement rock?
- c. Are intrusive equivalents of the Bishop Tuff present? If so, do they represent a feeder for the early central vent or the top of the main chamber? If the former, during what portion of the climactic eruption was it active? If the latter, does it preserve the chemical zonation of the Bishop Tuff?
- d. Were there repeated distinct pulses of magma intruded beneath the resurgent dome or is there evidence for a single body persisting and evolving since caldera formation?
- e. Is there geologic evidence of recent intrusion?

These objectives can be discussed in the context of the geologic regimes to be encountered in drilling.

A. Intracaldera Fill

The history of intrusive activity and surface deformation is reflected in volcanic activity and sedimentation in calderas. These clues are necessary for interpretations of processes within the magma chamber(s) and for understanding the present thermal state of a caldera. After caldera-collapse, smaller, less explosive eruptions occur within the caldera margins; usually, this activity is often concentrated along ring faults or faults crossing the caldera, although this structural association is not

particularly strong at Long Valley. Post-caldera-collapse eruptions record the evolution of the caldera magma chamber and the most recent eruptions are the best indication of current magmatic conditions. At Long Valley, the most recent eruptions are rhyodacitic to rhyolitic in composition.

Immediately after collapse the caldera is a closed sedimentary basin and a crater lake may form. This is the site for fluvial and lacustrine sedimentation until the caldera wall is breached. Interbedded with post-caldera volcanic rocks, these deposits offer a series of "level-lines" that, along with dated interbedded tuffs, can be used to study structural resurgence. The elevations, thicknesses, and grain size of these deposits, when compared (and correlated) with similar deposits in other drillholes, can supply useful data on the process and timing of resurgence. Both the volcanic and sedimentary deposits of the intracaldera fill are thus important to understanding the present thermal regime.

B. Bishop Tuff

Primary interest in intracaldera Bishop Tuff is its chemical gradient and what that might reveal about timing of caldera collapse, as ascertained by comparison with chemical gradient in outflow sheets and relative volumes of early and late components. Because the zonation is subtle, adequate chemical data probably can be obtained only from continuous core, from which discrete pumice fragments could be extracted for analysis. Bulk rock samples obtained from sidehole coring may be too small to remove lithic contaminants, and thus might give spurious results. However, sidewall-core at about 500' intervals (over 2000-3000' thickness) would be worthwhile. Cuttings are less satisfactory for chemical studies because of severe uphole mixing and sorting in the collection flowline.

Useful information about the timing of collapse might be gained from recognition of softer zones between sub-cooling units, as ascertained from drilling rate and examination of standard logs, and by comparing subunit thicknesses with those in outflow sheet.

Gross variation in hydrothermal alteration mineralogy of Bishop Tuff may be provided by cuttings, provided they were coarse enough (>3 mm) so that textural relations are observable. Sidehole coring at intervals would be a definite advantage in such studies.

C. Hydrothermal System

The quantity of energy released by crystallizing magmatic bodies can be estimated from available thermodynamic data. The fate of this energy, however, is less evident. Energy released by crystallizing magma can be apportioned between circulating hydrothermal systems, conductive transport, mass redistribution, and recrystallization of the enclosing country rock. To understand the energy dynamics of such a system requires access to an actively cooling pluton. In that sense the Long Valley drilling program could provide an opportunity to quantify the energy budget of, and the energy flux from, a cooling magma body.

An important result would involve establishing, within reasonable uncertainty limits, the distribution of energy among the various dynamical elements of the caldera system. For example, the amount of energy contained in the circulating hydrothermal fluid can be estimated by measuring fluid flow rates, fluid temperature and fluid composition from packed off sections of the hole. The fluid composition can be used to estimate the enthalpy of the fluid at the measured temperatures. Energy

apportioned to conductive heat flow would, of course, be estimated from the measured heat flow. Energy apportioned to recrystallization would be determined from changes in mineral composition in samples of rock overlying the heat source.

These activities could be supported by obtaining fluid samples and flow rates at selected packed-off intervals, and detailed petrographic and electron microprobe analysis of sidewall samples in the critical contact region overlying the crystallizing pluton.

D. Central Pluton

The critical hypothesis used in locating the drill site is that a young, and consequently hot, central pluton underlies the Long Valley caldera. Thus, recognition and chemical characterization of this body is one of the principal scientific objectives of the project. Most likely, the central pluton will be a complex of numerous intrusives perhaps related to several of the volcanic units. These are the ~3-2 my pre-caldera mafic and intermediate lavas; ~2-0.7 my Glass Mountain - Bishop Tuff rhyolites; ~0.6-0.2 my early and moat rhyolites; and >0.2 my basalts, quartz latites, and <0.1 my rhyolites of the western caldera and Inyo chain. Alternatively, early intrusive units may have been stopped out by later intrusions, so that only a few large, late intrusions are present. We anticipate that the granitic intrusions can be distinguished from the granite basement on the basis of their fine-grained texture, as was the case for the intrusion encountered in the Unocal Clay Pit hole (CP-1). However, as the depth of observation increases this distinction may become more difficult and other criteria may need to be used. For example, Quaternary intrusions should exhibit less texture evidence at deformation than the basement.

At least three approaches can be used in an attempt to date the various intrusives of the "central pluton". First, the relative ages can be established by cross-cutting relations. In some cases this may be the most reliable age information, and for these, core is essential. Second, whole rock major and trace element chemistry may be useful in relating intrusive to volcanic rocks. Linking volcanic events to plutonic events is essential in reconstructing the magmatic and thermal history of the caldera. Third, there is absolute dating of the various intrusions by geochronology. This depends largely on the state of alteration of the rocks. If the minerals are fresh, then phases such as hornblende can be dated by K-Ar. Uranium-thorium series disequilibria may be useful in dating very young rocks (<300,000 years). U-Pb zircon and Rb-Sr mineral isochrons will not yield precise ages for rocks only a few million years old, but they will at least establish that the intrusives are not Mesozoic basement.

E. Basement Rocks

Research goals for studying basement rocks include determining (1) the thermal and chemical effects of the Long Valley pluton and hydrothermal system on the Sierran basement rocks; (2) the chemical interaction between basement rocks and Long Valley magma; (3) strontium isotopic fingerprinting of basement rocks to evaluate the role of those rocks in the evolution of hydrothermal fluids; and (4) the structural effects of Long Valley intrusion on the basement rocks.

The possibility of accomplishing these research goals is strongly dependent on being able to identify and characterize basement rock types and features like dikes, filled fractures, and alteration/breccia zones as well as possible. These data are needed in making correlations between units

identified in the magma hole and basement rocks in surface exposures and other drill holes. In addition, these observations are also needed to help sort out the effects of multiple alteration and deformation events. There is a large element of uncertainty as to how well one can characterize basement rocks from cuttings. Experience gained from the Fenton Hill Hot Dry Rock and the Cajon Pass drilling projects has shown that in some cases it is possible to gain a great deal of information from cuttings alone, especially when the drilling fluid density is high enough to return relatively large cuttings ($> 1-2$ mm). Availability of core would be highly desirable.

Characterization of cuttings should include examination by stereomicroscope, petrographic microscope, SEM, x-ray diffraction, and electron microprobe. Geophysical logs, including spectral gamma, if available, can be used as aids in identifying rock units.

IX. HEAT FLUX AND HYDROTHERMAL SYSTEMS (Group Chairman: David Blackwell, SMU)

Previous drilling has been aimed at defining the shallow hydrothermal regime within the caldera. As yet, there are no observations or samples at depths in excess of 2 km. The most important questions in understanding the hydrothermal system are :

- a. How is heat transported from the magmatic source region (if any) into the surficial hydrothermal system?
- b. What chemical changes occur within the hydrothermal fluids as a function of depth and temperature?
- c. Are there distinct conductive and convective regimes, and what is the role of lateral advection of heat via hydrothermal fluids?

A. Hydrothermal System

In the shallower parts of the hole the fluid chemistry and pressures are primarily of interest for the shallow hydrothermal system and the information this gives on well conditions. In the first phase of drilling, chemistry of Bishop Tuff aquifers should be obtained by typical chemical studies as well as isotopic measurements (He^3 , H, O, C). Residence times, fluid flow velocities, and formation pressures should be measured as accurately as possible. These studies are necessary for understanding the nature of the hydrothermal system in the caldera fill within the resurgent dome, and as baseline data for evaluating the impact of future geothermal development. Specifically, cuttings should be obtained at a rate of .5-.8 kg/m and cores of host rock and fracture fillings obtained from the rathole (i.e., the short length of corehole drilled at the conclusion of operations). Fluids should be sampled downhole or by limited hole cleanout,

especially if a fluid zone is encountered in the rathole. The best opportunities may involve analysis of fluid inclusions, but these are difficult to analyze and the fluids may not be representative of current conditions. The mud log capability should include gas analyses for CO_2 , H_2S , and C_1 to C_4 . Gases should ideally be collected from the mud stream at least once per shift for C isotopes and He^3/He^4 (if air contamination can be handled).

Downhole logs should include natural gamma and spectral gamma for sample selection, dipmeter for fractures and stress, and temperature logs. In the rathole a fluid sample should be collected immediately after coring. A tracer should be used in the coring fluid. The sample can be collected by flow after cleanout or by a downhole sampler.

In the second phase of drilling, it is expected that rock types will be metamorphic roof pendants, Cretaceous granites, and Quaternary intrusions. To characterize the magmatic imprint on the hydrothermal (rock/fluid) system and for comparison with ore deposits, it will be necessary to determine the change with depth of gas chemistry (e.g., C^{13} in CO_2 , and the contribution of basaltic magma as measured by He^3/He^4).

In addition, it will be of interest to study rock/fluid interactions and roots of the hydrothermal system. Particular items to be studied are fluid chemistry, fracture-filling chemistry, alteration mineralogy, resident times and origins of fluids. These measurements will allow characterization of the transition zone between hydrothermal and magmatic systems. Moreover, study of fluid chemistry will be important for the effect on materials that may be used for energy recovery systems. Finally, thermal logs should be made at every opportunity to study thermal and fluid dynamics in the well.

B. Thermal and Heat Flow Measurements

Between each phase, it would be desirable to run a time series of temperature logs. Measured temperatures will then be used to extrapolate equilibrium logs. At various times cold injection tests might be run to study permeable zones. An idealized program would include (1) temperature log at the beginning (and end) of each logging period (1800' per hour logging, 12,000' per hour coming up); (2) time-series of temperature logs during each furlough (ideally, 1 week, 1 month, 2 months, 4 months, 7 months, and 11 months post-drilling); (3) heat-flow estimates using rathole as a flux-plate during each furlough. Detailed temperature measurements combined with thermal conductivity measurements on preserved core at ambient pressure and temperature; (4) estimate of equilibrium temperature-profile obtained by extrapolation of temperature-time series to infinite time; (5) thermal-conductivity measurements on drill cuttings. Grain conductivity corrected for porosity and temperature at each depth. Comparison of these results with measurements on core from rathole and spot-cored intervals; (6) heat-flow estimates from (4) and (5); (7) modeling heat-flow as a function of depth.

X. STRESS, ROCK MECHANICS, AND PHYSICAL PROPERTIES OF CORE.
(Group Chairman: Herbert Wang, University of Wisconsin)

The observation of in situ stress has two important products, one scientific and the other engineering. The scientific importance lies in obtaining a better understanding of the regional tectonics, and of the physical processes associated with volcanism. The engineering importance is in the assessment of the stability of the wellbore as a function of depth and temperature. With these issues as a background the critical questions to be answered are:

- a. What is the state of stress at depth in the caldera, and can it be related to the regional tectonic and volcanic history of the area?
- b. Why does Long Valley caldera sit astride a transitional boundary between the Basin and Range extensional province, and the compressional Sierran province?
- c. Is it possible to relate observed temporal changes in stress to the ongoing seismicity and crustal strain?
- d. Can boreholes in pressure and temperature regimes above an active magma reservoir be made stable?
- e. Can instrumentation be developed to measure in situ stress at temperatures in excess of 300°C?

In situ stress, including formation fluid pressures, together with temperature, define the thermodynamic state of the Long Valley region. The depth dependence of in situ stress in the deep hole is fundamental to analysis and interpretation of seismicity, geophysical measurements, regional and magma-related tectonics, fracture systems, borehole stability, emplacement of dikes, and hydrothermal circulation. Stress history, if it

can be interpreted from cores and fractures, can constrain models of caldera subsidence and resurgence. The importance of stress measurements, and the difficulties associated with obtaining reliable results, require that multiple techniques be attempted as much as possible. Advancement of stress measurement techniques at high temperature is an important scientific objective. Currently accepted, or developing techniques, include

- (i) hydraulic fracturing
- (ii) anelastic strain recovery
- (iii) residual strain measurement
- (iv) strain relaxation
- (v) borehole breakout analysis
- (vi) acoustic emission monitoring
- (vii) core petrography

Physical properties of core are necessary for interpretation of borehole logs and other geophysical measurements. Permeability is a critical property for interpreting hydrothermal circulation. Knowledge of rock strength is needed for borehole breakout analysis. Thermal and stress relief cracking upon removal of core from the borehole needs to be recognized as a limitation on the direct use of physical property results. These effects, if properly understood, may serve to improve the micromechanical understanding of the effects of temperature and stress required for some methods of stress measurement.

Perhaps more than any other area, the measurement of in situ stress demands the use and further development of sophisticated techniques.

Several stress measurement techniques are limited to temperatures below ~250°C due to packer and cable design, and improvements should be encouraged. Development opportunities that might be accomplished by Phase 4 of the drilling include:

- (i) centralizer/stabilizers for highly eccentric holes
- (ii) Dewar techniques
- (iii) downhole power and data acquisition

A. Magma Tectonics

A simple elastic model which includes the interaction between a lithostatic stress field and a spherical-like magma chamber shows that the larger the magma chamber, the greater the stress gradient in the region above the magma chamber. The first of these models was proposed by Rundle and Whitcomb (1984). Wu and Wang (1988) used three spherical magma chambers with radii 1, 3, and 5 km, respectively, to display stress differences. All sizes can fit the deformation at Long Valley for a particular period 1975-1982. However, the stress gradient for the 5 km radius magma chamber is more than twice that for the 1 km radius case above 4 km depth. Above that depth, the 1 km radius magma chamber has a stress gradient which is about the same as that for a lithostatic stress field. This suggests a possibility of using stress measurement data in the deep hole to justify the size of the magma body when the well extends to 3-4 km depth. The stress field is basically independent of the temperature profile at low temperature. It is possible that even when the temperature in the deep hole is still much lower than 500°C, the stress data may indicate that a sizeable magma chamber is only about 1 or 2 km below. Thus, stress data may be important and useful in providing a better picture of the magma body beneath the resurgent dome of the caldera.

Since the regional tectonic stresses at Long Valley have not been incorporated in the stress model, uncertainties are contained in the above stress predictions. Moreover, study of the South Moat Fault (e.g., Rundle and Hill, 1988) in relation to in-situ stress measurements in the deep well indicates that the effect of the fault on the stress measurements may be substantially stronger if the tectonic stress level is high. In such a case, the South Moat Fault may obscure stress interpretation of the magma chamber.

B. Dike Orientation

Dike orientation is one of the primary means of interpreting paleostress directions in tectonic reconstructions. The geometry of dikes is controlled by conditions in the parent magma body and rheologic properties of the host rock, as well as by the state of stress in the crust. Data collected as part of the DOE-sponsored Inyo Scientific Drilling Project in the western part of Long Valley caldera provided the first opportunity to quantitatively assess these relationships. The planned Magma Energy drillhole will allow refinement of dike emplacement models which in turn can help define the state of stress and thermal regime in Long Valley caldera and can aid in the interpretation of paleostress conditions in ancient volcanic terrains.

Igneous dikes commonly exhibit an echelon geometry. The parent dike divides at depth into many segments which rotate about a vertical axis as they approach the surface. Two models have been proposed to explain this phenomenon. Pollard et al. (1975, 1982) attribute the breakup of a dike to vertical variations in the orientation of principle horizontal stress axes. The dike accommodates the changing stress state through segmentation and

rotation. In contrast, Reches and Fink (1988) relate the segmentation to changes in the temperature-controlled (and hence, depth-controlled) fracture behavior of the host rock. They cite experimental and theoretical evidence that rocks in deeper, ductile, crustal zones respond to tensile stress by fracturing perpendicular to the maximum extension direction, whereas stretching of rocks in the shallow, cooler, brittle zone causes conjugate sets of fractures at an angle to the maximum tension. Dikes crossing the transition from ductile to brittle zones will fill fractures whose orientations change with depth, resulting in the echelon geometry.

Downhole measurements of stress direction and fracture orientation can allow these two models to be tested. Systematic rotation of stress directions with depth would support the Pollard model, whereas changes in fracture orientation from shallow multiple directions to more uniform directions at depth would support the Reches and Fink model.

Once the factors controlling dike geometry are determined, available emplacement models (Reches & Fink, 1988) permit the calculation of a range of physical properties including volatile pressure in the parent magma body, fracture strength, and elastic resistance to dilation of the host rock, and the viscous resistance to flow of magma through dikes to the surface.

C. Borehole Stability

There are only three ways to control the stability of wellbore:

(1) increase the strength of casing; (2) change the mudweight; (3) change the orientation of the hole in the stress field. The first method can be applied by a driller in response to hole conditions as he finds them, but is the most expensive. The second method is credited with saving the Siljan hole, is cheap, and is rapidly applied, but can be used only with the

current open hole and relies on casing above that. The third method, deviate the hole, is the final option. The first method requires little knowledge of the in situ stress. The second method requires knowledge of stress conditions in the plane normal to the wellbore ("2D stresses"). The third method requires knowledge of the stress field in three dimensions.

Two competing failure mechanisms control the stability of deep bores. These are tensile failure (the hydrofracturing condition) and shear failure (the wellbore breakout or collapse condition). In between is a zone of maximum stability. In coordinates attached to the wellbore, the state of effective stress (that is, framework stresses reduced by pore pressure) can be written in terms of radial, tangential (near-horizontal) and longitudinal (near-vertical) components. Tensile fracture happens when the tangential component reduces to zero. The result is a vertical fracture, and this is induced by increasing the mudweight. The condition for shear fracture can be expressed, approximately, as a reduction in the effective radial stress to zero (that is, when the borehole pressure falls to that of the native formation fluids) so that collapse can be induced by decreasing the mudweight. During drilling, maximum stability of the open hole section is achieved by balancing the mudweight so that the radial and tangential stresses are equal. This condition must be maintained in the face of variations in formation fluid pressure, in-situ stress and hole deviation. It would be desirable, in support of the drilling, to predict these conditions ahead of the bit. This can be achieved by measuring the state of stress at the end of each drilling phase and making predictions for the next phase by linear extrapolation.

Because different components of in-situ stress may vary with depth at different rates, it is desirable at each drilling phase to measure the load, formation pressure and physical properties of rock as well as measurements of the deviatoric components. It should be noted that it is impossible to balance mudweight for great lengths of a hole, so that all that can be done is to control conditions at the bit. Behind the bit there are imbalances that must be controlled by casing.

Additional complications are created by heterogeneous materials (particularly weak rocks) and abnormal (over or under) pressurized zones. Little can be done about heterogeneities. However, homogeneous processes, such as anisotropic physical properties or high tectonic stresses, can be ameliorated by deviating the hole. An example is the differences seen in hole stability at Fenton Hill, almost-certainly due to differences in orientation. Another example is the discovery, in the Norwegian oil fields, that hole stability is improved by inclining the hole away from vertical, to align more with the least principal stress.

With all other variables constrained, change in hole inclination might be the only means left to maintain hole stability at great depth. This option will only be available if work at shallower depths has determined the orientation of the stress tensor in three dimensions and established appropriate gradients in depth.

Since many types of borehole stress measurements establish only the horizontal (perpendicular to the wellbore) components of deviatoric stress, a means of finding the orientation of the near-vertical principal axis of stress is desirable. This would require drilling short, deviated holes at each phase, in order to provide stress measurements in three

dimensions. A preliminary suggestion is three holes, 120° apart initially, deviated at 30-35° from the main bore in the longitudinal deviation. These would need to be of sufficient diameter (6") to enable televiewer observation of wellbore stability.

D. Measurement and Analysis of Wellbore Breakouts

The occurrence of borehole breakout is common in boreholes drilled to deep depths, under high stress conditions, and in weak rock. The orientation and shape of stress-induced wellbore breakouts being controlled by the ambient stress state and rock strength. The prediction of breakouts under known stress conditions and material properties, and the interpretation of in situ stresses from measured breakouts, has been calculated with good confidence in many instances (Barton and Zoback, 1988). The orientation of the crustal stresses throughout the deep borehole can be determined by interactive digital analysis of the naturally-occurring breakouts. A recently developed stress measurement method uses information from borehole televiewers on the size and shape of wellbore breakouts, rock strength and the magnitude of the least principal compressive stress, as determined at casing set points from leak-off test or by hydraulic fracturing, to determine the magnitude of the maximum horizontal principal stress. Thus, by combining a comprehensive breakout analysis with limited leak-off data, hydraulic fracturing data and rock strength measurements, borehole televiewer analyses can yield a complete and continuous measure of stress magnitude and orientation as a function of depth in the wellbore. An important aspect of such calculations is that they only depend on the minimum horizontal principal stress, S_{Hmin} which is easily available from hydraulic fracturing experiments. The breakout analysis provides an

independent measurement of S_{Hmax} , the maximum horizontal principal stress which is quite difficult to determine from hydraulic fracturing, especially where the rock does not deform elastically or the hole is not round.

The deep experimental drillhole in Long Valley caldera poses several intriguing and important problems with regard to borehole breakout. Temperatures up to 500°C may be encountered as the hole approached a magmatic body. This could lead to breakout phenomena that have not been analyzed up to the present time.

Moreover, breakout of the experimental hole at Long Valley may hinder experiments being planned in the well that require a borehole to be sealed off, such as for hydraulic fracturing.

In order to determine the effects of high temperature and stress conditions on the occurrence of borehole breakout at Long Valley, experimental, theoretical, and numerical studies should be conducted.

Laboratory studies of borehole breakout in hollow rock cylinders subjected to external and internal pressures have shown that breakout in brittle rocks occurs by the growth, interaction, and coalescence of extensile microcracks, similar in many ways to the progressive failure in uniaxial compression tests. Tests such as these should be conducted on cores from the Long Valley hole at the high temperatures encountered in the hole.

F. Measurement of Fracture Distribution Orientation and Apparent Aperture

Determination of the natural fracture distribution in the Long Valley research well is important to the assessment of the in-situ stress state, the hydraulic conductivity and thermal conductivity with depth. Fracture analyses, when used in conjunction with other geophysical logs (e.g., full waveform sonic) provide information on formation permeability. Fracture studies are important to understanding the dike geometry and general crustal rheology at Long Valley. Fracture distribution and orientation with depth may be controlled by lithology, the ambient stress field, or paleostresses. Discrete fracture populations may correlate with lithology or stress state.

Temperature anomalies, minima or maxima in the thermal gradient, will occur where fractures are conducting fluids at depth. Anomalies related to hydrothermal circulation detected in measurements of the electrical conductivity of the borehole fluid will also depend on fracture width. Routine drilling information such as drilling breaks may be correlated with fracture data to assess permeable zones.

Borehole televiewer provides excellent data for the analysis of natural fracture distribution with depth. The televiewer images the fracture at its intersection with the borehole wall. With the effects of

mechanical erosion or the fracture due to fluid circulation and the destructive drilling process, it is likely that the fracture width is smaller away from the borehole than it is at the borehole wall as measured by the BHTV. Very large aperture fractures imaged by the BHTV may actually be zones of finer scale fractures or fault zones. Source data with a depth of penetration of a few meters into the formation has the ability to "see" the fracture away from the borehole. For this reason, companion logs such as the full waveform sonic log are essential to the analysis of fracture data. A detailed analysis of natural fracture distribution, orientation, and apparent aperture can be performed through the analysis of borehole televiewer (BHTV) data.

G. Core Fabrics and Microstructures

Core material is a fundamental source of data for interpreting stress measurements and stress history, and measurement of physical properties. This is because it shows deformation features and processes directly. In contrast, the borehole televiewer, formation microscanner and other logging tools are remote sensing techniques. Results from these indirect methods require interpreting from "ground truth" established by reference to cores. From the point of view of stress, mechanics, and physical properties, the core is likely to contain several features of particular interest:

- (1) Tectonic fractures and microfractures. These uniquely constrain the direction of least principal stress since they form perpendicular to σ_3 , and also constrain σ_1 to lie within the plane of the fracture. They have been reported from the Shady Rest corehole in Long Valley by Wollenberg et al., (1987).

- (2) Thermally-induced fractures and microfractures.
- (3) Primary igneous textures and fabrics. These may influence the results of measurements such as hydrofracture and physical properties.

Core material may also contain faults and evidence of plastic deformation mechanisms from higher temperature samples.

Some of the most important measurements to make on core material will be fracture type, fracture dimensions, fracture orientation, fracture density, lineation types, and directions. On a more detailed scale, the fabrics and microstructures of the core can be examined by optical microscopy, scanning electron microscopy, transmission electron microscopy, x-ray photography, x-ray diffraction and electron microprobe. These techniques are useful for examining microfractures, the timing relationships between fractures, and the nature of fracture filling material. Characterizing the core in this way is essential to understanding the mechanical properties of the drillhole.

Core material also enables measurements of physical properties to be made in the laboratory, such as strength and failure characteristics, seismic velocity, porosity and permeability, and conductivity. These results are useful for interpreting logs and other indirect measurements of in situ properties.

H. Resistivity Logging

Resistivity logs contain a large quantity of information in addition to the direct resistivity of the rock. For example, two types of log are the Dual Laterolog (DLL) and the Formation Microscanner (FMS). The first measures current between a downhole electrode and a remote return, over a relatively large volume of rock. This can be inverted to give total intergranular, fracture and matrix porosity.

The Formation Microscanner (FMS) is a new high resolution sensor giving conductivity of the rock to a depth of a few centimeters into the borehole wall and thus responding to small-scale variations in physical properties. The cause of the variations (e.g., fractures or foliation) can be deduced because of the wide dynamic range and high vertical resolution of the instrument (Pezard et al., 1987). Comparison of both types of electrical measurement allows discrimination between drill-induced fractures that are small and therefore restricted to the FMS log, and larger fractures that are seen on both types of log (Pezard et al., 1987).

The core material can be orientated by comparing the mapped core features with the FMS electrical images (Pezard and Luthi, in press). This is the basis for deducing quantitative information about the fabrics and stress systems of the core material.

I. Residual Stress Determinations

Residual stresses can be determined from strain measurements made on cores recovered from the ratholes at the end of each drilling phase. These measurements are made in the laboratory. If core can be recovered, then measurements can be made even when downhole packers and televiwers fail.

There are limitations. The core must be oriented in some fashion. Often this can be done by comparison of wireline logging signatures of the hole with similar measurements on the core. Velocity anisotropy, fracture orientation or orientation relative to structural features can also be used. The technique only measures a "locked in" or paleo stress. There is often ambiguity in trying to determine a complete 3-D strain tensor from these measurements. Finally, there is always some uncertainty involved in converting strain measurements to stresses.

The technique is inexpensive (once the core is in hand), a few hundred dollars per determination. The technique can be evaluated in the first rathole to be drilled against the other more direct techniques such as hydrofracturing, borehole breakouts, and anelastic strain recovery. If the results seem reasonable, then residual strain analysis can be used at any depth from which core is recovered.

Two laboratory techniques have evolved. One involves the measurement of residual strains in quartz grains using x-ray diffraction and the other requires bonding of strain gages to the rock surfaces and then trepanning or overcoring the gages. The x-ray technique is used only when a large volumetric fraction of the rock is quartz. It is likely that the strain-gage technique will be more applicable to the Long Valley rocks.

J. Sidewall Coring

Sidewall coring devices provide an opportunity for inexpensive recovery of large numbers of small core samples. The benefits of this procedure are linked to material properties studies of the recovered samples as well as observation of the influence of in situ stresses upon the holes produced by this coring operation.

Currently two types of tools are available - the impulsively driven type and the diamond coring type. Only the diamond coring type will be suitable. Of this type, current commercial tools have core size and operating temperature limitations of about 1-inch diameter and 250°F, respectively. Significant improvements are possible through routine redesign of the tool. Also, in highly elongated holes it will be necessary to have the capability of orienting the tool to, for example, the minor axis

this tool will be greatly improved through coupling its function with holographics and/or acoustic imaging techniques.

K. Development Needs in Downhole Power and Data Acquisition

In the lower portions of the hole where extreme pressure and temperatures are likely, all of the stress measurement techniques will run into common difficulties. While temperature hardening will no doubt be accomplished for the basic instruments and sensors, fundamental problems remain. Ultrahigh temperature cables are likely to be one or two conductor assemblies rather than 7-conductor. It will be difficult to get instrument power, operational signals and responses, and data signals up and down this limited pathway at an adequate rate. Putting the instrument power supply downhole along with perhaps a data capture and storage systems leaves the cable available for instrument control and response signals. While it does not seem to be intrinsically difficult to put the power supplies and data loggers in dewatered downhole assemblies, this needs to be done and tested within the next 2 to 3 years to be ready for Phase 3 and beyond.

Both of these seismic techniques have been proven effective in previous studies in Long Valley. The proposed experiments, however, will provide a considerable increase in the data quality and quantity allowing the kind of detailed structural information that could be tested by the borehole information and probably extend the borehole interpretations to depth and laterally. The in-hole seismic array should be designed by all groups interested in seismic experiments at the borehole, both active and passive source. The in-hole array use can be maximized by using the same instruments for all seismic experiments.

XI. EXPECTED RESULTS

The concept that large bodies of silicic magma presently exist at the shallow depth in the Earth's crust is well-supported by the abundance of granitic bodies in the geologic record, by the sudden eruption of large volumes of silicic magma as ash-flow sheets in recent geologic time, and by the extensive subsidence of the source regions of such eruptions to form calderas. Long Valley in California is one of the Earth's outstanding young calderas. By its persistent volcanic activity and present-day uplift, seismicity, and geophysical anomalies, it gives evidence that a substantial body of magma still exists beneath it. Exploring 6 km into the center of the caldera will provide an unprecedented test of our concept of where magma exists in the crust. If this concept is confirmed, the hole will provide the first direct observations in the immediate environment of a large magma body. By intersecting frozen or freezing intrusions beneath the caldera, it will provide new observations on the evolution of large magma chambers with time. In addition, the challenge of making scientific observations under the expected hostile conditions will likely motivate important advances in logging and analytical techniques.

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