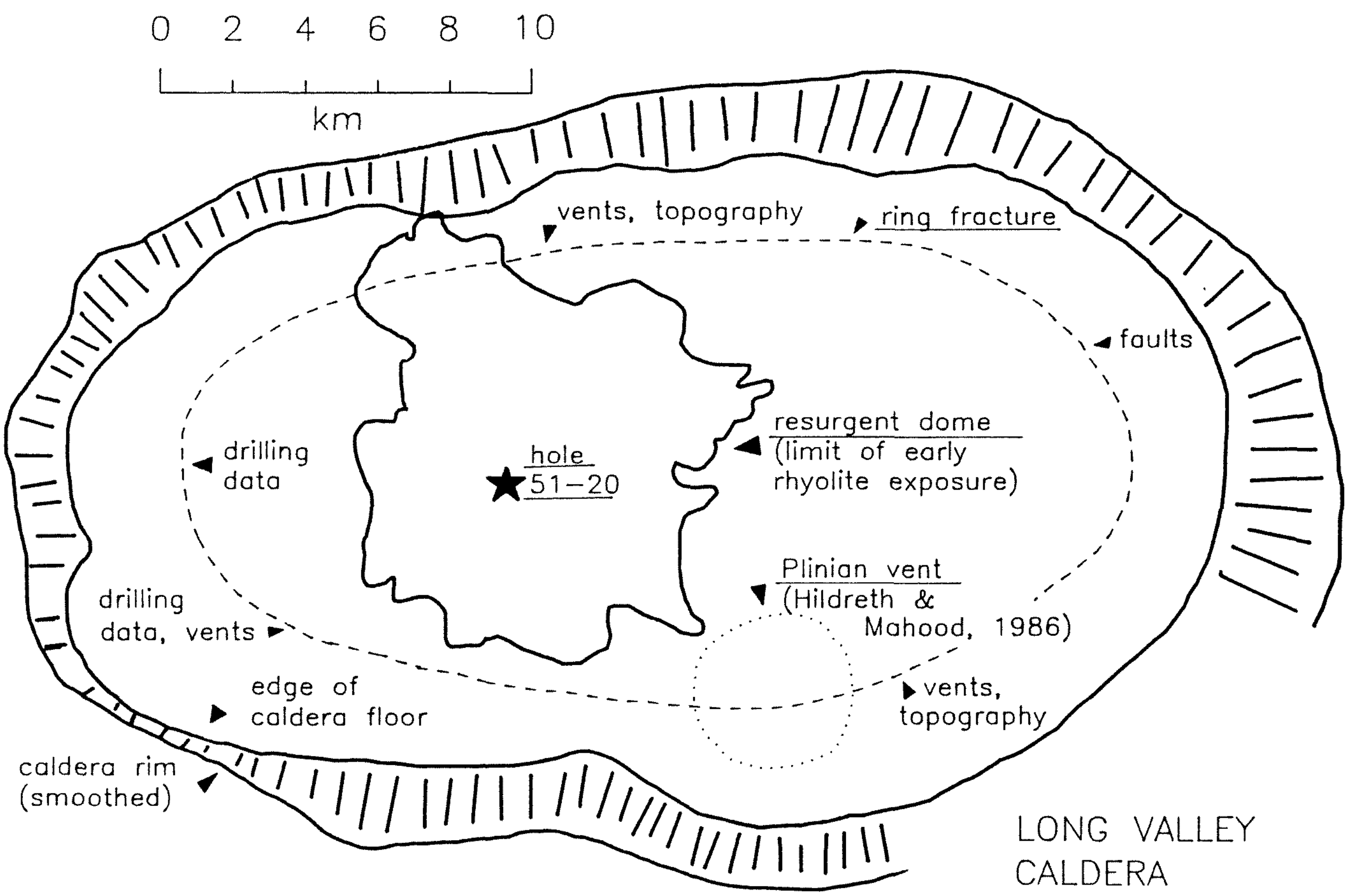
Figure 1. Caldera map showing hole location and principal geological features of the caldera. Dashed line deontes inferred position of the main fault zone along which the caldera block subsided and through which most of the Bishop Tuff is thought to have erupted. The basis for its interpreted position is also indicated. The ring fracture is thought to approximately outline the magma body at the time of caldera formation, 700,000 years ago. The first outbreak of Bishop magma occurred on the south side of the caldera, the Plinian vent, giving rise to an air-fall tephra deposit that underlies the Bishop Tuff.



The Magma Energy Exploratory Well

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Introduction

The centerpiece of the Magma Energy Program is the exploratory well in Long Valley caldera (Figure 1). This well is designed to be drilled in four yearly phases (Figure 2), with scientific work in the borehole during the intervals between drilling operations.

Testing the fundamental hypothesis of the magma energy concept, that large bodies of magma reside at accessible depths, is clearly an esstential step in advancement of this program. Although geological and geophysical evidence indicate that a magma body lies beneath Long Valley caldera, this must be confirmed by drilling so close to the body that downhole thermal and seismic measurements will give unequivocal results. Engineers will gain crucial insight to techniques for development of the magma energy concept, and scientists will have a unique opportunity to observe the near-magmatic environment in this well. There will be other payoffs as well. Definition of the hydrothermal regime could stimulate commercial geothermal development in the central caldera region. The ability to test advanced high-temperature drilling hardware in the hottest big hole ever drilled will improve the tools available for drilling in high-temperature geothermal reservoirs.

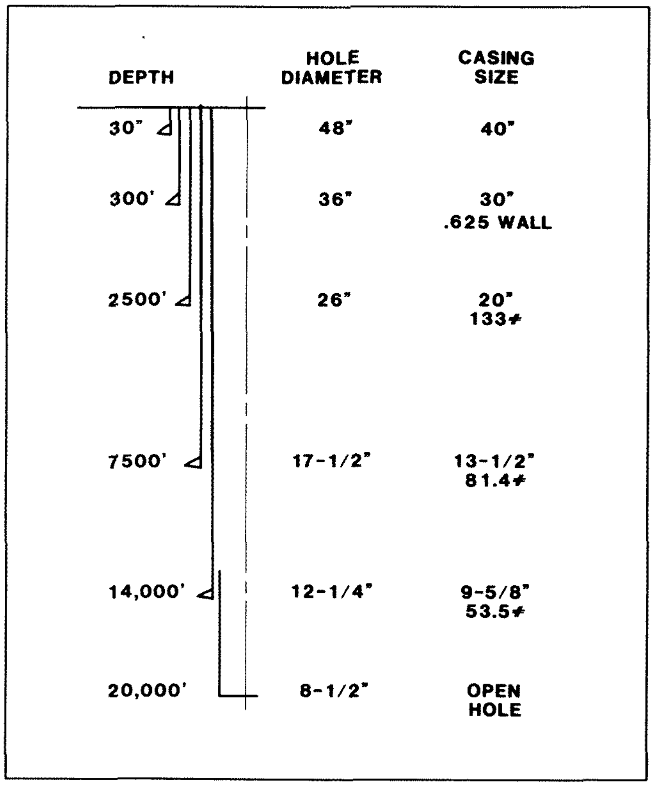

Figure 2. Magma exploratory well design.

Selection of the drilling location in Long Valley caldera followed the review of 21 other potential sites in the United States (Hardee, 1984, and Carson, 1985). The actual drill site lies just south of the center of the resurgent dome (Figure 1). The site had been prepared by a commercial geothermal company for drilling a 10,000 feet exploratory well; their drilling plans did not materialize, and they signed an agreement for Sandia to use the site. This article describes the drilling operations and preliminary scientific results for Phase I of the Magma Energy Exploratory Well. Phase I funding was provided by the DOE's Geothermal Technology Division in support of the Magma Energy Program.

Drilling Activities

We spudded the hole for the first drilling phase on 2 August 1989. Target depth for this phase was 2,500 feet (760 m), the 20 inch (51 cm) casing point shown in Figure 2.

Loffland Brothers Company, headquartered in Tulsa, but managing our project from their Bakersfield office, received the contract for this phase of the operation. The rig was Loffland's Number 202, famous in the oil patch for having drilled the two deepest wells (both deeper than 30,000 feet (9.1 km)) in the United States. With three 1100 horsepower diesels as prime movers and a 750 ton (680 metric ton) hook load rating, this rig has ample capacity to drill the complete well to 20,000 feet (6 km).

Because a 40 inch (102 cm) mud riser (surface pipe) was already in place to a depth of 39 feet (12 m) the first rotary drilling was a 36 inch hole for 30 inch casing to a depth of approximately 300 feet (90 m). A 26 inch (66 cm) bit with a 36 inch (91 cm) hole opener was the drilling assembly for this interval. We had not drilled more than 15 feet (5 m) out of the mud riser when we encountered massive lost circulation. There were no returns at all, and in fact the bottom of the hole was dry. Conventional lost circulation material (LCM) was ineffective, so unopened bags of bentonite and cement, along with approximately 400 empty mud sacks, were thrown into the hole and milled into a slurry with the drilling assembly. This provided sufficient plug that a conventional cememt job could be placed, restoring circulation and allowing drilling to continue.

This experience was a harbinger for the next 3 weeks of drilling, we placed 29 cement plugs to fight lost circulation between 70 and 1,000 feet (20 and 300 m). Fluid losses were generally extreme (hundreds of barrels in a few minutes), and a wide variety of LCMs gave little benefit. Below 1,000 feet (300 m), however, the formation is more competent, and we had no further lost circulation to the 20 inch (51 cm) casing point.

Persistent northward drift in the wellbore also required use of a downhole mud motor to keep deviation at or under 1 degree. This problem diminished after we entered the Bishop Tuff at approximately 2,040 feet (622 m) and we drilled the last 500 feet (150 m) with conventional rotary methods. Drilling in the Bishop Tuff was generally good, although the penetration rate varied from 10 to 30 feet/ hour (3 to 9 m/h), apparently because of hard intrusions.

After reaching TD of 2,568 feet (783 m) on 4 September, we conditioned the hole, ran a small suite of wireline logs, and rigged to run the 20 inch (51 cm) casing. This went smoothly; the casing crew ran 66 joints in 12 hours, and we got a good cement job with full returns and little evidence of mud contamination. Installation and testing of the wellhead completed the major part of the Phase I exploratory drilling, but we continued with a short coring run for scientific purposes (funded by DOE's Office of Basic Energy Science as part of the Continental Scientific Drilling Program).

The coring technique, adapted from that used by the Ocean Drilling Program (ODP), used wireline-retrievable core barrels and mining-type core rods, all inside an oilfield-type drillstring (Figure 3). In ODP drilling, the outer drillstring has a large bit with a hole in the center that passes over the core rods; the large bit opens the core hole and the drillstring provides a guide for the core rods. For this project, the ODP drilling group at Texas A&M provided drillpipe with a uniform inside diameter. We used a large core bit to drill this pipe a few feet into the cement plug at the bottom of the 20 inch (52 cm) casing. This drillpipe acted as an "artificial wellbore" to guide the rods from a small core rig set on the large rig floor. We took approximately 186 feet (57 m) of 2-½ inch (64 cm (HG)) core in the Bishop Tuff below the 20 inch casing. Core recovery in this interval was 99 percent. Coring ended when the core rods became stuck. Although this situation precludes open-hole experiments, it should not be an impediment to continuing the hole by rotary drilling.

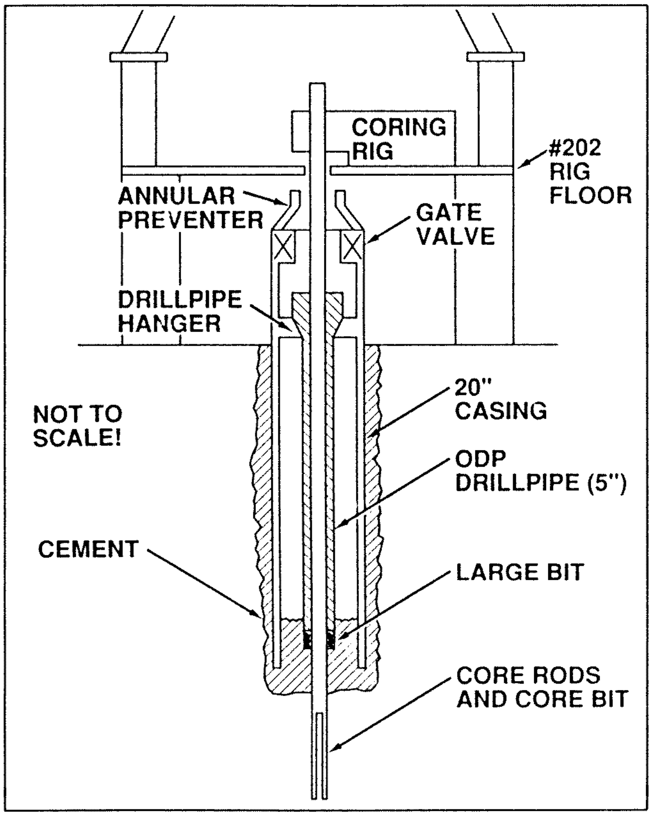

Figure 3. Coring with ODP drillpipe.

At present, the data available from this hole comprises the daily drilling reports, the mud logs (including the lithology from cuttings), the wireline logs conducted in the 26 inch (66 cm) hole (acoustic, gamma, dual induction, temperature and caliper), the analysis of the core, and a series of long-term temperature measurements made in the core hole.

Geological Results from Phase I

The first phase of drilling the Magma exploratory hole did not explore new territory in terms of depth. A number of holes within the caldera have penetrated as deep or deeper (Suemnicht and Varga, 1988). However, the hole did provide the first core from a central caldera location (Figure 1) and, fortuitously, this core included significant intervals of post-caldera intrusives (Figure 4). Thus, even at this early stage, the hole has added significant insight to understanding the structure and history of Long Valley caldera.

Long Valley caldera is a 12 x 18 mi (20 x 30 km) depression formed by collapse during eruption of some 130 mi^3 (600 km^3) of rhyolitic magma 0.7 my ago (Bailey and others, 1976). The actual region of collapse is somewhat smaller than the present-day depression, because the caldera wall has retreated outward, first by landsliding and later by normal erosion. The catastrophically erupted magma formed the Bishop Tuff, represented by an extensive outflow sheet and a thicker intracaldera deposit. The greater thickness of the tuff within the caldera is due to ponding during syneruptive collapse. The intracaldera tuff is wholly buried by later eruptives totaling more than 20 mi^3 (100 km^3). As with most calderas of this size, collapse was closely followed by resurgence of the central caldera floor due to continued upwelling of magma.

The Bishop Tuff is an important stratigraphic marker because its surface should have been relatively flat within the caldera when emplacement was complete. Neglecting the complicating factor of Sierran tectonic activity, the difference between the elevation of the top of undisturbed Bishop Tuff inside the caldera and just outside in the outflow sheet should reflect post-eruption caldera collapse, and the difference between the elevation of the top of the Bishop under the resurgent dome and under the caldera moat should reflect resurgence. Using this line of reasoning, results from holes drilled within the caldera indicate 2,300 feet (700 m) of post-eruptive collapse and about 1,600 feet (500 m) of resurgence. These are significant displacements, even when compared with the approximately 7,000 feet (2,000 m) average total subsidence of the caldera block associated with the Bishop eruption.

The new hole adds to this picture by showing that there is considerable local relief on the Bishop Tuff surface: 700 feet (200 m) over a horizontal distance of 3,000 feet (1,000 m). Because this relief is not expressed in surface topography and is at too low an elevation to have resulted from erosion, it must have resulted from faulting before much of the post-caldera volcanic sequence had developed. Apparently, post Bishop-eruption collapse and resurgence was irregular, breaking the Bishop surface. The new hole also shows that the post-caldera eruptive sequence is exceptionally tephra-rich at this central location compared to sites on the flanks of the resurgent dome, where lavas predominate. The reason for this distribution of lithologies is not known.

Within the Bishop Tuff, reached at 2,040- feet (622 m) depth, the hole encountered 5 intrusions that petrologically resemble the overlying early post-caldera volcanic units. These intrusions range in intersected length from 0.6 to 230 feet (20 to 70 cm) and were encountered over a depth range of 2,050 to 2,750 feet (625-829 m). They evidently represent a swarm of dikes or sills or a single, large, irregularly shaped intrusion. As might be expected, the intrusion differs from its erupted equivalents by being divertrified, except for glassy margins (Figure 5) on its shallower portions. In places it is intact, unaltered, and exhibits weak flow banding, but in others it is altered or brecciated, and some of the brecciated zones are mineralized. In the one cored contact between the Bishop Tuff and a major intrusive interval, the tuff is intensely fractured within a few feet (meters) of the contact. One other hole on the resurgent dome encountered an intrusion, at 4,650 feet (1,420 m) depth on the east flank of the dome. Although there are

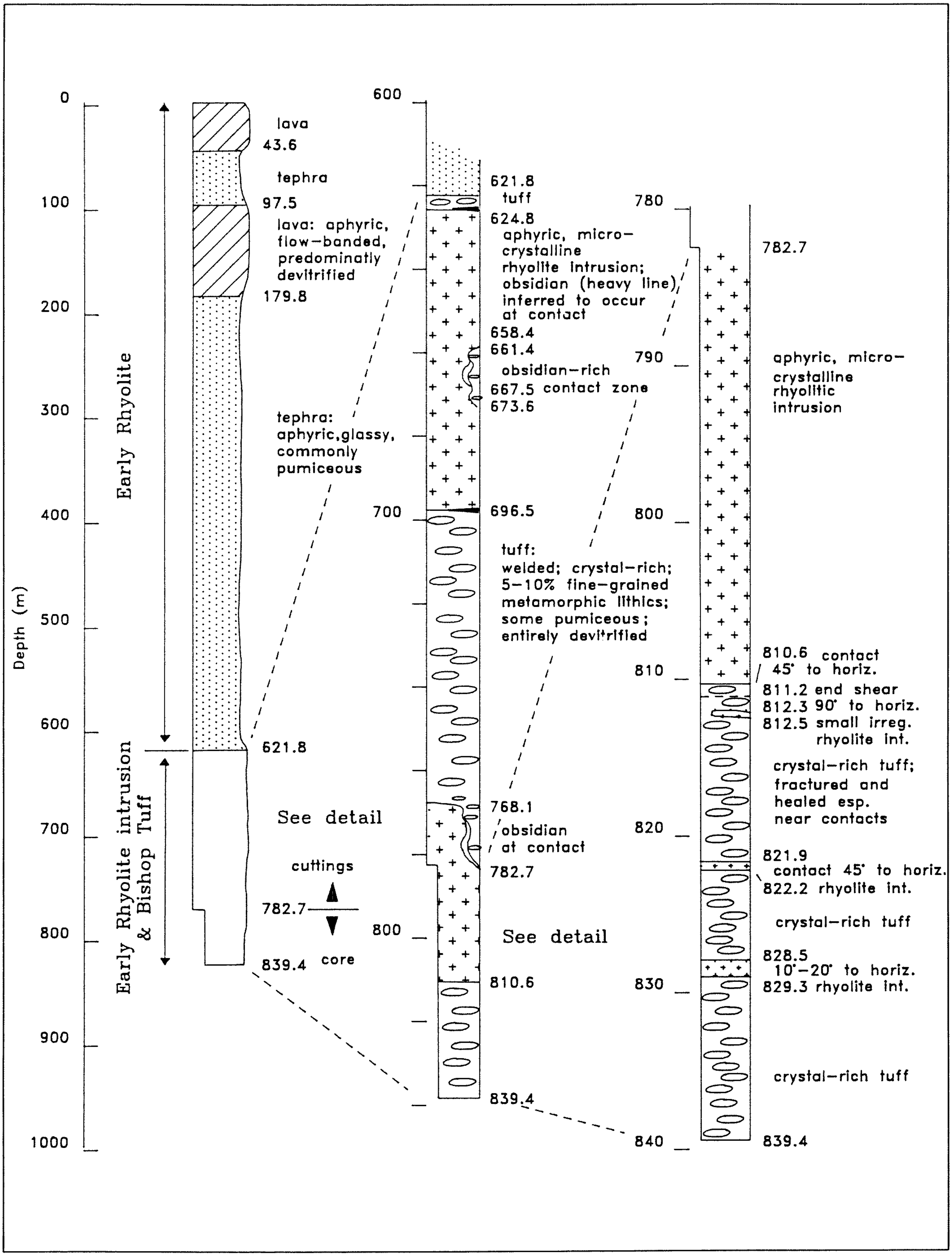

Figure 4. Stratigraphy of the magma exploratory well

insufficient data at this early stage of drilling to generalize, we may speculate that the central caldera location of the exploratory hole is one of intense intrusive activity. The hole may encounter many more such features as it advances toward the central pluton beneath the caldera. Indeed, it is entirely possible that the accepted cartoons are wrong and no basement exists under the site, having been displaced downward by the rising, long-lived pool of magma. When linked chemically to their dated eruptive equivalents, these intrusions will provide a valuable history of activity of the Long Valley magma chamber.

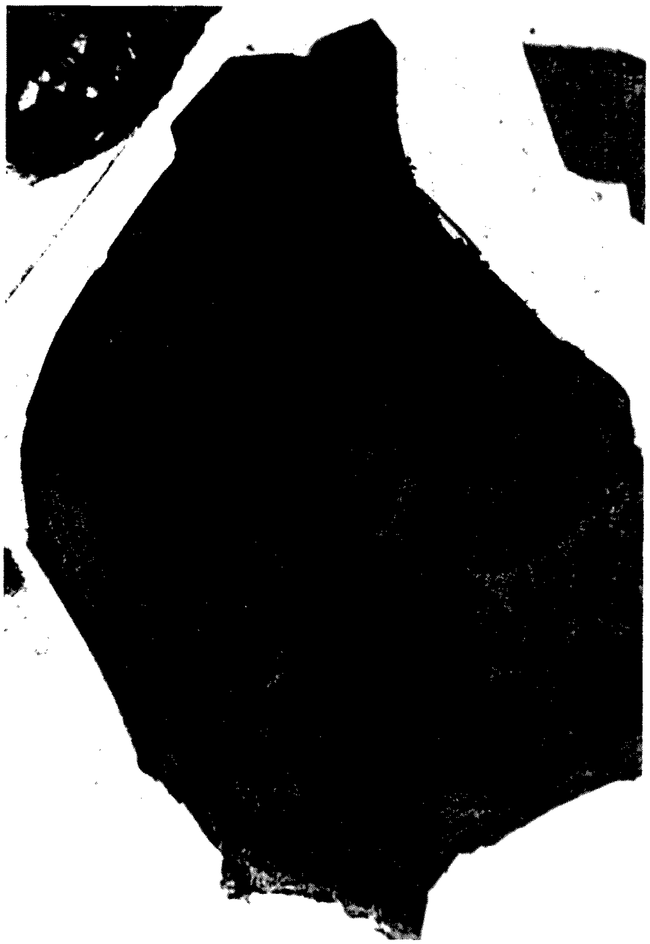

Figure 5. Photomicrograph of dense, brown, crystal-free rhyolite glass from the chilled margin of an early post-caldera intrusive at 2,170 feet (661.4 m) depth.

Expected Scientific Results from the Completed Hole

The exploratory hole is planned to stop at 900°F (500°C) and so it will not reach the present-day magma chamber, the margin of which should begin at 1300°F (700°C). However, it will be by far the deepest hole ever drilled into the center of a young caldera. As such it will provide an unprecedented test of geologic models for calderas. Existing models rely on analogy to eroded volcanic and intrusive structures, presumed to represent deeper levels of caldera systems. The dominant model, at least in this country, is that the caldera block is an ill-fitting piston that has dropped, largely intact, along a cylindrical fracture system (Smith and Bailey, 1966). Granitic magma has invaded this fracture zone to form a ring dike and has domed the block upward by rise and inflation of a central pluton. The hole will test the existence of intact basement and a young granitic pluton beneath the center of the caldera. Alternatively, it is possible that these features are not present, but instead multiple small intrusions and vent-fill and fragmental basement will not be intersected, as in the Japanese model (Aramaki, 1984). Assuming that the crystallized periphery of the still-molten central pluton is reached, comparison of intrusive lithologies with surface eruptives will elucidate the history of the magma chamber. Will frozen remnants of the chemically zoned magma chamber that gave rise to Bishop Tuff be found? If so, this would provide a critical test of the way zoned tuff sheets are used to interpret magmatic processes and new insight into how tuff sheets are erupted. Alternatively, it may be found that new plutons have partly or completely displaced their predecessors, erasing the early record.

Of equal importance will be the evidence of past and present hydrothermal activity. To date, the main hydrothermal system of Long Valley caldera has not been located. The two candidates for its location are the west moat and the resurgent dome. Temperatures encountered by drilling to date have tended to favor the west moat (Suemnicht and Varga, 1988), but a deep source within the resurgent dome has not been ruled out and is, in fact, supported by geophysical evidence that the heat source, magma, is centered there (Rundle and Hill, 1988). This evidence includes ongoing inflation, centered near the exploratory hole drill site. If the hydrothermal system is present under the dome and the hole succeeds in reaching 900°F (500°C), it will provide a complete section through the system, perhaps reaching the conductive near-magma zone as discussed previously. In any event, the evidence of past and present hydrothermal alteration deep beneath the resurgent dome and its relationship to the magmatic heat source will add immensely to our understanding of caldera thermal regimes.

Technology Needs for Future Drilling

Phase I operations had no problems that were distinct from conventional drilling. This will not be true in subsequent phases. The combination of depth, formation, fluid chemistry and temperature will require either new technology or technology currently used in extreme geothermal drilling conditions. Each of these factors can be crucial, but most of the new technology needs will be driven by high temperature. High temperature accelerates bit wear, drilling fluid degradation, drillstring corrosion, and wellbore instability. With current instrumentation, high temperature also imposes significant limits on the kinds and accuracy of data that can be collected in the hole.

In future phases of drilling the present well, various items will become critical when increasing drilling depth. The following synopsis shows a likely schedule for technology development:

Phase II — At the Phase II depth of 7,500 feet (2,300 m), we expect the temperature to still be relatively low, under 300° F (150° C). These temperatures are commonly found in conventional geothermal drilling and should present no unusual problems. Much of the drilled formation will be Bishop Tuff, which should be good drilling with little lost circulation, but the deeper section will be in Sierran basement or in young granitic intrusions, which may be hard and abrasive. Except for bit wear and possible corrosives in the pore fluids, this phase does not seem likely to pose problems requiring technology development.

Phase III — This phase will extend to 14,000 feet (4,300 m) or a temperature of (600° F) 300° C, whichever comes first, and will be in mostly granitic or metamorphic basement rock or young granitic intrusions. These conditions are similar to those in very hot geothermal reservoirs that have already been drilled, but there will be problems which deserve attention. Retention of basic drilling fluid properties, corrosion control, adequate bit life, cementing casing, and logging at this temperature are all within the current state-of-the-art, but all could use improvement.

Phase IV — This final phase of the explatory well will reach near 20,000 feet (6,000 m) and 900° F (500° C). All the problems mentioned in Phase III will become worse, generally beyound present technology. We will try to use very simple drilling fluids, because additives that will survive these conditions may be very exotic and expensive. Corrosion will be aggravated by more complex fluid chemistry and by temperatures that accelerte corrosion rates by orders of magnitude. This implies rigorous requirements for corrosion control additives and for selection of tubular goods. Acceptable bit life will depend on new types of bearing systems for roller-cone bits or on drag bits usable in hard rock. Casing cements do not exist for 900° F (500° C) application, so wellbore stability will become vitally important. Finally, a set of rewarded, downhole memory logging tools is needed for logging at the combinaion of 900° F (500° C) and 20,000 foot (6,000 m) depth. Most of the problems described for Phases III and IV can be eliminated or mitigated if we can keep the drilling fluid (relatively) cool. This is possible with insulated drillpipe (IDP) and surface mud coolers. Analysis using a finite-element code that calculates drilling fluid temperature shows that a modest amount of insulation in the drillpipe allows the drilling fluid to reach the bottom of the 900° F (500° C) hole at less than 212° F (100° C). Although the fluid returns to the surface are hot enough to require mud coolers, this technique transforms many of the problems encountered at high temperature into the equivalent of conventional drilling.

In summary, there are several technology developments which can improve the drilling performance in the upper parts of the exploratory well, but for the very hot conditions in Phase IV, it seems that insulated drillpipe should be of highest priority for further work. ☐

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