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Research Drilling at Inyo Domes, Long Valley Caldera, California

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A 150-m hole has been cored through Obsidian Dome, and drilling is in progress to reach the conduit of Obsidian Dome and the dike believed to underlie the dome chain.

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Introduction

While a great deal of attention has been focused on inferring conditions within deep magma reservoirs, much of the action in terms of magmatic processes such as degassing, explosive fragmentation, and fluid/melt interaction occurs at depths of a few hundred meters to a few kilometers. Our understanding of what happens to magma in this important subvolcanic regime is primitive and inconsistent. For example, eruption models assume that magma is a chemically closed system during ascent, but geochemical models tacitly assume it is an open system (but only to H_2O and perhaps a few other volatile components). Thermal models are well developed but untested. The extent of magma/wallrock/fluid interaction is unknown. Yet we must understand the processes in this regime not only to understand the mechanisms of explosive eruption and hydrothermal circulation but to correctly interpret evidence of the deep plutonic conditions as well.

The only way to address these problems properly is by direct observation of young subvolcanic intrusions. Fortunately, much of the required information can be obtained with standard drilling and coring techniques at costs similar to surface geophysical observations. Samples and conditions in the intrusive environment record the response of magma and host to rapidly changed pressure and temperature conditions on a time and size scale that cannot be duplicated experimentally. Among the unique kinds of data that drilling can provide are temperatures in and near a cooling intrusion, composition of pristine intrusive glass representing magma quenched under known load, and the structure and composition of the intrusive portion of a system for which the eruption history and eruption product composition are well known. In the areas of mechanical effects of intrusion and mass transfer between magma and host, drilling can provide a far higher quality of data than sampling of exposed fossil systems through the generally greater continuity of the section sampled and the knowledge that the intrusion and its environment have been unaltered by subsequent, unrelated geologic events.

A program of research drilling has begun at the Inyo Domes volcanic chain which cuts north-south across the northwest rim of Long Valley Caldera (Figure 1). The youngest features of this chain (four magmatic vents, at least six phreatic vents, and associated normal faults) are believed to be the surface expression of a dike or system of dikes which is at least 8 km long and was emplaced approximately 600 years ago [*Miller*, 1983] (Figure 2). During October 1983, a vertical 150-m hole was cored through Obsidian Dome, northernmost of the young magmatic vents. Work is now underway on a 600-m slant core hole to intersect the conduit which fed Obsidian Dome and a 1000-m slant core hole to intersect the Inyo Dike between Obsidian Dome and the Glass Creek Flow. Additional holes, both inside and outside the caldera, have been proposed for subsequent years.

Both the drilling and supporting research are funded by the Office of Basic Energy Sciences of the U.S. Department of Energy (DOE). As an investigation of processes of heat and mass transport in an anomalously hot region of the earth's crust, this effort represents part of the national Continental Scientific Drilling Program (CSDP). Inyo drilling was initiated under a proposal for shallow drilling at Long Valley, Valles Caldera, and Salton Sea submitted to DOE in 1983 by four DOE labs. The broader program described here is an outgrowth of the initial shallow drilling effort and resulted from a proposal submitted to DOE in 1984 by a consortium consisting of three national laboratories, the U.S. Geological Survey, and five universities. Participants are listed in Table 1.

Scientific Objectives

The Inyo chain is particularly well suited for research drilling for a number of reasons: (1) Although dike propagation is thought to be the dominant mode of magma movement in the subvolcanic regime [*Pollard et al.*, 1983], at very few sites can the position of a young dike be as well constrained from surface evidence as at Inyo Domes. (2) As the most recent rhyolitic magmatic event in the western United States, the intrusion should be neither thermally equilibrated nor the glass of the intrusion hydrated. (3) Because the Inyo Chain cuts across the structural boundary of the caldera, the dike is emplaced in two contrasting environments pertinent to consideration of continental volcanism. One is thick, porous, permeable, and water-saturated volcanic pile represented by the caldera fill. The other is silicic crystalline basement, represented by Sierran granitic rocks. (4) Finally, the dike is the most recent leak from the evolving Long Valley Caldera magma system [*Bailey et al.*, 1983] and an accessible analog to intrusions which may be forming now at greater depth beneath the seismically and tectonically active southwest caldera moat and the resurgent dome [*Hermance*, 1983].

The scientific objectives for drilling the Inyo system are to characterize and compare

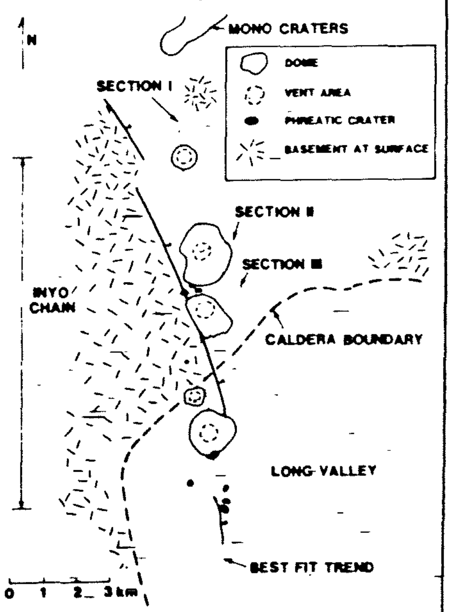

Fig. 1. Generalized geologic map of the Inyo Chain and vicinity, showing locations of cross sections. The three largest domes and the small dome on section III are thought to have erupted during the most recent event [*Miller*, 1983].

Cover. Coring through a 600-year-old obsidian flow near Long Valley Caldera, Calif. This hole, the first of a series to probe the subvolcanic environment of the Inyo Domes chain, penetrated 55 m of flow and bottomed at 152 m in precaldera andesite. (Photo by J. C. Eichelberger. See article, "Research Drilling at Inyo Domes, Long Valley Caldera, California," by J. C. Eichelberger, P. C. Lysne, and L. W. Yonker.)

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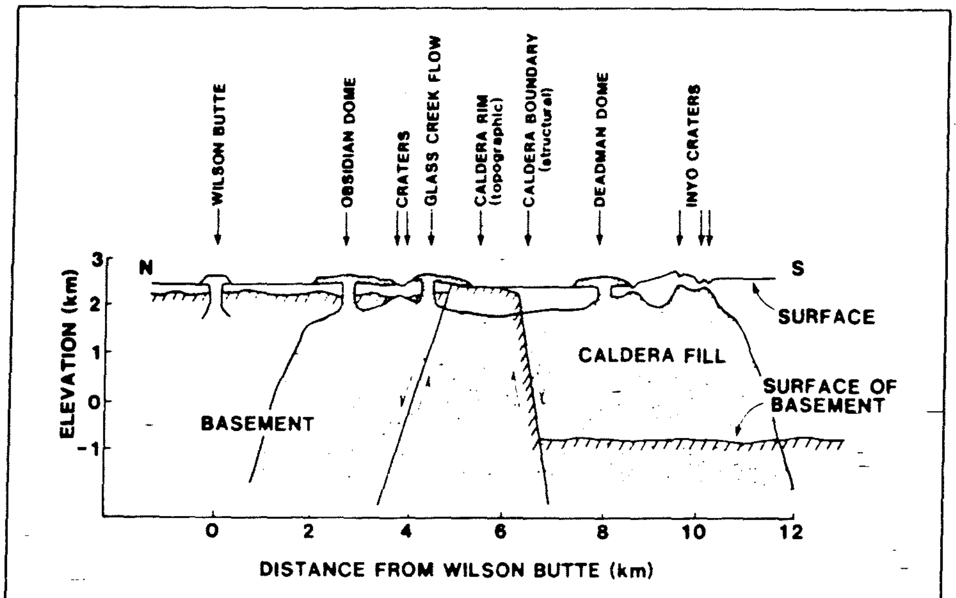

Fig 2. Cross section along the Inyo trend. The postulated Inyo Dike reaches the surface at Obsidian Dome, the Glass Creek Flow, and Deadman Dome and the near surface beneath the contemporaneous phreatic craters.

the thermal, chemical, and mechanical behavior of magma in the contrasting environments of caldera fill and crystalline basement. In discussing how these objectives are to be achieved, it is useful to consider the zones that should be penetrated by a core hole slanted into a conduit or dike. The intrusion itself should consist of an outer quenched glassy zone and a crystalline interior, while the host can be divided into a far-field undistrubed zone and a near-field disturbed or contact metamorphic zone. The importance of sampling and analyzing the undisturbed host is that it represents initial, pre-intrusion conditions. The contact metamorphic zone represents host material altered by the intrusive event. Processes contributing to these changes may include dike propagation, rapid heating to high termperature, and circulation of hot fluids of magmatic or meteoric origin.

The next zone to be encountered will be the quenched, glassy outer portion of the intrusion. This material is of special importance because it records the state of the magma in terms of phase assemblage, phase composition, and bulk composition including volatile content at the time of intrusion. It will differ from surface samples because it was quenched while under substantial pressure and from the quenched margins of exposed fossil intrusions because it is sufficiently young that it has not been contaminated by meteoric water through hydration. In terms of geochemical observations, the data should be comparable to what could be gained by coring into an active magma body.

As the drill penetrates deeper into the intrusion it will encounter magmatic material which cooled more slowly, with the result that higher crystal content and lower glass content should be expected. Important factors controlling crystallization behavior are likely to be retained magmatic volatile content and cooling rate, and these will vary with depth and distance from the contact. In order to gain maximum information on intrusion geometry and the character of each zone, holes will be planned so as to completely penetrate their magmatic targets.

Perhaps the most basic observations to be made in the drill holes are the position and orientation of intrusions relative to their surface volcanic expression. The model to be tested, but which we are confident enough about to use as a basis for siting the holes, is that a long, near-vertical dike extends upward to shallow depth (few hundred meters) and joins large-diameter conduits which continue to the surface at the magmatic vents [*Miller*, 1983; *Fink and Pollard*, 1983]. Information about the size and structure of the dike and conduits will provide insights into the eruption process, since the eruption history at the surface is well known. Likewise, surface geochemical data will be compared with composition of the intrusive portion of the system. It is usually assumed that, given sufficient care in sampling, samples collected at the surface from eruption products are a faithful representation of magma chemistry in the parent chamber, with the exception of gases lost during eruption. This concept, although universally used, has never been tested. Processes that may lead to differences between the extrusive and intrusive portion of a system include vapor transport during degassing and magma-wallrock interaction. In addition, batches of magma may remain unchanged during ascent, but tapping of a zoned chamber or mixing of magmas from different chambers may result in changing composition with time during eruption and lead to differences betweeen the extrusive and intrusive portions of the sytem [*Bailey et al.*, 1976, 1983].

Another very basic observation to be made is temperature. High temperatures due ultimately to magmatic heat have been observed at depth in many areas but not where the heat could be attributed to a single, well-defined intrusive event. Observations of elevated temperatures due to individual magmatic events are limited to extrusive bodies. Drilling the Inyo system will provide an opportunity to directly observe the cooling process and to determine the relative roles of conduction and convection in two environments of contrasting permeability. Calculations (J. C. Dunn, unpublished data, 1984) show that if the dike is 10 m or more wide and cooled dominantly by conduction, then magmatic heat will still be detected only a few hundred meters below the top of the basement and will have diffused outward approximately 500 m.

Observation of retained magmatic volatile content in the glassy chill zone will provide new information on how magmas degas. Through solubility data for various volatile species, vapor pressure at the time the system chemically closed can be inferred from volatile concentration and compared with the known lithostatic load. By sampling chill zones at multiple depths, the pressure (depth) dependence of degassing behavior can be determined. Alternatively, if no degassing occurs except by explosive fragmentation, volatile content will be independent of depth. For magma under lithostatic load at 1000 m, the solubility of water in melt is an order of magnitude higher than water contents observed in Obsidian Dome. Although it might be expected that degassing would result in water contents near the solubility curve, in fact equilibration with surface conditions (0.1 MPa) extends to at least 100 m (2 MPa) [*Eichelberger and Reece*, 1983]. While degassing to 1 atmosphere water vapor pressure is certainly not expected to extend to depths of 500 or 1000 m, glasses at these depths may be substantially water undersaturated (at magmatic temperature) if the magma behaves during ascent as a stiff, permeable foam.

The problem of dike emplacement will be investigated in detail. Fracture experiments will be used to characterize current conditions in the vicinity of the dike in terms of joint orientation and stress orientation and magnitude. Evidence for the mechanism of dike propagation is provided by fractures and other mechanical damage near the dike. Predictions of fracture distribution from existing dike propagation models (*Pollard et al.*, 1983) can be compared with actual fractures mapped from core examination and bore hole televiewer studies, which may also reveal pathways of fluid flow relevant to the geochemical and thermal investigations.

Processes of mass transport within the dike and between the dike and its host will be investigated largely through trace element and isotopic techniques. The isotopic composition of oxygen and hydrogen is a sensitive indicator to processes involving water, such as magmatic degassing and interaction between meteoric water and magma [e.g., *Taylor et al.*, 1983]. The isotopic contrast between Sierra basement and Inyo magma for Sr and Pb isotopes will provide a sensitive test of the extent of assimilation [e.g., *Doe et al.*, 1969; *Lipman et al.*, 1978]. The glassy margin of the intrusion represents magma subjected to an extreme temperature gradient and provides an opportunity to test current ideas about thermally driven diffusion (Soret effect) and its role in development of highly evolved silicic magmas by looking for gradients in rare earth element concentration.

Finally, the holes will be used to test and refine application of geophysical techniques to volcanic terranes. Deep drilling in the CSDP thermal regimes effort will rely heavily on geophysics for definition of magmatic targets, yet these techniques are largely untested due to limited drilling of magmatic features. Both electrical and seismic reflection surveys will be run across the dike trend inside and

TABLE 1. Institutions and Investigators Currently Involved in the Inyo Drilling Program

Institution	Investigators	Investigations
Lawrence Berkeley Laboratory	A. F. White	fluid geochemistry
Lawrence Livermore National Laboratory	N. R. Burkhard, P. W. Kasameyer L. W. Younker	seismic reflection, thermal/chemical relationships
Los Alamos National Laboratory	J. N. Albright, F. E. Goff H. D. Murphy	fracturing experiments
Sandia National Laboratories	C. R. Carrigan, J. C. Dunn, J. C. Eichelberger, T. M. Gerlach, P. C. Lysne	volatile geochemistry, thermal modeling
U.S. Geological Survey	R. A. Bailey, C. D. Miller	petrology geochemistry
Arizona State University	J. H. Fink	structure
Brown University	J. F. Hermance	electromagnetic survey
Michigan State University	T. A. Vogel	thermal chemical relationships
Stanford University	D. D. Pollard	structure
Canadian Geological Survey	B. E. Taylor	H, C, O isotopes

*Combined list from interlab shallow drilling proposal and interagency Inyo proposal.

outside the caldera. Results will be compared with "ground truth" from the core holes.

Program Evolution

Intersecting a subsurface intrusion with a drill hole is not a trivial problem, however unambiguous the surface evidence. Therefore, the drilling program will be developed with holes of increasing depth, cost, and target complexity so that results from each hole can be used in design of the subsequent hole. Work was initiated outside the caldera because of ease of access and target definition, relative conceptual simplicity of the geologic environment, favorable drilling conditions due to expected hole stability in granite, and greater likelihood of encountering residual heat from the intrusion at shallow depth due to expected low permeability of the environment. Work within the caldera is planned to lag work in the northern part of the chain by approximately 1 year. Table 2 shows current drilling plans, which are, of course, subject to revision based on drilling results and funding constraints. The present project will culminate with two deep (3-km) holes into the dike, one inside and one outside the caldera. The more immediate goal is to intersect the Obsidian Dome conduit and the northern part of the dike at approximately the 500- and 1000-m levels, respectively. In the remainder of this section, we describe the completed 150-m Obsidian Dome hole and the conduit and dike holes which are in progress.

The first hole was conceived as a relatively low-cost shallow vertical hole to investigate structure and chemistry of the Obsidian Dome. The hole was also intended to address the problems of wire line diamond coring in the flow and underlying stratigraphy in order to design properly the later, more expensive holes. A site near the southern distal end of the flow was chosen because the second hole will penetrate a proximal section of the flow before intersecting the conduit. Comparison of the flow sections sampled by these two holes will permit investigation of the effects of surface flowage on flow structure, bubble growth or collapse, and degassing, and of changes in magma chemistry with time. A truck-mounted wire line diamond core rig of the type commonly used in hard rock mining was employed. Coring was required to meet the scientific objectives of the hole. Further, conventional rotary drilling that relies on return fluid flow to bring cuttings to the surface would have been impossible in the highly fractured dome. Boyles Brothers of Reno spudded the hole on October 20, 1983, and completed it on November 4 at a total depth of 152 m. The hole was cored NC (93-mm diameter) to 124 m, cased NX to 122 m, and then cored NX (76-mm) to 152 m. Surprisingly, little difficulty was encountered penetrating Obsidian Dome, and recovery averaged 90% (close to 100% in the unfractured interior), even though drilling proceeded without circulation. The cost was about $170/m of which $36/m was drilling fluid. The only significant drilling problem was an unstable hole in the nonwelded Bishop Tuff, which eventually necessitated casing. The hole terminated in precaldera andesite. Major scientific results concerning the flow were absence of a basal vesicular zone postulated from surface observations([*Fink*, 1983]; a coarsely vesicular zone was encountered at 14.5–21.5 m), evidence of nearly complete degassing to one atmosphere water vapor pressure [*Eichelberger and Westrich*, 1984], and large variations in concentration of certain trace elements (H. W. Stockman and H. R. Westrich, unpublished data, 1984). These results will be reported in a subsequent technical paper. Of interest here is that the hole demonstrated the practicality of small coring rigs as a research tool for probing the Inyo environment.

Plans for the conduit and dike holes are based on these results and are shown schematically in Figures 3 and 4. Both holes are being drilled by Tonto Drilling Company of Salt Lake City, Utah. The primary objective of the conduit hole is to provide the first samples of the intrusive portion of the Inyo system at its most easily accessible point. At the projected depth of intersection of the conduit of 450 m, significant differences from surface samples in terms of degassing and crystallization behavior should already be apparent. Additional important observations will be the size and structure of the conduit and the nonvolatile chemical composition relative to tephra and flow samples.

The position of the conduit is well expressed topographically by the vent region of the flow. The vent region is a 500 × 800-m area of smooth, vertically projecting spines which is elongate along the trend of the Inyo chain and rises 50 m above the general flow surface. The drill site is a bulldozed area within a pumice claim on the flow just west of

TABLE 2. Inyo Research Holes

Year	Glass Creek Area (Outside Caldera)	Deadman-Inyo Area (Inside Caldera)
1983 (completed)	150 m vertical core hole, Obsidian Dome	
1984 (in progress)	600 m slant core, Obsidian Dome conduit 1000 m slant core, dike at Glass Creek	
1985 (proposed)	two 500 m temperature gradient holes near dike one 150 m seismic observation hole for fracture experiments	1000 m slant core, dike
1986		two 500 m temperature gradient holes near dike
1987	3 km hole	
1988		3 km hole

the vent region. Advantages of this site are ease of access for equipment and favorable geometry for intersecting the conduit from the side by a slant hole. A hole from a more central location in the vent area might simply travel down the funnel-shaped vent without intersecting the quenched margin. A more distant hole would be more expensive and might miss the target altogether. On the basis of observations of exposed fossil conduits, the target is expected to be large (>100 m), particularly in the north-south direction, relative to possible lateral deviation of the hole. Coring of the entire hole is planned, and the hole should be completed by late summer.

With the exception of being slanted, the hole into the conduit of Obsidian Dome (Figure 3) should be similar to last year's vertical hole. Since the conduit hole is deeper, the initial hole size will be larger, thus allowing for more casing steps should they be required. A Bureau of Land Management permit requirement for drilling in geothermal areas is that a casing be set at least at 10% of the final hole depth or at 61 m (200 ft) in this case. After installation and testing of blowout-preventer equipment, coring ahead will continue through the andesitic flows at a hole diameter of 96 mm. A second string of casing may be set when granite basement is reached. If the hole is stable through the granite and conduit material, the remaining hole will be open and will be 76 mm in diameter. Two additional coring steps are possible should the hole prove to be unstable.

The dike hole will be spudded immediately following completion of the conduit hole. This hole will formally begin the interagency Inyo effort and will involve the full range of scientific investigations outlined earlier in this article. The hole will be sited near Glass Creek, where there is the closest spacing of Inyo vents. The site lies between Obsidian Dome and the Glass Creek Flow and just east of two phreatic explosion craters and one small cratered dome (Figures 1 and 4). Because the dike is expected to be near vertical and trend north-south, the hole will be slanted in the east-west plane so as to laterally traverse the expected zone of intrusion. If the dike is inclined, it most likely dips to the east as the nearby Sierran frontal fault (Hartley Springs) dips to the east. Therefore the chosen drill site is east of the expected dike position, and the hole will dip to the west. The strongest local alignment of features, and therefore the best indication of the position of the underlying dike segment, is formed by a phreatic crater (which we will call Dry Crater) elongated north-south and located just south of Glass Creek; a presumed crater intersected by the first hole; a long, narrow ridge of spines extending southward from the main vent area of Obsidian Dome; and the central depression of the vent area. Hole geometry has been chosen so that the midpoint of the hole will pass directly under Dry Crater and penetrate the Hartley Springs Fault at a point down dip from the small dome which erupted on the fault. An upper limit on the dip of the fault is taken to be 80°E (R. A. Bailey, unpublished data, 1984), and the hole will be designed to reach the fault in this worst case. The hole should thus intersect structures related to at least one and possibly two phreatic craters, one magmatic vent, and a major, active tectonic feature. The design of the dike hole is similar to the conduit hole, except that core will not be taken in the first ~150 m.

The dike hole is scheduled for completion in fall 1984. Results of core and borehole investigations will be used to site an array of shallow holes for seismic and further temperature observations and to plan a similar experiment inside the caldera.

Borehole Logging and Instrumentation

The standard suite of logs (electric, nuclear, sonic, and temperature) logs will be run on the conduit and dike wells. In addition, the holes will be surveyed to accurately locate the conduit and dike as well as to provide input data for borehole to surface and borehole to borehole geophysical experiments. Owing to the size of the hole, slim hole logging tools (~50 mm) will be required. Also, the tools will have to be calibrated to obtain rock parameters (porosity, density, etc.) from the measured values of resistivity, neutron, and gamma transport parameters and sonic velocities. In addition to this work, some nonstandard downhole measurements will be made, and three are mentioned below.

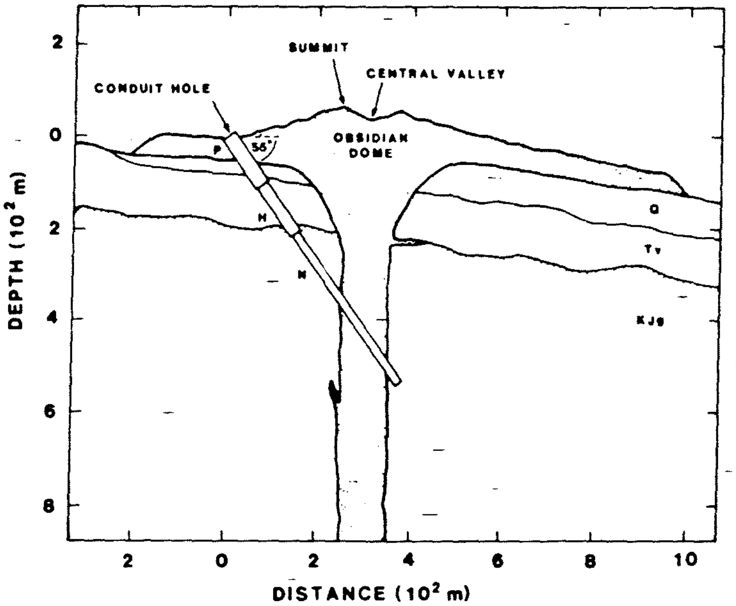

Fig. 3. Cross section II, showing plans for the conduit Hole. Hole sizes are P = 123 mm, H = 96 mm, N = 76 mm. Conduit position is inferred from topography on the dome, and conduit size is inferred from fossil analogs. Q is Inyo tephra, colluvium, and Bishop Tuff. Tv is andesitic flows and cinders. KJg is dominantly granodiorite and quartz monzonite. Depth to basement (KJg) is not known, but expected to be shallow.

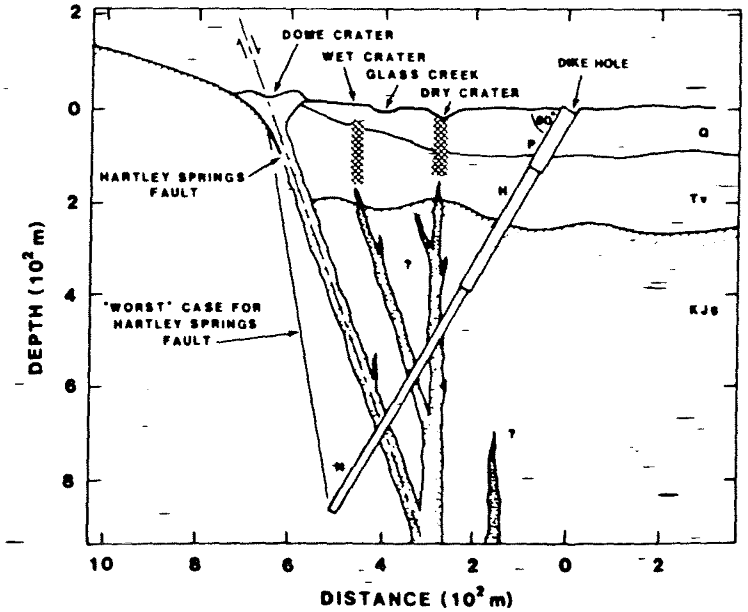

Fig. 4. Cross section III, showing plans for dike hole. Intrusive configuration is speculative, but the hole must pass between vents and the main intrusion. Crater names are informal. Wet crater (dotted) is 200 m north of the section plane.

A knowledge of the in situ stress is required to generate models for the intrusion of magma into overlying rocks. If hole conditions permit, classical hydraulic fracture techniques can be used to determine these parameters. However, the traditional assumption that the maximum principal stress is vertical is not likely to be valid in the vicinity of the dike. Thus a combination of experiments will be performed. They include an accurate calipering of the hole using a borehole televiewer and a monitoring of the strain relief of oriented core specimens. Both of these techniques have been demonstrated in recent work [*Bell and Gough*, 1983; *Teufel*, 1983].

Triaxial geophones will be cemented into outlying shallow holes (Table 2) to monitor acoustic emission due to fracture propagation during two different fluid injection experiments. The first experiment involves injection of dilute acid into the well in order to induce slippage of preexisting stressd joints. This will permit mapping of joint orientation in the vicinity of the dike well beyond the bore hole. The second experiment, mentioned previously, involves observation of the orientation of fractures formed during injection of fluids at high pressure and hence the orientation of the present stress field near the dike.

A significant contrast in resistivity may exist between the dike and its surroundings. The dike may be significantly less resistive than the crystalline basement if it is porous due to vesicularity or thermally induced fractures. Similarly, high fracture density in the basement adjacent to the dike may make the vicinity of the dike less resistive than the far field. The downhole electrical experiment will consist of a vertical magnetic induction coil used in conjunction with an active source at the surface. It allows determination of formation to surface electrical resistivities away from the borehole and will be useful for both calibrating surface to surface electrical measurements and for "stripping-off" the effect of surficial geology from the signatures of deeper structures. In addition, a number of vertical profiles will be run in each drill hole for a variety of different source field locations and configurations. This allows discrimination among the effects from structures to the side of the drill hole, the formation itself, and structures below the drill hole.

Opportunities for Additional Investigations

Although the effort outlined here is a broad, interdisciplinary program, it does not address every aspect of the subvolcanic Inyo environment. Investigators interested in utilizing the core or borehole in their research are encouraged to communicate with one of the authors of this report.

Author's Note

The conduit of Obsidian Dome was intersected at a slant depth of 487 m on September 6.

Acknowledgments

This report summarizes the combined efforts and plans of geoscientists listed in Table 1. The Inyo program is possible because of the interest on the part of members of the Office of Basic Energy Science of the U.S. Department of Energy in Continental Scientific Drilling. This work was supported by the U.S. Department of Energy at Sandia National Laboratories under contract DE-AC04-76DP00789 and at Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

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Peter Lysne *received his BA from Grinnell College in 1961. He then attended Arizona State University, which granted him first a NASA traineeship and then a Ph.D. in Physics in 1966. Past activities have included research in thermodynamics as applied to the constitutive relations of solids and liquids at very high pressure and the coordination of geological and geophysical field projects, from which he learned that those who spend nights on drilling rigs must possess a sense of humor. Current research activities deal with neutron logging techniques and the electrical constitutive relations of inhomogeeous materials.*

Leland W. Younker is *a Group Leader at the Earth Sciences Department of Laurence Livermore National Laboratory. He is currently involved in research on the evolution of high-level silicic systems at both Inyo Domes and southern Nevada as part of the Office of Basic Energy Sciences CSDP project. Earlier projects at Laurence Livermore included modeling the Salton Sea hydrothermal system, developing remote geophysical techniques for monitoring subsurface fluid movement in geothermal systems, and acting as a support geologist for seismic verification of nuclear test ban compliance. He received his Ph.D. in Geology from Michigan State University in 1974.*