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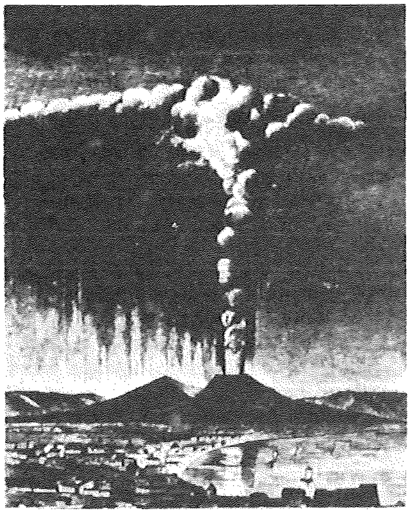

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Understanding Thermal Energy and Mass Transport in Major Volcanic Centers

John F. Hermance

An understanding of the thermal regions of the earth's interior and their associated dynamic processes is of central importance, not only to basic science but to a number of national priorities including resource and the mitigation of volcanic and earthquake hazards. Major thermal anomalies over large regions of the continent are associated with intraplate rifts and transform faults (e.g., the Salton Trough and the Rio Grande Rift), distributed extensional tectonics (e.g., the Basin and Range Province), and plate margins (e.g., the Cascade Range). However, it is clear that of all classes of volcanic phenomena within the conterminous United States, the major intraplate silicic caldera complexes (e.g., Yellowstone, the Valles Caldera, the Long Valley/Mono Craters volcanic complex) appear to have, according to present estimates, the highest accessible geothermal resource base and the greatest destructive power during major eruptive phases. In addition, the exhumed fossil analogs of these systems are associated with extensive mineralization and economic ore deposits. What is lacking, however, is a predictive scientific theory describing the fundamental physio-chemical processes responsible for the development and long-term sustenance of these major volcanic centers in space and time.

Therefore, in response to a growing interest among earth scientists, geotechnologiests, and government policy makers, a coordinated research effort is being mobilized by the U. S. Geological Survey (USGS), the national laboratories, industry, and universities to develop a comprehensive understanding of the morphology and dynamical evolution of these major tectono-magmatic features. Of particular interest are questions regarding the transfer of energy and mass between magma reservoirs deep seated in the crust and the shallower hydrothermal systems which they drive.

Rationale for Scientific Experiments in Intermediate and Deep Drillholes

Insight into the dynamics of these systems can be achieved by iterative use of various direct and indirect measurements to refine conceptual and mathematical models. Approaches used to date include extrapolation of surface geology, interpretation of surface geophysics, direct measurements in shallow and intermediate-depth drillholes, inferences from fluid geochemistry, and comparison with fossil magma-hydrothermal systems.

Our understanding of the total system, however, is limited by our inability to sample more than the upper and cooler parts of the active hydrothermal system itself. Although geothermal wells have been drilled to depths greater than 4 km and 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. Although perhaps possible someday, at present it seems realistic to restrict our objectives to temperatures of less than 400°C and to depths of less than 4 km; in many cases this would allow one to study the "roots" of the hydrothermal systems. Direct sampling of this environment through drilling, while representing a distinct challenge to present technology, would represent a dramatic improvement in our understanding of active physio-chemical processes in this regime not obtainable in any other way.

Information from a deep drillhole to a temperature of 400°C in a magma-hydrothermal system would serve a number of purposes, only four of which are identified here.

1. A complete characterization, from top to bottom, of the natural hydrothermal system.
2. Evaluation of conceptual models for the evolution of the overall magma-hydrothermal system in space and time.
3. Quantitative parameterization of energy and mass transfer mechanisms throughout the total system.
4. Evaluation of interpretations from surface geophysical and geological observations. The drill-hole offers an opportunity to validate and to refine surface techniques in what is essentially a "calibrated" environment. This would go a long way toward optimizing pre-drilling exploration activities in less-studied systems elsewhere.

Background on Potential Drilling Sites

Each of the three young, large silicic volcanic complexes in the western United States (the Valles caldera, New Mexico; the Yellowstone caldera, Wyoming; and the Long Valley caldera, California) has an associated hydrothermal system and has been subjected, in some degree, to a wide variety of earth science investigations, including in some cases drilling to intermediate depths (less than 2 km). However, in none of the three areas do we have direct drill-hole knowledge of the roots of the hydrothermal systems (2–5 km) and how these hydrothermal systems derive energy from molten rock sources within the earth's crust (from depths greater than 5 km). A number of workers concur that in choosing one or more of these caldera complexes for deep driling, the following criteria should be considered: (1) the system should represent an active counterpart of fossil caldera systems; (2) a well-defined magma body should be present; (3) the target should represent a clearly defined stage in the evolution of silicic centers; (4) a complete, compatible set of geological, geophysical, and intermediate-depth drilling data should exist; (5) a significant area of the caldera should be available to drilling in terms of both geographic accessibility and environmental sensitivity; (6) siting of the actual deep drill-hole(s) should be based on a reasonable certainty of encountering temperatures of 400°C or greater at depths of 5 km; (7) drilling and maintaining the drill-hole(s) should be technically feasible; and (8) consideration should be given to the benefits from add-on commercial drilling.

A preliminary evaluation of the three candidate caldera systems, in terms of criteria such as these, indicate that no single candidate system meets them all. On the basis of available data, the Valles caldera might appear to be reasonably favorable, primarily because of the already demonstrated high-temperature geothermal system at the Union Baca hydrothermal site, the large amount of intermediate-depth drilling by industry, and the possibility (though not certainty) of good access logistically. However, commercial drilling in the area suggests that the required hole may be extremely difficult to drill because of the underpressured nature of the formation. This situation may be encountered in the other two candidate areas as well. Such conditions may result in poor borehole stability, and the hole may be lost while drilling. Safeguarding against this exigency makes open-hole scientific experiments difficult. In turn, the need to use air or aerated drilling fluids increases corrosion and limits the ability to cool downhole equipment with the circulating fluid. It must also be recognized that massive invasion of cement into the formation during cementing operations could preclude successful perforation of the zones of

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interest. In addition, the presence of cement could lead to contamination of recovered samples. These problems will cause higher costs and risks for these wells than for similar wells drilled elsewhere into hydrostatically pressured formations. Some of these concerns might be mitigated by drilling outside the Union Baca hydrothermal field on Redondo dome or elsewhere in the caldera.

A recent workshop (*Eos.*, June 28, 1983, p. 434) underscored the attraction of the Valles caldera as a site for continental scientific drilling since there exists a considerable background in regional and local geology, geophysics, and geochemistry. In addition, lithologic, geochemical, and thermal data have been obtained from a number of intermediate depth holes within and around the Baca geothermal field, as well as from the Hot Dry Rock project on Fenton Hill at a location immediately outside the caldera, where a hole has already been drilled to 4.5 km in basement, encountering temperatures of 325°C. To supplement these data, it has been recommended that a number of intermediate depth holes (on the order of 1 km, with one perhaps going as deep as 3 km) be drilled to better qualify (1) the magma-hydrothermaltic model, (2) features within the intrusive aureole of the principal magma chamber, (3) the stratigraphic record within the caldera structure, or (4) the possibility of interstitial melt being still present at upper levels in the crust (i.e., above 10 km).

Yellowstone clearly represents the most intense magmatic and geothermal anomaly in the conterminous United States but is an evironmentally sensitive area. Even for drill-holes dedicated to purely scientific objectives, scientists and environmentalists are concerned regarding the potential hazard to geyser activity from any hydrologic disturbance. The CSDC has recently established a task group under the direction of Bob Fournier of the USGS to study these issues further and to identify unique scientific questions that can only be addressed through drilling in Yellowstone. If drilling is recommended for this area, it will, of course, be for purely scientific reasons and with full regard for mitigating any negative impact whatsoever on one of our finest national parks.

The thermal regime beneath Long Valley caldera is clearly dominated by hydrologic factors; unfortunately, however, unlike the case for the other two caldera, the hydrothermal system does not appear to have high temperatures at shallow levels. This in itself is a paradox and poses some intriguing scientific questions. Both geological and geophysical field evidence suggests the presence of a molten magma system at depths of only 8–10 km. Moreover, geochemical indicators suggest that the thermal waters, although now relatively low temperature, have derived from reservoirs where temperatures were as high as 210°-280°C.

In addition, recent tectonic deformation, seismicity patterns, and the reactivation of fumarolic activity, caused the USGS to issue, on May 25, 1982, a notice that a potential volcanic hazard exists for the southwestern segment of Long Valley caldera. If, as has been proposed, magma has intruded the upper crust of this area, surface geophysics in conjunction with borehole observations may be employed to monitor tectonic and magmatic activity associated with such a phenomenon.

An additional factor to consider in the Long Valley area is that several young volcanic systems (Inyo, Mono, and Coso), which may be in a pre-caldera stage of evolution, exist along the eastern Sierra front nearby. Studying several of these geologically related, but geographically separated, caldera systems at various stages in their evolution offers distinct advantages over concentrating studies within a single member of these silicic complexes. By restricting studies to a single system, it may be difficult to sort out various stages of geologic overprinting which occurs as these complexes evolve.

Research Needs

One of the major problems in designing a long-term drilling program and assigning drilling priorities in young silicic calderas is that the data sets on which site selections are based are not presently comparable for the three areas. Therefore, as a prelude to a deep drilling (i.e., greater than 4.0 km) at any site, a program of intermediate-depth drilling (1.0–4.0 km), needs to be carried out immediately in conjunction with geological, geochemical, and geophysical field studies at the surface in several of the candidate areas. These investigations, along with theoretical modeling of physical processes, will enable the long-term drilling objectives to be identified more closely. Neither the scientific rationale, nor the cost effectiveness of drilling versus amount of information recovered, have been articulated in terms of specific physiochemical models for this class of system. For example, it is not completely clear what phase of the evolutionary history of a magma-hydrothermal system needs to be drilled for greatest understanding. Do we drill a young system in an early stage of development to determine the initial evolutionary conditions, or do we drill a mature system in a late stage of development? What is the basis for deciding between one hole going to great depth (10 km?) in a single system or a number of intermediate-depth holes drilled into a single system or a number of holes drilled into several systems at various stages of development? It is clear to most workers that to address these issues, geophysical and geochemical field studies, along with a program of intermediate-depth drilling (1–4.0 km), need to be intensified in these areas immediately in order to determine which of these systems have identifiable magma chambers and to characterize as closely as possible the gross features of their hydrothermal systems.

It is equally clear that the best way to achieve this is to let the science continue to evolve within the interdisciplinary, multi-institutional framework which has developed quite naturally. The role of the agencies—the National Science Foundation, the USGS, Department of Energy, and Department of Defense—should be to minimize the artificial, though sometimes real, obstruction of good science by institutional boundaries. We should get on with the business of having scientists talk to scientists regardless of the agency which actually funds individual projects.

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