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CHARACTERIZING THERMAL ENERGY AND MASS TRANSPORT IN VOLCANIC CALDERA COMPLEXES; THE ROLE OF SCIENTIFIC DRILLING

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Introduction

Of all the geologic features on the earth's surface, the major silicic caldera complexes are one of the most fascinating and fundamental phenomena. Not only do they represent profound thermal anomalies in the lithosphere which potentially may be exploited for energy and economic ore deposits, they also offer grave volcanic and earthquake hazards during major eruptive phases.

The nation's attention, of course, was focused on these hazards by the May 18, 1980 eruption of Mt. St. Helens in the northwest United States. In spite its dramatic nature, however, the total volume of material erupted during this event (2 - 3 km^3) was a small fraction of those volumes associated with the caldera forming eruptions of the intraplate silicic volcanic complexes. Three of these centers are thought to be still active in the United States: the Valles Caldera in north-central New Mexico which, during its climax, erupted more than 500 km^3 of material; the Long Valley/Mono Craters Volcanic Complex in eastern California which erupted 600 km^3; and Yellowstone Caldera in southwestern Wyoming whose most recent climactic eruption released approximately 1000 km^3 of material. In short, the geologically recent caldera forming eruptions, associated with what we call the major silicic caldera complexes, are typically several orders of magnitude larger than the Mt. St. Helens class of volcanic eruptions.

Whereas these phenomena have captured the interest of geologists and geophysicists for decades, we are coming to realize that a fundamental understanding of the thermal regime and the associated dynamical processes of the major silicic complexes is of central importance, not only to basic science but to a number of national priorities ranging from resource assessment to the mitigation of volcanic and earthquake hazards. It is clear that of all classes of volcanic phenomena within the conterminous Unites States, the active caldera complexes have the highest accessible geothermal resource base, as well as 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 physiochemical processes responsible for the development and long-term sustenance of these major volcanic centers in space and time; a theory which is testable.

Therefore, in response to a growing interest among earth scientists, geotechnologists and government policy-makers, a coordinated research

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Observation of the Continental Crust
through Drilling I (ed. by C.B. Raleigh)

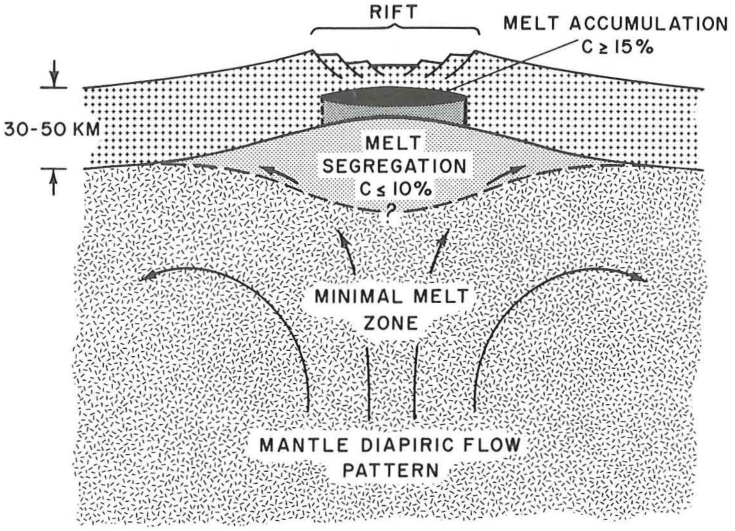


Fig. 1

effort is being mobilized by the DOE National Laboratories, the USGS, NSF, industry and universities to develop a comprehensive understanding of the morphology and dynamical evolution of these first-order tectonomagmatic features (EOS; June 26, 1984). 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. A key tool in these studies has been and will continue to be scientific drilling.

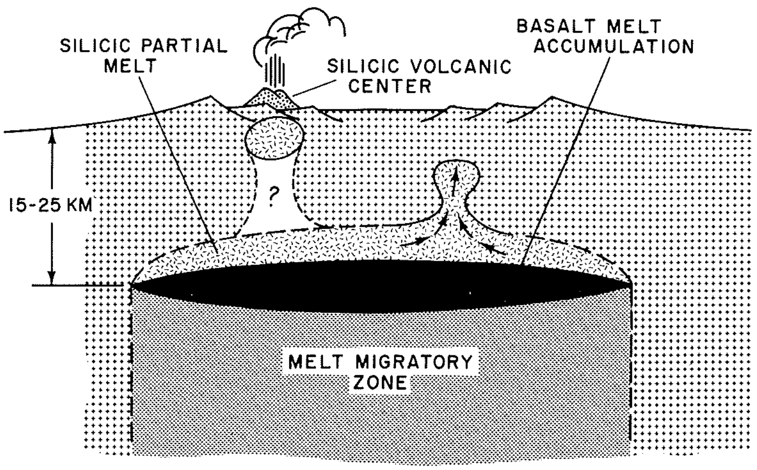
Conceptual Models for the Thermal Regime of Major Silicic Centers

Regional Processes

In order to focus the following discussion, we summarize some of the current geophysical and geological constraints on these systems as reported by Hermance (1982). It is well known that centers of silicic volcanism are regionally associated with zones of extensional tectonics. It has also been suggested by a number of workers that these silicic centers have developed through partial melting (anatexis) of crustal material through interaction with more primitive basaltic magma at depth. Recent geophysical investigations support the idea that beneath zones of extensional tectonics (e.g., mid-oceanic and intracontinental rift systems), ascending masses of material from the mantle are intimately coupled with regional doming and the morphotectonic development of rift features (Fig. 1). Since crustal temperature gradients are on the order of 40 to 100°C km^{-1} in these regions, and gradients in the upper mantle appear to be less than a few °C km^{-1}, heat transfer mechanisms in the mantle must be extremely efficient. This implies mass transport. In addition, electrical resistivities are such that minimal melt is thought to be present at depths greater than 50 km or so. In Figure 1 this is indicated as the "minimal melt zone".

At the top of the mantle diapir, lowered values of the bulk resistivity indicate, in some areas, a slight enhancement of a partial melt fraction

Fig. 2



which may be associated with a seismic low-velocity pillow seen beneath many rifts. In Figure 1 this is indicated as the zone of "melt segregation".

It does not seem plausible that melt, having segregated and formed a concentration of greater than a few percent of the total volume, can be dynamically stable (Walker et al. 1978). Therefore, melt in the upper mantle probably migrates either laterally as part of the diapiric flow pattern, or vertically in response to a combination of buoyancy and lithostatic pressures, and accumulates at a preferred level which is presumably hydrostatically controlled at the base of, or within, the crust. This is shown as the zone of "melt accumulation" in Figures 1 and 2. Geophysical interpretations place this zone of magma accumulation at the base of the crust beneath some areas whereas it seems to be at intracrustal levels beneath others.

Implicit in the above discussion is the concept that basalt melt *segregates* from a source region in the mantle, which at any given time has a low concentration of liquid, and *accumulates* at some level in the lithosphere.

Figure 2 represents an enlarged version of the uppermost section of Figure 1 and shows the presence of a melt migratory zone. The nature of such a zone separating the region of melt segregation in the mantle from the zone of melt accumulation at the base of, or within, the crust is obscure at the present time, and its character undoubtedly varies from region to region. In some areas, such as the central and north-central Rio Grande rift, the zone of melt accumulation seems to be a discrete layer at intermediate levels in the crust which can be clearly distinguished from its anomalous roots in the mantle. In other regions, such as Iceland, the zone of melt accumulation may be more intimately coupled to its mantle origins.

The level at which basaltic magma from the upper mantle accumulates must depend to a marked degree on its depth of origin as well as on the overall character of temperature and density gradients in the lithosphere and asthenosphere. Moreover, the frequency and mass flux with which the magma zone is replenished and sustained determines the extent to which the thermal regime of the lower crust is perturbed from a conductive environment to a convective environment.

Relationship to Extrusive Silicic Volcanism

We suggest (Fig. 2) that the emplacement of a molten (1200 °C) basaltic lens at depth will thermally perturb the surrounding country rock, which may undergo local secondary remelting (to temperatures apparently as low as 750 - 800°C; Bailey et al. 1976). In this case, up to 400 cal g^{-1} of excess heat is available in the basaltic intrusion to locally remelt the crust. Assuming for the sake of illustration that the latent heat of fusion for basalt and granite are approximately equal (i.e., 100 cal g^{-1}), then one unit of basalt can mobilize up to four units of silicic material.

The partial melt will segregate as a rhyolite magma (Fig. 2) and, because of its lower density, will tend to rise as a silicic diapir, which, if it reaches the surface, will lead to extrusive volcanism. We submit that episodic silicic volcanism at the surface is associated with the episodic replenishment of the basaltic magma layer at depth. Moreover we emphasize, as a corollary to this observation, that long periods of dormancy in which the magma reservoir is unreplenished – and may even approach a solidified state – is a fundamental feature of the known thermal regime of these systems.

Consider, for example, the expected scale-size of the ultimate magma reservoir. Smith and Shaw argue that even during a *major* eruption, only 10% of the magma present is erupted. Therefore, for a typical erupted volume of 500 km^3, this implies a reservoir capacity of 5000 km^3, or a totally molten body having a typical diameter of 20 km (for a sphere-like body), emplaced at midlevel in the crust (as implied by certain fluid inclusion and other data). Such thermal perturbations do not seem to be a steady-state feature of the major caldera systems.

Thus the model in Figure 2, driven by episodic mobilization and upward migration of basalt from the upper mantle, provides a basis for relating geophysically delineated structures in the deep earth to the genesis of major centers of silicic volcanic activity.

Coupling of Hydrothermal Systems to Deeper Magma Bodies

Insight into the dynamics of how hydrothermal systems in the upper crust are driven by deeper magma bodies has relied on both direct and indirect measurements to refine conceptual and physio-mathematical models. Approaches by previous workers have included extrapolation of surface geology and geophysics, direct measurements in a number of shallow and a few intermediate-depth drillholes, inferences from fluid geochemistry, and comparison with fossil magma-hydrothermal systems which have been exhumed and dissected by erosion.

Scientific drilling by the USGS in the 1950's and 60's laid much of the foundation for understanding ground water circulation in hydrothermal systems. White (1973) proposed a model in which low temperature meteoric water percolates downward along fractures and is driven laterally by a hydraulic pressure imbalance while being heated from below. An uprising plume develops and the hot water rises essentially adiabatically until it encounters its boiling point and flashes to steam. A two-phase mixture of fluid and gas then persists to the surface.

This model, while conceptually satisfying, remains essentially untested in the major caldera systems. In particular the region of heating at depth, and the degree to which the fluid interacts with the country rock and the molten magma reservoir itself (in dissolving and redistributing mineral components, some of which have economic value), is completely unstudied.

Rationale for Scientific Experiments in Intermediate and Deep Drillholes

Our understanding of the overall system is limited primarily by our being able to sample only the upper, lower temperature portions 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 magmahydrothermal system, to magmatic temperatures (>900°C) and to depths well within the crust (>10 km). Although this may be technically feasible in the near future, 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 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 scientific drillholes to temperatures of 400°C in magmahydrothermal systems would serve a number of purposes:

1. An overall characterization – from top to bottom – of the natural hydrothermal system.
2. Evaluation of conceptual models for the evolution of the overall magmahydrothermal 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 other less-studied systems elsewhere.

Background on Potential Drilling Sites

Each of the three young, large silicic volcanic complexes in the western U.S. – 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 commercial drilling to depths on the order of 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 scientific drilling, 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. Actual siting of scientific 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.
8. Consideration should be given to the benefits from add-on commercial drilling.

The Valles Caldera

The Valles Caldera resulted from a climactic eruption of the Jemez Mts. Volcanic Complex in north-central New Mexico 1.1 m.y. ago. This eruption was preceded at 1.4 Ma by the formation of the Toledo Caldera which is now largely obscured by the most recent event. The eruptives from both calderas are generally known as the Bandelier Tuff, which has an estimated volume of approximately 600 km^3 (Smith 1979).

Volcanism in the Jemez Mts. spans the time interval from 13 m.y. to less than 0.1 Ma ago, and by most standards (including recent seismicity), the complex is likely to be still active.

The Valles Caldera was the classic type-example used by Smith et al. (1961) to develop their concept of resurgent calderas (Fig. 3). The fundamental features of the Valles system are extraordinarily well developed, from the physiographic boundary fault to the spectacular resurgent dome and a number of discrete post-climactic rhyolite dome extrusions along the intracaldera ring fracture.

Smith and Bailey (1968) visualized the following series of stages in the development of resurgent calderas (Fig. 3):

1. Regional tumescence and the development of ring fractures culminating in caldera forming eruptions (Fig. 3A).
2. Caldera collapse and post-caldera volcanism (Fig. 3B).
3. Resurgent doming and major ring fracture volcanism (Fig. 3C).
4. Continuing ring fractures volcanism, primarily in the form of extrusive rhyolite domes. The development of keystone graben-like features on the resurgent dome (Fig. 3D).

It is important to note that each of the three major silicic centers with which we are concerned have resurgent calderas, and generally have progressed through the above sequence – some, perhaps, several times.

On the basis of available data, the Valles caldera appears to be a highly favorable site for scientific drilling, 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, drilling at Fenton Hill by Los Alamos National Laboratory, and the possibility of good access logistically because of a single land-owner for most of the caldera and a single commercial leasee. At present, however, access to this site is restricted because of pending legal and environment issues.

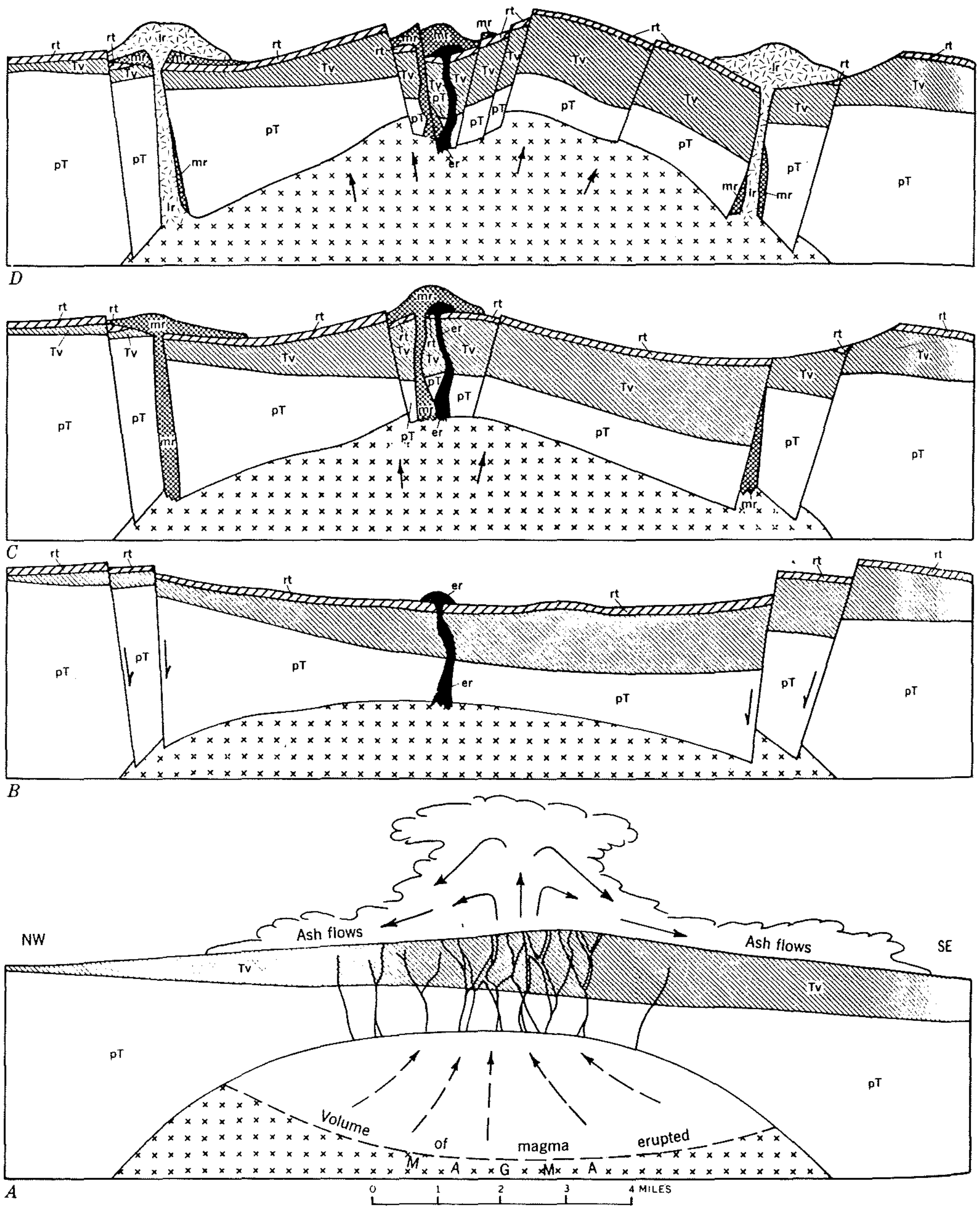


Fig. 3

A recent workshop hosted by Los Alamos National Laboratories and the USGS (EOS June 28, 1983) underscored the attraction of the Valles caldera as a site for continental scientific drilling. A number of participants argued that there already exists a considerable background in regional and local geology, geophysics, and geochemistry. In addi-

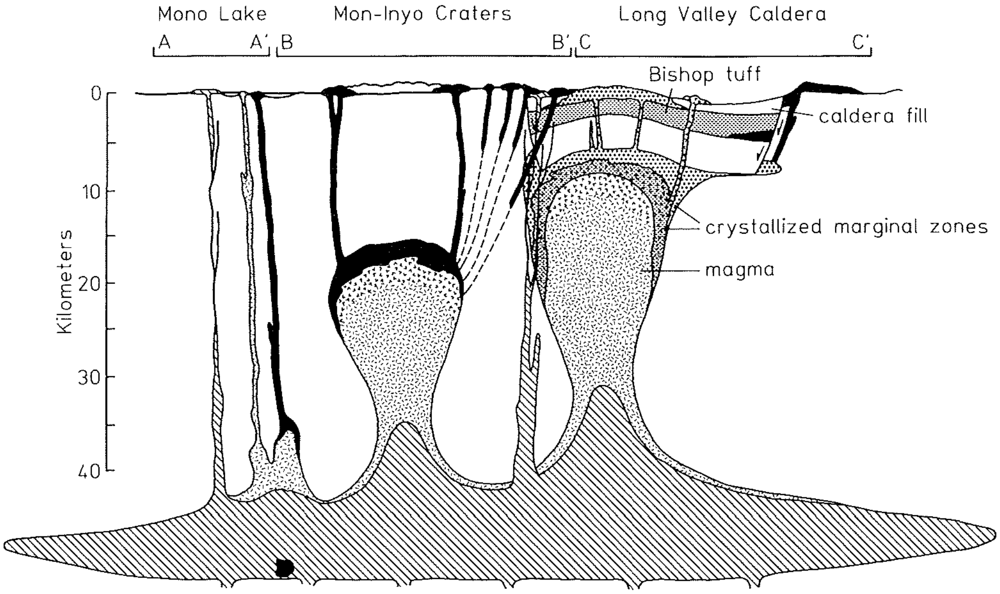


Fig. 4

tion, 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 (a) the magma-hydrothermal model, (b) features within the intrusive aureole of the principal magma chamber, (c) the stratigraphic record within the caldera structure, (d) the possibility of interstitial melt being still present at upper levels in the crust (i.e., above 10 km).

Although it is not likely that a major magma chamber presently exists in a molten state at shallow levels in the crust, there is very good reason to expect that one did exist in the recent past, but is now largely solidified. Scientific drilling in the Valles Caldera therefore offers an opportunity, in terms of presently available technology of drilling into and even *through* a high level magma chamber which has been active so recently that significant retrograde metamorphism has not obscured the basic petrologic signatures of processes which were in effect when the system was still active.

The Long Valley/Mono Craters Volcanic Complex

Long Valley Caldera is associated with a structural embayment in the northerly trending frontal fault system of the Sierra Nevadas, and is one of several young volcanic centers in the area. Volcanism in the vicinity of Long Valley began about 3×10^6 yr ago with scattered eruption of basalt and andesite, becoming localized about 2×10^6 yr ago with the eruption of the Glass Mountain rhyolite, and culminating with the tremendous eruption of 600 km^3 of rhyolitic Bishop Tuff, 0.7×10^6 yr ago. The subsequent collapse of a shallow, zoned magma chamber produced the Long Valley caldera, 17 × 32 km in size (Bailey et al. 1976). This was followed by resurgent doming of the caldera floor and episodic intracaldera volcanism as recently as 0.05 m.y. ago. Bailey (1982) has suggested that the volcanism responsible for forming Long Valley caldera itself has probably completed the cycle usually associated with resurgent activity.

Long Valley Caldera is the southern-most and oldest member of a succession of three progressively younger volcanic complexes each in different stages of evolution (Bailey 1980). These are in decreasing age, Long Valley (3.0 - 0.05 m.y.), Mono Craters (40 k.y.-1 k.y.), and the centers in Mono Lake (<2000 yr).

According to a conceptual model of Bailey (1982), Mono Craters (1300 yr) may have evolved through stages 1 and 2 described for Long Valley above, and the centers in Mono Lake form the smallest and youngest complex, and seem to be in stage 1 (Fig. 4). Mono Craters are chemically homogenous which, along with their recent age and frequency of eruption, suggests that they were extruded from a single magma chamber, largely molten and perhaps still rising to the surface. The crescent-shaped trend of Mono Craters has been used to infer the outer margin of this inferred magma chamber, and its center may be beneath Pumice Valley.

In contrast to the chemical *homogeneity* of Mono Craters, the chemical *heterogeneity* of the underdeveloped volcanic centers in Mono Lake seems to suggest that they may have issued from small, multiple, and relatively deep magma bodies that have not yet coalesced (Fig. 4). We therefore have available in these three volcanic complexes a set of field examples, each of which represents a different stage in their tectonomagmatic evolution.

The Inyo Domes and Craters

The youngest volcanic features in Long Valley caldera are the Inyo craters and domes which lie on a linear trend extending north from the northwest sector of the caldera, across the caldera rim, to Mono Craters (Bailey et al. 1976). The five Inyo domes are roughly rhyolitic in composition, and the youngest are less than 550 yr old (Miller 1984). Early studies indicate that Inyo domes are chemically heterogeneous, which suggests that they may be a product of mixing magmas from the Long Valley chamber and the possible chamber beneath Mono Craters to the north (Bailey et al. 1976). Recently, however, Bailey (pers. commun. 1982) found evidence that the Inyo volcanoes may have derived from a single source associated with the Mono Craters. Thus, geological evidence suggests the possibility that a rather extensive magma reservoir (or system of reservoirs) may exist beneath the northwestern section of Long Valley caldera and extend 30 - 35 km north to Mono Lake (Hermance 1983).

Following a major earthquake sequence in 1980, a significant increase of tectonic activity in Long Valley caldera has lead some workers to infer that magma has intruded the upper crust, and there has been concern about possible renewed volcanic activity at the surface. The three most compelling pieces of evidence for this are the recency of volcanism along Inyo Domes (550 yr), the localization of spasmodic tremor in the southwest moat, and the recent uplift of the resurgent dome (Fig. 5).

All these phenomena are particularly striking when it is realized that volcanism in the Long Valley/Mono Craters complex is the most recent of any of the major silicic centers we are discussing. In fact there

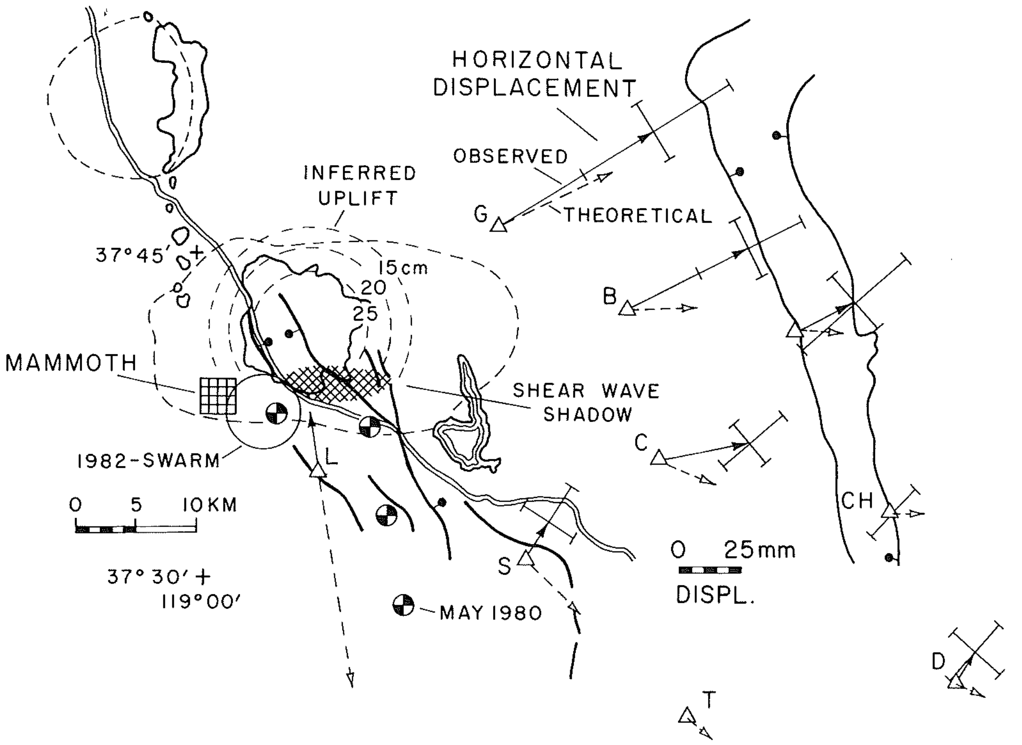


Fig. 5

may have been a historic eruption beneath Mono Lakes in the late 1800's. Volcanism in both the Yellowstone and the Valles Calderas is most likely older than 50,000 years.

Yellowstone Caldera

Yellowstone Caldera is the youngest major element of a 7500 km^2 caldera complex at the terminus of what many workers feel is a mantle hot-spot track (Christiansen 1984). The volcanic center occurs at the confluence of three major mega-tectonic stress trends: the downwarped northeast trending Snake River Plain (the hot-spot trace), and Basin-Range type faulting which trends both southwards to the south of the Caldera and northwestward to its north. Seismicity occurs throughout the region (smaller events are shown as open circles in Figure 6 with some of the largest earthquakes in this region of the Rockies occurring close to the northern rim and shown by stars; Smith and Christiansen 1980).

The volcanic complex, itself, formed over three major eruptive cycles at 2.0, 1.3, and 0.63 m.y. ago. The latter event is the best understood because it is the least obscurred by subsequent eruptions. It produced 1000 km^3 of the Lava Creek Tuff and formed the 45 × 70 km Yellowstone Caldera proper. Resurgence of the caldera floor followed the main eruptive phase, with intracaldera eruptions occurring up to 0.075 m.y. ago. Many workers feel that a massive magma reservoir still persists beneath a portion of the caldera, but this is not conclusive. Clearly, however, some high temperature source is needed to sustain the vigorous hydro-

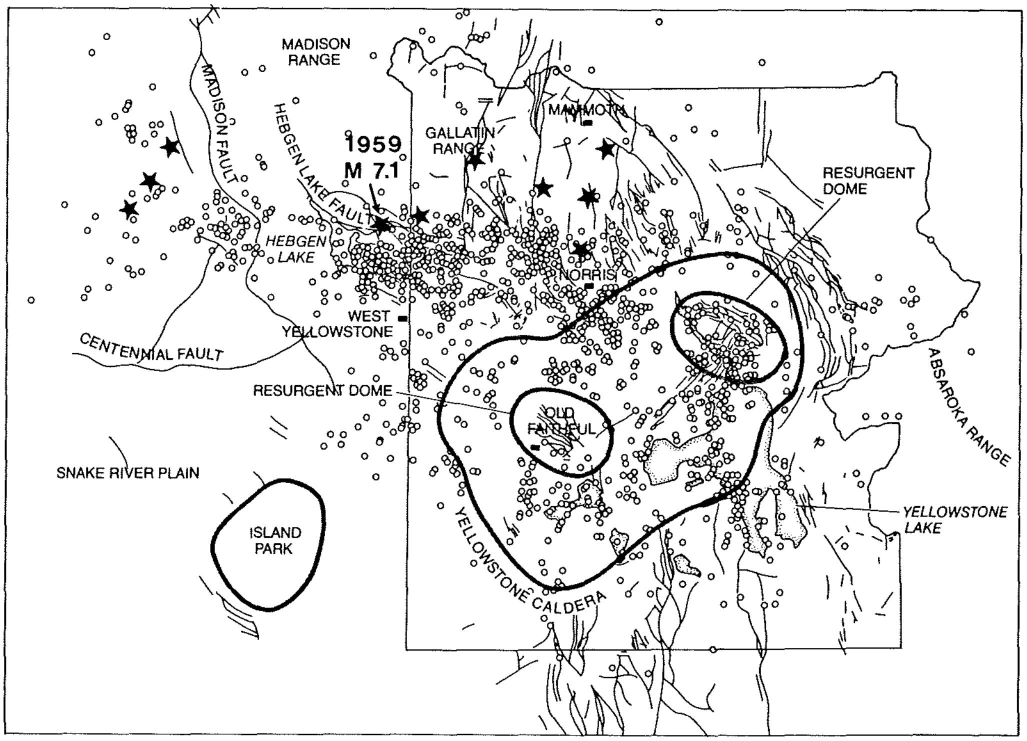


Fig. 6

thermal system which accounts for the present average advected heat flow of 1700 mW m^{-2} (60 mW m^{-2} is considered normal for a stable geologic province). Christiansen (1984) argues that only magma can account for such a high sustained thermal discharge.

There is little argument, therefore, that Yellowstone Caldera represents the most intense magmatic and geothermal anomaly in the conterminous U.S., but at the same time, being in a National Park, this area is environmentally sensitive to studies using scientific drilling. 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 Continental Scientific Drilling Committee 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 which can only be addressed through drilling in Yellowstone. If drilling is recommended for this area, it will, of course, be strictly limited geographically and for purely scientific reasons with full regard for mitigating any negative impact whatsoever on one of our finest national parks.

In summarizing the characteristics of these three silicic calderas we note that:

1. Each is associated with a locally complex stress field.
2. Each is characterized by episodic volcanism preceding and following major caldera forming eruptions.

3. Each is associated with a hydrothermal system which is largely fault-controlled at the surface.
4. But, we emphasize, each is in a different stage of their tectono-magmatic evolution which makes them each uniquely and equally attractive for scientific drilling in the type of generic research program we are describing.

Priorities and Tradeoffs in Terms of Cost Versus Recovered Information

An integral step in the foreplay that goes into planning a program of scientific drilling needs to involve a careful assessment of the progressive tradeoffs in cost and technological development on one hand and the quantity and quality of information recovered on the other. Planning a scientific drillhole will involve considering the following stages:

1. Drilling
2. Temperature logging
3. Recovery of cuttings
4. Pressure measurements
5. Reservoir testing
6. Core recovery
7. Conventional logging
8. Short-term downhole instrumentation
9. Long-term (observatory?) downhole instrumentation

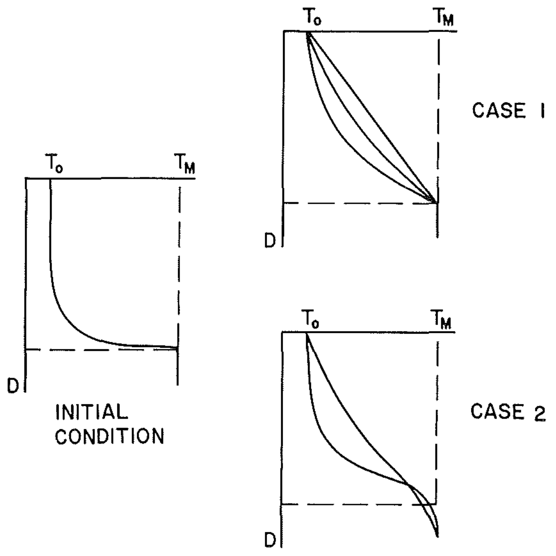
Are each of these activities as critical to the success of the experiment as the others? As we go down this list we progressively increase the total cost of the experiment, while at the same time, of course, we hopefully recover more information. The question we have to ask is, where in the cost structure does the rate of information returned become offset by the enormous cost of retrieving that last data point?

Can One Constrain in-Situ Physical Processes with Minimal Information?

Perhaps a more positive way to view the above exercise is to ask what minimal experiment justifies the cost of drilling a given hole? One might argue that in some cases simply temperature and perhaps cuttings might be sufficient. Anything else that one can cram down or pull out of the hole would be frosting on the cake.

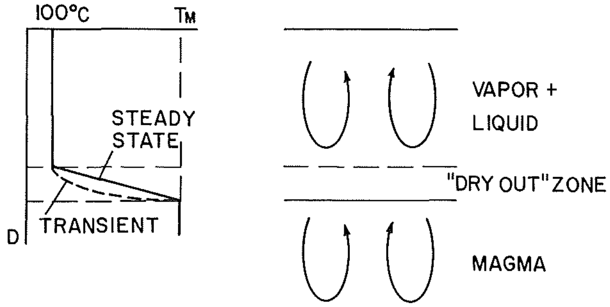
Temperature, after all, can be directly and readily measured — in fact to temperatures in excess of 1000°C. Knowing the in-situ temperature provides a great deal of insight into physical processes. This can be illustrated with a set of simple models. It is important to recognize that constraints on dynamical processes do not always require exotic instrumentation and/or sample recovery methods downhole. Fundamental constraints often come from the simplest measurements.

Figure 7 illustrates a set of possible temperature profiles following the intrusion of magma at a temperature of T_m at a depth D. The left hand panel shows the initial transient condition at an early time after the intrusion so that temperatures at shallow depth are unperturbed from their "normal" value. (To simplify our present discussion, we neglect the contribution of the normal background temperature gradient and the fact that the boiling point of water increases with pressure



INTRUSION - SOLID CONDUCTION

Fig. 7



INTRUSION-CONVECTION DOMINATED

Fig. 8

and depth.) Case 1 in the right hand set of panels shows the temperature stabilizing toward some steady-state temperature gradient – this of course implies that T(D) = T_m for all time, which in turn implies that the magma body is large and is actively convecting.

Case 2 illustrates the case where temperatures in the magma systematically *decrease* with time while they *increase* at shallow levels in the crust – at least for a while. Such a situation implies that the magma body is quite small, is quite viscous, or is not convecting at all.

The point we would make is that the physical process is reflected in the nature of the temperature distribution.

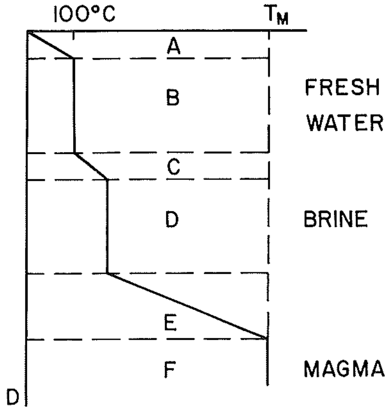


Fig. 9

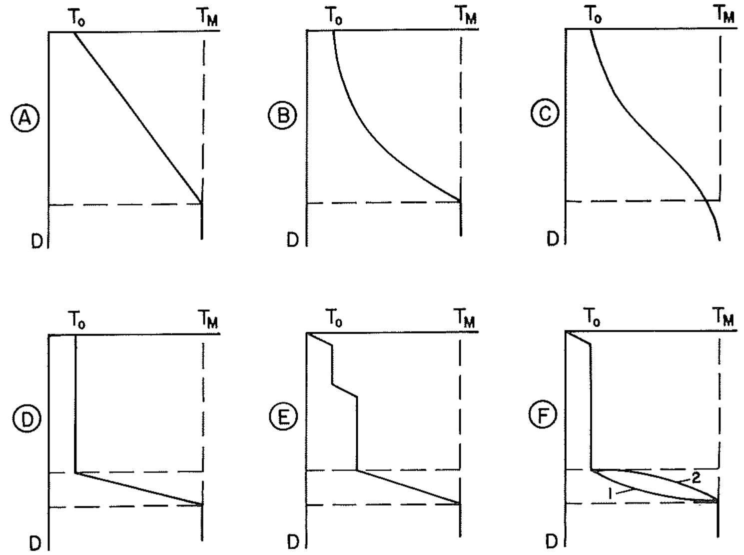


Fig. 10

Next we consider in Figure 8 the case of an intrusive in which heat transfer is convection-dominated both in the magma and in the overlying crust. Following an initial transient stage, a quasi steady state is reached where temperatures are essentially constant with depth in the overlying crust, rise along a constant gradient in a thin boundary layer, and are again constant in the magma at the magmatic temperature.

An example of "stacked" convection cells is illustrated in Figure 9 (following Fournier 1983). Here a high density brine will convect at a higher temperature than a lighter freshwater layer above. The interface at C may be simply a thermal boundary layer or may in fact be a physically impermeable zone generated by deposition of minerals exsolved from the brine below.

These situations are resummarized in Figure 10. A, B and C represent conduction-dominated situations. A is a steady state constant gradient requiring a considerable reservoir of convecting magma at depth. B reflects a transient temperature build-up due to a recent intrusion. C represents a cooling magma reservoir and a heating crustal layer above. This will continue to be a transient situation until all the heat from the magma reservoir is depleted. D, E, and F represent the effects of convection-dominated heat transfer in an aquifer overlying the magma reservoir.

Case F is particularly interesting because the two profiles in this panel (1 and 2), while their difference is fairly subtle in detail, can in fact be resolved in actual field studies and represent dramatically different histories for the intrusion. Case F1 illustrates a transient "start-up" condition in which the intrusion is very recent and the heat flux above the magma source is still increasing.

On the other hand, Case F2 represents a transient *cooling* condition which has been well-documented in studies of Kilauea Iki Lava Lake on Hawaii (Hardee 1980; Helz 1980; Hermance and Colp 1982). The lake was caused by a lava flow from the November-Dezember 1959 eruption of Kilauea volcano which ponded in Kilauea Iki pit crater. The lava flow was approximately 120 m deep and had a diameter of 750 m. Over the years a number of scientific drillholes have recorded its cooling history and a variety of geophysical measurements have been employed to remotely sense the status of its molten core (see, for example, the review by Hermance and Colp 1982).

Hardee (1980) noted that over a significant portion of the colling history of the lava lake, temperatures in its lower conduction-dominated zone showed a systematic concave-downward curvature with depth (Case F2 in Figure 10). In a simplistic sense, curvature of the geotherm represents either a change of thermal conductivity or a non-zero divergence of the heat flux. Hardee argues, however, that in this case the change of conductivity is too small, and may even have the wrong sense, to account for the curvature. Hence, it seemed reasonable to explain this feature as divergence of the heat flux.

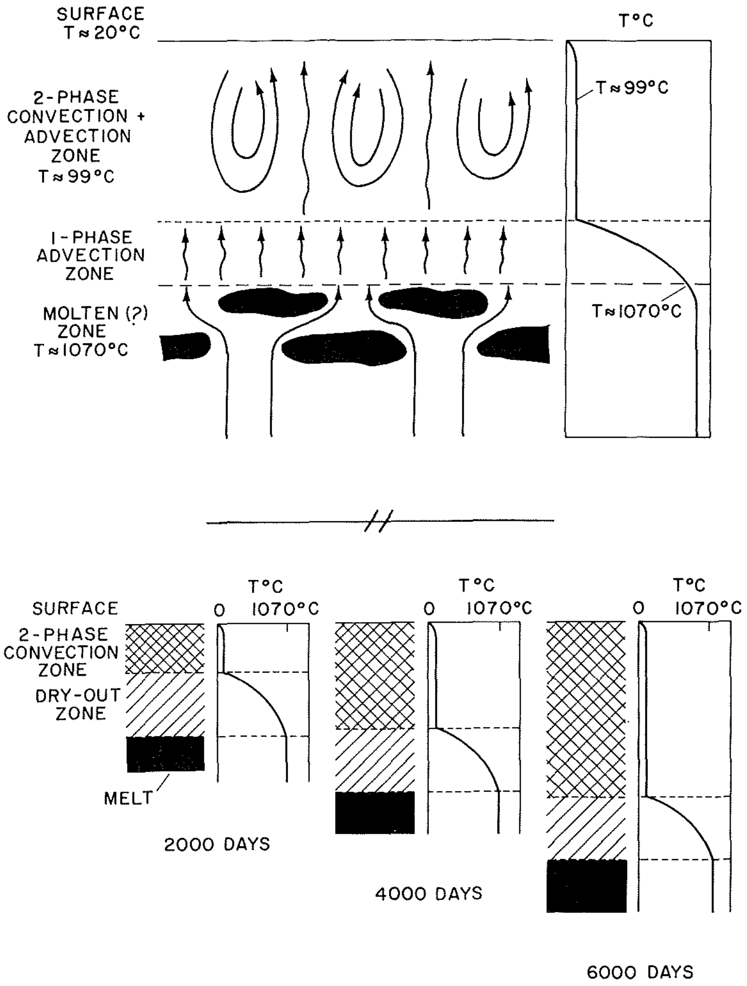
In the conventional one-dimensional heat flow equation

$$\partial^2 T/\partial z^2 = -H_s/k + (\rho C_p/k)\partial T/\partial t + (\rho C_p/k)v\cdot\nabla\mathbf{T}$$

the curvature of the temperature field is embodied in the second derivative on the left-hand side. The heat productivity H_s due to radioactivity is small for basalt, therefore only the transient cooling effect $\partial T/\partial t$ and the advection term $v\cdot\nabla T$ were possible contributors to the negtive curvature in the geotherm of Kilauea Iki Lava Lake. Originally it was suggested that advection of steam through a disconnected zone of molten inclusions (Fig. 11, top panel) could explain the temperature field above the melt zone. But the results of electromagnetic sounding experiments were incompatible with a discontinuous melt phase for the molten zone; its conductivity was too high. Geophysical considerations, therefore, required a macroscopically continuous zone of thoroughly interconnected melt for the molten core.

Hardee (1980) presented a model in which the transient cooling term dominates the curvature of the temperature field. He argued that although the solidification of the crust followed the square-root-of-time law early in the history of the lake (e.g., proposed by Peck et al. 1964 for Alae), the crust then began solidifying at a nearly constant rate (Fig. 11, bottom panel). The observed constant solidifications rate appeared to result from a natural heat flux balance between the two zones of the crust, the upper two-phase convection-dominated zone and the lower zone dominated by transient conduction effects due to the moving solidification front. Hardee argued that the curvature

Fig. 11



of the temperature profile is fundamentally related to the rate of solidification, and that the rate of solidification can be determined directly from the temperature profile.

The lessons to be learned here are that physical processes do, in fact, have distinctive signatures in the thermal field. Much can be learned about a system from simple measurements of temperature. Nevertheless the ultimate interpretation of the temperature profile was ambiguous – did the cooling term ($\partial T/\partial t$) or did the advective term ($v \cdot \nabla T$) dominate the divergence of the heat flux? In this case a single drillhole was insufficient to discriminate between these two possibilities and recourse was made to surface geophysical-electromagnetic sounding measurements.

The underlying theme of the Kilauea Iki experiment was based on recognizing the basic ambiguities in proposed models, then sharpening the questions to be asked to the point where drilling becomes a cost-effective, in fact the *only*, solution.

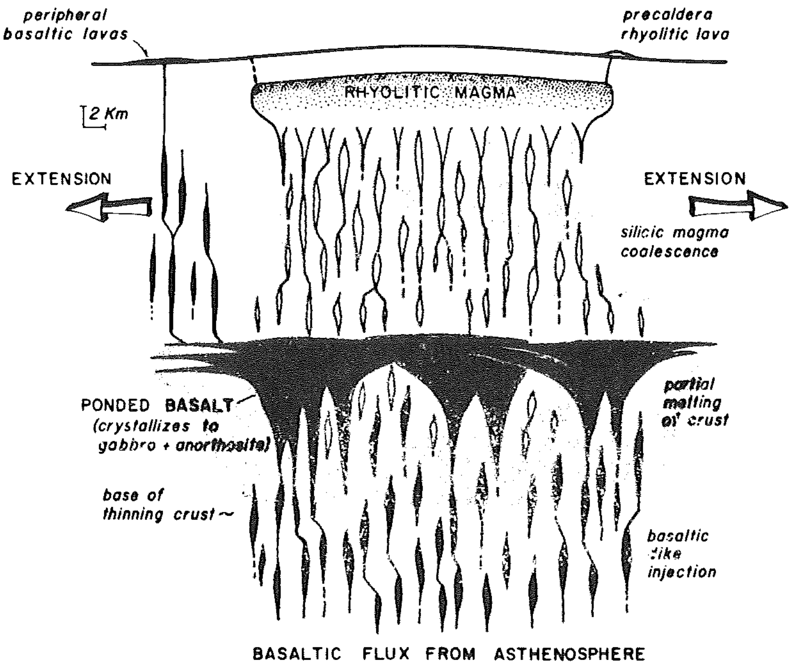


Fig. 12

Some Testable Concepts for Scientific Drilling

The above discussion argued that a great deal of insight into physical processes in magma-hydrothermal systems can be obtained through relatively simple measurements in drillholes using present-day technology. It was also argued that the interpretation of such measurements can be ambiguous – supporting the position that while a single suite of measurements from a drillhole may be acceptable, this is generally not the most desireable nor cost-effective use of limited funds. The prospect of a single, super-deep hole into such systems is particularly inadvisable.

We now consider a final example which is not only concerned with *physical* processes associated with magma-hydrothermal systems but *chemical* processes as well.

Hildreth (1981) has proposed a model for the evolution of zoned silicic magma chambers (Fig. 12) based on an impressive synthesis of data from the class of caldera complexes described above. Through a process described earlier, basalt flux (T approx. 1200°C) from the asthenosphere ponds at the base of the crust causing partial melting of silicic material having a low melting point (700° - 800°C). The silicic magma thus formed rises and collects in a magma chamber at high levels in the crust. Such a shallow depth appears to be compatible with gas inclusion studies of the erupted products. Needless to say, if such bodies exist at such shallow levels they are indeed exciting geophysical and scientific drilling targets.

A conceptual model is shown in Figure 13 (following Hardee 1982) for the hydrothermal system associated with such a magma chamber at a depth of 5 km or so. A zone of conduction dominated heat flow (Zone B in

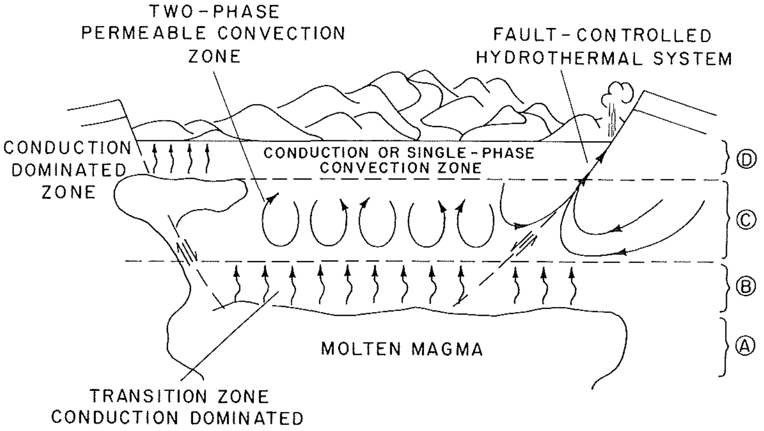


Fig. 13

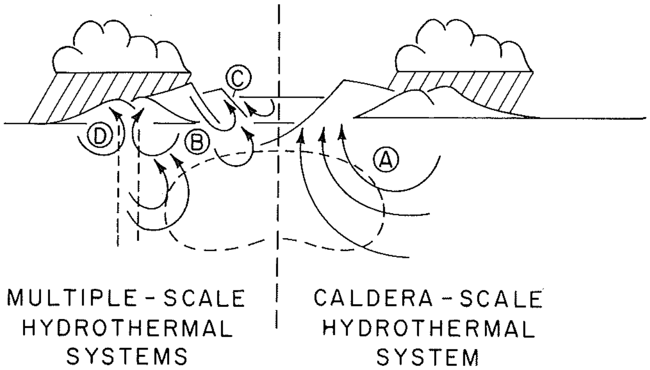


Fig. 14

Figure 13), probably highly resistive and somewhat ductile, is thought to be present directly above the molten magma chamber (A in Figure 13). The high heat flux from the parent magma body forces the hydrothermal system to convect as a two-phase flow (liquid water plus steam) in a permeable zone (C). Some of the fluids may leak to the surface along faults and fractures. Above the convection zone (C), heat may be transferred by solid conduction or by single-phase advection or convection along systems of fractures (Zone D, Fig. 13).

The essential features of this model is that during a significant portion of its lifetime, a vigorous hydrothermal system is maintained through a mechanism in which the magmatic source is cooled through a downward moving solidification front, in analogy with the process described for Kilauea Iki Lava Lake.

It seems that hydrothermal systems which totally penetrate an intrusive body, as visualized a number of years ago by Taylor and Forester (1971), occur in a late stage of the evolution of these systems, when the intrusive has essentially solidified. It is quite likely, in fact, that the pattern of hydrothermal circulation is somewhat more complicated than visualized by Taylor and Forester. In Figure 14 we show two possible modes for penetrative convection of hydrothermal fluids. On the right hand side, A indicates a single caldera-scale hydrothermal cell which geochemists seem to readily visualize, but of which we do not know of a single documented example. On the left hand side of Figure 14, we see hydrothermal systems having multiple-scales: B represents a small convective system penetrating the periphery of a much larger scale solid pluton; C is a fault-controlled high level hydrothermal system, driven essentially by high heat flow from below; D represents convection totally penetrating a local stock. Most electromagnetic workers who have surveyed specific geothermal targets with a dense coverage of sites will be all too familar with the small scale electrical anomalies which are implied by the phenomena illustrated on the left hand side of Figure 14.

The fundamental questions we are posing here – which are only several of many which workers might pose – are at what stage does penetrative hydrothermal convection occur in the evolution of massive magma chambers? – and what is the scale-size of the deep-lying convection cells? Is it reasonable to consider a model in which the hydrothermal system progressively evolves from being dominated by a moving solidification front (Figure 13) during its early history, to a caldera-scale convection cell which totally penetrates the parent magma body during its later history (Fig. 14, left side)? Or does a caldera-scale hydrothermal system *ever* exist in the evolution of these complexes? – does the hydrothermal system always consist of multiple, randomly placed small scale units?

We would argue that our models are becoming sufficiently quantitative so that proposed hypotheses can be tested. The generic program we are describing here will attempt to characterize the roots of these hydrothermal systems, particularly emphasizing the transfer of mass and energy throughout the magma-hydrothermal system. What is the effect of the magnitude and recency of volcanism? Is a brine layer present as a ubiquitous feature in all of these systems? What is the nature of processes at the magma-hydrothermal interface as it evolves in space and time?

These are first-order questions which can only be addressed through scientific drilling..., and only through drilling in a number of target areas at different stages in their evolution.

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