RESULTS FROM SHALLOW RESEARCH DRILLING AT INYO DOMES, LONG VALLEY CALDERA, CALIFORNIA AND SALTON SEA GEOTHERMAL FIELD, SALTON TROUGH, CALIFORNIA

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INTRODUCTION

A goal of the thermal regimes sector of the U.S. Continental Scientific Drilling Program is to understand the intrusion of magma into the crust, the release of heat and volatiles from these intrusions, and the development of associated hydrothermal systems. These processes result in the formation and modification of continental crust. Magmatic processes of interest include tectonic constraints on intrusions, intrusion mechanisms, cooling behavior, geochemical evolution, interaction with crustal rocks and fluids, degassing, volcanic eruption mechanisms, and coupling of the hydrothermal system to the heat source. Hydrothermal processes of interest include interaction between magma and near-surface fluids, fluid flow pathways, circulation patterns, flow rates, barriers to flow, rock/water interactions, and development of mineral deposits.

The scientific promise of drilling into contemporary magma/hydrothermal systems and unraveling the details of these processes is potentially very large. Our present knowledge of how magma behaves in the upper crust is based on observation and analysis of surface manifestations (volcanism), remote sensing of the subsurface through geophysical techniques, laboratory experiments in silicate systems at elevated pressure and temperature, piecing together information from geological studies of analogous fossil systems, and application of thermal, chemical and mechanical models. All of these approaches have inherent limitations that render inferences about intrusive systems uncertain. Magmatic materials sampled at the surface have lost gases, perhaps other components, and may have undergone crystallization and contamination during shallow intrusion and eruption. Subsurface magmatic features inferred from geophysical data in volcanic terrains are, in general, untested by direct observation. Laboratory experiments are limited in time and volume and in knowledge of initial magmatic composition and conditions. Interpretations based on fossil systems are limited by incomplete exposures, uncertainty as to whether systems exposed at different levels are really analogous, and by post-emplacement deformation and alteration. Modeling depends on assumptions concerning unknown subsurface conditions. Extensive geological, geophysical, and geochemical research at young volcanoes and well-exposed fossil volcanic fields have accurately described the physical and chemical end point of magma in its path to the surface and provided testable models concerning the subsurface. Eventually, it is anticipated that direct observation of active magma reservoirs through ultra-deep drilling will define initial conditions in similar detail. However, early exploration of the quenched and non-quenched portions of a young magmatic intrusion, at depths of less than a few kilometers, would provide fundamentally new information concerning the chemical and physical path of ascending magma in a regime where processes of great interest, explosive volcanism and hydrothermal circulation, occur. There is also a potential for gaining new knowledge of hydrothermal systems at modest expense, even though many holes have been drilled for geothermal purposes. Holes extending somewhat deeper or laterally away from the main zone of economic interest can greatly improve models for large-scale mass and heat transfer. Continuous core from the zone supplements the more limited view of reservoir conditions obtained from cuttings from geothermal wells.

In spite of this high potential return, nagging questions about the role of drilling persist. Proponents of drilling in thermal regimes argue that drilling provides the scientist with an opportunity to observe active processes in situ, and obtain information from the third dimension, linking surface and subsurface features. Critics counter that the drill hole is myopic, yielding too limited a view of the system under investigation. They argue that because of these limitations the high cost of drilling may not be justified. Indeed, if continental drilling is to realize its potential and be worth the cost, it must provide unique information pertinent to understanding fundamental crustal processes, and the models developed on the basis of this information must be broadly applicable.

In at least the initial stages of research drilling, multiple shallow or intermediate-depth holes can provide valuable information leading to the development of models or a conceptual framework for systems under investigation. These models can help provide the rationale for future deep drilling projects as well as the framework in which the results of deep drilling can be interpreted.

In this report we review the results from two shallow drilling programs recently completed as part of the United States Department of Energy Continental Scientific Drilling Program. Our purpose is to provide a broad overview of the objectives and results of the projects, and to analyze these results in the context of the promise and potential of research drilling in crustal thermal regimes.

The Inyo Domes drilling project has involved drilling 4 shallow research holes into the 600-year-old Inyo Domes chain, the youngest rhyolitic event in the coterminous United States and the youngest volcanic event in Long Valley Caldera, California (Fig. 1). The purpose of the drilling at Inyo was to understand the thermal, chemical and mechanical behavior of silicic magma as it intrudes the upper crust (Eichelberger et al. 1983, 1985). This behavior, which involves the response of magma to decompression and cooling, is closely related to both eruptive phenomena and the establishment of hydrothermal circulation. The Salton Sea shallow research drilling project involved drilling 19 shallow research holes into the Salton Sea geothermal field, California (Fig. 2). The purpose of this drilling was to bound the thermal anomaly, constrain hydrothermal flow pathways, and assess the thermal budget of the field (Newmark et al. 1986). Constraints on the thermal budget links the local hydrothermal system to the general processes of crustal rifting in the Salton Trough.

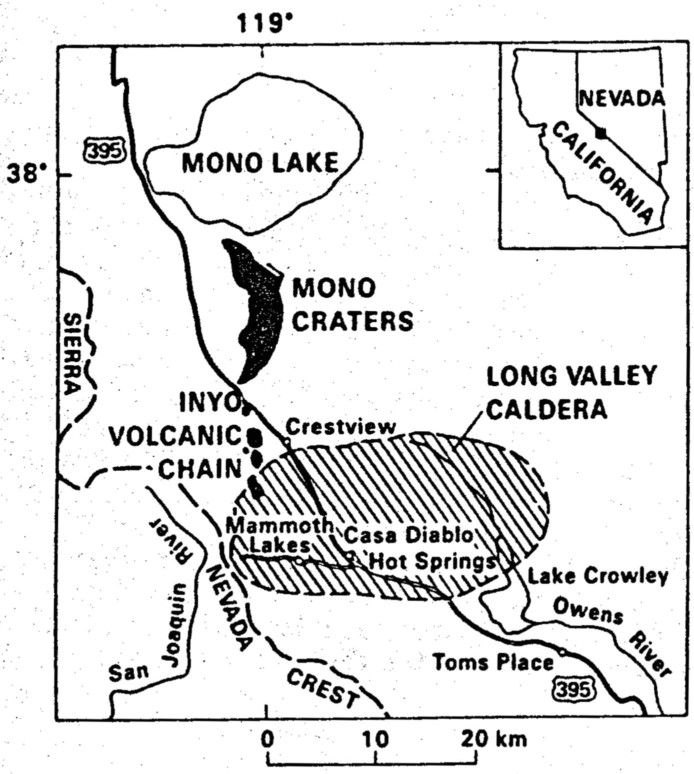


Fig. 1 Map of Long Valley Caldera in eastern California. The Inyo volcanic chain, site of the shallow research drilling program, cuts across the northwest rim of the caldera.

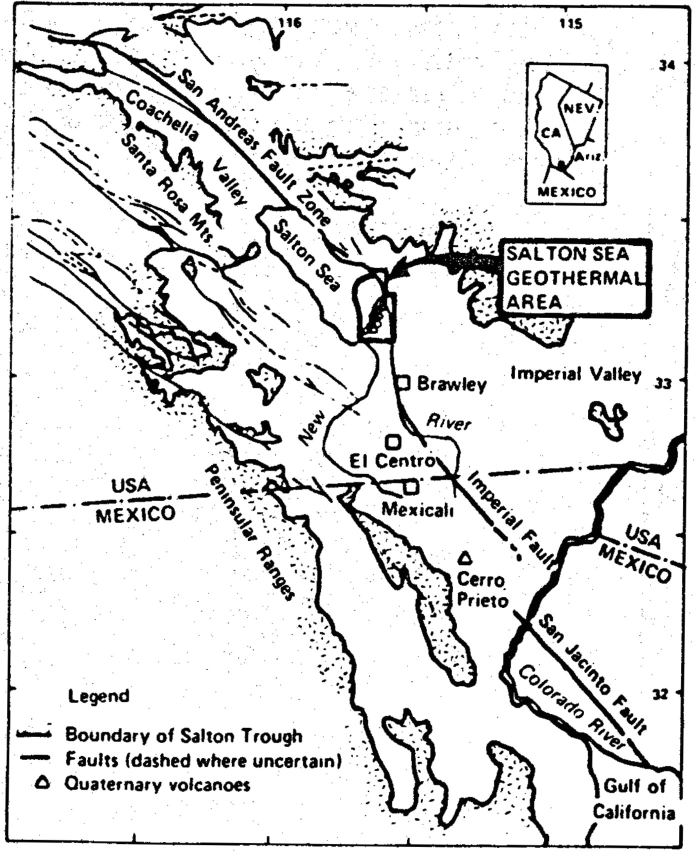


Fig. 2 Generalized geologic map of the Salton Trough, showing approximate locations of major faults and geothermal areas. The Salton Sea geothermal area, site of the shallow research drilling program, is located near the southern shore of the Salton Sea in the pull apart region between the San Andreas and Brawley fault zones.

INYO DOMES CALIFORNIA SHALLOW RESEARCH DRILLING

Geological Setting

The Inyo volcanic chain is a north-south-trending linear array of 7 rhyolite domes, at least 15 explosively excavated craters, and numerous normal faults and fissures (Fig. 3; Miller 1985). The array is 16 km long and is bisected by the northwest rim of Long Valley Caldera. Magmatic vents of the chain lie near or outside the caldera boundary and the craters and normal faults are better developed inside. The earliest activity clearly identifiable as belonging to the Inyo system was the eruption of a small dome north of Deadman Creek roughly 6000 y ago. This was followed 1200–1300 y ago by the eruption of Wilson Butte at the north end of the trend. Six hundred years ago there occurred the youngest and largest event, and the one of primary interest here. Three major magmatic vents and numerous phreatic craters erupted within a short interval of time. Each of the magmatic vents produced tephra followed by a lava dome. The sequence of initiation of activity did not progress in a single direction. The southernmost vent, Deadman Dome, erupted first, followed by the Obsidian Dome vent to the north, followed by the intervening Glass Creek Flow vent. Although the interval of time over which these events occurred was long enough for shifts in wind direction to occur, it was sufficiently short that no erosion of the delicate tephra sheets occurred between deposition of layers, and all explosive eruptions were complete before extrusion of the three domes began.

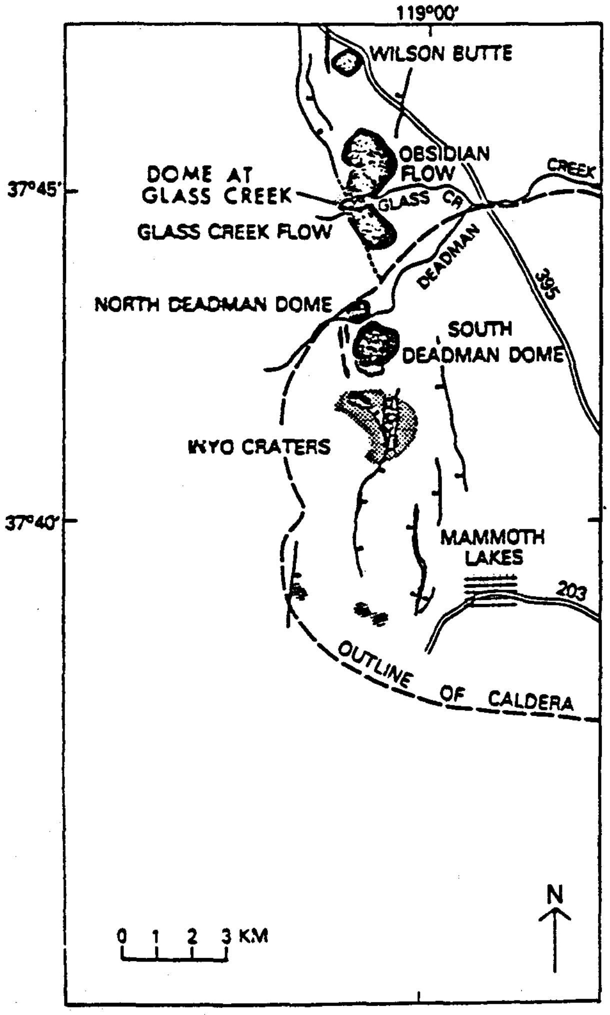


Fig. 3 Map of the Inyo volcanic chain and western part of the Long Valley Caldera. Black areas are Inyo rhyolite domes and flows (includes some vents older than 600 y). Circles with hachures are phreatic vents. Stippled areas are phreatic explosion debris. Elongate lens shaped patterns mark open fissures (after Miller, 1985).

The linear arrangement of these features and their near-simultaneous formation led Miller (1985) to postulate that the 600-y activity was the surface expression of the emplacement of a rhyolite dike that reached the near-surface over a distance of 10 km. Similarly, Pollard (1984) and Fink (1985), arguing on the basis of the development of coincident linear grabens and open fissures, the abundance of rhyolitic dikes in the geologic record, and the mechanical facility of intruding magma as a dike rather than a finger, proposed the existence of a shallow dike beneath the chain.

Research Drilling Objectives and Approach

The purpose of drilling at Inyo Domes is to understand the behavior of silicic magma as it intrudes the upper crust. The Inyo chain was chosen for study because it is the youngest rhyolitic system in coterminous United States, and because Inyo magma intruded the contrasting geologic environments of caldera fill and granitic basement, permitting an assessment of the influence of the intrusive environment upon magmatic behavior. The approach was to sample, at the surface and at depth, a very young igneous system that is unchanged by events subsequent to its emplacement.

Research Drilling Results

Three relatively shallow (<700m) core holes located outside the caldera in Sierran granitic basement have sampled the distal and proximal portions of the largest lava dome (Obsidian Dome) and the vented and unvented portions of the underlying dike (Eichelberger et al. 1985). The holes were sited on the basis of surface geology, and drilling results demonstrated that the intersected intrusive structures were within 4° of vertical (Fig. 4). The 0.2 km^3 lava dome was fed by a conduit that is 36 m wide at 450 m depth, and lies within a 52-m-wide zone of fall-back tephra and comagmatic rhyolite fingers (Fig. 5). One kilometer to the south, the comagmatic and coplanar unvented portion of the dike is 6 m thick at a depth of 640 m. In the granite wallrock, pyroclast-bearing hydrofractures were encountered as far as 130 m from the dike.

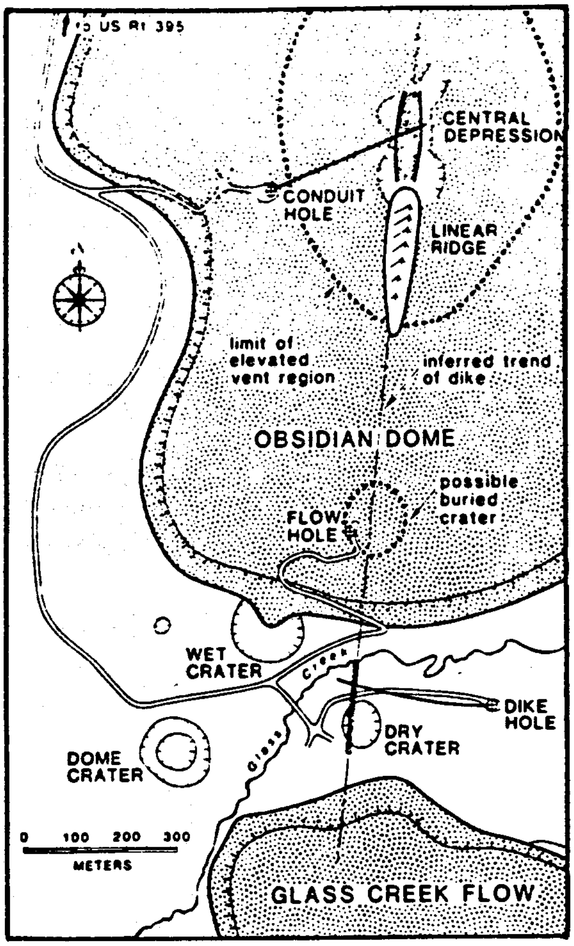


Fig. 4 Map showing volcanic features of the Inyo chain in the vicinity of Glass Creek, and plan views of the core holes and intersected intrusions. The flow hole is a vertical hole drilled near the southern margin of Obsidian Dome in 1983. The conduit hole extends from outside the elevated vent region of the Dome and passes beneath a central depression where it intersected the conduit as shown by the darkly shaded region. The dike hole slants west toward Dry Crater, a double phreatic crater with north-south elongation and curves to the north.

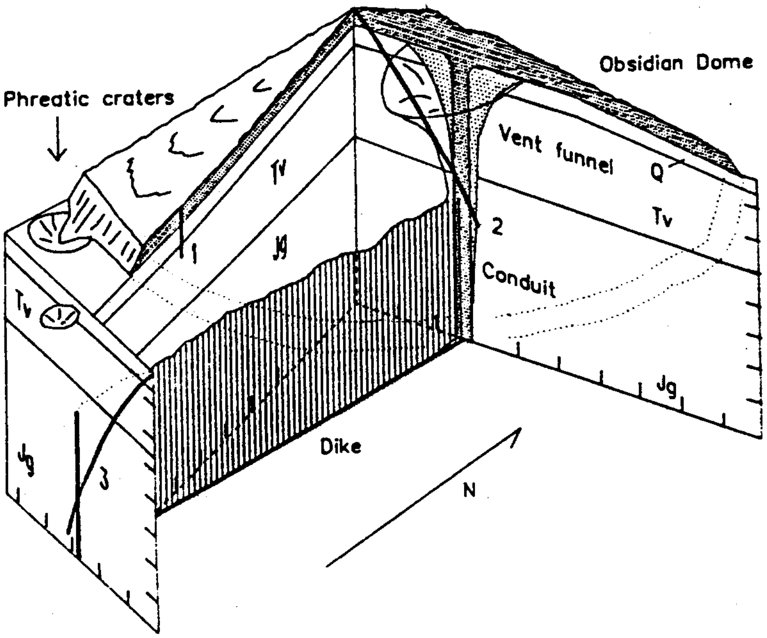


Fig. 5 Cutaway view of the Obsidian Dome lava flow, showing its vent funnel, conduit, and feeder dike. Divisions mark 100-m intervals. Research holes are also shown and are numbered in the order they were drilled.

Interpretation of the Drilling Results

Some of the relationships between the different kinds of observations used to develop and test models for behavior of Inyo magma are shown in Fig. 6. We are concerned with three time scales. The decompression phase spans days to months and involves a dynamic system as magma as intrudes, erupts and deforms the host rock. Decompression of melt results in rapid loss of volatiles. Heat loss from the system results in freezing of early magma on the walls of the conduit, and stops the dike before it reaches the surface over much of its length. The crystallization phase follows emplacement and spans tens of years; the magma is static and crystallizes, and any volatiles that were not lost during the decompression phase are lost by second boiling. Heat diffuses a substantial distance from the intrusion and hydrothermal circulation is established, resulting in chemical alteration of both the intrusion and host rock. The final subsolidus phase extends to the present, when cooling of the intrusion approaches completion, and chemical changes are dominated by crystal/aqueous fluid equilibria.

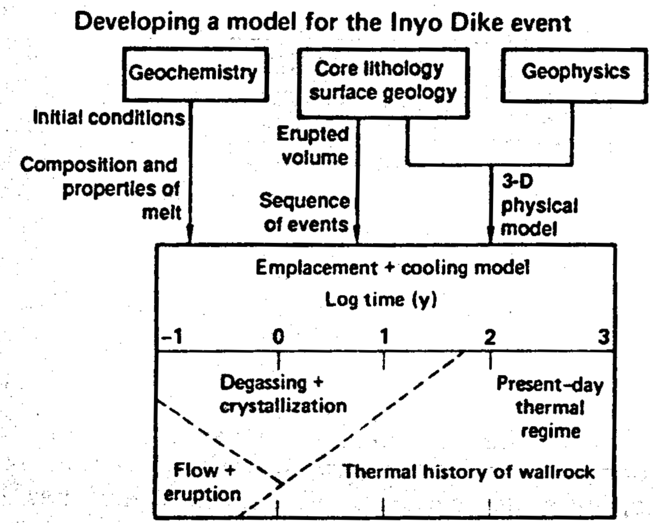
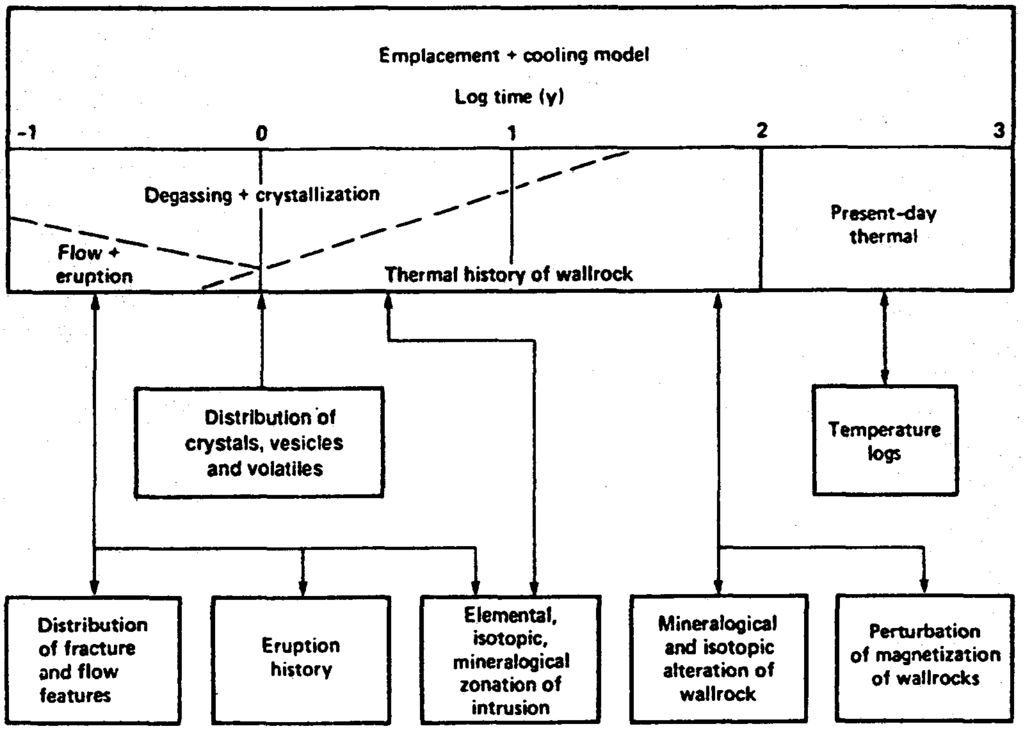


Fig. 6A Relationship of scientific investigations to developing (6A) and testing (6B) models for behavior of Inyo Intrusion.

Testing the model for the Inyo Dike event

Fig. 6B



Interpretation of the detailed results has lead to the development of several generalized models for shallow magma behavior during the decompression phase time span. Observations on the distribution of glass, crystals, bubbles, permeability and residual volatiles as a function of position in the Inyo system, coupled with observations on the existence and nature of the vent funnel, have been used to develop a model for shallow magma degassing (Eichelberger et al. 1986). Implications of the model are that silicic magma ascends as a permeable foam and that the extent of degassing and, hence, eruptive behavior depends strongly on the permeability of the intruded environment. Non-explosive silicic volcanism is due to the escape of gas from magma in the form of permeable foam during the final few hundred meters, and few hours of ascent to the surface. A quantitative model for this process indicates that critical parameters determining whether the foam fragments explosively are rate of ascent, width of the magma column, and permeability of the wallrock.

The bulk concentrations of major, chemically bound volatile components, and their spatial distribution in the Inyo system, have been used to document chemical changes in rhyolitic magma during the decompression and crystallization phases (Westrich et al. 1987). The effects of crystallization or second boiling on the composition of the melt are interpreted to be superimposed on the effects of decompression. The relative importance of the two stages varies with depth, with second boiling dominating below 1 Km.

Confirmation of the dike model, contrasting size and features of the conduit and dike, and chemical variability throughout the Inyo system have been used to confirm a general model for the processes involved in the development of dike-fed eruptive events (Vogel et al. 1987). A magma filled fracture propagates upward from a chamber roof by the process of dilation of host rock. Near the surface, extensive fracturing and excavation of a pluglike conduit occurs just prior to or during the earliest phase of the eruption. Detailed comparisons between the chemical and mineralogical characteristics of the dike, conduit and dome provide insights into shallow magma transport processes, and, in particular, highlight the magma mixing processes associated with the development of the conduit and the subsequent localization of flow to feed the eruptive center.

Constraints on the subsolidus cooling phase of the intrusion have been obtained by comparing initial estimates of emplacement temperatures based on oxide data with the data on the resetting of K-Ar mineral ages in the surrounding host rock (Ryerson et al. 1985). Reheating of the granite country rock by the Inyo intrusion opens the microcline to radiogenic Ar loss. The fractional loss is a function of the time-integrated temperature history. Alternative cooling models can be tested by comparing Ar loss as a function of position with the estimates of intrusion temperatures based on geothermometers. The agreement using a conductive cooling model is excellent, at least down to 160°C, the closure temperature of the system.

SALTON SEA CALIFORNIA SHALLOW RESEARCH DRILLING

Geological Setting

The Salton Trough is a sediment-filled rift zone resulting from the oblique motion of the North American and Pacific tectonic plates over the last 4-5 my. It represents the transition between oceanic spreading in the Gulf of California to the south and the San Andreas continental transform fault system to the north (Elders et al. 1972). The thermal and structural processes that formed the Salton Trough were initiated when the East Pacific Rise intersected the North American plate margin, about 30 my ago. Since that time, the northward migration of the Mendocino triple junction and the southward migration of the Rivera triple junction marked the termination of subduction and the initiation of transform shear over a broad region (Atwater 1970). This shear eventually produced the system of offset strike slip faults observed in the Trough. At present, the relative plate motion takes place primarily along transform faults such as the Imperial and San Andreas faults, with local zones of extension occurring wherever the faults are offset in a right-lateral sense. These offsets allow magmatic intrusions to "leak" into the crust, providing heat sources to drive hydrothermal activity. Several small Quaternary volcanic domes on the southeastern shore of the Salton Sea are direct evidence of the location of one of these "leaks."

The geothermal field to the southeast of the volcanic domes has been extensively studied through deep and shallow drilling as well as by geochemical and geophysical methods (e.g. Helgeson 1968, Younker et al. 1982, Elders and Cohen 1983). The portion of the hydrothermal system to the northwest has not been as extensively explored, as the sea makes exploration and resource utilization more difficult. Regional studies including seismicity and gravity and magnetics surveys all indicate that the "pull-apart" zone extends under the Salton Sea, and that the hydrothermal system probably does as well (Younker et al. 1982).

Crustal extension in the Trough is perceived to occur on different scales, by different authors (Fig. 7). The thermal zones, like the Salton Sea geothermal field, are perceived by many to be the locus of spreading (e.g. Elders et al. 1972). They are each less than about 10 km long. The zone of modern intense seismicity suggests to some that a zone perhaps 30 km long is deforming (e.g. Fuis et al. 1982, 1984). Regional tectonic modeling by Lachenbruch et al. (1985) requires basalt intrusion into a diffuse zone of deformation 150 km long. Any model for this area must successfully reconcile observations made at all these scales.

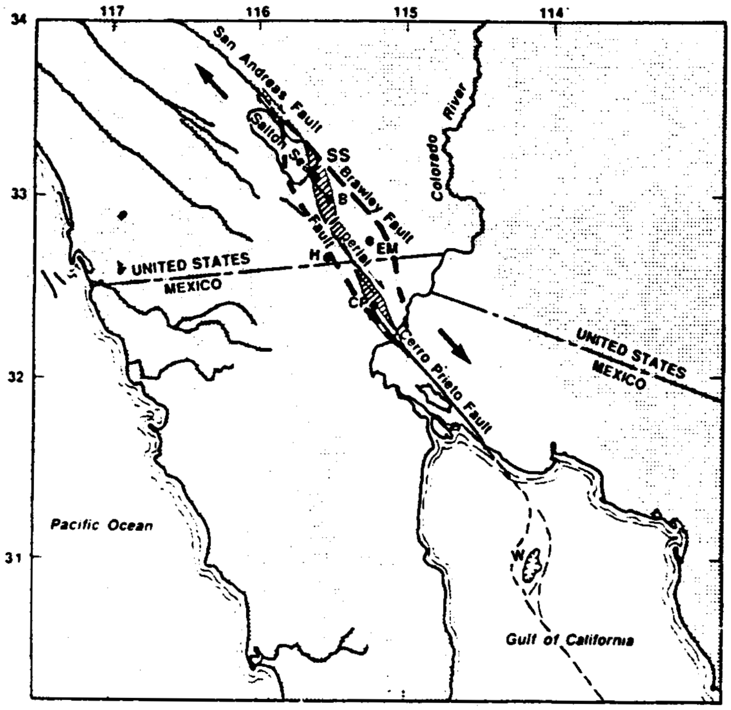


Fig. 7 Three scales of deformation in the Salton Trough (Lachenbruch et al. 1985). Dots represent the thermal zones in which spreading is perceived to take place in zones less than 10 km wide (Elders et al. 1972). Dark regions in the center of the valley represent modern intense seismicity zones, approximately 30 km across (Fuis et al. 1984). The broad region outlined by the dotted lines represents a diffuse zone of basin wide extension (Lachenbruch et al. 1985). What is the relationship between these three scales of deformation?

The heat flow data suggest that the localized areas are of limited importance. Figure 8 shows a histogram of the heat-flow values averaged over 5 km x 5 km regions used by Lachenbruch et al. (1985) in a tectonic model for crustal rifting in the Salton Trough. Ten percent of the zones are geothermal fields with anomalously high heat flow, but they contribute only 25% of the total heat flow out of the valley. Perhaps they contribute only a relatively insignificant amount to the rifting processes as well.

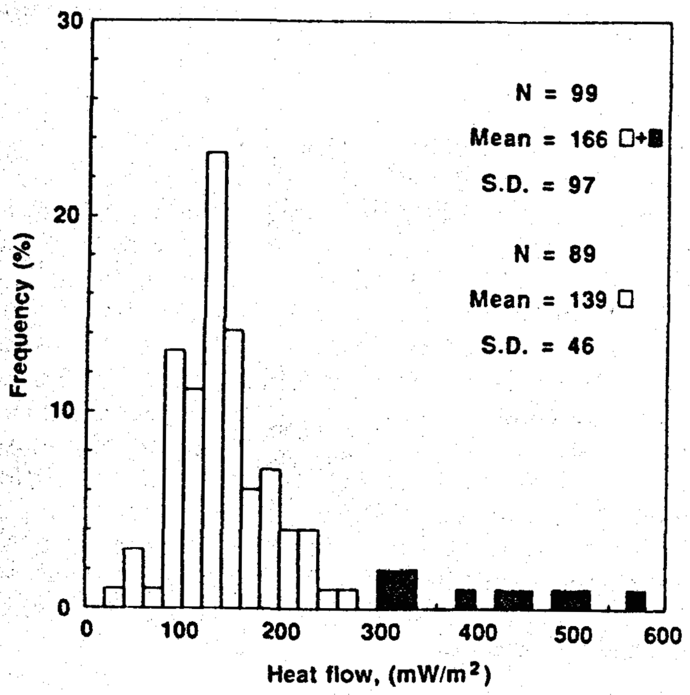


Fig. 8 Distribution of average heat flows from 3 arc min x 3 arc min regions in the Imperial Valley, Salton Trough. Statistics for N = 99 include all values; statistics for N = 89 exclude regions with mean heat flows ≥300 mW/m^{-2} (dark). (Figure from Lachenbruch et al. 1985.)

Alternatively, to assert that the local zones are indeed the locus of all the spreading at this time, we need to assume that there is no anomalous heat transport into the other areas throughout the Trough, which must be cooling off. To maintain the observed average rate of heat influx, which is required to keep the Salton Trough near sea level (Lachenbruch et al. 1985), the heat input rate to the hydrothermal systems must be larger than the heat flow out, by a factor of four or more. Thus, by examining the ratio of heat flux out to heat accumulation rate, we can test whether it is possible that all the spreading takes place at these zones.

Drilling Program Objectives

The total area and heat flux coming from the Salton Sea Geothermal Field (SSGF), the thickness of the circulating zone, and the abruptness of the transition from high to low gradients are the principal data constraining the rate of heat flux into the field. Our previous studies of the SSGF led to the development of a simple conceptual model of the flow in the sampled portions of the field (Kasameyer et al. 1984). Horizontal flow outward from a heat source located near the volcanic domes produces thermal fields that match the observations in the field. Several factors were unknown when we published the model. Most notably, thermal gradients were measured only in part of the anomaly, and none of the high heat-flow contours were closed (Fig. 9).

The objectives of the drilling program were to remove this uncertainty by completing the surficial coverage of the thermal anomaly offshore in the region north of the line of exposed volcanoes thought to represent the center of thermal anomaly. Previous drilling in the field had revealed the presence of a relatively thick thermal conductive cap, indicating that shallow temperature measurements could be used to constrain the boundaries of the thermal anomaly.

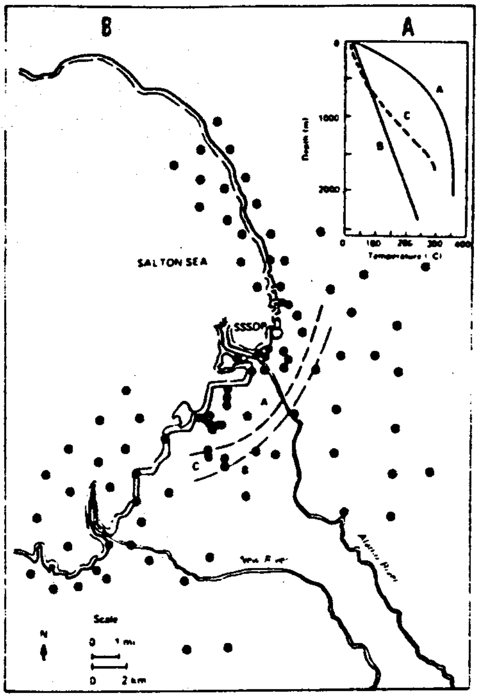


Fig. 9 Characteristics of the geothermal anomaly. Closed circles indicate the locations of existing data points, including both deep wells (300 m or 1000 ft.), shallow holes (40–100 m or 120–250 ft.), and short (10 m or 30 ft.) probe measurements. (a) Temperature profiles from the central part of the field (A), the transition region (C), and the outer region (B). (b) Interpreted regions within the Salton Sea Geothermal Field [after Younker et al. 1982]. Central part of the field (A) is characterized by relatively low heat flow. The narrow transition region between A and B is characterized by relatively low heat flow near the surface, but the gradient increases with depth. Note the absence of data in the region offshore from the high temperature anomaly.

Research Drilling Results

Thermal measurements were obtained in 18 shallow (76.2 m) depth holes located offshore along the southern margin of the Salton Sea in the Imperial Valley, California (Newmark et al. 1987). These data complete the surficial coverage of the thermal anomaly, revealing the shape and lateral extent of the hydrothermal system (Fig. 10). The thermal data show the region of high thermal gradients to extend only a short distance offshore to the north of the Quaternary volcanic domes which are exposed along the southern shore of the Salton Sea. The thermal anomaly has an arcuate shape, about 4 km wide and 12 km long. The transition zone between locations exhibiting high thermal gradients and those exhibiting regional thermal gradients is quite narrow. Thermal gradients rise from near regional (0.09°C/m) to extreme (0.85°C/m) in only 2.4 km (1.5 miles). The heat flow in the central part of the anomaly is >600mW/m^2 and in some areas exceeds 1200mW/m^2. The shape of the thermal anomaly is asymmetric with respect to the line of volcanoes previously thought to represent the center of the field, with its center line offset south of the volcanic buttes.

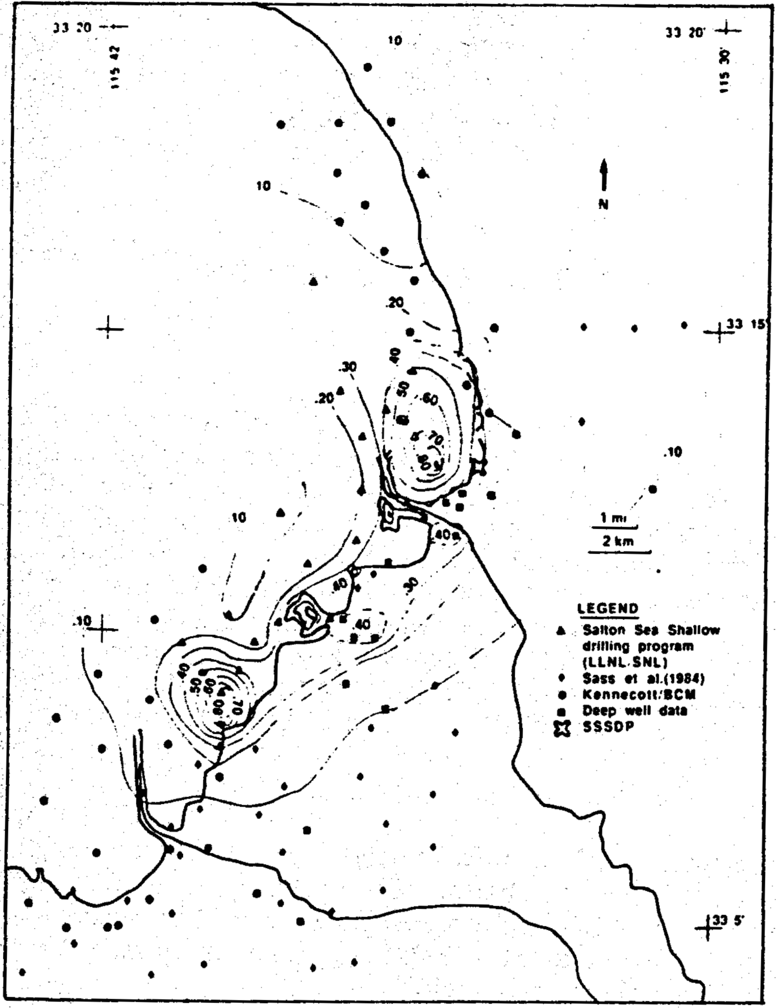


Fig. 10 Heat flow map for the Salton Sea Geothermal Field. Recent subsea shallow drilling program provided data to close the high heat flow contours to the northwest of the volcanic buttes.

Interpretation of the Drilling Results

The shallow drilling results have bounded the thermal anomaly to the northwest. Superimposed on the main thermal anomaly are two small ($\geq$2 km across) shallow zones of extreme heat flux, thermal "bullseyes." Comparison of the shape and area of the main thermal anomaly with other features presumably related to the heat source and flow pathways, including geophysical anomalies and surface manifestations, provides support for a conceptual model for the hydrothermal system. In that model the northwest boundary of the thermal anomaly and the arcuate pattern of the buttes mark the location of hot upwelling fluids. These hot fluids are channelized to the southeast by horizontal flow in a reservoir beneath an impermeable cap.

Kasameyer et al.'s (1984) simple lateral flow model calculates temperature gradient profiles for comparison with observations in the field. Field observations help constrain values of various parameters relating the ratio of the heat influx, the heat capacity, and the age of the system. To fit the observations from the Salton Sea geothermal area, the ratio of heat flux into the system by advection to the rate of heat flux from the top of the system by conduction is somewhere between 2.8 and 10. Since the average heat flow in the area is about 3 times normal, these values correspond to between 6 and 24 times "normal" heat flow. The geothermal systems in the Imperial Valley account for about 1/10 the total area (Lachenbruch et al. 1985). If the predictions of this model are valid, and if other local hot spots are growing as rapidly as the Salton Sea Geothermal Field, then these small, ephemeral geothermal systems may account for the total heat flux from the entire Salton Trough.

CONTINENTAL SCIENTIFIC DRILLING IN CRUSTAL THERMAL REGIMES

Discussion

Drilling provides access to the interior of the continental crust, allowing the direct observation of active processes and the collection of relatively undisturbed samples of the materials resulting from these processes. Unfortunately the drill hole is myopic and these observations and samples are valuable only if they can be viewed in context and provide insights into more general applications. Continental drilling, if it is to be successful and financially justified, must provide unique data, and those data must provide insights into models of major crustal processes. In this report we reviewed the results of two shallow research drilling programs focused on major processes associated with crustal magma/hydrothermal systems. Specifically the drilling programs addressed these questions: (1) What factors control the behavior of silicic magma as it intrudes the upper crust? (2) What is the relationship between individual localized hydrothermal systems and the regional crustal rifting process in the Salton Trough, southern California?

In both cases the drilling programs supplied unique information directly relevant to these issues. At Inyo Domes, for the first time we have samples linking recent surface magmatic activity with the subsurface plumbing system responsible for that activity. At the Salton Sea, we have defined the shape and lateral extent of an important thermal anomaly by drilling in a relatively inaccessible subsea region.

In both cases the results from these drilling projects have been applied to processes of broad-scale interest in continental crustal evolution. At Inyo, the results have demonstrated that shallow dike emplacement is directly related to dome extrusion and phreatic activity, delineated chemically tagged flow paths in the extrusive/intrusive system, documented the excavation of a vent funnel prior to extrusion, and demonstrated the contrasting crystallization behavior of extruded and shallowly intruded magma. These observations provide support for a general model for the development of dike-fed eruptive centers based on structural studies of eroded fossil systems. They also indicate that ascending magmas are chemically open systems and that the decompression path rather than cooling path dominates the crystallization behavior of magma. One of the conclusions reached in interpretation of the results is that silicic magma ascends as permeable foam and that the extent of degassing and, hence, eruptive behavior depends strongly on the permeability of the intruded environment.

At the Salton Sea, the drilling results indicate that the anomaly has an arcuate shape, not circular as previously thought, and it extends only a short distance offshore. The transition from high to regional heat flow occurs over a very narrow zone. Thermal budgets based on these constraints indicate that the heat influx rate for these geothermal anomalies could be large enough to account for the rate of heat flux from the entire Salton Trough. A model in which extension occurs in small ephemeral zones throughout the Trough may reconcile crustal rifting models based on observations at diverse scales.

The results of these two modest shallow drilling programs have provided some general lessons for research drilling in crustal thermal regimes. First, the scientific frontier in crustal thermal regimes is relatively shallow in depth. With regard to magmatic processes, it is clear that large changes in the composition and physical properties of magmas occur in the last kilometer of ascent to surface. Drilling at Inyo in this depth range (<1 km) has provided insight into these important magmatic changes and processes. With regard to hydrothermal systems, it is clear that shallow fluid transport substantially affects the nature of crustal thermal anomalies. Understanding this flow regime is essential for drawing inferences about the deeper heat sources, their location and character. Shallow drilling at the Salton Sea has helped to constrain these flow pathways and provided information necessary for estimating the thermal budget of that hydrothermal system. Because of the complexities of these systems, it is also clear that drilling programs must be based on testable hypothesis, that make specific predictions for the targeted region. These hypotheses themselves must be based on extensive site investigations, including geophysical surveys, field studies and prior drilling, if available. The drilling program at Inyo was in part based on the dike hypotheses (Pollard et al. 1984; Miller 1985) and models for the behavior of magmatic volatiles in the eruptive process. The drilling program at the Salton Sea was based on a conceptual and quantitative model for the Salton Sea system (Kasameyer et al. 1984).

A related observation is that in this initial stage of thermal regimes drilling, multiple holes are probably essential in order to remove fundamental ambiquities, and put the drilling results into context. Temperature will always be a prime observation in any thermal regimes drilling program, and yet isolated observations provided by single boreholes are likely to be uninterpretable due to the possibility of complex flow patterns. At both Inyo and the Salton Sea we have had the advantage of multiple shallow probes into the system, and these shallow measurements should provide the context in which deeper observations can be interpreted.

In spite of the fact that the drilling programs were very modest extensions into previously well characterized systems, the results, in both cases, were quite surprising. At Inyo, the position of the intrusion was accurately foreseen from the surface geology, corroborating the dike model. Many of the details of the physical and chemical features of the intrusions could, however, not have been predicted. These include the extreme chemical variation found in the conduit, the scarcity of glass in the intrusion, and the contrasting bubble contents of the proximal and distal section of the dome. At the Salton Sea the value of shallow temperature measurements in the conductive cap were corroborated, but the distribution of the thermal anomaly around the volcanic buttes was a surprise. These unexpected results support the contention that Continental Scientific drilling is providing new and valuable information for unravelling the major processes involved in the evolution of crustal thermal regimes.

While the scientific frontier in crustal thermal regimes is currently quite shallow, it is evident that scientific rationale and target definition will soon follow for deep drilling. At both Inyo and the Salton Sea arguments have been, and will continue to be, developed for deep drilling into the roots of these systems. Scientific curiosity and justification will soon exceed the technological ability to investigate the deep high temperature roots of crustal thermal regimes. A parallel research effort needs to be undertaken directed at improving high temperature drilling, logging and sampling capabilities in order to ensure that Continental Scientific Drilling in crustal thermal regimes realizes its full potential.

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