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RESEARCH DRILLING IN YOUNG SILICIC VOLCANOES *

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Abstract

Magmatic activity, and particularly silicic magmatic activity, is the fundamental process by which continental crust forms and evolves. The transport of magma from deep crustal reservoirs to the surface is a neglected but important aspect of magmatic phenomena. It encompasses problems of eruptive behavior, hydrothermal circulation, and ore deposition, and must be understood in order to properly interpret deeper processes. Drilling provides a means for determining the relationship of shallow intrusive processes to eruption processes at young volcanoes where eruptions are best understood. Drilling also provides a means for directly observing the processes of heat and mass transfer by which recently emplaced intrusions approach equilibrium with their new environment. Drilling in the Inyo Chain, a 600-year-old chain of volcanic vents in California, has shown the close relationship of silicic eruption to shallow dike emplacement, the control of eruptive style by shallow porous-flow degassing, the origin of obsidian by welding, the development of igneous zonation by viscosity segregation, and the character and size of conduits in relation to well-understood magmatic and phreatic eruptions. Planned drilling at the site of the largest eruption of the century, in the Mt. Katmai region of Alaska,

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will test models for explosive eruptions, elucidate the process of vapor-transport of metals, and provide the first measurements of rates of cooling and chemical alteration in a relatively simple, non-composite igneous system.

Introduction

An understanding of the continents must begin with an understanding of how silicic igneous rocks, their characteristic ingredient, form. This has been a topic of igneous petrology for more than a century. Although much has been learned, basic concepts remain largely untested, and so much of what passes for knowledge could be seriously in error.

A magma system can be visualized as consisting of zones of melting in the upper mantle and deep crust, of accumulation, storage and evolution in reservoirs in the middle to upper crust, of transport in dikes and conduits in the upper crust, and of eruption on the surface. We do not know with confidence how magma segregates from its source, how it collects and evolves in reservoirs, how it changes during ascent to the surface, and how this subsurface behavior influences its eruption. There are a number of well-developed hypotheses concerning these processes. A proper course for research is to test them by direct observation in exemplary igneous systems. Direct observation, which can only be accomplished by drilling, is in progress in the shallow domain of magma transport and appears feasible in the deeper domain of magma storage and differentiation. It is the purpose of this paper to report on two projects of the U. S. Continental Scientific

Drilling Program, one completed and one planned (Fig. 1), that address problems of the magma transport regime.

Importance of drilling observations in the magma-transport regime

Although readily accessible to the drill, the shallow magmatic regime, in which episodic transport between long-lived reservoirs and the surface occurs, has been relatively neglected by science. This is perhaps due to the traditional subdivision of effort into the "volcanology" of surface deposits and the "petrology" of deep intrusions. But if our inferences as to conditions of crustal magma storage are correct, then it is here that magma is transformed during ascent from a thermodynamically stable, volatile-rich melt to a volatile-depleted, super-cooled foam (Eichelberger et al., 1986). It is also here that the highest flow rates in the magma system are attained (excepting expanded, vapor-continuous magma following fragmentation) and hence the greatest likelihood for dynamical effects such as segregation or redistribution of magmatic components (Carrigan and Eichelberger, 1989). Because of the changes that occur during transport, observation of volcanism may be an imperfect guide to understanding conditions and behavior of magma in the crust. Transport-induced changes must be understood in order to properly interpret deeper conditions. The shallow regime is also where the causes of explosive versus non-explosive eruption are to be sought and where contact between magma and aqueous fluid occurs. The latter gives rise to phreatic phenomena, hydrothermal circulation, amd migration and concentration of metals.

Drilling provides a number of critical observations, not obtainable through surface studies of young volcanic systems or of old exposed intrusive systems. First, it permits sampling of intrusive structures underlying young volcanoes, where the timing and character of eruptive events are best understood. In this way, the relationship between processes of intrusion and eruption can be established. Secondly, it permits sampling of the system before effects superimposed by subsequent igneous, tectonic, hydrothermal, and weathering processes cloud interpretation of the phenomena of interest. This is especially important for observation of volatiles in glasses, whose distribution holds a key to eruptive behavior but which are rapidly changed by hydration and alteration. Finally, in very young systems the rates of cooling and alteration can be measured and characteristics of these processes directly observed.

A difficulty with drilling observations is that, unlike cliff faces or road cuts, drilling provides a volumetrically limited sample. This requires selection of the simplest possible igneous systems for investigation so as to minimize ambiguities of interpretation that may arise. Such simplicity is to be found in single-event systems in contrast to the more common composite volcanoes, and where the wallrock is uniform and lithologically distinct from the target intrusion. An attribute of drilling is that the quality and continuity of samples obtained by continuous coring are greater than commonly provided by natural outcrop. As will be seen, drilling at young volcanoes has revealed features that would likely have been missed in natural exposures of comparable eroded systems.

Continuous coring is important in research drilling in volcanic systems because many of the features of interest are small and their locations imprecisely known from surface data. Slanted holes are advantageous because they increase the likelihood of intersecting the near-vertical targets and provide laterally extensive sections through them. However, in slanting a core hole inward toward the center of a volcano to intersect the underlying intrusion, it is necessary to allow for some droop in the hole's trajectory (Eichelberger et al., 1988).

Inyo Domes

The Inyo Domes volcanic chain (Fig. 1 and 2) of eastern California was chosen for study because it represents the youngest rhyolitic system in the coterminous United States, and because its simple linear geometry and relatively simple eruption history suggested the likelihood that its source intrusion could be intersected and readily interpreted. The surface features of the chain had been thoroughly studied (Miller, 1985), and a hypothesis had been developed for the subsurface structure. It was believed that the 600-year-old vents were fed from a shallowly emplaced dike (Miller, 1983, 1985; Fink and Pollard, 1983; Fink, 1985), and that the phreatic character of the southern eruptive vents reflected the encounter of that portion of the dike with the thick, wet fill of Long Valley Caldera. In contrast, the portion of the dike outside this large Quaternary rhyolite caldera passed through Sierra Nevada granitic basement to within a few hundred meters of the surface, and phreatic activity was subordinate to magmatic eruptions. Four core holes totaling 2.4 km were drilled

(Fig. 2-4). Three penetrated extrusive and intrusive sections of the northern, magmatic portion of the system outside the caldera. The fourth penetrated the feeder of the largest of the phreatic vents within the caldera.

System geometry

The most basic result of the drilling was to provide constraints on the subsurface geometry of the system (Fig. 3 and 4). Such information is critical to modeling eruption and cooling, because it determines mass and heat diffusion path lengths and the dynamics of magmatic flow. The form of intrusions, whether dike-like or finger-like, indicates whether magma rises by fracture propagation or by some combination of stoping and explosive excavation. Prior to drilling, estimates of the size of the conduit of Obsidian Dome ranged through two orders of magnitude. Because of this large uncertainty in the size of the Inyo intrusion and suggestive evidence that current hydrothermal activity in the caldera was new, it was believed possible that the intrusion remained a significant heat source (Blackwell, 1985). Based upon interpretation of the surface deformation (Fink and Pollard, 1983), it was expected that the dike reached within a few hundred meters of the surface between vents, but other viewpoints existed.

Drilling verified the existence of a dike at shallow depth between vents in the northern portion of the chain. Further, the intersected intrusion was found to chemically match a portion of the early-erupted tephra and not the later domes, suggesting that the dike was emplaced early in the eruption sequence (Vogel et al., 1987, 1989). This lends support to the model of Pollard et al. (1983) that magma reaches the near surface as a dike and that conduits develop with time as flow becomes channelized.

Although a close relationship between a shallow dike and rhyolite dome was demonstrated, the expected relationship between surface extension and size of the dike (Fink and Pollard, 1983; Mastin, 1988) was not verified. Outside the caldera where the dike was intersected, its position is marked by tight linear alignment and elongation of vents. Inside the caldera, there is both alignment of vents and spectacular open fractures of similar trend, with an estimated total extension of 40 m (Mastin, 1988). It was therefore expected that the dike was thicker where extension was evident, at least as thick as the surface extension. Instead, drilling beneath the largest of the phreatic craters in the region of greatest extension encountered no intact dike at 600 m depth where the slanted hole crossed the chain trend. At this position, the hole encountered a 17-m-wide breccia pipe, the feeder for the phreatic eruption, with a juvenile component (Fig. 5) that could amount to only a few meters in equivalent width (Eichelberger et al., 1988). The remainder of the pipe is locally derived wallrock. This result suggests that surface deformation, although common to silicic vent chains, is not a simple predicter of subsurface intrusions. In the Inyo case the deformation may reflect slumping over or motion on a buried caldera ring fault. The core hole in combination with a commercially drilled geothermal well (Suemnicht and Varga, 1988) closely constrained the location of the fault as lying beneath the vent chain and determined its displacement to be 900 m. The drilling observations generally support, but do not prove, the concept that the wet caldera environment favored phreatic activity. Influx of water to the rising magma may have occurred in a till encountered at 750 m below the crater (Fig. 4). In any case, the magma both vesiculated and fragmented below the depth of observation of the breccia pipe, 600 m.

Degassing

Non-explosive eruptions of rhyolite lava generally follow explosive eruptions of tephra, a sequence that can be interpreted as reflecting sequential withdrawal of a volatile-rich cap and deeper volatile-poor magma from a zoned reservoir (e.g., Fink, 1983). On the other hand, geochemical estimates of intial volatile contents of lavas are as high as for associated tephras, and volatile contents required to avoid explosive fragmentation of magma to tephra seem implausibly low for rhyolitic magmas (Eichelberger, 1989). If so, dome lavas must be degassed. One of the goals of Inyo drilling was to discover through observation of retained volatiles and bubbles (vesicles) with depth whether the rising magma had behaved as an open or closed system with respect to volatiles. This approach was possible because if degassing does occur during rise, it must occur substantially in the final few hundred meters of ascent in order to reach the very low water contents observed in domes (Taylor et al., 1983). Figures 5 and 6 depict some of the pertinent observations from Inyo drilling. It was found that only the distal portion of Obsidian Dome, is bubble-free (Fig. 5), that the dome is uniformly low in water content with a concentration approximating the one-atmosphere solubility value (Fig. 6), that vesicles occur in the intrusive feeder at the deepest levels of observation (Fig. 5), and that water contents at depth lie near the lithostatically controlled value (Fig. 6; Westrich et al., 1988). This clearly requires open-system behavior, and so the problem becomes that of suggesting how so much gas could escape the magma in the limited time available. That time was short. The system geometry revealed by drilling requires that if the dome emerged in the order of a month, then the magma rose the last 500 m in a few hours. Bubble migration in melt would be negligible in such a viscous system and would not explain the nearly complete degassing of the dome's interior. Measurement of gas permeability on core and surface samples of various porosities indicated that bubbles in the magma would have become interconnected when the growing bubbles reached about 60 vol.% of the system. It was therefore proposed that the dome magma degassed as a permeable foam by porous flow as it rose through the breccia-filled vent funnel (Fig. 3; Eichelberger et al., 1986)). The degassed foam then collapsed to obsidian as it flowed outward from the vent. A numerical model for porous-flow degassing indicates that rate of rise of magma, width of the rising magma column, and permeability of wallrock determine whether an event is explosive or non-explosive. Excavation of a vent funnel during the initial explosive phase may provide the necessary environment for shallow degassing without fragmentation and explain the typical eruptive sequence of explosive to effusive activity (Eichelberger et al., 1986).

Degassing apparently had a controlling effect on crystallization. Glass boundary zones on the flow are 10 m to 20 m thick, whereas those on the intrusion are 0 cm to 10 cm. It seems unlikely that this difference could be explained by faster cooling of the flow, which is the largest part of the system. Rather, it appears that the order-of-magnitude decrease of water concentration in melt between the ~500 m depth regime and the surface (Fig. 6) suppressed crystallization (Westrich et al., 1988; Swanson et al., 1989). The effect of decompression and attendant water loss is to decrease mass diffusivities in melt and raise the liquidus and solidus of the system, so that the lava is actually extruded below its solidus (Westrich et al., 1988). While much more remains to be learned about crystallization in this metastable system, it is clear that these observations imply a different view of glassy volcanic rocks from the conventional interpretation that they are simply quenched magma.

Chemical zonation

An unexpected discovery made by drilling was the symmetrical zonation of the Obsidian Dome conduit (Fig. 7) and matching zonation of the lava. The conduit is zoned from rhyolite to rhyodacite outward and the lava from rhyolite to rhyodacite downward. The zonation is quite subtle in terms of major elements, but concentrations of trace components vary by as much as a factor of four. The pattern of thin, relatively mafic margins enclosing a broad, uniform, silicic interior is known to be a common pattern of zoning of heterogeneous intrusions (Walker and Skelhorn, 1966). The usual interpretation is that the pattern results from sequential emplacement. The mafic component opens a dike and plates its walls, and silicic magma immediately follows the mafic intrusion's centerline. However, because drilling sampled both the eruptive and intrusive portions of the Obsidian Dome system, an important new constraint on timing is provided. The zoned intrusion clearly fed a single zoned lava dome that lacks internal discontinuities suggestive of a time break. More significantly, the basal breccia of the dome, which formed by avalanches sweeping off the advancing flow front, contains blocks of both rhyolite and rhyodacite. This requires that the two magma types were flowing simultaneously, not sequentially. Carrigan and Eichelberger (1989) noted that the zonal distribution of the two magmas minimizes viscous dissipation in the system, because the less viscous rhyodacitic magma is in the region of higher shear near the walls. Indeed, such an arrangement by segregation during flow of an initially heterogeneous system is expected based on both theory and experiment (Joseph et al., 1984).

This result has important implications for the interpretation of zonations in eruption products. Such zonations are often used to suggest the chemical stratigraphy of the source magma reservoir. The result from Obsidian Dome suggests that, at least in the small-volume case where aspect ratios of the transport regime are largest, zonations may be dominated by dynamical effects during shallow flow.

Chemical complexity

Diversity of magmas is often regarded as a product of protracted fractionation in large reservoirs. The chemical complexity of the small-volume Inyo system was recognized from surface samples (Sampson and Cameron, 1987) but the thorough sampling that drilling provided has made this complexity more evident. Vogel et al. (1987, 1989) have identified three to five distinct silicic components in the system. The observations require either fine-scale zoning of a single parent reservoir or simultaneous tapping of multiple pockets of magma in the post-caldera system.

Mechanism of intrusion

Drilling recovered intact samples of the finely brecciated contact zone of the Inyo dike (Fig. 5). Such delicate features would likely not survive exhumation. Fragments of dike material occur intimately intermixed with granite at least 0.4 m outside the intrusion. The fragments show plastic deformation and alignment parallel to the contact as if by flow. They thus provide support for high boundary temperatures and high driving forces for silicic dikes, recently argued on theoretical grounds by Carrigan and Schubert (1988 and in preparation).

Other topics

The core has been used to address problems of development of bubble textures (Manley and Fink, 1987; Fink and Manley, 1987) and crystal textures (Swanson et al., 1989). Intrusive tephras suggestive of substantial fluid overpressures at depth during intrusion were discovered (Heiken et al., 1988). The behavior of magmatic volatiles in addition to water has been explored (Higgins, 1988; Westrich et al., 1988). The sampling of the conduit and adjacent wallrock of a recent and perfectly preserved phreatic vent provided the basis for thorough investigation of the dynamics of phreatic eruption (Mastin, 1989).

Additional opportunities remain. Of special note are the evidence that the dike contact zone may hold of intrusion processes and that the vent breccia may provide of fragmentation.

Katmai

Although Inyo drilling provided a unique view of vent structures and a young intrusion, the system was found to have cooled entirely. A logical next step is to drill into an igneous system that is still cooling. This would permit measurement of the distribution of heat and mobile elements around and within an intrusion at a known point in time following emplacement, thereby determining the rates and mechanisms of cooling and alteration. In such an experiment, simplicity is even more important than it was in interpreting results at Inyo. One must be assured that temperature and chemical profiles result from the event of interest before they can be used to interpret the processes of heat and mass transport.

An ideal system for this line of study, that in addition to simplicity presents the attributes of great size and important ash-flow volcanism, is the vent that erupted in 1912 in the Mt. Katmai region of Alaska (Fig. 8). Fifteen cubic kilometers (pre-vesiculation volume) of rhyolitic to andesitic magma vented in 60 hours to produce extensive Plinian air-fall deposits, the Valley of Ten Thousand Smokes ash-flow sheet, and a lava dome (Hildreth, 1983). Vigorous high-temperature fumarolic activity that persisted for several years after the eruption produced notable concentrations of trace metals at the surface. This vigorous activity has ceased, but areas of the vent region remain warm.

The eruption was the largest of the century and the largest eruption of rhyolitic magma in 2000 years. What makes it exceptionally attractive for a drilling investigation, and indeed for surface geophysical investigations, of the subvolcanic regime is that magma rose through uniform basement at a site where little volcanic activity had occurred prior to 1912, and none has occurred since. Thus, the system provides a single, well-defined event whose structural, thermal, and chemical effects can be readily interpreted. Moreover, the collapse due to subsurface withdrawal of magma that normally accompanies eruptions of this magnitude occurred 10 km away on the crest of the Aleutian Range, leaving primary vent structures intact.

The vent is believed, on the basis of surface structure, analogy to other systems, lithic content of the ejecta, and gas dynamical considerations to be a flared funnel about 2 km in diameter and less than 1.5 km deep (Hildreth, 1983, 1987). It probably reached its full size during the early Plinian and ash-flow phase. Within this large structure are nested the vent for a second Plinian phase and the feeder of the lava dome.

There are three objectives of project (Eichelberger et al., 1988):

1. To test and improve physical and chemical models of silicic eruptions through three-dimensional investigation of a well-preserved ash-flow sheet/ vent system.
2. To determine the source, mechanism, and conditions of the fumarolic transport of metals that occurred following ash-flow emplacement by means of geochemical profiles through a system not yet degraded by weathering or alteration.

3. To establish the rates and mechanisms of ongoing cooling through measurement and interpretation of equilibrium temperature profiles and hydrothermal mineral assemblages in core holes within a simple system of known young age.

Achieving these goals requires sampling and temperature measurement in four regimes. The ash-flow sheet provides a record of changes in magma chemistry, vent excavation (through its lithic content), and eruptive style with time through much of the eruption. The composition-time information can be used to reconstruct the evolution of the vent by chemically matching vent units encountered at depth with their erupted equivalents. The sheet is also of interest because of the metals transport that occurred within it. The source zone, deposition zone, and mechanisms of release and transport can be investigated in the sheet, where involvement of meteoric fluids may have been significant, and compared with metals transport in the chimney-like vent, where magmatic fluids may have been dominant. The position and deformational characteristics of the vent wall, together with the volume and distribution of lithic fragments in the system, will constrain the size and shape of the vent and its mechanism of formation, whether by excavation or collapse or both. The vent wall should also contain the thermal front that has propagated outward into the cold basement since 1912, and contact metamorphic effects. Because the vent wall should provide a relatively cool and competent environment, it is an advantageous site for installing a downhole seismometer for listening for events deeper in the system such as high-temperature thermal cracking. The stratigraphy of the vent fill, when matched with the eruption record, will reveal the timing of development of the vent. The physical characteristics of the vent fill provide evidence of the dynamics of flow during explosive eruption. Intrusions within the vent and their relationship to the pyroclastic fill will constrain changes in fragmentation level with time and, by comparison with eruptive equivalents, the changes in magma that accompany fragmentation. They are likely to be the hottest part of the system.

Figure 9 shows the holes planned to penetrate these four environments. A shallow hole of about 200 m will provide a complete section through the ash-flow sheet. The hole will be slanted so as to intersect at multiple depths vertical fractures that carried metal-rich vapors, thereby describing the system of vapor transport. It is to be sited about 5 km from the vent, close enough for full development of welding zones and vapor transport, but far enough to eliminate "noise" in the stratigraphic record from small-scale explosive events. The other holes will be sited in the center of the vent. The first of these will provide a reliable water supply for subsequent drilling (much of the drilling will likely be in winter conditions, making use of surface water difficult) and provide information on subsurface conditions valuable for planning the deeper holes. The second vent hole will slant under Novarupta, the lava dome, and reach a total length of 1000 m. This hole should provide a complete stratigraphic section of the vent, as the vent is expected to have a concentric, inward-dipping stratigraphy, and sample the intrusive feeder of Novarupta and the vent wall. It will provide measurement of the size of the overall vent, the vent for the second Plinian phase nested within it, and the Novarupta feeder. The final hole will be vertical and is planned to reach 1200 m, near or below the base of the vent funnel and therefore within intact intrusive equivalents of the main explosive phases.

The drilling will be preceded by surface geophysical studies planned to begin in summer 1989. These will further define the vent, now known primarily through interpretation of surface fractures around Novarupta, and begin a project-long series of replicate magnetic, gravity, and geodetic measurements to detect changes related to continued cooling or renewed intrusion of magma.

This work is expected to provide an unprecedentedly complete test of widely accepted theories concerning explosive eruption, the first information on the distribution of metals in an essentially unweathered system where significant vapor transport has occurred, and the first information on the distribution of heat and the extent of hydrothermal alteration in a still-cooling non-composite system. The early surface explorations of Katmai beginning with the Griggs expeditions (Griggs, 1918,1922) have had a profound effect upon the evolution of modern concepts regarding explosive volcanism, ash-flow tuffs, calderas, magma chambers, ore deposits, and the chemical evolution of magmas. Results of exploration of the subsurface should be no less significant.

Future directions

The present results suggest some future directions, not all of which involve drilling. The likely presence of shallow dikes must be considered in inferring the subsurface structure and interpreting the surface deformation of silicic volcanoes. The results pertaining to degassing indicate that eruptive style should be investigated in relation to shallow geological characteristics, particularly wallrock permeability and feeder geometry, not just in relation to magma chemistry. They also suggest the need for further experimental exploration of bubble growth and collapse and crystal growth at low water contents for proper understanding of volcanic textures. The chemical and mineralogical differences and similarities between associated lavas and tephras merit closer study. The zonation of intrusions and eruptive sequences should be reexamined to assess the extent to which these may result from segregation by viscosity during transport, rather than solely reflecting stratigraphy of the source reservoir.

In terms of drilling, much can be learned in the upper 1-2 km by extending this type of investigation to different kinds of igneous systems and, as technology and volcanic opportunity permit, to younger and hotter systems. The greatest foreseeable future achievement, however, will be to penetrate, quench, and sample melt at depth. Such an achievement would test geophysical inference of the location of magma reservoirs and geochemical inference of their conditions and volatile content, upon which many existing concepts of igneous processes are based. Further, the boundary zone of crustal magma reservoirs has assumed an almost magical role in current thought. Gradients that arise in temperature, composition, and melt/crystal content at this boundary are believed to produce counterbouyant flows that ultimately result in differentiation and stratification of silicic magmas (e.g., Shaw, 1974; McBirney et al., 1985; Nilson et al., 1985). Because such boundaries do not survive crystallization in the plutonic environment and subsequent exhumation and are apparently not sampled by eruptions, models relying on boundary-layer processes can only be tested by drilling. This may, indeed, be possible. An exploratory hole designed to penetrate the near-magmatic environment beneath Long Valley Caldera will be spudded this summer (Rundle and Eichelberger, 1989). If this 6 km hole does confirm the existence of magma beneath the center of the caldera and encounters an environment sufficiently benign for deeper drilling, a subsequent hole may succeed in sampling the boundary zone of a large crustal magma chamber.

<u>Summary</u>

In view of the extensive work that has been conducted in understanding volcanic systems, it is easy to accept that problems of magma emplacement, fragmentation, degassing, crystallization, and cooling are well understood. Cartoons of the subvolcanic portions of eruptive systems seem believable, especially when based on sound consideration of gas dynamics and mechanical deformation theory. Similarly, the thermal domains that are generated following emplacement of a molten intrusion are readily postulated from knowledge of the properties of typical rocks and hydrothermal fluids and application of heat-flow theory. It is likely, however, that many of these concepts, while sophisticated in approach, are primitive descriptions of natural systems. Yet, we will not progress beyond a cartoon-like understanding of volcanism without the examination of young intact volcanic systems by drilling. Given the composite nature of most such systems, it is imperative that early investigations probe the simplest possible cases of important styles of igneous activity. Drilling at Inyo Domes has provided new information on how magma intrudes and erupts, and how igneous textures and zonations develop. Drilling at Katmai will add observations of a still-cooling system of great size and with important ash-flow volcanism. Future drilling holds the hope of directly sampling crustal magma.

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Figure captions

Figure 1: Oblique aerial views of the drill sites discussed in this paper: (a) Westward view of the 600-year-old Obsidian Dome volcano in the Inyo Volcanic Chain of eastern California. The dome has a volume of 0.2 km^3 and is 2 km in north-south dimension (right to left). Three core holes penetrated portions of the dome distal and proximal to its vent, the underlying conduit, and an unvented portion of the feeder dike 1 km to the south of the dome's center. (b) Northward view of the 600-year-old phreatic craters at the south end of the Inyo Volcanic Chain, within Long Valley Caldera. South Inyo Crater, in the foreground, is 200 m in diameter. A core hole was drilled on a slanted trajectory from west to east (left to right) beneath this crater and intersected its feeder breccia pipe at a depth of 600 m. (c) Southeastward view across the 1912 vent for the Valley of Ten Thousand Smokes eruption in the Mt. Katmai region of the Alaska Peninsula. The steaming 400-m-diameter Novarupta lava dome is surrounded by a tephra ring, formed late in the eruption, which is in turn encompassed by the rim of the 1912 vent, the low cliff band in the middle background. On the skyline are the summits of Trident Volcano. The vent, which is believed to be funnel

shaped, its contained intrusions and its wall will be sampled by vertical and radially outward slanted core holes sited at the northeast (left) edge of the dome.

Figure 2: Map showing major geologic features of the portion of the Inyo Volcanic Chain that was active 600 years ago and environs. The densely shaded portions of the lava domes mark their elevated vent regions. The area of Long Valley Caldera shown is part of the west moat, a low region between the west rim and resurgent dome. Locations of the Inyo research holes are numbered in the order drilled. Precaldera rocks are Sierran granitic intrusives and metamorphic roof pendants, with subordinate Tertiary lavas.

Figure 3: Block diagram showing results from coring the 600-year-old extrusive/intrusive system at Obsidian Dome. Holes are numbered as in Figure 2. Note that the slanted holes followed a drooping trajectory. Finely stippled regions are cross sections of the lava dome and its conduit, in planes containing Inyo holes 1 and 2. The coarsely stippled region is vent breccia, within the interpreted vent funnel and intruded by the dome conduit. The feeder dike, as intersected by Inyo hole 3 and as interpreted to connect with the conduit, is shown as a heavy line (width to scale) and vertically ruled pattern. The dotted curves are the dome margin removed in this cutaway view. Tv and Jg refer to Tertiary volcanic (basalt flows and cinders) and Jurassic granitic rocks of the Sierra batholith, respectively.

Figure 4: Path of Inyo hole 4 beneath South Inyo Crater with generalized stratigraphy and interpreted breccia structure. Inset shows the path of the hole in plan view with heavy bars where the breccia zones were intersected.

Figure 5: Photomicrographs of selected features in Inyo cores (bars show scale): (a) Contact between Inyo dike (upper half of image) and comminuted granitic wallrock at 650.2 m depth (hole length = 715.6 m), from Inyo hole 3. The comminuted zone contains admixed glass shards (lower portion and center of image) from the dike, aligned parallel to the contact. (b) Detail of contact glass at 650.2 m depth showing bubble-rich texture. (c) Detail of glass in lava dome at 12.8 m depth (Inyo hole 1) showing bubble-free (but microlite-rich) texture. (d) Highly inflated juvenile rhyolite pumice clast from breccia pipe beneath South Inyo Crater at 592.8 m depth (hole length = 639.0 m in Inyo hole 4).

Figure 6: Bulk water content of glass as a function of depth in the Obsidian Dome system. Analytical precision (2esd) is shown by error bars. Water solubility in melt as a function of depth is also shown (solid curve) assuming that overburden density is 2000 and 2500 kg/m^3 for depths <60 and >280 m, respectively (after Westrich et al., 1988).

Figure 7: Chemical profiles across the conduit of Obsidian Dome. Inset shows location.

Figure 8: Map of the Valley of Ten Thousand Smokes, showing locations of the ash-flow sheet, Novarupta and Katmai Calderas, and neighboring volcanoes. Abbreviations are as follows: Ba = Baked Mountain, Br = Broken Mountain, C = Mount Cerberus, F = Falling Mountain, N = Novarupta. Inset shows location (after Hildreth, 1983).

Figure 9: Schematic cross section on an approximately east-west line through the 1912 vent and ash-flow sheet, illustrating geologic objectives of the planned holes. The orientation of hole #4 will be chosen based upon results from surface geophysical work and from hole #3.

Figure 1

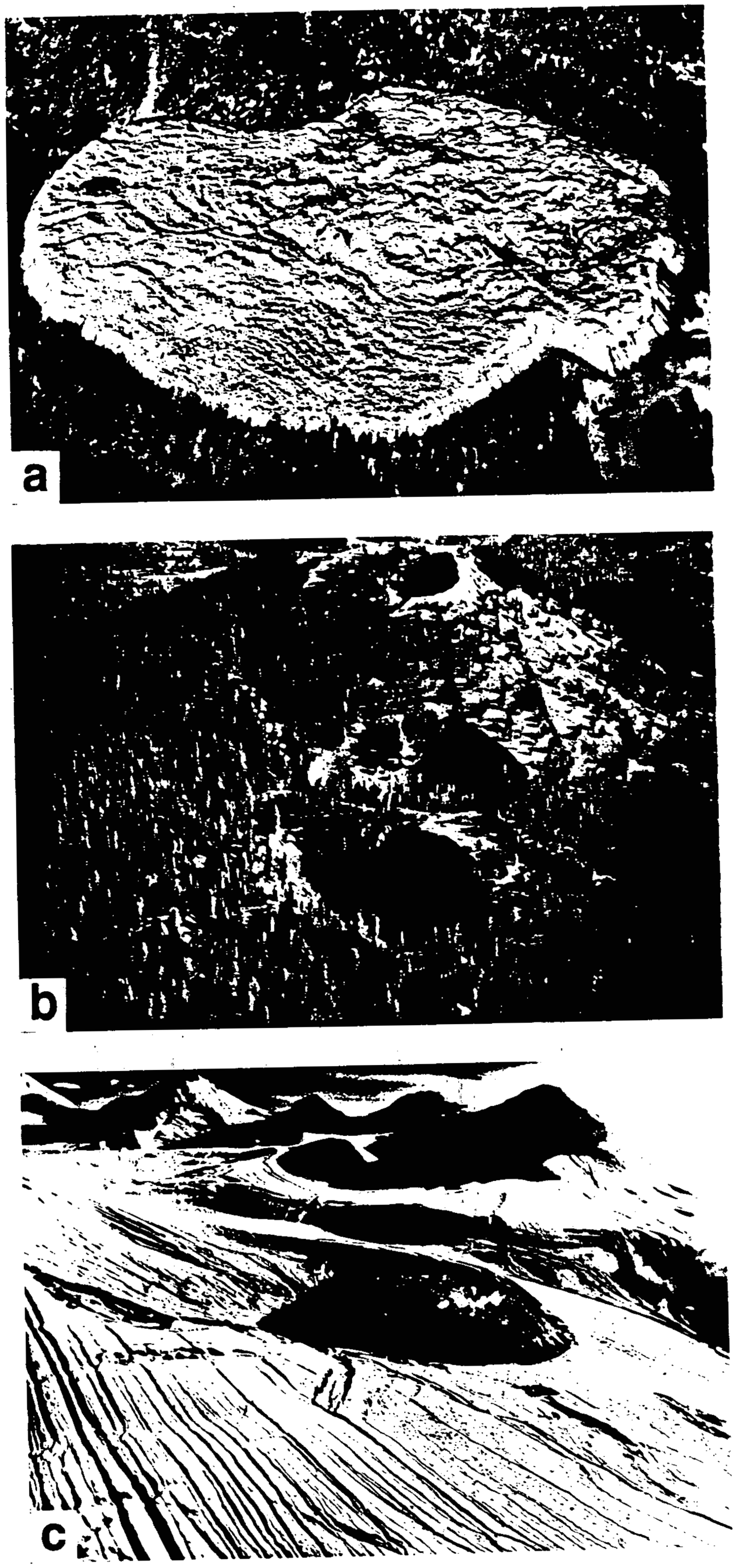


Figure 2

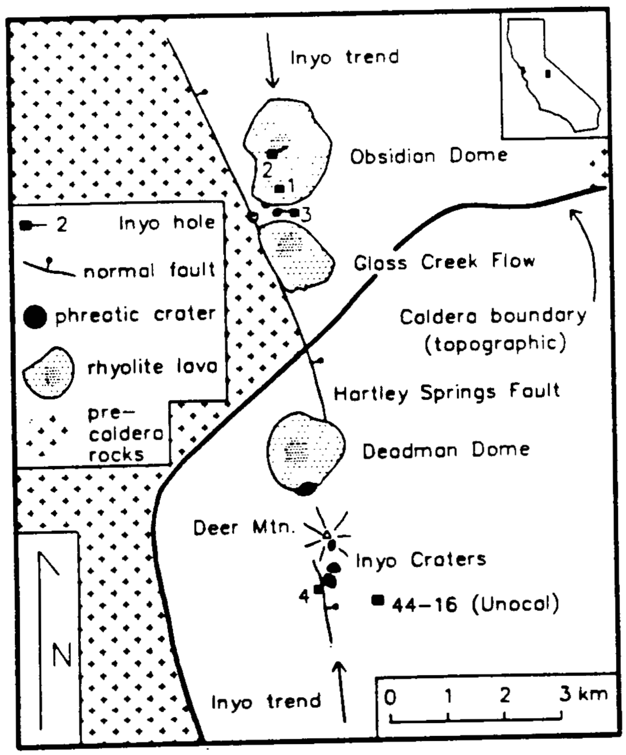

Inyo trend
Obsidian Dome
2
1
3
Inyo hole
normal fault
phreatic crater
rhyolite lava
pre-caldera rocks
Glass Creek Flow
Caldera boundary (topographic)
Hartley Springs Fault
Deadman Dome
Deer Mtn.
Inyo Craters
4
44-16 (Unocal)
N
Inyo trend
0 1 2 3 km

Figure 3

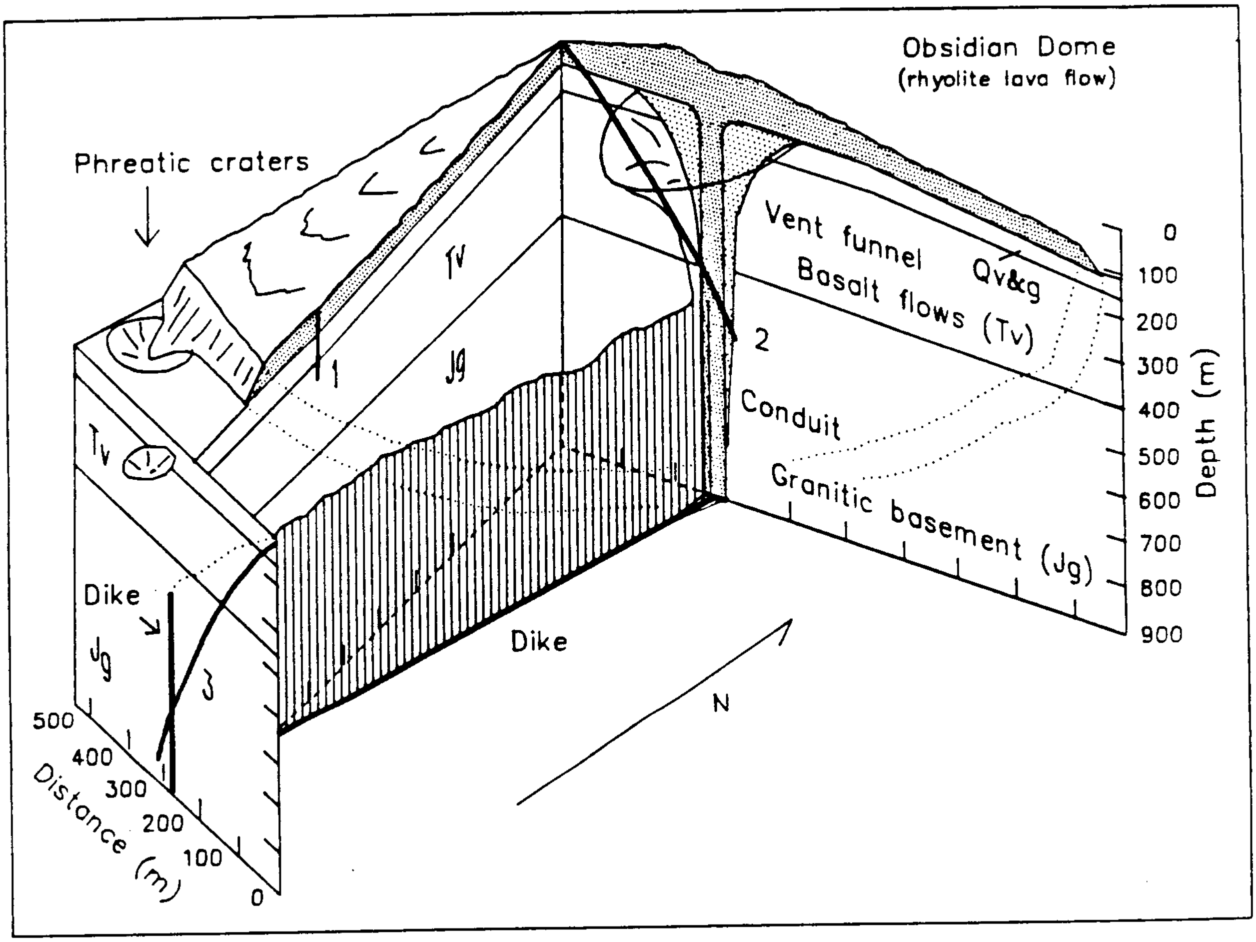
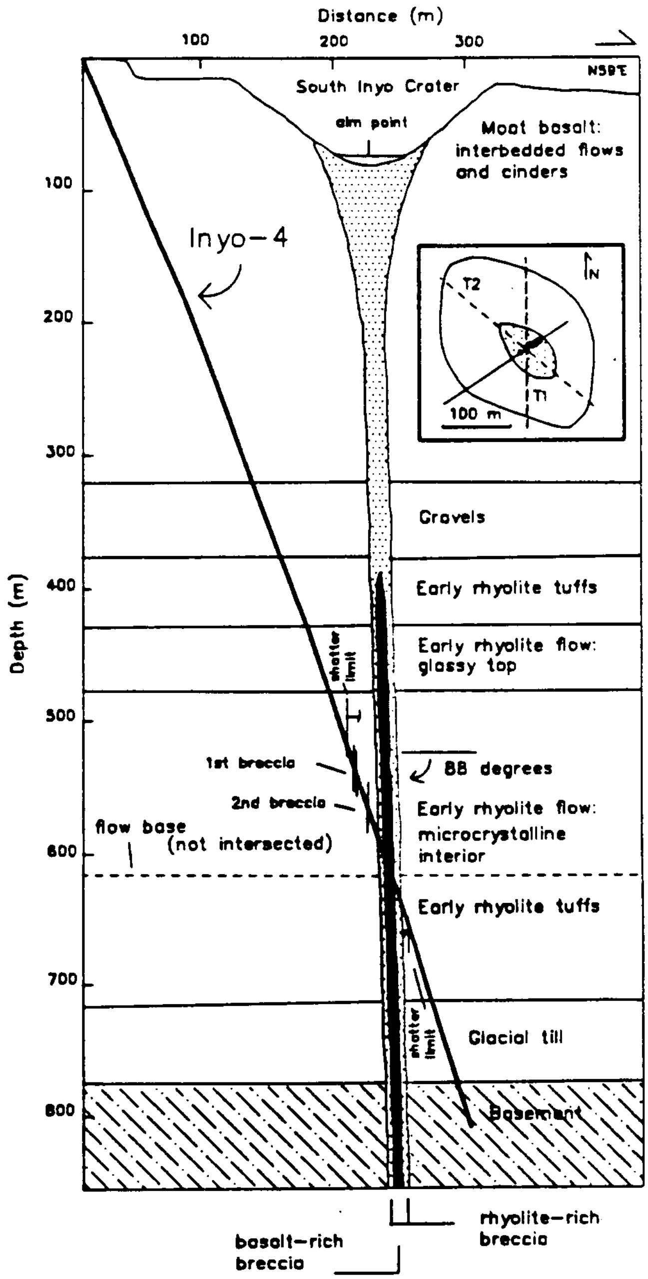

Obsidian Dome
(rhyolite lava flow)
Phreatic craters
Tv
Jg
1
2
3
Vent funnel
Qv&g
Basalt flows (Tv)
Conduit
Granitic basement (Jg)
Tv
Dike
Jg
Dike
N
0
100
200
300
400
500
600
700
800
900
Depth (m)
500
400
300
200
100
0
Distance (m)

Figure 4



Distance (m)
100
200
300
N59°E
South Inyo Crater
aim point
Moat basalt: interbedded flows and cinders
Inyo-4
T2
N
T1
100 m
Gravels
Early rhyolite tuffs
Early rhyolite flow: glassy top
shatter limit
1st breccia
2nd breccia
88 degrees
Early rhyolite flow: microcrystalline interior
flow base (not intersected)
Early rhyolite tuffs
shatter limit
Glacial till
Basement
Depth (m)
100
200
300
400
500
600
700
800
basalt-rich breccia
rhyolite-rich breccia

Figure 5

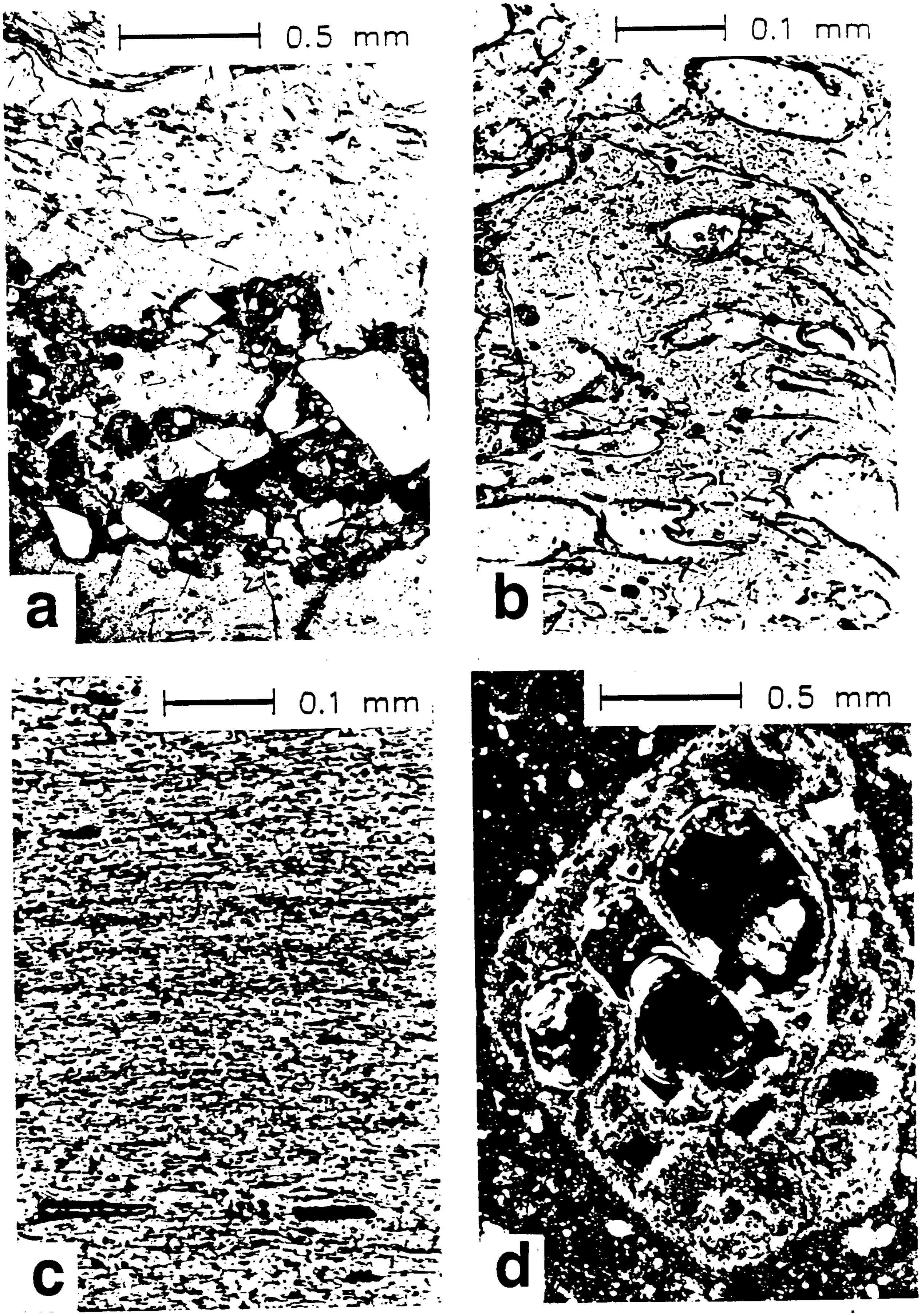
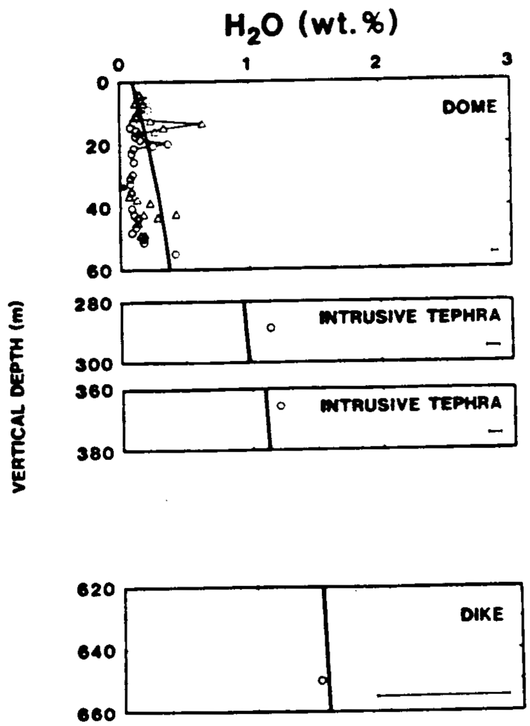


Figure 6



H2O (wt.%)
0
1
2
3
DOME
INTRUSIVE TEPHRA
INTRUSIVE TEPHRA
DIKE
VERTICAL DEPTH (m)
0
20
40
60
280
300
360
380
620
640
660

Figure 7

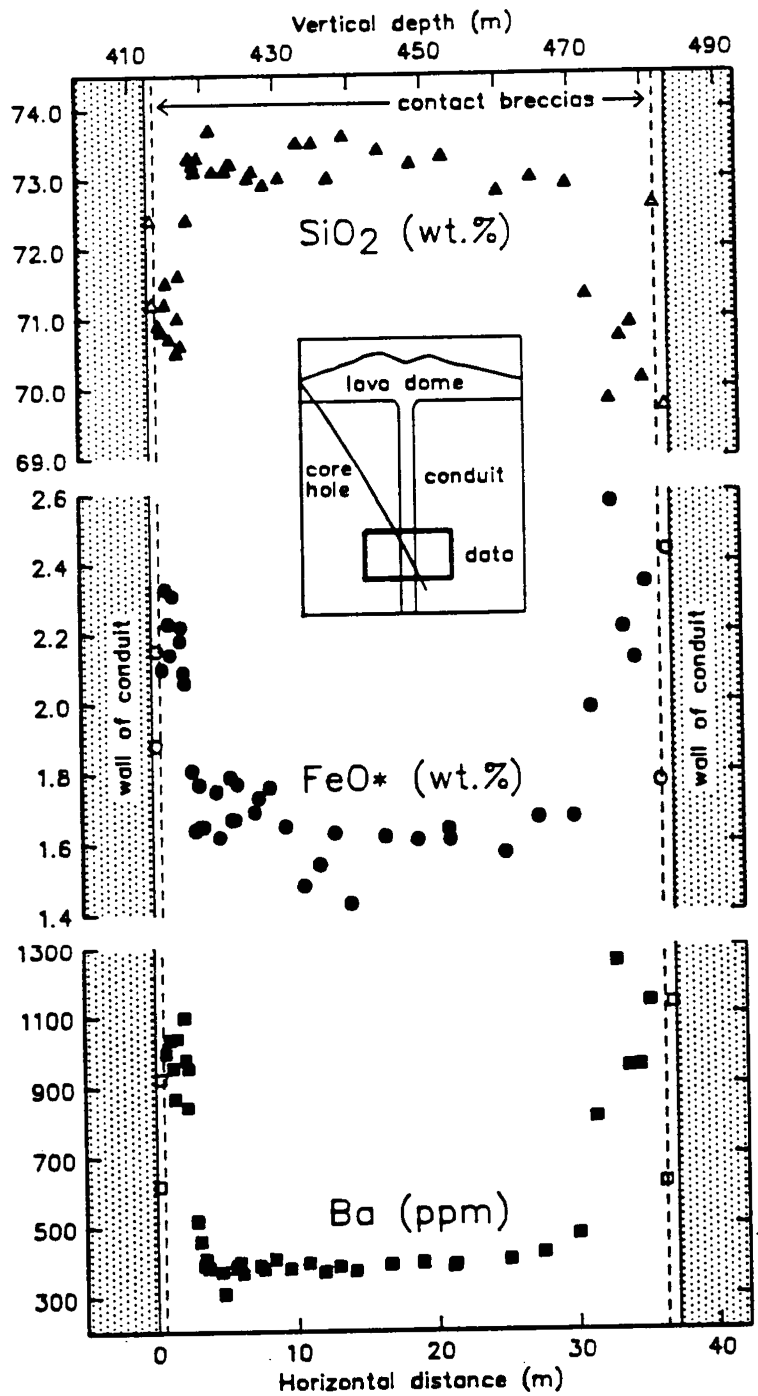
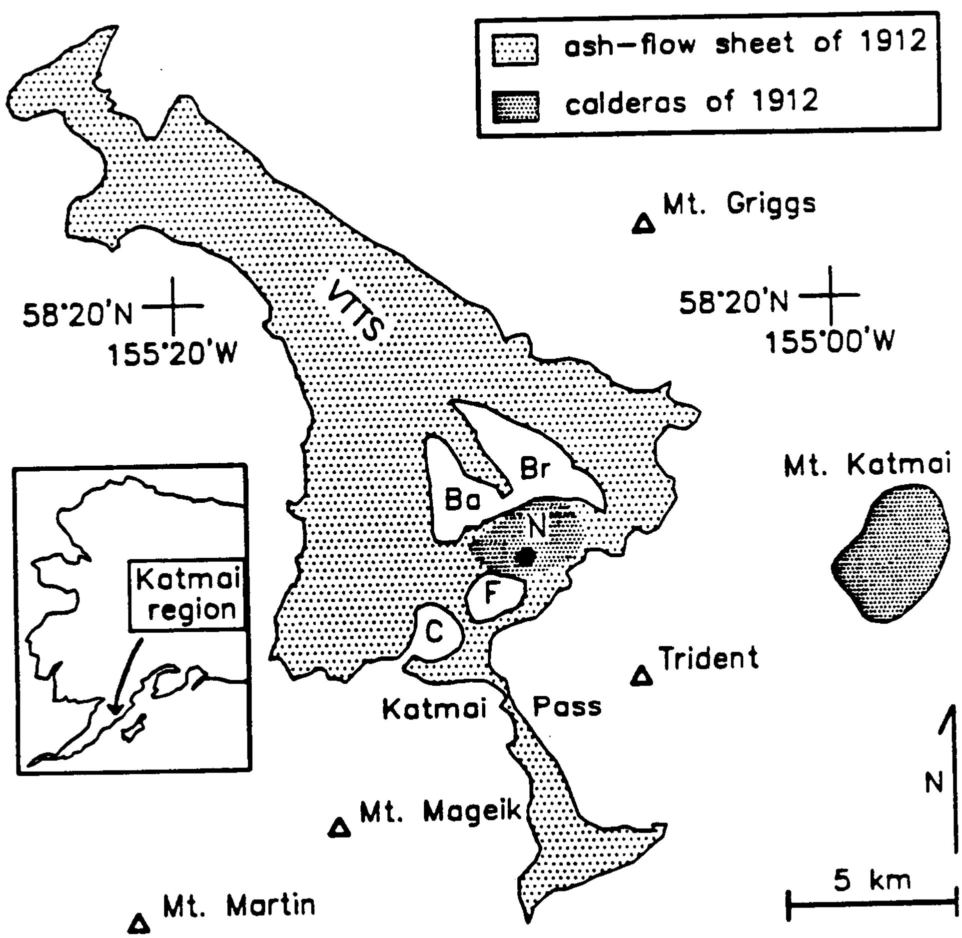
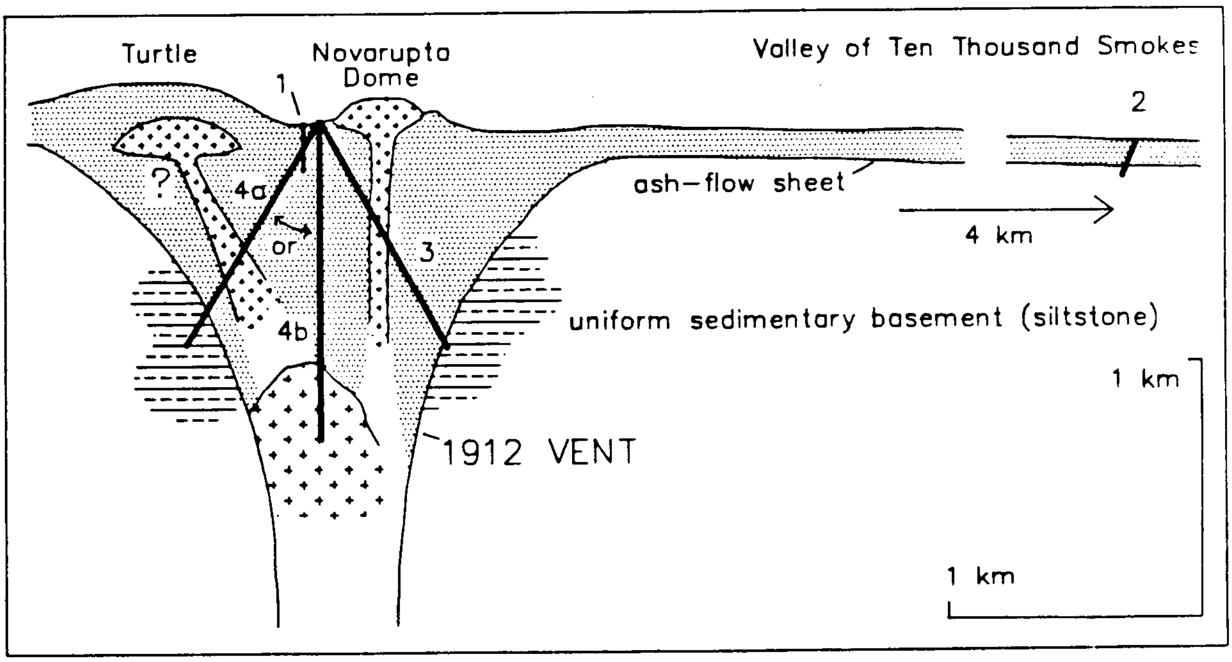

Vertical depth (m)
410
430
450
470
490
contact breccias
74.0
73.0
72.0
71.0
70.0
69.0
SiO2 (wt.%)
lava dome
core hole
conduit
data
2.6
2.4
2.2
2.0
1.8
1.6
1.4
FeO* (wt.%)
wall of conduit
wall of conduit
1300
1100
900
700
500
300
Ba (ppm)
0
10
20
30
40
Horizontal distance (m)

Figure 8



ash–flow sheet of 1912
calderas of 1912
Mt. Griggs
58°20'N
155°20'W
58°20'N
155°00'W
VTTS
Br
Ba
N
F
C
Mt. Katmai
Katmai
region
Trident
Katmai
Pass
Mt. Mageik
Mt. Martin
N
5 km

Figure 9



Turtle
Novarupta
Dome
Valley of Ten Thousand Smokes
1
2
?
4a
or
3
4b
ash–flow sheet
4 km
uniform sedimentary basement (siltstone)
1 km
1912 VENT
1 km