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DIRECT OBSERVATION OF A YOUNG IGNEOUS SYSTEM: A SCIENCE PLAN FOR RESEARCH DRILLING IN KATMAI NATIONAL PARK, ALASKA

NON-TECHNICAL VERSION*

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ABSTRACT

Volcanism is a process by which our planet continues to evolve. By taking samples and making measurements inside a simple, young volcano soon after its eruption, we can greatly improve our knowledge of how magma* behaves as it approaches the Earth's surface, and what changes it causes in the surrounding rocks of the Earth's crust. As part of the Continental Scientific Drilling Program (CSDP), we propose a program of core drilling and closely related research to investigate active volcanic processes at the site of the historically important 1912 eruption at Katmai, Alaska. Primary objectives of the project are to:

1) Test models for explosive eruptions through three-dimensional investigation of a well-preserved volcanic vent* and the ash-flow sheet* it produced.
2) Determine how metals contained in the magma were transported and concentrated by gases following the eruption, by obtaining geochemical profiles through the deposits, which are not yet degraded by weathering or alteration.*
3) Find out how fast and by what processes the igneous* rock is cooling through measurement and interpretation of temperature profiles within a simple system of known very young age.

Katmai is uniquely suited to achievement of these objectives because the 1912 activity was a single, well-described volcanic event in a simple, uniform geologic setting. Moreover, structures of the volcano have not been modified by the large-scale collapse that normally accompanies eruptions of this size.

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*A term defined in the glossary.

The proposed observations will provide the first view of early post-eruption conditions inside a major igneous system.

The motivation for this project is a basic scientific curiosity about how the planet works. Some of the results may find application elsewhere (only basic scientific research can be conducted in a National Park) in evaluating the hazards of explosive volcanoes, in finding and using ore deposits, in finding and using geothermal energy, and in predicting how sites of burial of radioactive waste would cool. This document is intended to present the scientific rationale and general plan for the proposed project to the non-technical audience. Specialized terms that could not be eliminated are starred at their first usage in the text and defined in a glossary at the end of this document. Those who wish a more technical presentation or information on budgets and scientific credentials of the project participants should consult the formal Science Plan, as submitted to the U.S. Government on July 26, 1988.

IMPORTANCE OF DRILLING INTO SILICIC*MAGMATIC*SYSTEMS

Volcanoes produce many different kinds of rocks, with a fairly wide range of compositions. Probably the most well-known are basalts*. They are dark in color and contain much iron, magnesium, and titanium. They form thin magmas that flow fairly easily. Most oceanic volcanoes produce basalts and those in Hawaii are examples. On the other hand, some volcanoes produce rocks that have little iron, magnesium, or titanium but much more silica, sodium, and potassium than basalts. This kind of rock, at the opposite end of the compositional range from basalt, is rhyolite*. It is usually light in color. Rhyloite magmas are very thick. Proceeding from basalt to rhyolite are the intermediate compositions andesite* and dacite*. Magmas of these compositions have intermediate properties. Silicic magmas, that is those of dacite to rhyolite composition tend to erupt explosively, such as at Mt. St. Helens, rather than flow down the sides of the volcano. This is apparently because gas is more abundant in them and cannot easily escape, as it can from basaltic liquids. Instead of being released gradually from the magma as it approaches the surface, it may be released suddenly. The magma is then shattered and sprayed into the air, to fall as volcanic ash* and pumice*. As a consequence, the rise of silicic magma toward the Earth's surface causes most of the Earth's explosive and hazardous volcanic activity. Because it ponds in large bodies or magma chambers in the upper crust, silicic magma sustains major hydrothermal* systems and, when crystallized as granite, imparts a continental (as opposed to oceanic) character to the crust. Silicic magmatism also results in the transport and concentration of economically important metals.

Although our understanding of silicic magmatism has relied heavily on geologists studying rocks exposed at the surface, there are two important limitations to such observations. First, details of the relationship between volcanic eruptions and the movement of magma underground, which are needed to develop a three-dimensional view of these systems, are poorly indicated by natural exposures. The best way to describe the course of eruptions is to study the deposits from very young eruptions, but information concerning the underground intrusions* that fed these uneroded systems is lacking. But at volcanoes whose intrusive roots have been well exposed by erosion the eruption records that lava flows and ash deposits provide are poor. Second, many of the processes that magmas undergo as they rise and cool cannot be studied by surface techniques. These processes include release of gas, solidification of the molten rock, and circulation of heated groundwater. Drilling provides the means to simultaneously examine both the surface and subsurface portions of an intact igneous system that hasn't changed since its formation. This will show how eruptions are related to intrusions. Drilling also provides a means of sampling materials and measuring conditions at known points in time following an eruption, as the system cools and is chemically altered. This will show how quickly igneous rocks cool and are altered.

While it is true that drilling provides only small samples and spatially limited measurements of very large systems, it is critically important that the samples and measurements can be <u>continuous</u> and can be taken from an <u>active</u> system. We have reached the stage in the investigation of igneous systems where models for intrusion, eruption, cooling, and alteration are well developed and widely accepted. They are, however, almost completely untested. Drilling, by providing continuous samples and measurements in an active system, can provide these tests.

It seems wise that early research drilling efforts be devoted to geologically simple volcanoes. The first step in interpreting drilling results is to identify the intrusion that fed a specific recent eruption, and to be able to assume that present underground temperature conditions reflect the effects of that eruption. But most volcanoes represent the accumulated effects of many similar eruptions, fed from many similar intrusions, over a long period of time. Interpretation of results in such systems would be a formidable task.

The approach of drilling into a simple, young volcanic system, unchanged by events after emplacement, follows that of recently completed drilling in the Inyo volcanic chain of eastern California (Eichelberger et al., 1985; Younker et al., 1988; Eichelberger et al., 1988). The site was chosen because it represents the youngest rhyolitic* activity in the contiguous (and therefore easily accessible) United States, because of its relative simplicity, and because a well-developed theory existed concerning its subsurface structure (Miller, 1985; Fink, 1983). Drilling yielded both confirmation and surprise. It confirmed the existence of a shallow feeder dike*, previously predicted from surface evidence, beneath the northern portion of the chain (Fig. 1 and 2; Eichelberger et al., 1985; Fink, 1985). But it showed that eruptions at the southern end resulted from an intrusion very different from that to the north (Figs. 3, 4 and 5; Eichelberger et al., 1988). Contrary to expectation, the intrusion was fragmented rather than intact and a few meters (yards) rather than tens of meters thick at the 600-m (2000-ft.) depth of sampling.

The project demonstrated that core holes carefully oriented on the basis of surface volcanic structures can intersect and sample the related below-ground rock units (Figs. 2 and 5), and in so doing can greatly expand understanding derived from surface observations. The Inyo system was, however, entirely cooled within the 0 to 700-m (0 to 2300-ft.)-depth interval

Figure 1: Oblique westward aerial view of Obsidian Dome in the Inyo volcanic chain of eastern California. The dome is a 600-year-old rhyolite lava flow with a volume of about 0.2 km^3 ($7x10^9$ ft^3), or about one hundreth the volume of the 1912 Katmai eruption. Its width in this view is 2 km (1.2 mi). The lava flowed radially outward from a vent near the dome's center (see Figure 2).



Figure 2: Block diagram showing the position of research coreholes (numbered) drilled into the 600-year-old extrusive/intrusive system at Obsidian Dome, California. The view is oblique and toward the northwest. Tick marks indicate 100 m (330 ft) intervals. Finely stippled regions are cross sections of the lava dome and its conduit, in planes containing holes #1 & 2. The coarsely stippled region is fragmental material that fills the vent funnel and was intruded by the dome conduit. The conduit is an enlarged portion of the feeder dike, which was intersected by hole #3 and is shown as a heavy line (width to scale) and vertically-ruled pattern. The dotted line is the dome margin, removed in this cutaway view. The phreatic craters are pits excavated by jets of steam during emplacement of the dike. Layer Qv&g (Quaternary volcanic and glacial deposits) is young pumice and glacially-transported boulders. Layer Tv (Tertiary volcanic deposit) consists of numerous old basalt flows. Jg (Jurassic granitic rocks) is the "basement" that extends to many kilometers depth in the Sierra Nevada.

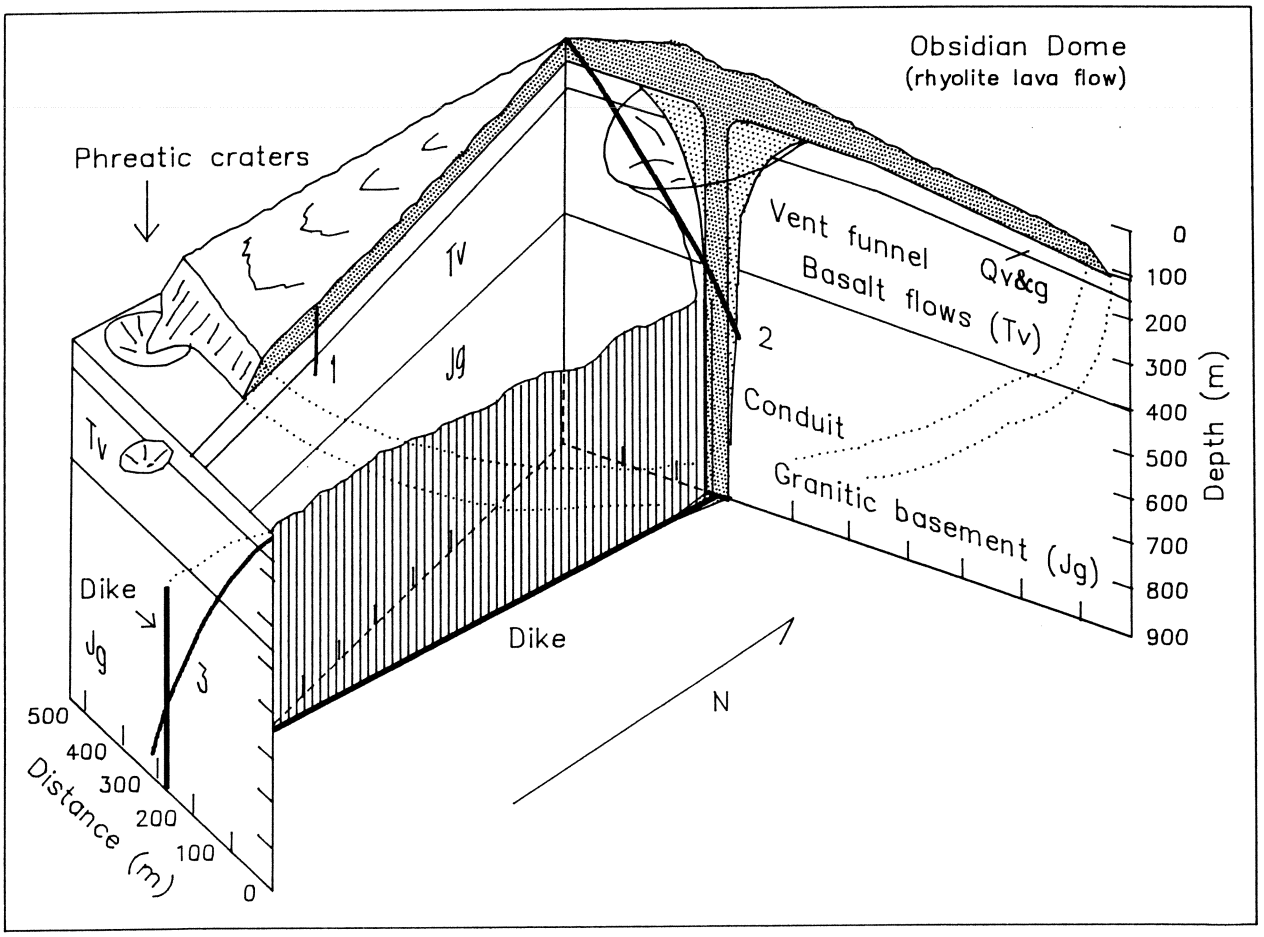


Figure 3: Oblique northward aerial view of Inyo Craters, at the south end of the Inyo volcanic cahin in eastern California. The 600-year-old craters were excavated as steam and a small amount of pumice escaped upward from a north-south dike of rhyolite magma. The conduit that fed South Inyo Crater, in the foreground, was sampled by a research corehole (see Figure 4). Drilling equipment is barely visible in the forest, midway between the left edge of the photo and the crater rim.



Figure 4: Map of South Inyo Crater, California with the projected trajectory of the research corehole. Tick marks along the hole show its vertical depth at 100-m (330 ft) intervals. The hole was slanted along a direction that took it beneath the center of the crater lake. Heavy black bars mark the position of the three intersected fragmental intrusions, the largest of which represents the feeder for the crater.

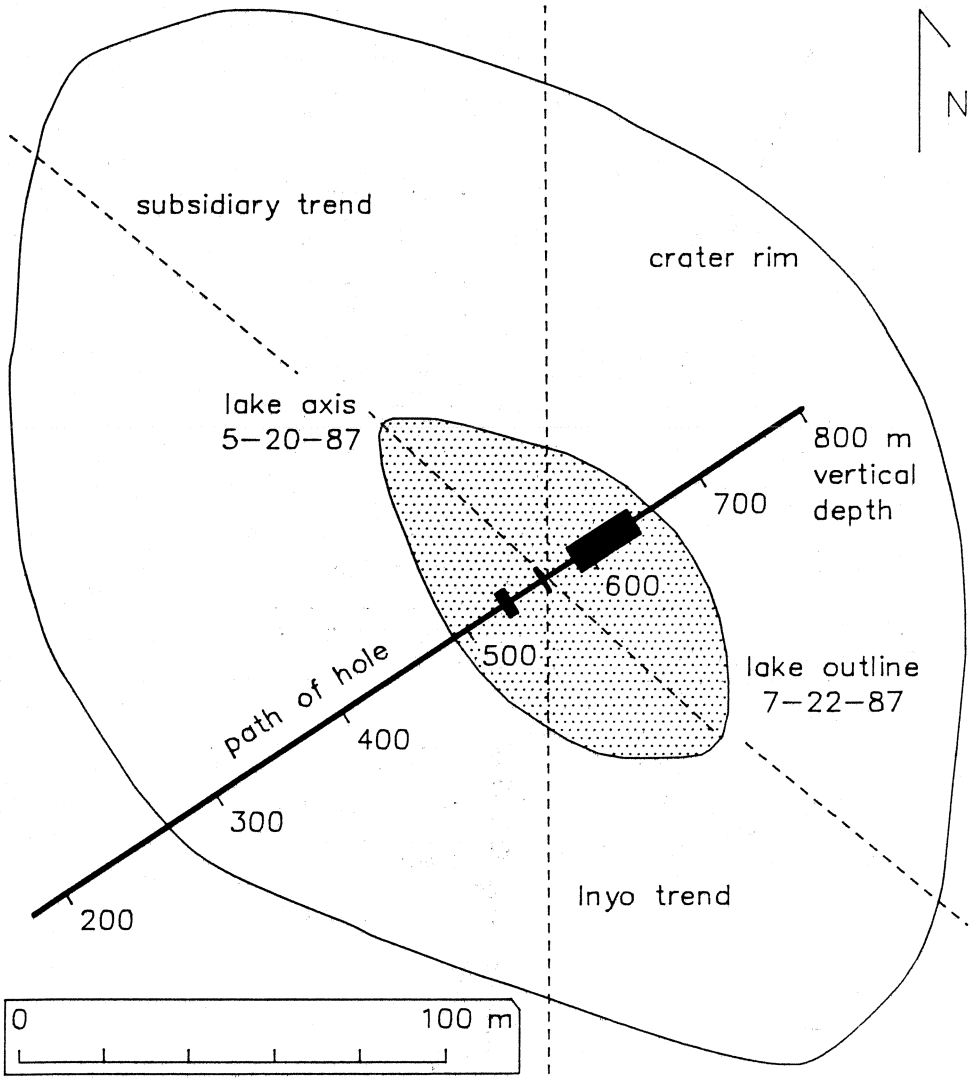
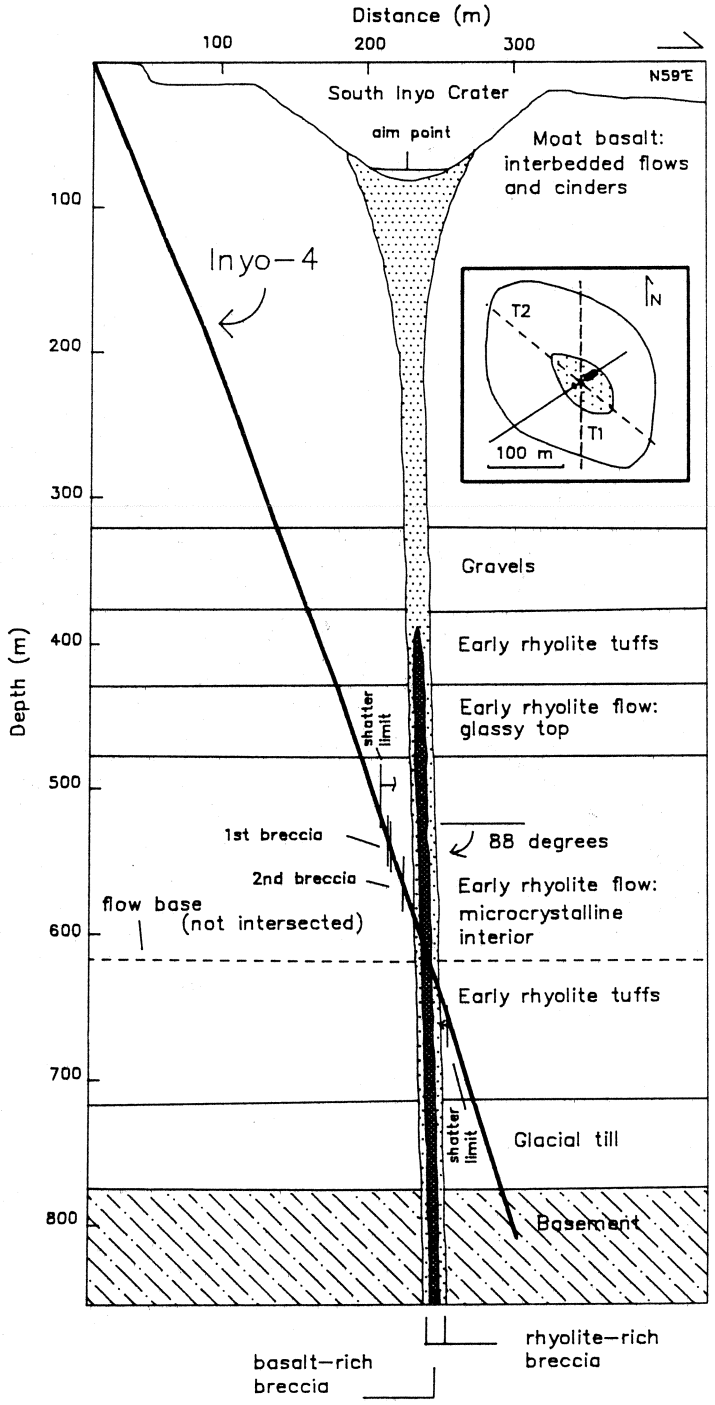


Figure 5: Path in cross section of the corehole (Inyo-4) shown in Figure 4. The feeder for the crater is a wallrock-rich fragmental deposit. This material, which also contains pumice derived from the magma that was causing the eruption, followed the path of an old basalt feeder. Results show that wallrock was carried to the surface from at least 800 m (2600 ft) depth. The structure represents an initial stage of an explosive rhyolite eruption, stopped by rapid influx of cold groundwater into the conduit.



of observation. Therefore, cooling behavior of the igneous rocks could not be observed. A logical next step in the scientific exploration of volcanoes is to drill into a simple system sufficiently large and/or young to still be hot in the 0 to 2 km (1.2 mi) depth interval where continuous core* collection is routinely conducted.

There have been a number of holes drilled for both commercial and scientific purposes in the volcanoes of New Zealand, the United States, Iceland, Italy, Japan, and elsewhere. None of these drilling programs have taken the approach of looking at intrusions related to specific eruptions and few involved extensive collection of core. Their results bear mainly on hydrothermal (hot groundwater) circulation, and so will not be reviewed here.

WHY KATMAI?

The 1912 eruption of the Novarupta center in the Katmai region (Fig. 6, 7, and 8) is by far the outstanding igneous event of this century. Investigations of the eruption, beginning with the Griggs expeditions (Griggs, 1918, 1922), have had a profound effect upon the development of modern concepts regarding explosive volcanic eruptions, ash-flow deposits, calderas*, ore deposits, and the chemical changes in magmas as they cool. The event is an ideal subject for a research drilling investigation of silicic magmatic processes for the following reasons:

1) Size: The eruption was the world's largest rhyolitic event in the last 1800 years, the only historic eruption to produce a welded tuff*, and the only historic rhyolitic eruption in the United States. Although 1/10 to 1/100 the size of the largest eruptions that occur on the Earth, the Katmai event is of a class of eruptions that are both large enough to be catastrophic in impact, while frequent enough to represent a serious

Figure 6: Map of the Valley of Ten Thousand Smokes, showing locations of the ash-flow sheet, Novarupta and Mount 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).

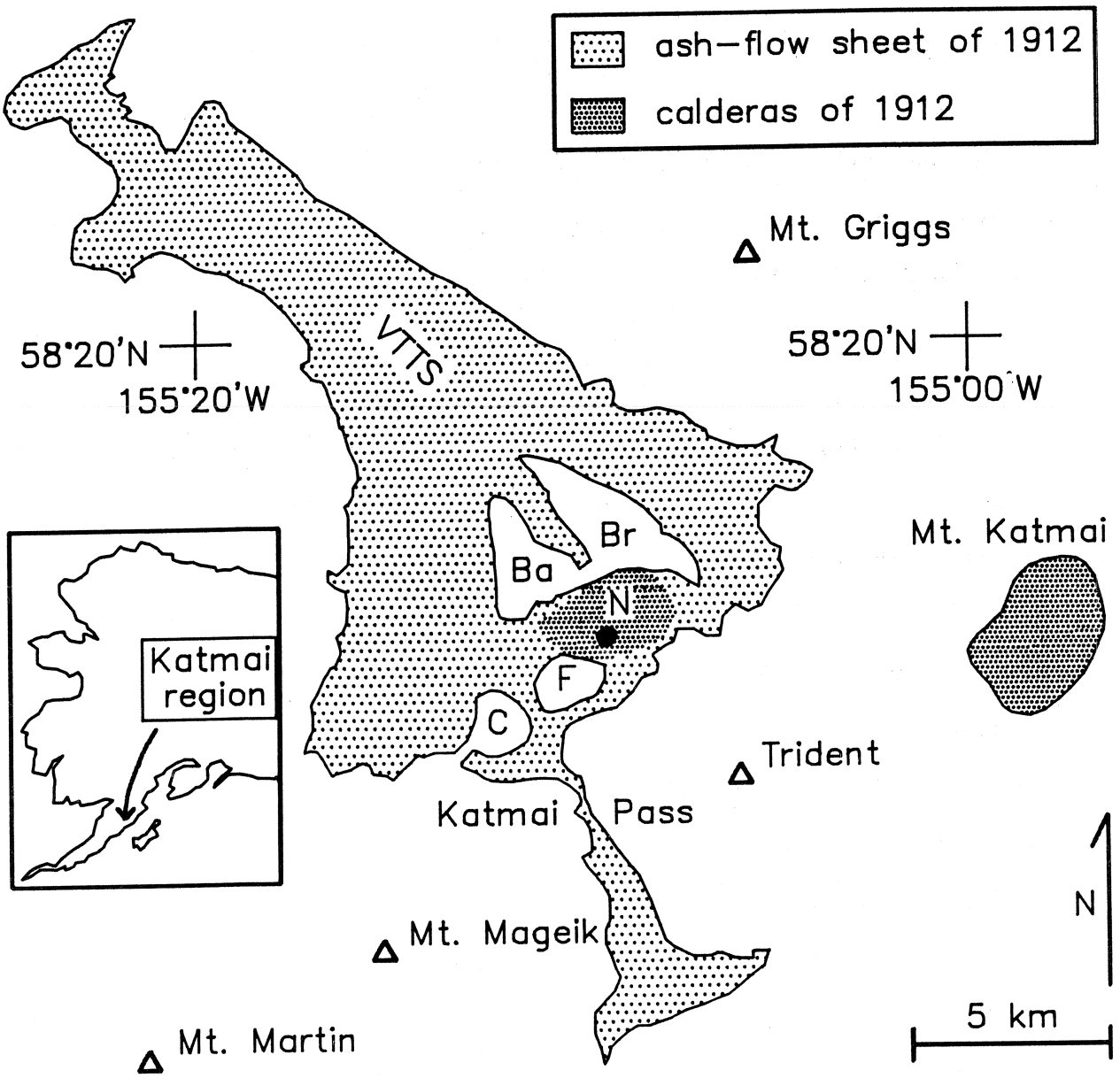


Figure 7: Oblique southward aerial view of Novarupta dome and a portion of Novarupta caldera. The dome, which consists of rhyolite lava, is 400 m (1300 ft) in diameter and 60 m (200 ft) thick. It represents the final phase of the 1912 eruption. The shadowed cliff in the background is the rim of Novarupta caldera, marking the edge of the 2-km-diameter vent that developed early in the event and gave rise to the regional air-fall pumice deposit and the Valley of Ten Thousand Smokes ash-flow sheet. Waning explosive activity then built the ring of pumice that surrounds the dome. Warm ground is visible as snow-free areas in front of the dome, and steam issues from its upper surface. Gullies in the foreground and within the inner crater formed since 1912 by erosion of the loose pumice surface. Three of the four research holes are proposed to be drilled from the flat surface on the floor of the inner crater immediately to the left of the dome.

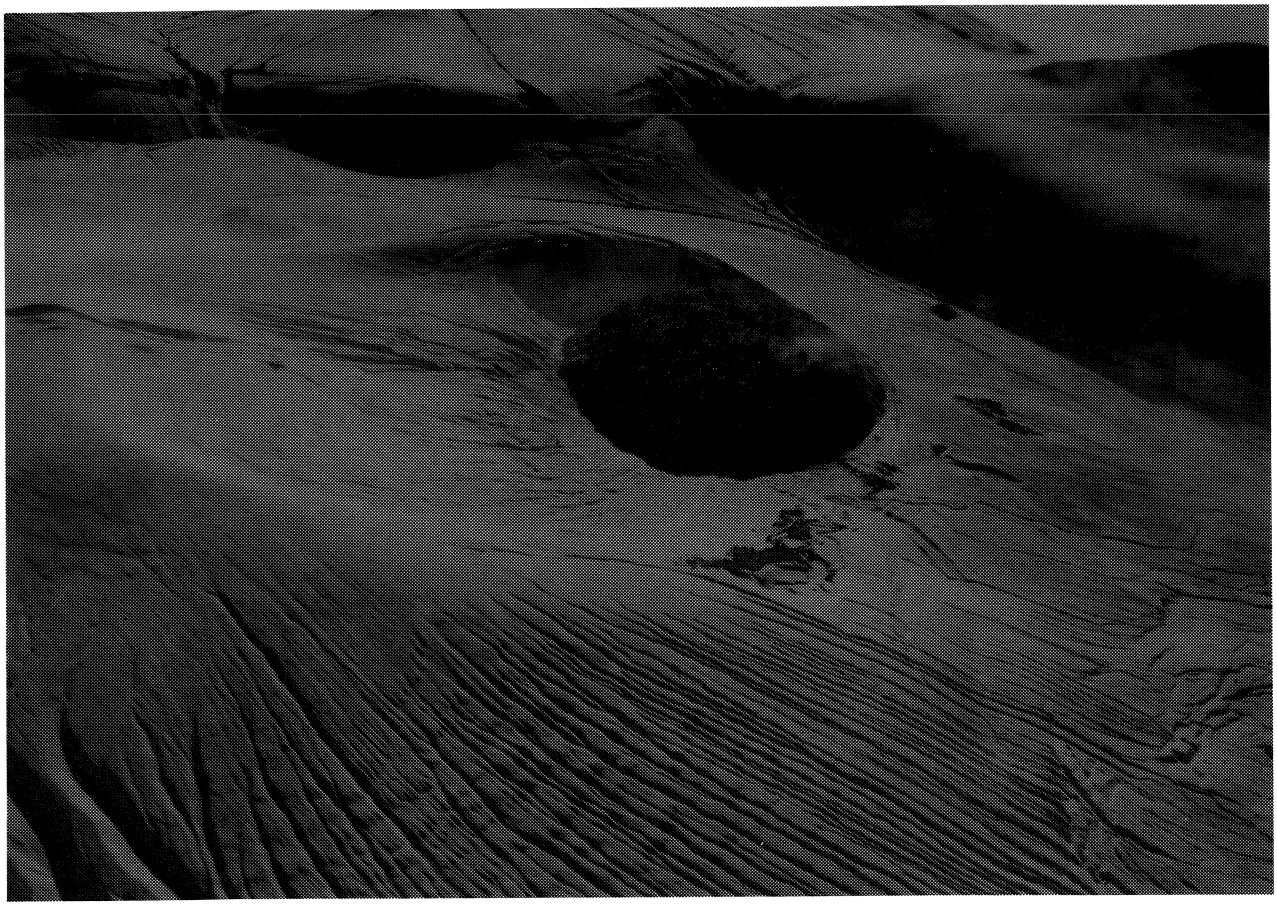


Figure 8: A complete section through the 1912 ash-flow sheet cut by the River Lethe in the lower part of the Valley of Ten Thousand Smokes. Only in the lower Valley where the sheet is relatively thin has erosion exposed its interior. The sheet formed from deposits of hot heavy clouds of magmatic gas, pumice, and ash that flowed along the ground surface from the vent. Because of its thickness, the sheet remained hot for years after the eruption and may still be warm in its interior beneath the upper Valley.



threat to human activities. Its great size contributed to retention of significant heat at shallow depth and undoubtedly to much post-eruptive migration of gases and metals.

2) Youth: Because the event is so recent, eyewitness accounts give us an idea of the timing of the eruption, and damage to deposits by erosion and weathering is minimal. Most importantly, the age and size of the system are such that the surface is cool, while elevated and perhaps very high temperatures persist within the upper 1 km (0.6 mi.). Thus, at this location, the cooling of an igneous intrusion can be directly observed for the first time. The very short time since emplacement also minimizes chemical alteration of rare, less resistant minerals and glasses.

3) Simplicity: The 1912 event was a single eruption of magma passing through uniform sedimentary bedrock at a site where little previous volcanic activity, none of it rhyolitic, had occurred. Thus, temperature, chemical, and structural observations at depth can be directly related to the 1912 event. In addition, the remarkable 10-km (6 mi.) separation between the eruption site and the site where collapse due to the subsurface withdrawal of magma took place uniquely permitted preservation of the structure of a major vent.

It is important to note that the size, youth, elevated temperature, and simplicity of the Novarupta vent make it an exceptional scientific target. A few basaltic volcanoes (Hawaii, Iceland) are hotter and have been active more recently, but they have complex eruption histories and lack the intriguing features of ash-flow volcanism and significant metals transport. Most of the great andesitic volcanic cones that ring the Pacific (e.g., Augustine Volcano in Alaska; Mt. St. Helens, Mt. Adams, and Mt. Rainier in Washington; Mt. Shasta in California, Mt. Hood in Oregon) are composite, representing dozens to

hundreds of individual magma batches erupted or intruded at high levels, forming very complicated mixtures of materials. Among explosive silicic volcanoes, Santorini in Greece (3500 years old), Taupo in New Zealand (1800 years old), and Krakatoa in Indonesia (105 years old) would be attractive drilling targets, but all three are now under water, the normal result of caldera collapse -- which did not take place at Novarupta. Moreover, the pre-caldera and post-caldera eruptive histories of Santorini and Krakatoa (like most other volcanoes) have hopelessly complicated the temperature profiles there. At Novarupta, on the other hand, the 1912 magma punched through cold, flat-lying, uniform sedimentary rocks, previously and subsequently undisturbed.

In terms of continuing the line of investigation begun at Inyo Domes, Katmai offers the certainty of encountering a still-cooling system, together with the added dimensions of great size, important metals transport, and significant ash-flow volcanism. It does so in a setting of unique simplicity and singular historical influence.

GEOLOGICAL AND GEOPHYSICAL SETTING

Volcanoes of the Katmai region rest on a platform of oceanic sedimentary rocks. The volcanoes occur in a 150-km-long (90 mi.) chain of closely spaced (5 to 20 km, or 3 to 12 mi.), fairly small volcanoes. Among these volcanoes are three young calderas, Kaguyak and two -- Katmai and Novarupta -- that formed in 1912. Eight centers are clustered in an area of less than 300 km^2 (approx. 100 sq. mi.): the Martin, Mageik, Griggs, Katmai, and Trident volcanoes, the Falling Mountain and Cerberus domes, and Novarupta (Fig. 6). Kubota and Berg (1967) and Matumoto (1971) observed disappearance of shear-waves from crustal earthquakes along paths passing beneath the cluster. Because shear-waves cannot pass through liquid rock, this

observation is evidence for magma beneath the cluster. Decker (1963) and Kienle (1969) identified a gravity low in the vicinity of Trident and the 1912 vent. Because liquid rock is less dense than solid rock, this observation also indicates the presence of magma. These observations suggest that a region of molten rock 10 to 15 km (6 to 9 mi.) in diameter has developed at a depth of less than 10 km (6 mi.) (Kienle et al., 1983). The crude semicircular arrangement of vents defining the cluster outlines the extent of the main zone of intrusion.

CHRONOLOGY OF THE 1912 ERUPTION

Reconnaissance of the Katmai area in 1898 gave no hint of the impending cataclysm (Spurr, 1900), but its onset is well documented as 1300 h June 6, 1912, by the sighting of a towering eruption cloud from a ship in Shelikof Strait. By the time several eruptive phases concluded about 60 hours later, 15 km^3 of magma (or equivalent to the content of four boxes each one mile on a side) had foamed and erupted to produce some 30 km^3 of eruption products (Hildreth, 1983). Approximately half of this volume is represented by the ash and pumice that fell like snow over a broad region, a deposit 30 cm (1 ft.) thick at Kodiak 170 km downwind. The other half is represented by the ash-flow sheet that filled the glacial valleys of Knife Creek and the River Lethe to a depth of up to 200 m (700 ft.; Curtis, 1968; Kienle, 1970, model F), forming the Valley of Ten Thousand Smokes (Fig. 8). The eruptive sequence ended with extrusion of lava to form Novarupta Dome* near the center of the 2-km-wide vent basin. This vent basin, Novarupta Caldera, lies at the head of the Valley. Some 10 km (6 mi.) away from Novarupta, the three summits of Mt. Katmai collapsed to form a second caldera, 3 km (2 mi.) in diameter and nearly

1 km (0.6 mi.) deep. Katmai Caldera has since filled with water to form a lake 200 m (700 ft.) deep.

Novarupta Caldera is bordered by Falling Mountain and Broken Mountain at the head of the Valley and is marked by a system of fractures over an area of 6 km^2 (2.2 $mi.^2$; Fig. 9 and 10). Early researchers neglected this feature in favor of the more spectacular Katmai Caldera, but the work of Curtis (1968) and Hildreth (1983) demonstrated that virtually all the magma emerged here. In addition to the Novarupta dome, the central region contains a structural dome-like feature, the Turtle. A cross-section of the 1912 vent is shown in Fig. 11. The closest known analog appears to be a 12,000-15,000-year-old caldera in Japan, identified by drilling (Dohnan Geothermal Energy Company, 1984). However, the geometry and internal structure of this class of small but important calderas remain poorly understood. Our current model for development of the 1912 vent is shown in Figure 12.

Chemically, the eruption at Katmai involved three distinct magmas: crystal-poor, high-silica rhyolite; crystal-rich dacite; and crystal-rich andesite. This was the first appearance of rhyolite in this group of volcanoes, and a voluminous one. The early airfall is rhyolite, and the initially rhyolitic ash-flow sheet becomes more andesite-rich upward and toward the vent (Fig. 13).

The name and much of the fame of the Valley of Ten Thousand Smokes are due to vigorous steaming of the ash-flow sheet at the time of its discovery. Indeed, this fumarolic* activity was so spectacular, and the nature and thickness of the ash-flow deposit so poorly understood, that early workers postulated that the heat and gas source was a huge magma body just beneath the valley floor (Griggs, 1922). Allen and Zies (1923) and Zies (1929) reported a wealth of data concerning transport of trace metals such as lead, zinc, copper, tin, and silver, as well as extraordinary amounts of iron in water-

Figure 9: Oblique northward aerial view of Broken Mountain (skyline), across the Turtle and the northern margin of Novarupta caldera (see Figure 10). The Turtle is a hill near the center of the caldera. It represents a very thick accumulation of pumice, a buried block of bedrock, or a shallow intrusion of magma. Steps on the face of Broken Mountain and the long parallel cracks below it are fractures marking the margin of the vent. They formed either by subsidence of the vent region due to withdrawal of magma from below it during eruption, or by compaction of debris filling the vent, or both. The origin of the shorter open fractures in the foreground on top of the Turtle is uncertain.

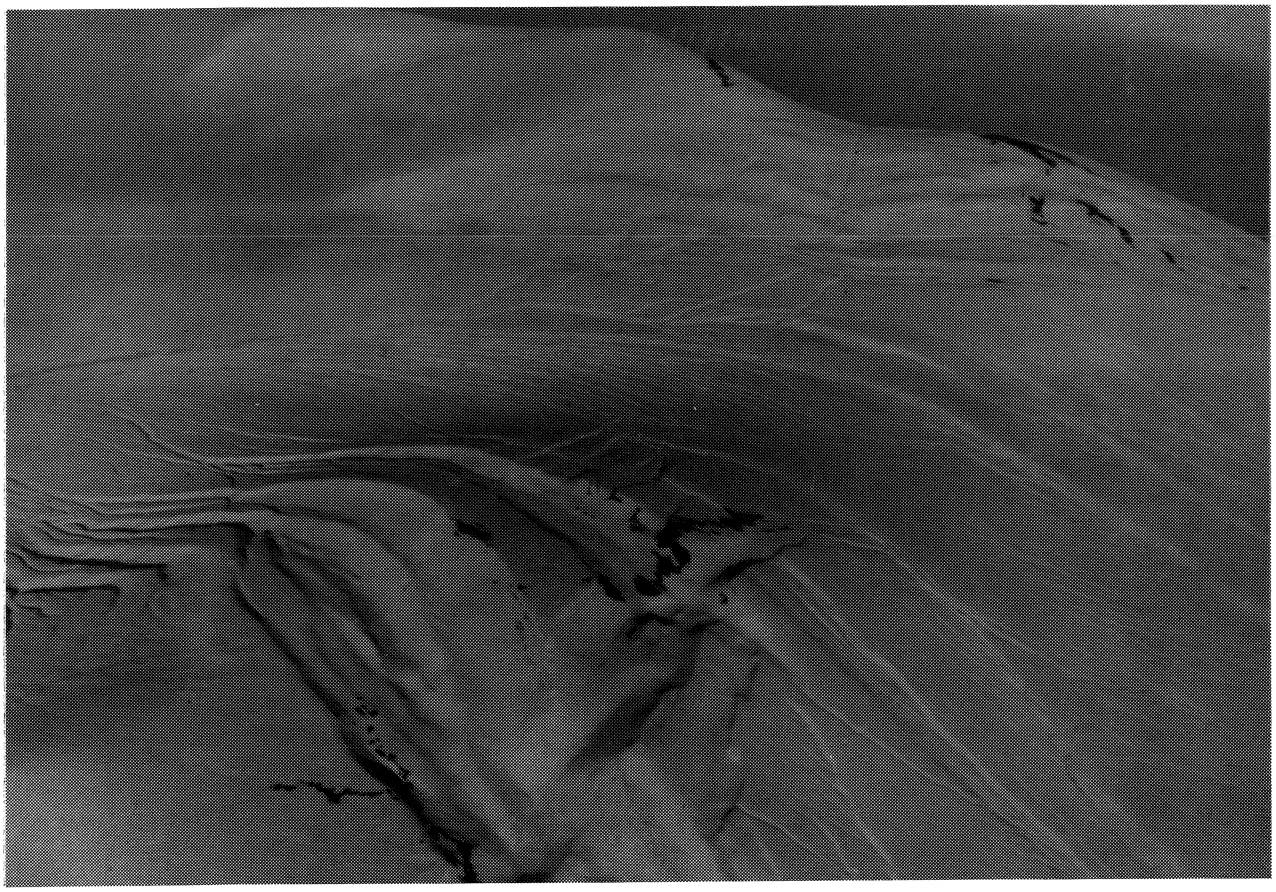


Figure 10: Map showing the fractures (Fig. 9) that define the 1912 vent in the vicinity of the Novarupta rhyolite dome. The line along which the cross section in Figure 11 is drawn is also shown. The darkly shaded area is Novarupta; light shading denotes the Turtle. The dotted line is the pumice ring (Fig. 7) built during waning explosions after eruption of the ash-flow sheet, but before extrusion of the lava dome.

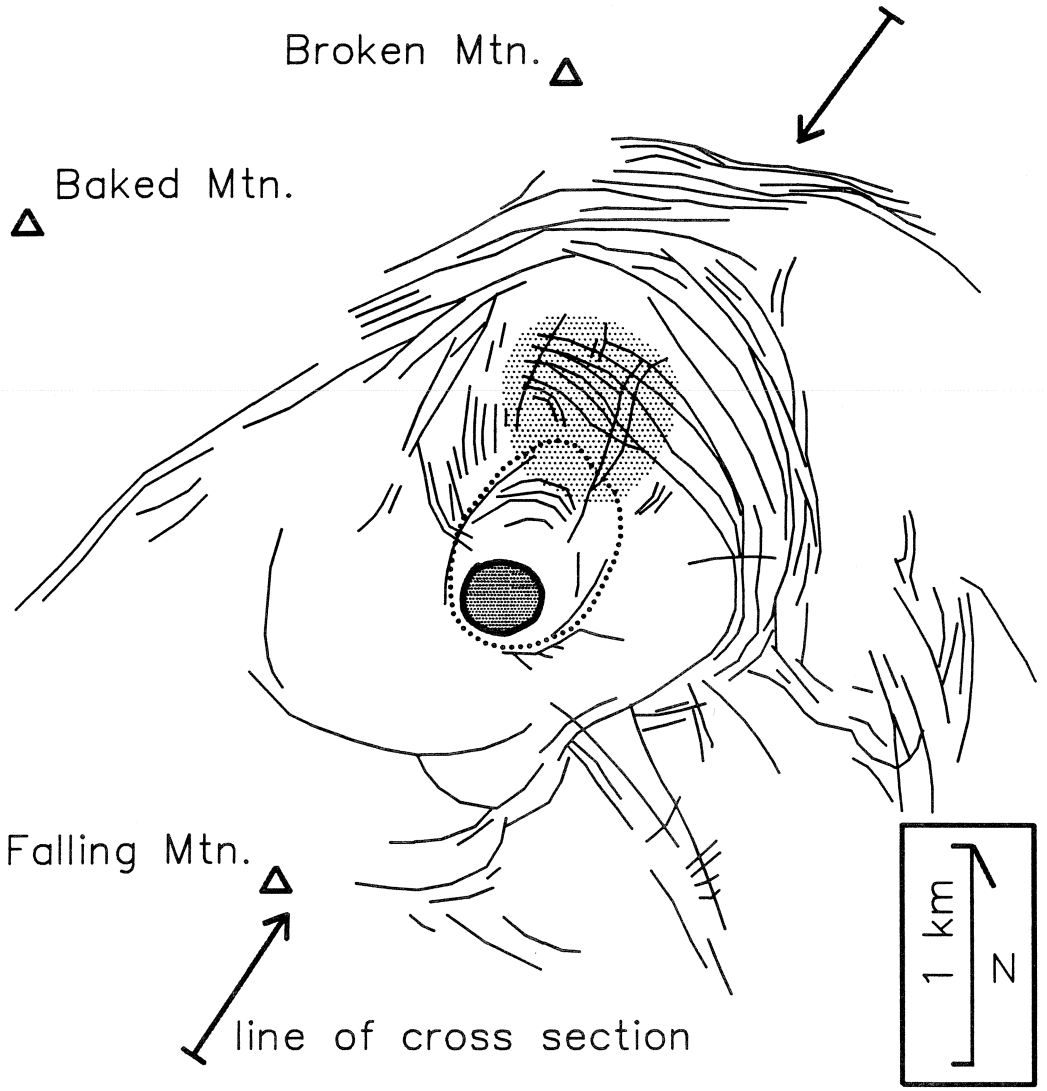


Figure 11: Perferred model for the 1912 vent. The cross section is drawn along the line shown in Figure 10. Vent shape is based on drilling results from Japan in a vent that is thought to be structurally similar (Dohnan Geothermal Energy Co. Ltd., 1984). Consistent with this model, wallrock fragments in the ejecta are dominantly of Naknek Formation, indicating that the entire excavated volume lies within about one kilometer (0.6 mi) of the surface. This large flared funnel is presumed to have formed early in the eruption during the regional air-fall pumice phase and/or during ash-flow sheet emplacement (see Figure 12). Vent fill may consist of fluidized-bed material that never reached the surface as well as ejected fragments that fell back into the vent. At some unknown depth, there must be a downward transition to the intact intrusive equivalents of the fragmental deposits of the explosive eruption phases. The vent-fill was intruded by intact magma which fed Novarupta dome, and possibly a buried dome or shallow intrusion beneath the Turtle. Nested within the large vent, and containing the Novarupta feeder, is the much smaller vent for the late dacitic explosive phase of the eruption. The vent thus became constricted with time (the ~60 hour duration of the eruption), from 2-km-(1.2 mi) diameter during the most vigorous activity to a few hundred meters during the final explosive phase, to a few tens of meters during extrusion of the dome.

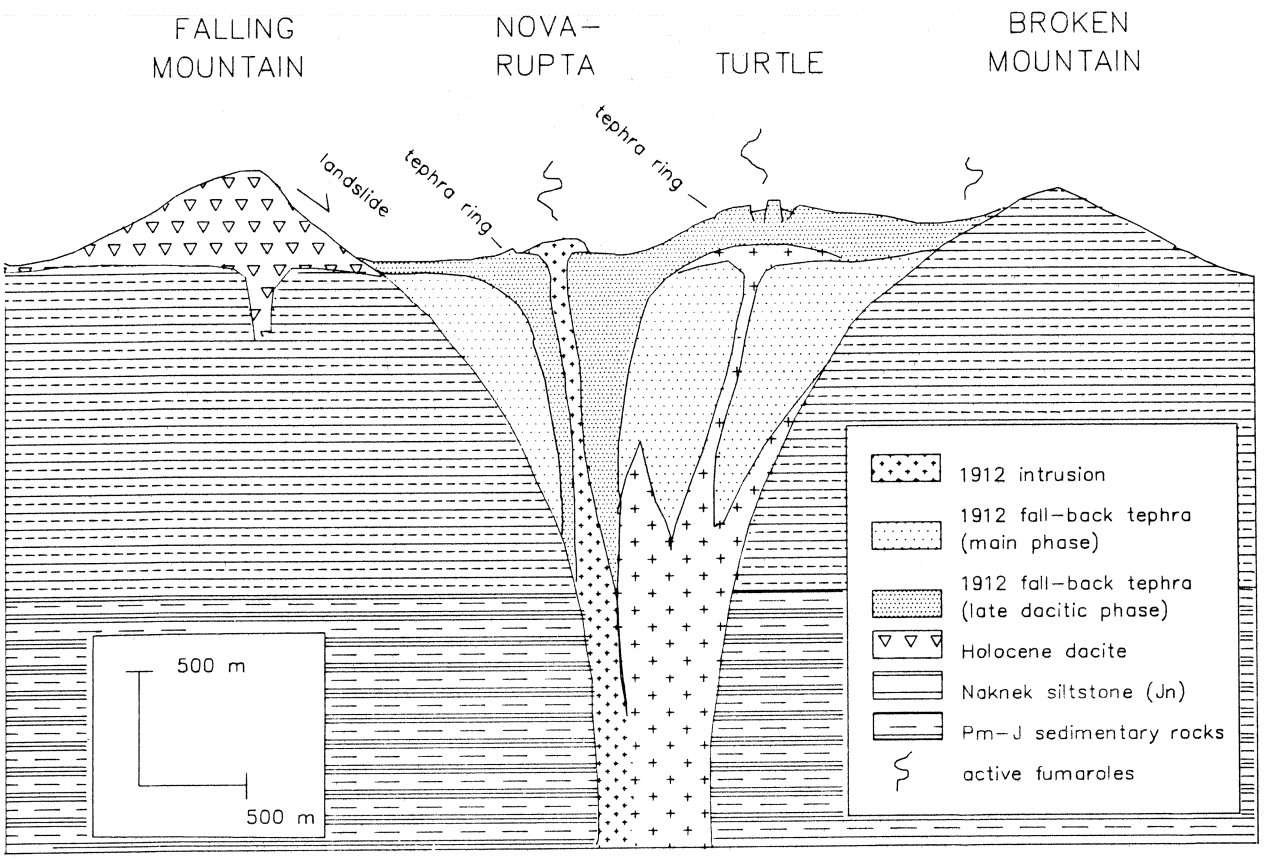


Figure 12: Preferred model for development of the 1912 vent. A finger, or more likely a crack-filling sheet (dike) of magma rises from a deep reservoir. This reservoir may be located under Mt. Katmai or Trident Volcano, rather than Novarupta. The early phase of eruption (A) is so violent that the eruption cloud reaches a height of 30-40 km (18-24 mi) and pumice and ash fall like snow over a broad area [30 cm (1 ft) thick at Kodiak 160 km (100 mi) away]. During its rise to feed the eruption, the magma begins growing bubbles at several kilometers depth. These increase in number and size until the magma can no longer remain intact. Upon reaching several hundred meters depth, the magma fragments to a spray of pumice and ash in hot gas. The exit velocity at the mouth of the vent is close to the speed of sound. Erupting high-velocity and highly abrasive pumice and ash-laden gas quickly erodes the vent wall to form a 2-km- (1.2 mi) funnel. Velocities subside and heavy mixtures of pumice, ash, and gas race outward along the ground surface (B), depositing the Valley of Ten Thousand Smokes ash-flow sheet in the River Lethe and Knife Creek valleys. As the violence of the eruption continues to wane, material is deposited on the walls of the vent and the active vent becomes smaller (C). Ash-flows continue to move out into the Valley. A final explosive pulse from the much-narrowed vent (D) builds the inner pumice ring. Continued rise of magma, now degassing into the debris-filled funnel, gives rise to Novarupta dome and concludes the eruption. The time span from A through D is 60 hours. Stage E was complete within 4 years (when the Valley was discovered) and more likely concluded a few weeks or months after D.

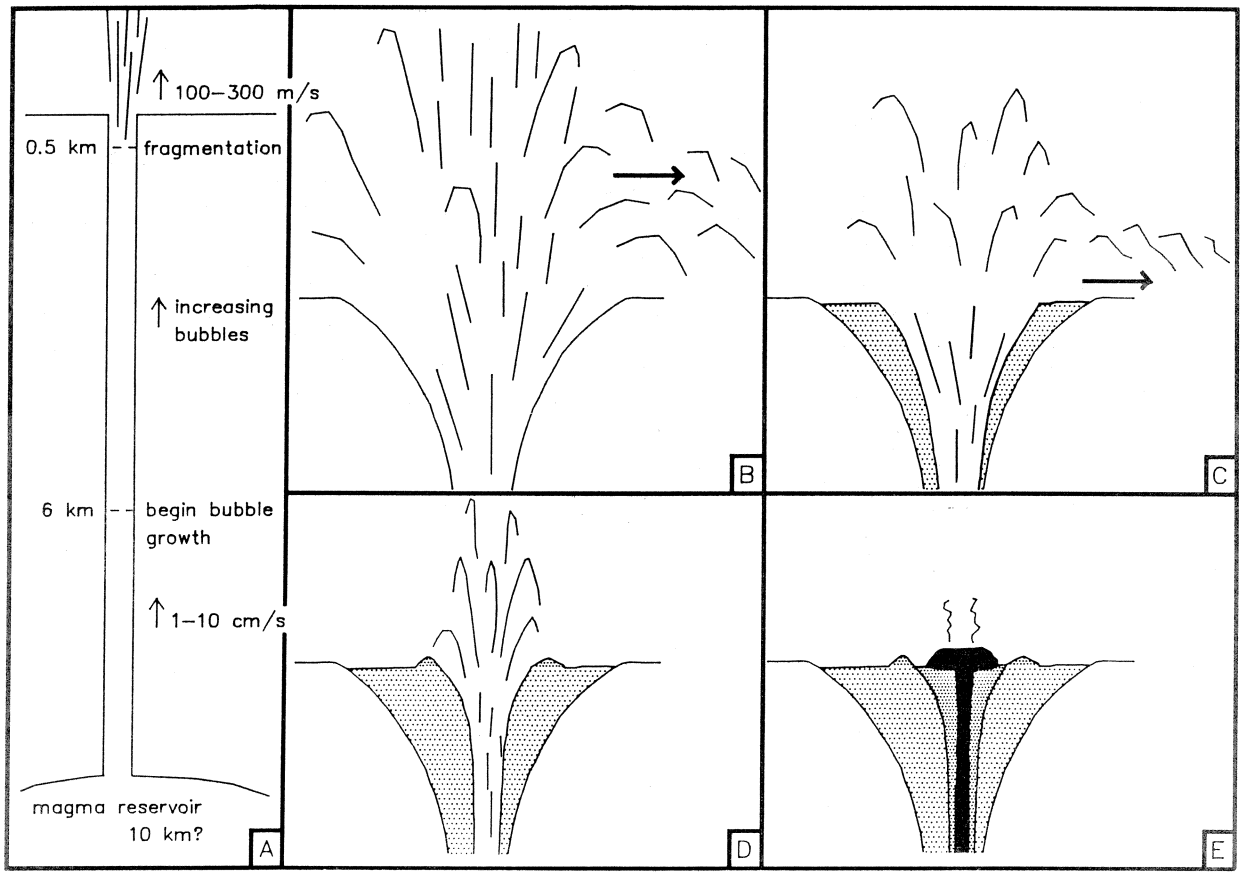
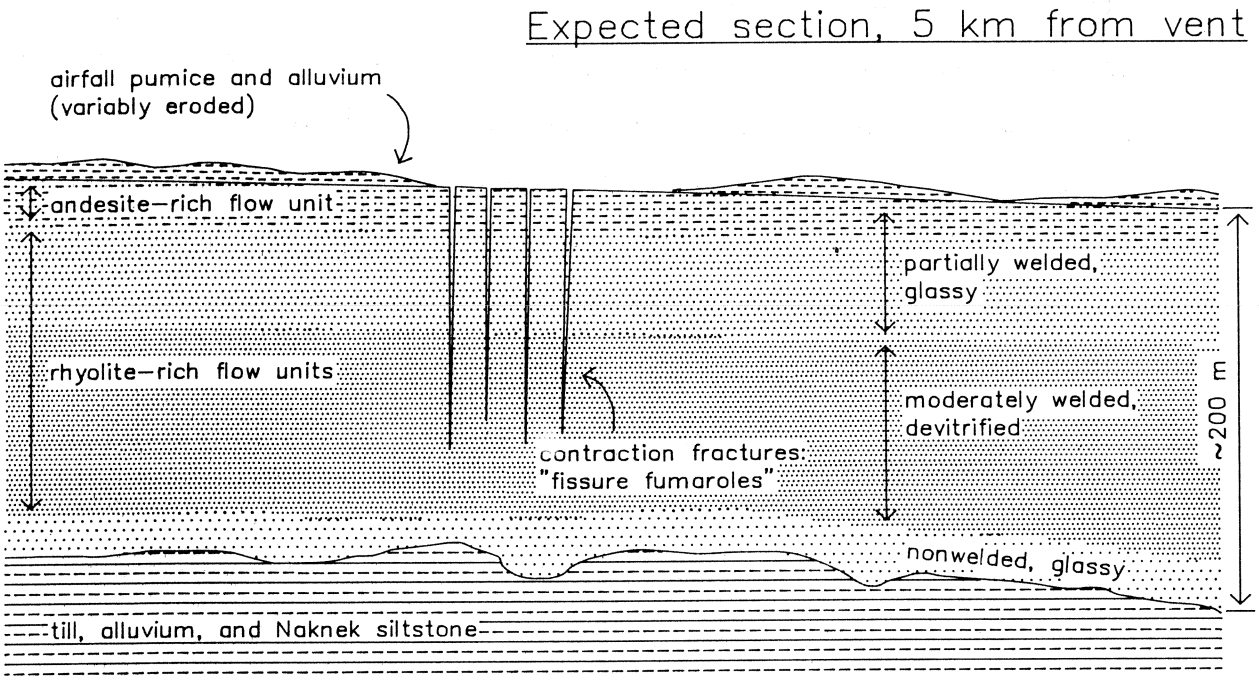


Figure 13: Expected features of the ash-flow sheet in the center of the upper River Lethe valley, 5 km (3 mi) from the vent. By coring this section at an angle from vertical, the fissure fumarole deposits can be sampled at multiple depths.



dominated gases that remained as hot as 650°C (1200°F) in 1919. As temperatures fell, reactions modified the original deposits around the fumaroles, ultimately allowing weathering to decompose many of them and to form numerous secondary minerals (Keith, 1984).

Early interest in the 1912 events centered on the "sand flow", as the ash-flow sheet was then called, and its fumaroles (Griggs, 1918; Fenner, 1923), the associated metals transport (Allen and Zies, 1923; Zies, 1929), and the distinctive, compositionally banded pumice (Fenner, 1950). Interpretation of the events was impeded, however, by the remoteness of the region, limited understanding of the formation of the deposits, and confusion about location of the eruptive vent. More recent studies by Curtis (1968) and Hildreth (1983) have reinterpreted the 1912 events in terms of current understanding of volcanic processes, but much remains to be learned about the ash-flow deposit, the vent, and the structures and conditions underground.

SCIENTIFIC OBJECTIVES AND TECHNICAL APPROACH

The following problems have been chosen as the primary objectives for the Katmai Project. Solutions to these problems will be applicable to the understanding of silicic igneous activity worldwide. Each requires pursuit of a number of lines of investigation in different disciplines, as summarized below.

Objective #1:Describe the physical and chemical behavior of magma and its host rock during intrusion and eruption.

The rapid flow of a large volume of thick, viscous magma upward through the rocks that comprise the Earth's Crust to the surface is a complex mechanical problem. Aspects of the problem include fracturing of bedrock by magma, flow of magma, growth of bubbles in the magma, expansion and break-up of the magma to ash, pumice, and gas and excavation of the vent. The

project will test existing theories about intrusion and eruption processes and geologic concepts of vent geometry and development. Some possibilities for Novarupta are illustrated in Figures 14 and 15. The problem can be divided naturally into the behavior of magma and the behavior of the conduit system.

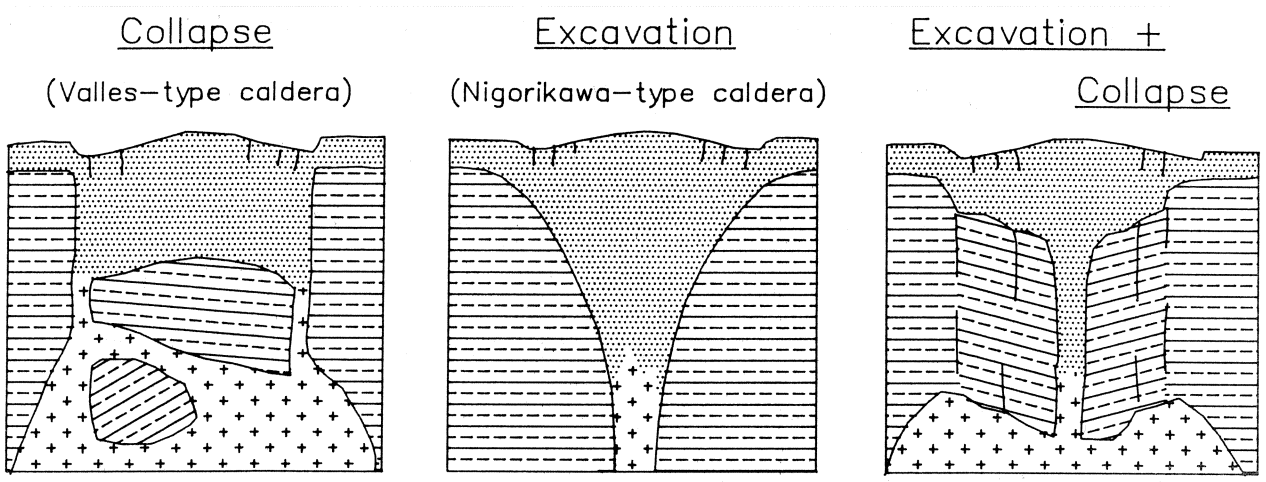
Approach:

Models for the behavior of molten rock during intrusion and eruption depend first of all on the size and geometry of the system. The geometry of the vent will be initially interpreted from surface rock exposures and structures, the amount (volume) and composition of ejected rock, and magnetic, gravity, and seismic data (discussed below). Results from the continuous core sections from the drill holes will provide a greatly improved view of vent structure. Drilling results will be combined with surface geological and geophysical observations to develop a fully consistent geometrical model of the vent. A complete section of core through the ash-flow sheet, together with surface geologic observations, will show the sequence in which the eruption deposits formed. Matching these deposits with equivalent layers encoutered by drilling inside the vent will show how the vent grew with time. The timing of periods of constriction of the vent, of collapse, and of intrusion can also be determined. The distribution of fragments of the vent wall in the vent-fill and the ash-flow sheet will show how the vent was excavated. Identification of down-dropped blocks of wallrock fragments relative to vent volume will show to what extent the vent formed by collapse of wallrock into magma, rather than by excavation of wallrock by erupting magma.

Glassy rocks in the vent, representing magma that cooled too quickly to grow crystals, will be analyzed for chemically bound gases. This will show how the gases in the magma changed as the magma approached the surface and

Figure 14: Conceptual end members for the 1912 vent. Fragmental magmatic material is dotted; intact intrusions are indicated with crosses. "Lithics" refers to wallrock fragments in the eruption products. "Welding" refers to compaction of the hot vent fill. Drilling and geophysical results will define the vent structure and eruption product characteristics, and thereby constrain processes of vent formation. The center case is the preferred model (see Figure 11). However, topography of the vent resembles Valles-type calderas (left case), with a ring-fracture pattern and central topographic high. Alternatively, the discrepancy in vent diameter between hydrodynamic model predictions and the larger apparent surface expression of the vent could be reconciled by postulating enlargement of the structure due to collapse (right case). Note that for collapse to play an important role, a shallow magma reservoir is required. The volume and distribution of wallrock fragments in the eruption deposits and vent fill provide a strong constraint on vent-forming processes, once volume of the vent is known.

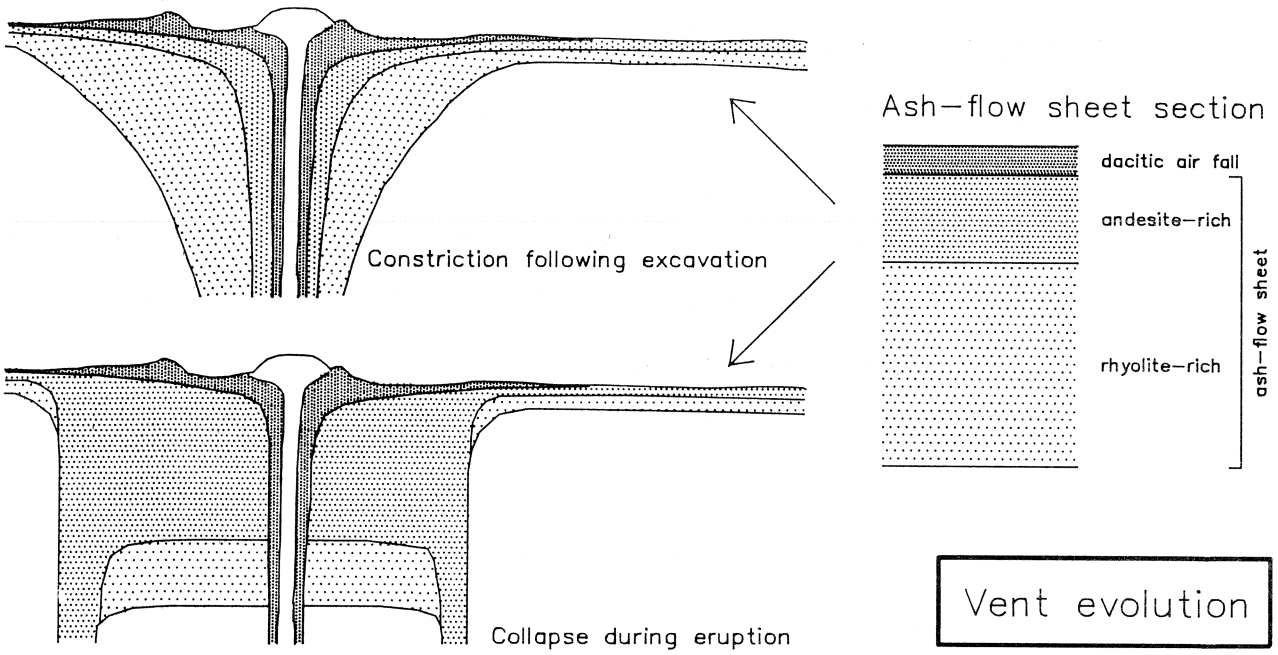
Vent–forming processes:



Characteristics:

Collapse (Valles–type caldera)	Excavation (Nigorikawa–type caldera)	Excavation + Collapse
Deep floor	Flared walls	Shallow floor
Fractures due to collapse+welding	Fractures due to welding	Fractures due to collapse
Volume lithics << Volume vent	Volume lithics = Volume vent	Volume lithics < Volume vent

Figure 15: The eruption sequence, as recorded by chemical zonation of the eruption products, can be used to interpret drilling results in terms of development of the vent with time. Two cases are shown. In the preferred model (top), the vent reaches maximum size early in the eruption, and develops a concentric stratigraphy by back filling during successive waning phases. In the caldera-collapse case (bottom), the vent fill has a horizontal stratigraphy, and ponded units record the timing of collapse.



pressure decreased. The amount and the composition of gases contained in the glass will indicate the source or sources of the gases (either from the interior of the Earth or the atmosphere). The core will also be studied to map glass-rich (quickly cooled) and crystal-rich (slowly cooled) zones. This will show how the magma solidified as it lost heat and gas. Zones of alteration will also be studied, because they may be indicators of prolonged exposure to circulating hot water. The relative timing of crystallization and alteration events, both before and after 1912, will be determined by radiometric dating.

Results of these investigations should tell us what happens during an explosive eruption and what controls whether an eruption will be explosive and ash-forming, or non-explosive and lava-forming.

Objective #2:Determine the source, mechanism, and conditions of metals transport.

Although the transport and near-surface deposition of metals that followed the 1912 eruption could be viewed as an aspect of the eruptive behavior of the magma, we separate it here for emphasis. Parts of this problem include identification of the source(s) of metals (whether unerupted magma, country (host) rock, or the ash itself), the cause and timing of release, the origin of the transporting vapors (whether from the erupted material or from snow and streams buried by the eruption), and identification of conditions (temperature, pressure, gas composition) controlling transport rates. Comparison of metals transport in the environments of the ash-flow sheet and the vent may be especially important. Conditions differed substantially between the ash-flow sheet, which is flat and is composed of individual ash particles and pumice fragments, and the vent, which is

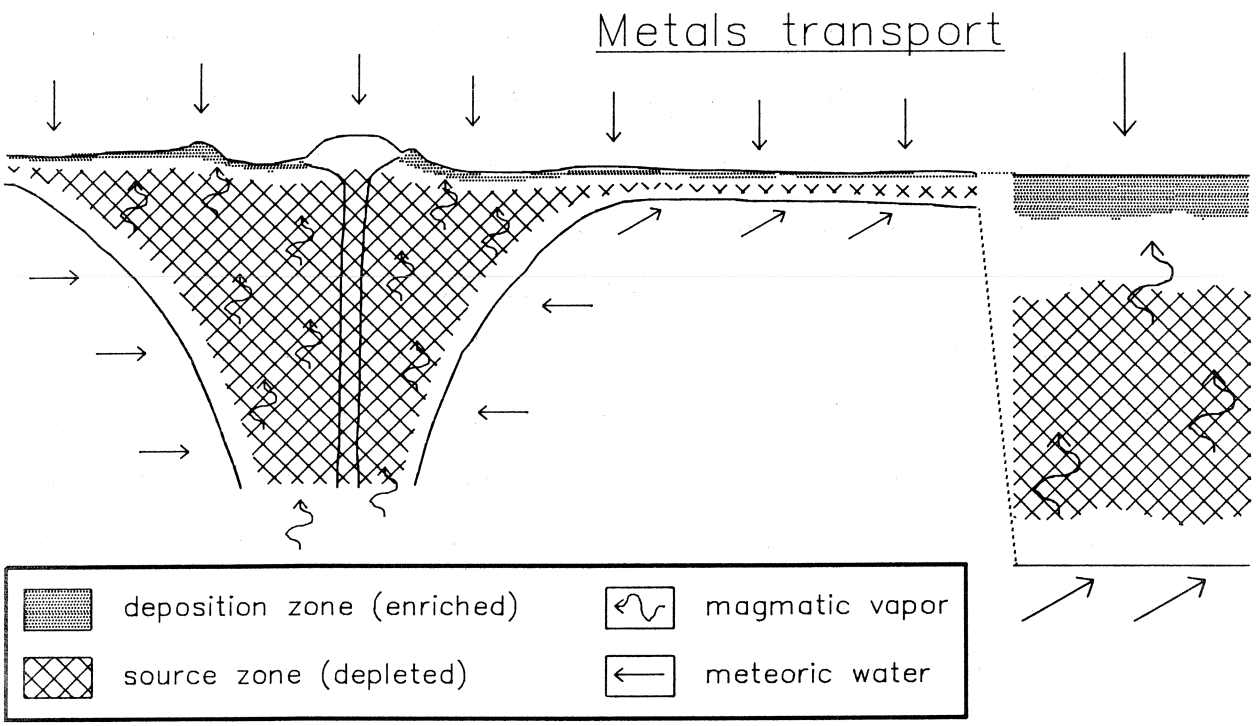
chimney-like and may contain a significant proportion of intact igneous rock (Fig. 16).

Approach:

The approach will be to fully describe the distribution of metals in the igneous/host rock system, and to interpret how portions of the system reached their present chemical state.

For the igneous portion of the system, initial metal concentrations in the magma prior to eruption will be estimated by analysis of glass inclusions* from each of the three magma types. The inclusions represent samples of liquid rock encapsulated in crystals and therefore protected from the reduction in pressure that caused the magma to lose gas and metals. Concentrations of metals in the magma immediately following eruption will be obtained by analyzing a complete collection of quenched* pumices. These baseline values will then be compared with observations from the multiple continuous core sections of the intrusive and eruptive portions of the system. Zones of enrichment and depletion of metals will be mapped and the relationship of the metals-depleted and metals-enriched volumes to zones of crystallization, specific magma types, fluid entry, and gas flow will be determined. These observations will be interpreted in terms of the roles of decompression (pressure reduction) during eruption and crystallization during cooling in metals release. Similarly, metals concentrations along profiles into the vent wall and into the valley floor beneath the ash-flow sheet will be obtained. These observations will be interpreted to show how the host rock interacted with magmatic gas and magmatically heated water. Conditions and mechanisms of metals transport will be deduced from considerations of the mineralogy of fumarolic deposits and analysis of inclusions of fluids in crystals deposited by fumaroles. Results will indicate the chemical and physical conditions

Figure 16: Subsurface mapping of zones of metals enrichment and depletion, the spatial relationship of these zones, and their isotopic character, will determine the conditions and mechanisms of metals migration. In the case depicted schematically here, mobilization of metals occurs during crystallization (other possibilities exist). Steam of magmatic and/or atmospheric origin transports the metals. Note that magmatic vapor may dominate in the chimney-like vent, while influx of atmospheric water may be more important in the slab-like ash-flow sheet.



controlling metals transport and will lead to conclusions concerning why metals are transported during some eruptions but not during others.

These investigations should find general applicability in interpretation of the processes responsible for the formation and preservation of volcanic-rock-hosted ore deposits.

Objective #3:Measure the current temperature distribution and test models for cooling of igneous systems.

Models predicting the rates and ways by which igneous intrusions cool and undergo changes in mineralogy as a result of cooling have not been tested by observation of actual cooling systems. The vent for the 1912 eruption and its contained intrusions are unquestionably still cooling (Figs. 17 and 18). We can theorize that the system has passed from molten conditions, through a very hot vapor stage when there was newly crystallized rock and steam in the vent, to a moderate-to low-temperature hydrothermal stage when hot water began circulating and altering the rocks to clay. Portions of the vent and conduit may remain in the vapor stage and could even still contain magma. Drilling into a simple, still-cooling system at a known point in time after its formation will provide fundamentally new information concerning how fast heat travels in the Earth's crust and how fast rocks change their composition. This is a very rare opportunity to determine the rates of major geologic processes.

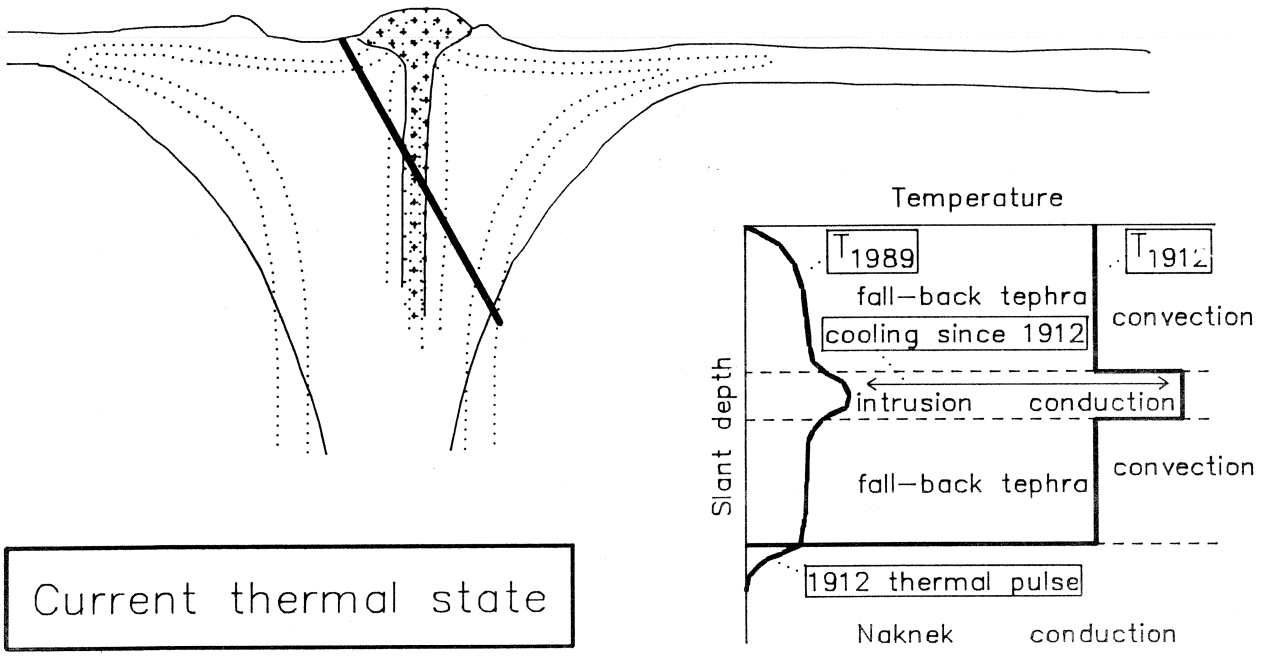
Approach:

The Katmai Project will observe and sample an active hydrothermal system only 80 years after its formation. This is very young geologically. Magmatic temperatures of 1912 ejecta have been deduced from mineral data (Hildreth, 1983), and these values can be used to estimate temperatures in and near the vent when it first formed. The present temperature conditions will

Figure 17: Warm ground in the central portion of the 1912 vent, on top of the Turtle. The view is toward the east. The heat is sufficient to have melted the snow from a mild mid-October storm.



Figure 18: Drilling will permit determination of the current distribution of heat in the system, through measurement of temperature profiles in the holes. Initial (1912) conditions can be inferred from analysis of core from the vent. Determination of extent of cooling for a know time of formation, geometry, and permeability of the system will provide a stringent test of the adequacy of existing thermal models for igneous systems. The figure suggests, in highly schematic fashion, features of the thermal regime that might be interpreted from temperature measurements in the holes. Isotherms (dotted), or lines of constant temperature, depict a convective hydrothermal regime established in relatively permeable vent fill, with residual magmatic heat associated with an impermeable intrusion, in this case the feeder for Novarupta (calculations indicate that such an anomaly could persist if the width of the intrusion were at least several tens of meters). A thermal front has propagated conductively into the vent wall of Naknek siltstone. Note that the vent fill was emplaced at a lower temperature than the intrusion because of incorporation of cold wall rock.



be described by determining the surface heat flow and by measuring the temperatures in boreholes. Zones of conduction, where heat flows through rock, and convection, where heat is carried by flowing water, will be identified. The relative timing of crystallization and alteration events will provide further information about the post-eruption history.

This first measurement of the rate at which an igneous intrusion has cooled will show how good our mathematical models for heat flow in the Earth's crust are. Results will be applicable to prediction of the behavior of repositories for isolation of radioactive waste, as well as for understanding volcanism. In the general case, volcanoes are repeatedly intruded by pulses of magma. Results at Katmai should permit an assessment of the extent to which heat from one eruption may influence the course of successive eruptions.

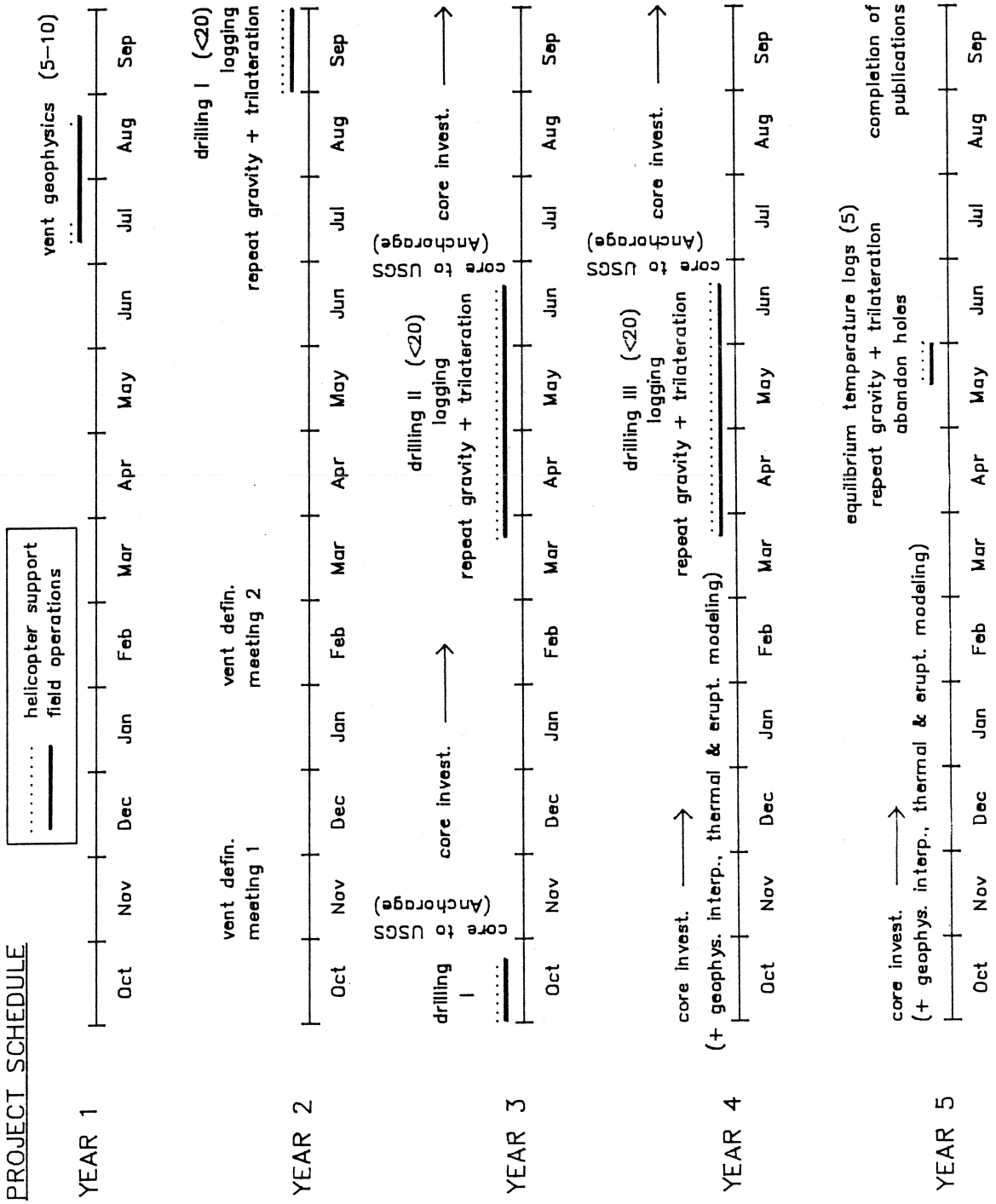
PROPOSED INVESTIGATIONS

Addressing these problems requires multiple holes to observe and sample the variety of environments within the upper 1 km or so of the 1912 system. In addition, the drilling observations should be extended by means of geophysical investigations. In this section we describe individual investigations that compose the proposed project. A duration of 5 years is planned, as outlined in Fig. 19.

PREDRILLING STUDIES: VENT DEFINITION

The focus of the drilling effort will be the 1912 vent. We want to learn as much as possible about the vent structure and underlying feeder conduit prior to drilling of the necessarily limited number of holes. Surface studies will therefore be used to develop an initial model for vent structure, which can then be tested and improved by drilling. Investigations proposed here are those with minimal environmental and logistical difficulties and with the

Figure 19: Proposed schedule for the project. Numbers in parentheses denote numbers of people in the field. Drilling phases are described in Figures 22 and 23 and in the text.

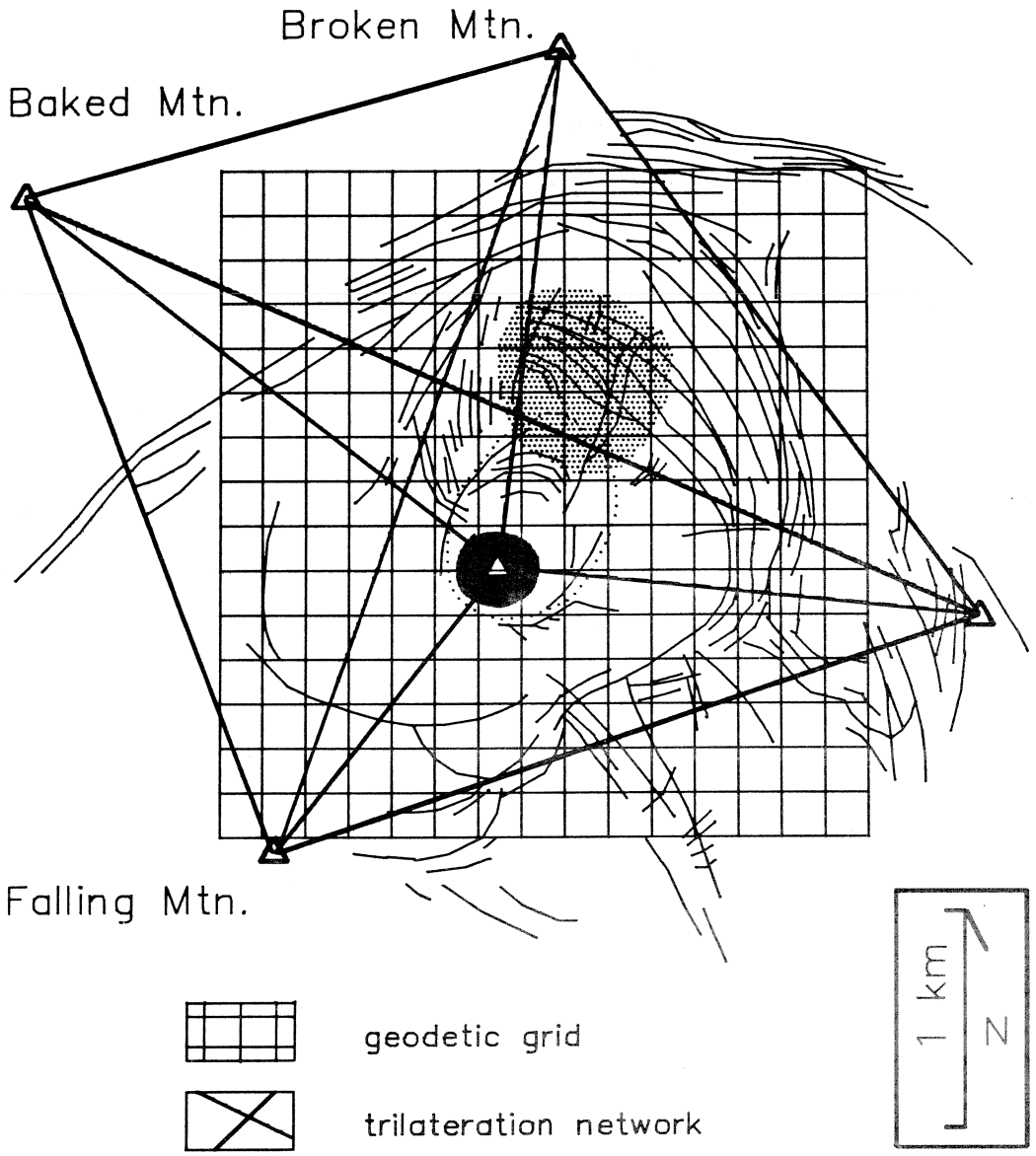


greatest promise for identifying scientifically important aspects of the vent. They represent a continuation, but in a more thorough and coordinated fashion, of the kinds of scientific investigations that have been conducted in the Valley since its discovery. They have scientific value independent of the drilling program, and so will represent an important advance in knowledge even if the subsequent drilling is not approved.

Geodetic* measurements (U.S. Geological Survey)

A surveyed network, or grid, covering the vent region will be established during the pre-drilling phase of the project so that geological and geophysical observations can be made at common points and readily compared. The grid (Fig. 20) will consist of points spaced 200 m (660 ft.) apart on a 3 km x 3 km (1.8 x 1.8 mi.) square (225 points). The points will be marked with wooden or plastic stakes, and all but 16 of the markers will be removed after about 6 weeks, at the completion of the initial geophysical survey. The remaining 16 will remain in place during the course of the 5-year project. They will be buried below the surface so as not to be visible and tagged with magnetic locators. Their purpose will be to see if changes in position, gravity, or the magnetic field (the magnetic locators will be removed for these measurements) are occurring in the vent area. The ground in active volcanic areas commonly shifts due to movement of magma or cooling of the volcano. The position of points on the grid will be known to within a few centimeters (about 1 inch). This is probably larger than changes that are now occurring in the vent. Therefore a more accurate network, that can detect changes of a few millimeters (changes of about a tenth of an inch) will be set up. Four benchmarks, such as the USGS uses routinely in surveying for topographic maps, will be installed on solid rock outcrops surrounding the vent and one within the vent on Novarupta Dome. Distances between the benchmarks will

Figure 20: Location of surface investigations proposed for Project Year 1 (Fig. 19) to define the vent. Curved lines denote the vent fracture system, as in Figure 10. The surveyed grid pattern will be used to co-locate subsequent gravity, magnetic, and heat flow observations. The trilateration network will detect relative horizontal surface motion as small as a centimeter, reflecting crustal readjustment from the 1912 event, continued cooling, and/or magma flow. The grid is an array of small temporary markers. The trilateration network consists of standard, permanent USGS benchmarks affixed to outcroppings of solid bedrock.



be measured each year with an electronic distance measuring (EDM) device that uses a light beam. Atmospheric conditions needed to calculate distance are measured by simultaneously flying a helicopter along the path of the light beam. These repeated measurements of the network, combined with gravity measurements, should allow us to determine what is causing ground movements. Knowing this will help us understand what is happening beneath the volcano.

Establishing the grid and the benchmarks will require 2-3 weeks for a 3-person team, working on foot. Surveying the benchmark network will require 2-3 days of helicopter support each year.

Structural mapping and modeling (Stanford University)

Large cracks, some forming cliffs over three meters (ten feet) high, are the main indication of the position of the vent. Study of these cracks (Figs. 9 and 10) will help us relate surface features to major subsurface structures. In particular, we will determine whether the pattern of fractures in the Novarupta basin is best explained by shifting and compaction of deposits of volcanic debris that filled and covered the vent, or by uplift and collapse of the ground due to subsurface movement of magma. Results from similar studies have shown that mapping of surface structures is a valuable tool for interpreting the nature of shallow intrusions (Pollard et al., 1983; Fink and Pollard, 1983).

We will carefully map all the fractures in Novarupta basin and will document the amount of movement by measuring the vertical or horizontal separation on the fractures. This work will involve a backpacking party of 2-3 people for a duration of about 6 weeks. In order to determine the position of pumice layers in the fracture cliffs, shallow (0.5 m) trenches will be hand-dug where the layers are covered by loose debris, and carefully filled in before the party leaves the site. In order to understand how fractures form

from compaction of ash alone, we will study the fractures at the edge of the ash-flow sheet near Mageik Lakes.

Once we understand the fractures in the field we will use models of clay and sand in the laboratory to understand how fractures may have formed in the Novarupta basin. Clay and sand are chosen to model elastic and loose materials, respectively. Our model studies will take into account gravity and magnetic data and should be instructive in identifying additional features to measure in the field, in interpreting field data, and in formulating theories of how the fractures formed.

Magnetic and gravity surveys (University of Alaska)

Precise measurement of the magnetic and gravity fields at the grid points in the Novarupta Basin can tell us much about the vent. As in the case of drilling, the uniformity of the rock outside the vent and the expected geometrical and structural simplicity of the vent should make the results readily interpretable. Both magnetic and gravity techniques depend on the likelihood that the properties of the contents of the vent will be different from those of the vent wall material, causing measurable differences in the gravity and magnetic fields at the surface. For example, intrusions within the vent should be much more magnetic, and pumice filling the vent should be much less dense than the sedimentary rock of the vent wall. Very hot rock and magma are not magnetic at all, so a hot, but cooling vent should show a strengthening of the magnetic field. If the vent is also subsiding because of cooling, it should show a strengthening gravity field. The gravity and magnetic experiments will use the surveyed grid. In addition, airborne magnetic measurements will be made at various altitudes above the vent. This will provide improved information on the depth of vent structures that give rise to variations in the magnetic field. Measurements will be repeated

annually during the course of the project at the 16 key grid points and at five neighboring bench marks. These repeat measurements will be compared with the first year's data and that obtained in much earlier studies to look for evidence of changes due to movement of magma or cooling.

The high precision gravity survey combined with multi-level magnetic data should help to answer the following questions:

1. Is there geophysical evidence for the geologically inferred caldera at Novarupta?
2. If so, what is the size and shape of the caldera? Is it a flared funnel produced by explosive excavation and slumping? Or is it a cylindrical vent similar to Mt. Katmai, produced by erosion of roof rocks by magma or by vertical collapse along a circular fracture?
3. What is the density and nature of the material that now fills the caldera? Are there large sunken blocks of dacite from Falling Mtn. and/or of Naknek Formation siltstone from Broken Mtn.?
4. Are there other near-surface intrusions besides the feeder for Novarupta?

Prior to going to the field, the magnetometer and navigation gear needed for airborne measurements will be made compatible with the recording devices and set up to allow easy transfer of the data to the computer systems to be used. In the field, tasks will include setting up the navigation stations, taking the ground-based gravity and magnetic readings, flying the airborne survey, recording the daily changes in the magnetic field, and sampling for magnetic property and density measurements. It is anticipated that approximately two weeks will be spent in the field by a three-person team, thus giving a margin of time for bad weather days. Work will proceed on foot,

except for helicopter support to take equipment into and out of the valley and one day of helicopter flying for the airborne survey.

Seismic survey in the vicinity of Novarupta (U.S. Geological Survey)

Interpretation of seismic waves (ground vibrations) is another way to gain information about subsurface geologic structures. In these studies, waves are artificially sent from a source through the ground to a receiver. The time required for the waves to travel to the receiver tells their average speed. The waves travel through different rocks at different speeds, so that the group of waves arriving at the receiver give us information about the types of rocks they travelled through. Finding the combination of rock types and shapes of deposits that best fit the speed and path of the waves can help us understand the geology below the surface. Seismic techniques can therefore provide important information about the structure of the 1912 vent and ash-flow sheet.

We will use a very simple, hand-carried system to do this. The wave source will be a 20-liter (5 gal.) water can dropped from a 3-m-high (10-ft.) tripod. The receiver will be a string of geophones (earth microphones) on a cable, attached to an electronic recording device. The first goal will be to determine the thickness of the ash-flow layer at the proposed drill site in the upper valley. We will make observations along three lines, each about 0.5-1 km (0.3-0.6 mi.) long, at this site. The second goal is to identify the wall of the Novarupta vent. If the vent is funnel-shaped, we should be able to determine the slope of the side of the funnel. To do this we will run several lines radially outward across the region where fractures indicate the vent wall should be. If we succeed in locating the edge of the vent, we will trace it around the basin as far as possible. The third task is to perform two perpendicular traverses across the Turtle to see if there is a buried block or intrusion.

This study is designed to be inexpensive and flexible. The work involves a two-man team proceeding on foot for a few weeks. Helicopter support will consist of transporting equipment into and out of the valley.

Resistivity survey (Lawrence Livermore National Laboratory)

It is desirable to obtain water for drilling in the vent from a centrally located well. Knowing where groundwater is may also help to show us vent structure and how the vent is cooling. Water-saturated rocks are more conductive (less resistive) than dry ones. As a result, electrical measurements on the ground surface can often locate groundwater.

We will use two techniques to determine resistivity at depth, and hence the location of ground water. The first will be used to study large areas in reconnaissance fashion. It consists of transmitting low-frequency radio signals between two 1-in-diameter loop antennas. The antennas are hand-held by a two-member survey team. The second technique gives better depth information, and will be used in small areas of greatest interest. It consists of sending an electrical current between a pair of 35-cm (14 inch) steel electrodes driven into the ground, and measuring the induced voltage at another pair of electrodes.

We will first try these techniques near the upper River Lethe, where we know that groundwater is present, and then move toward the vent where we wish to locate groundwater. The survey will require a two-person party working on foot for 2-3 weeks.

Heat flow survey (Sandia National Laboratories)

The amount and distribution of heat flowing from below the surface in the vent region is important for understanding how the vent is cooling and what conditions are like at depth. The rate at which heat is flowing will be measured with 5 cm x 5 cm (2 in x 2 in) pads that electronically measure the

temperature difference between their two surfaces. The sensors will be placed 0.6 m (2 ft.) below the surface in hand-dug holes, deep enough to avoid fluctuations due to day to night temperature changes. Seasonal effects will be taken into account. Measurements will be made at selected points in the surveyed grid and at more densely spaced points on warm areas, for a total of about 100 observations. After each measurement, the surface that was disturbed by digging will be carefully smoothed. The field portion of this task requires a three-week effort by a three-person team working on foot.

Airborne multispectral observations (Jet Propulsion Laboratory)

All objects and surfaces emit radiation, but unless the material is very hot (such as red-hot or white-hot), this radiation is not visible. New technology allows invisible, infrared radiation to be measured from aircraft and used to determine the temperature of the ground surface of an active volcanic area, with a sensitivity of $0.1^{o}C$.

A continuous thermal map of all the relevant Katmai deposits and structures will provide an unprecedented opportunity to integrate the series of in-ground measurements with airborne measurements to give a virtually complete and instantaneous estimate of the temperature conditions of the upper part of the vent system. These observations will be supplemented by other instruments on the aircraft operating at high resolution and over the full range of visible light and near-infrared wavelengths. The full multispectral remote sensing characterization of the Katmai area at high resolution may reveal structures, eruption deposits, and alteration zones that surface geologic studies and conventional aerial photography have missed.

This task will produce maps of the valley and vent basin displaying surface-temperature contours and spectrally distinguished geologic units. We will combine the surface-temperature and shallow heat flow observations to

produce a map of heat flow in the vent basin and an estimate of total heat output of the system.

The observations will be made by flying a fixed-wing aircraft over the Valley, under the auspices of the NASA Aircraft Research Program.

Surface Study of the 1912 deposits (U.S. Geological Survey)

The total volume and the proportions of rhyolitic, dacitic, and andesitic magma in the 1912 eruption are known only within rough limits (Hildreth, 1983, 1987). It is important to refine these values because they are important to understanding of the dynamics of eruption and the temperatures and volatile conditions within the vent. Drilling through the thick part of the ash-flow sheet in the upper Valley of Ten Thousand Smokes, discussed in the next section, will greatly improve our estimates of its volume and composition. The other major uncertainty concerns the volume and rhyolite-dacite-andesite proportions of the downwind ash and pumice fallout, which may represent as much as half of the total volume erupted. Although our studies of the sequence of eruptive pulses, their particle sizes, and their crystal-rock-glass proportions are well underway (Fierstein and Hildreth, 1984, 1986), the data are mostly from in and near the Valley, whereas remote areas of fallout are poorly represented. Our downwind data set will be expanded by means of boat traverses and opportunistic use of helicopters assigned to other tasks. A boat traverse of the Kodiak-Afognak Islands side of Shelikof Strait was completed in 1987 and of the mainland side in 1988.

The principal eruptive phases were also accompanied and separated by near-vent blasts, andesite-bearing fallout, and thin, hot ash flows that left deposits exposed only on clifts, ridge crests, and gully walls within about 3 km (1.8 mi.) of Novarupta. Such deposits provide information, not well-recorded in the regional geology, about the pulsating nature and energetics of

the eruption sequence. Study of the detailed characteristics of these deposits, initiated in 1986, is being continued in 1988 and 1989 with the aim of completion prior to drilling. Particle-size and porosity investigations seek to define intervals of open-vent and choked-vent activity, wall-collapse events, and pulses caused by flow of ground-water into the vent. We have already established that rock fragments in the initial ash-flow deposits were excavated almost entirely from bedrock at depths shallower than 1500 m (5000 ft.); the later dacite deposits, however, are poor in bedrock fragments because their vent (less than 500 m wide) was located inside the larger vent of the earlier eruptive phases (Hildreth and Fierstein, 1986; Hildreth, 1987). Although more than 0.2 km^3 of vent-fill was re-ejected by the later outbursts, there was not any substantial additional excavation of the bedrock.

Subsequent integration of the surface data with that from drill cores will permit us to reconstruct how the vent was excavated. If a large bedrock "deficit" relative to the size (volume) of the vent were to be indicated, then some amount of subsidence or collapse would be suggested to account for "missing" material. In addition, mapping the distribution of ballistic ejecta (many pieces larger than one meter across) will provide a basis for estimating the velocity with which material was ejected from the vent.

SCHEDULE FOR PREDRILLING INVESTIGATIONS

The main field effort in the vent-definition investigations will occur during the summer of the first project year. This effort will be carefully coordinated to minimize the number of people in the field and the duration and cost of helicopter support. All travel within the Valley, and most travel by investigators into and out of the Valley, will be on foot. Equipment and supplies will be flown to Baked Mountain hut at the start of the field program. This will require about 5 flights over a one- to two-day period. The

helicopter will then provide three days of support for the establishment of the survey grids. It will also fly the aeromagnetic survey. Once these operations are complete, the helicopter will leave and the survey team will proceed with establishment of the 3 km x 3 km grid. The intersections on the grid will then be occupied by the gravity and magnetics team and the heat flow survey team. In addition, the seismic team and the resistivity team will in part locate themselves by reference to the grid. The total duration of the observations requiring the grid will be about four weeks. At the end of this period all grid markers will be removed except for those required for repeat measurements, as discussed previously. The helicopter will return and fly out the geophysical equipment in approximately 5 flights over a one or two day period. The entire operation is expected to require about 6 weeks.

Data from these investigations will be analyzed following the field operation. Since the field work will occur toward the end of the first fiscal year of the project (government fiscal years run from October 1 to September 30), analysis and interpretation will be a major activity during the second year. In November, or about three months after the field work is complete, a meeting of the researchers will be held to develop a model for the vent consistent with all available data. At this time, any inadequacies or inconsistencies in the data that may require additional surface observations will be identified, and any additional needed observations planned for the next summer. Because this will be the first meeting of investigators since they have analyzed their data, we anticipate that there will be substantial differences in approaches and interpretations and that alternative models will have to be considered for some data sets in order to formulate a unified view of the vent. A second meeting, tentatively set for February of the second year, will conclude consideration of problems identified at the previous session

and, barring unexpected problems with the data and interpretation, will formulate a best-fit model for subsurface structure. The likely ways in which improved understanding of vent structure will affect the drilling plan are discussed in the next section. Field operations during the second year will consist of reoccupation of the network and selected gravity and magnetic stations, and a small-scale drilling operation.

DRILLING OPERATIONS

The drilling program is designed to provide representative samples of and measurements in the important underground igneous environments of the 1912 vent and ash-flow sheet. Interpretation of the drilling samples and measurements will be greatly aided by the perfect state of preservation of the volcano, by the uniformity of the host rock, and by the likelihood that all igneous rocks intersected will be products of the 1912 event. The absence of fragments of the sedimentary bedrock in the ejecta from deeper than about 1 km (Hildreth and Fierstein, 1986) indicates that the vent structure is within about 1 km of the surface. The inferred thickness of the ash-flow sheet is less than 200 m (Curtis, 1968). Thus, most of the system lies within easy reach of a small drill rig (Fig. 21). It is apparent from consideration of the scientific objectives that the following subsurface environments are of primary interest for investigation by drilling (Fig. 22 and 23):

1) Middle-distance in the ash-flow sheet (5 km; hole #2): At this distance, the ash-flow sheet should contain only major layers from large eruption pulses (not small near-vent deposits), providing an uncomplicated record of the main ash-flow sequence. Fumarole deposits are well-developed at this distance, but cuts made by streams permit us to see only to depths less than about 10 m (33 ft.).

Figure 21: A core-drilling rig of the kind needed to drill the proposed holes. The equipment requires a 2-to 3- person crew, and is operated in shifts around the clock in order to keep the hole cool and stable. The hole is cut by a ring-shaped diamond-impregnated bit, usually 8-13 cm (3-5 in) in diameter. This leaves a cylinder of rock, the core, at the center of the hole. The core is retrieved at 1.5-3.0 m (5-10 ft) intervals.

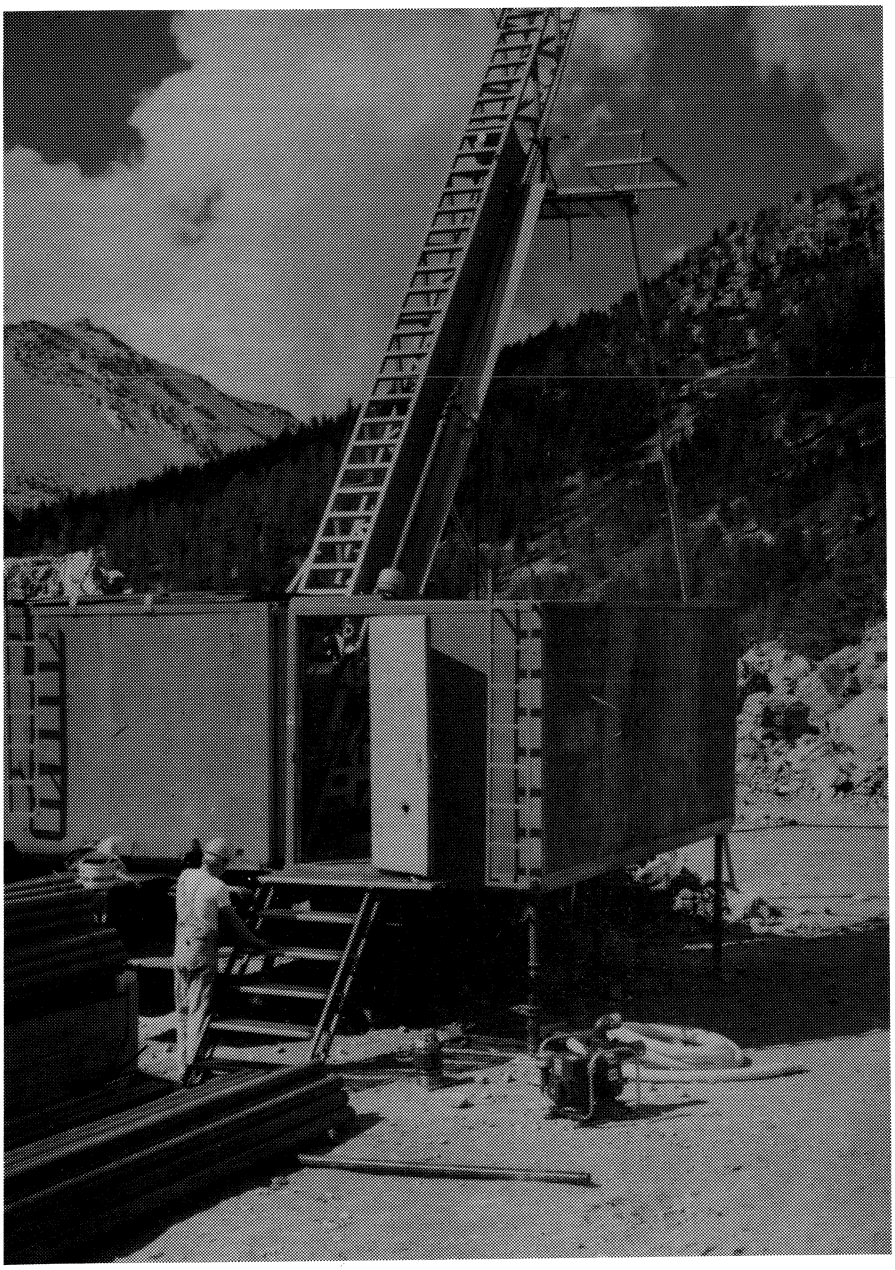


Figure 22a: Schematic cross section of the vent and ash-flow sheet along a curved line containing the two drilling sites and the Turtle, illustrating geologic objectives of the proposed holes.

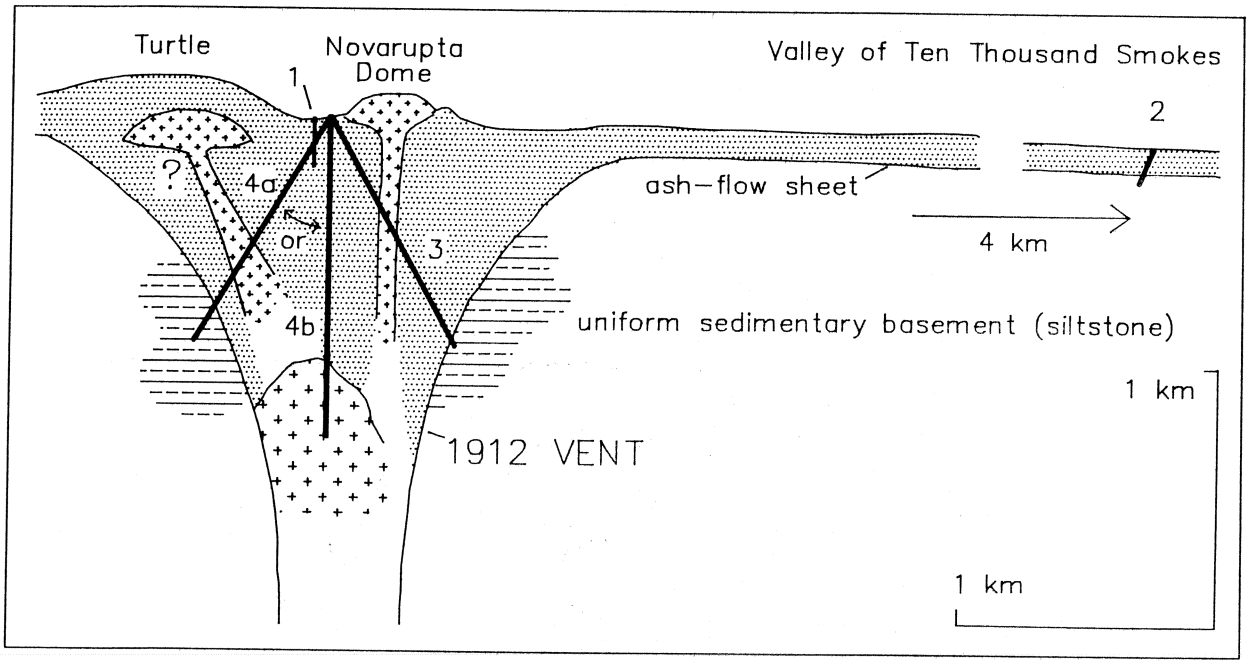
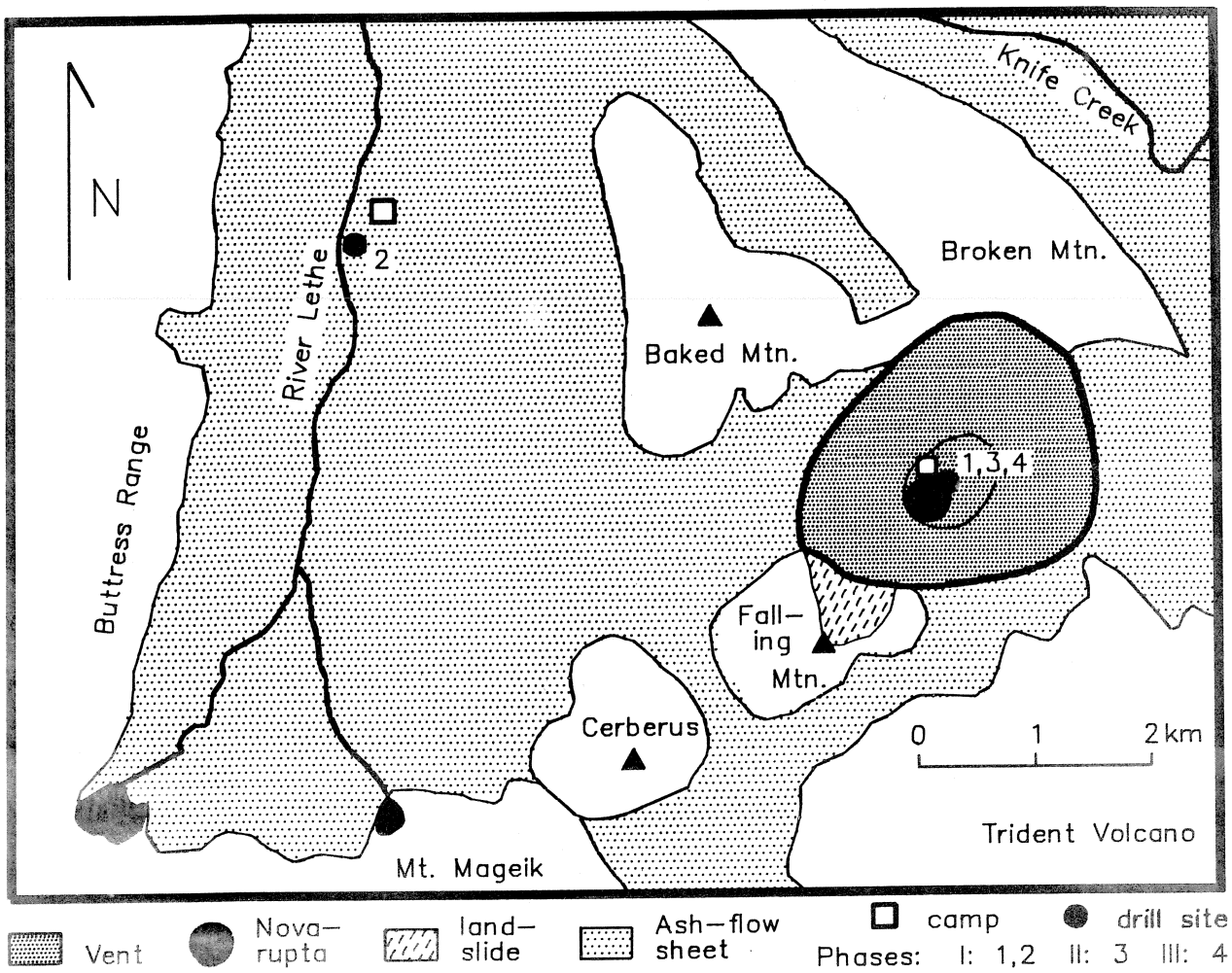


Figure 22b: Summary of proposed holes.

SUMMARY OF PROPOSED HOLES

	Hole	Location	Depth	Orient.	Objectives	Basis for siting
Phase I	1	center of vent	200 m	90°	Water well Drilling conditions Vent center stratigraphy	Proximity to holes 3+4
	2	5 km from vent	200 m	60°	Complete mid–distance ash–flow sheet section Fissure fumarolic deposits	Distance from vent Distribution of fumarolic deposits "Sand line" development
Phase II	3	center of vent	1000 m	60°	Novarupta conduit Center to wall vent stratigraphy Vent conditions Deep vent wall	Position and structure of Novarupta Dome
Phase III	4a	center of vent	1000 m	60°	Structures (intrusion?) beneath Turtle Center to wall vent stratigraphy Vent conditions Deep vent wall Measure vent diameter with holes 3+4	Position of Turtle
	or					
	4b	center of vent	1200 m	90°	Intrusive equivalents of pyroclastic units Deep structure and stratigraphy Highest temperature regime	Previous drilling results, surface geophysics

Figure 23: Map of the upper River Lethe valley and Novarupta basin, showing locations of proposed holes.



2) Vent margin (holes #3, 4a): Intersecting the vent wall with drill holes will allow us to determine size and shape of the vent. Evidence of bending or breaking in rocks of the vent wall, together with distribution of rock fragments in the ejecta and vent fill, will reveal how the vent was formed. Sampling of deposits adjacent to the wall will help determine when during the eruption the vent was excavated to its maximum size, or alternatively, when the vent was undergoing collapse. The expected low temperature and solid rock of the vent wall provide a good place for detecting faint seismic signals with geophones.

3) Vent center (holes #1, 3, 4a or 4b): This region contains the intrusive feeder of the Novarupta dome and perhaps other intrusions. It is probably the hottest part of the volcano. It is also anticipated that the vent is a concentric arrangement of nested funnels, with youngest material to the inside, and oldest material on the outside. This zonation would reflect the gradual narrowing of the vent following achievement of maximum size during ash-flow emplacement and/or eruption of the first regional pumice layer. If so, all the major deposits in the vent can be sampled by slanting a hole outward from its center.

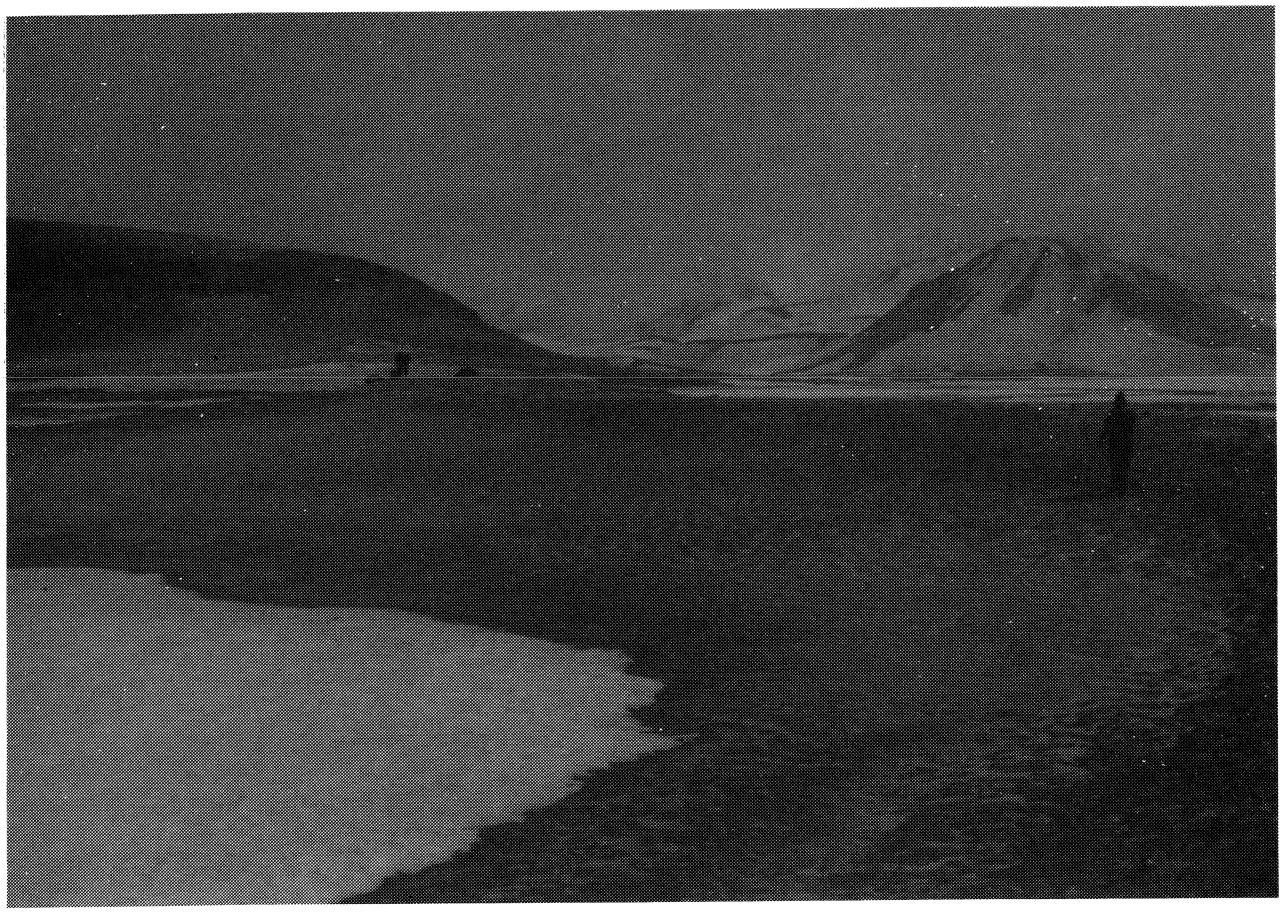
Three factors must be considered in planning the drilling. First, the area of interest is entirely within a reserve that is both a National Park and Wilderness Area. Conduct of the operation in a manner that is environmentally sound, as specified by the National Park Service, is of foremost importance. Drilling is possible in this restricted area only if it is for purely scientific objectives that cannot be accomplished elsewhere and if it does not endanger the physical, biological, and recreational values of the Park.

Accordingly, the duration and size of the field operation will be held to the minimum required for attainment of the scientific objectives, and the site will be meticulously restored to its original condition. Second, Katmai is a remote area. While drilling operations in comparable environments are carried out by industry routinely and should pose no special problem, transportation costs will be similar to those of the drilling itself. Third, the drilling conditions (rock types, temperature, underground fluids) are poorly known, because drilling into a large young vent has never before been attempted, and because the system is so young that only its uppermost portion is exposed. As a result, the drilling program needs to be flexible and to be phased.

Figure 20 shows the plan for drilling and summarizes the objectives of each hole. Four holes will be drilled to depths ranging from 200 m (700 ft.) to about 1200 m (4000 ft.). The mid-distance ash-flow sheet site (#2; Fig. 24) was chosen because of its fumarole deposits and surface evidence that this part of the sheet is welded. The ground surface at this site is loose pumice and ash that is frequently moved by water and wind. There is no vegetation.

The most clearly defined drilling target in the center of the vent is the intrusive feeder of Novarupta Dome, presumably marking the center of the vent complex. The existence of a northwest-trending fracture system adjacent to the dome suggests that the dome's feeder may follow that trend. Therefore the hole to reach the feeder should slant in from either the southwest or northeast, perpendicular to the trend. The latter choice is, in view of the off-center position of the dome in the vent basin, more likely to reach the vent wall. It also affords a site that is sheltered and on flat ground on the floor of the central crater (Fig 7). The ground surface is coarse pumice that is actively falling off the Turtle. There is no vegetation.

Figure 24: View of the vicinity of the site for the proposed ash-flow sheet hole. The site is located in the upper portion of the River Lethe valley. There is no vegetation, and the surface is loose pumice and ash. The low ridge in the foreground is the rim of a small crater, formed shortly after emplacement of the sheet when water from a buried stream or snow gained access to the sheet's hot interior.



Predrilling geophysical investigations may suggest the depth at which this slant hole will reach the wall. Given that the wall is intersected, the best way to measure vent diameter at that depth is to slant a hole (#4a) from the same site on the opposite direction, under the Turtle (Fig. 20). Because holes #3 and #4a should pass outward through the wall of the inner vent, whose surface expression is the ring of volcanic debris surrounding Navarupta Dome, they should provide a measurement of the diameter of that structure as well. The best way to reach the hottest and, presumably, main intrusion below the level where magma was fragmenting to produce pumice and ash is to drill a hole vertically down from this central site. Whether #4 a or b is drilled will depend upon results from hole #3. Drilling multiple holes from this site makes sense geometrically in view of the expected funnel shape of the vent and minimizes the area that the operation will occupy.

DRILLING SCHEDULE

An important practical issue is that of supplying water to the drill rigs. Options are to pump water several kilometers from either Mageik Lake or Knife Creek, or to drill a water well. Pumping the water is possible but requires multiple heaters enroute and a significant maintenance effort (Pisto and Lysne, written communication, 1987). Having a central water well would greatly decrease the area occupied by the operation and the level of effort that maintenance of the water supply will require. The abundant precipitation and anticipated high permeability of the vent suggest that water could be obtained by this method. It is necessary, however, to ensure an adequate water supply before the deep-drilling phases are begun. Therefore, a small initial drilling operation is planned. This operation will occur in September of the second project year, after the main visitor season but while there is still abundant surface water. In addition to obtaining a central water supply, this

drilling (hole #1) will provide valuable information about where to set and cement casing* in the deeper central vent holes, an important engineering consideration if high temperatures are encountered. The best site, therefore, is the site from which holes 3 and 4 will be drilled. Drilling the ash-flow sheet hole (#2) is best done as part of the water-well operation when the adjacent River Lethe is flowing and snow-free.

April, May and early June appear to be the most desirable times for the deep-drilling activities. This time period avoids the main visitor season (July and August), coincides with the most stable weather period, and because of snow cover minimizes disturbance of the ground surface by foot traffic and problems from airborne pumice and ash to workers and to helicopter operations. Having two deep-drilling operations, phases two and three, appears to be the best approach, and follows recommendations of the Continental Scientific Drilling Review Group. These phases are scheduled for the third and fourth project years. In the second phase, the slant hole under Novarupta Dome (#3) will be drilled. The final hole (#4a or 4b), whose target position will be determined by earlier drilling and downhole geophysical experiments, will be drilled in the third phase. It will be intended to reach the deep (and presumably hottest) portion of the vent or the igneous structures and vent wall beneath the Turtle.

A small team of experienced scientists will be present at all times at the drill sites during drilling operations to properly box, label, and log the core as it is extracted from the holes and to conduct experiments in the holes. It is anticipated that a National Park Service ranger will also be present to monitor compliance with environmental regulations, to stop the operation if hazards to the environment arise, and to manage any encounters with bears.

Mobilization of each of the three drilling phases will be by ship or air to King Salmon, and by helicopter from King Salmon to the site. Routine support of the operation will be by daily helicopter flights from King Salmon. Excess drilling fluids and other waste will be returned to King Salmon for later disposal in an environmentally sound manner outside the Park. Personnel will walk to the drill sites along designated paths from a nearby camp. All holes will be plugged and abandoned in May of the fifth project year in a manner acceptable to the National Park Service and all evidence of the operation removed.

Because the drilling will result in a very large increase in basic knowledge about the 1912 eruption, we anticipate that it will be of interest to visitors to Katmai National Park. Therefore, we will write, publish and annually update a general interest booklet concerning the predrilling and drilling results for distribution to the public by the National Park Service. Such a booklet was provided to Inyo National Forest during drilling of the most recent Inyo research hole in California (McConnell and Eichelberger, 1987).

INVESTIGATIONS OF CORE

The drilling proposed here will produce approximately 2.5 km (1.5 mi.) of core. Geochemical and physical investigations of the core are presented here proceeding from the most general and descriptive to more specialized techniques. The major portion of the geochemical work is divided into three main themes that differ generally in analytical approach and in the scientific issues they address. However, each theme relies on data developed under the other two, so the entire geochemical program will be carefully coordinated.

Description of core [(Sandia National Laboratories (SNL), South Dakota School of Mines and Technology (SDSM&T), U.S. Geological Survey (USGS)]

The initial logging of the core will be conducted under cramped conditions in the field. It will be difficult to compare core from different parts of a hole during the drilling. Thus, a more detailed description and mapping of the core will be undertaken at USGS facilities in Anchorage immediately after its arrival there. Large sections of the core can be laid out for comparative study, and prelimary interpretations developed. Emphasis will be placed on rock types and the contacts between them, and, in the erupted material, the degree of welding, bedrock fragment content, rhyolite-dacite-andesite proportions, amount and condition of glass, nature of alteration, and orientation and distribution of hydrothermal veins. This logging will be conducted over a 2-3 week period. A summary log and report will be prepared and will form the basis for briefing the various investigators and for developing the sampling strategy. This strategy will be carefully designed to achieve the scientific objectives and to be consistent with guidelines established by the funding agencies. These guidelines recognize core obtained in research drilling as a national treasure that must be archived for future study as well as fully investigated by currently available techniques. One investigator from each of the laboratories involved in the core studies will come to Anchorage to review the report and the core and to receive samples. The sampling will be supervised and documented by the Core Curation Office.

Quantitative textural analysis (Princeton U.)

The textures of volcanic rocks (size, shape, arrangement of the crystal grains composing the rocks) reflect the pressure and temperature conditions to which the sample has been exposed, and so provide a record of the history of the sample beyond that available from chemical analysis alone. For example, an increased rate of cooling of magma can yield smaller and more numerous crystal grains, and two periods of cooling may yield two populations of crystals. The amount of water that a magma has lost also affects the way it crystallizes. Because water escapes as magma rises, crystallization behavior changes with depth.

Textural descriptions have long been a basis for classification of volcanic samples. Recent advances in automated image analysis have provided a new tool for quantitative microscopic textural analysis. Volcanic features observable with a microscope include the size, shape, and quantity of crystals and vesicles*.

The Katmai drilling program will provide a unique opportunity to study the evolution of textures in the subvolcanic and volcanic environments. Quantitative determination of crystal size distributions throughout the 1912 vent and ash-flow sheet will permit estimates of rates of crystal formation (nucleation) and growth (e.g. Cashman, 1988) for different parts of the system. The dependence of these rates upon cooling can be determined by comparing samples from different distances from cold boundaries of the system. The dependence upon loss of water and other gases can be determined by comparing samples from different depths. In addition, magma of the 1912 eruption spans a large range of composition; it is thus expected that chemically different samples from physically similar environments will also be

obtained so that the effect of magma composition on crystallization behavior can be studied. Textural analysis will be made using a Compaq-386 computer-based optical image analysis system.

Measurements of the size, shape and abundance of vesicles in samples from different levels of the volcanic conduit will be used to study bubble formation and growth, which depend upon gas content of the magma and on release of pressure during eruption (Sparks, 1978). Pressure on the magma decreases as it rises toward the surface. Bubbles form and gas is released from the liquid rock, as when a carbonated beverage container is opened. Quantitative analysis of bubble textures will be used to: 1) estimate rates of bubble formation and growth; 2) determine where in the system the maximum amount of bubble expansion was achieved; 3) recognize different populations of bubbles representing different stages of bubble formation (e.g. Sparks and Brazier, 1982; Witham and Sparks, 1986); and 4) identify the processes acting to modify original bubble size distributions. Processes that could be recognized texturally include annealing (dissolution of small bubbles and corresponding growth of large ones), combination (coalescence) of numerous bubbles into fewer, larger ones (e.g. Sahagian, 1985), and compaction (welding). The combination of textural studies with measurements of retained magmatic gas contents in the fresh 1912 material and determination of initital gas contents (discussed later) will produce an unprecedented data set for interpreting bubble formation in a magmatic system.

Chemical and mineralogical zonation of the system [(SDSMT; New Mexico Institute of Mining and Technology (NMIMT); University of Alaska(UA)]

The first analytical task is to describe the chemical and mineralogical variations of the system. The first interpretive task is to determine which variations represent original, preeruption variations in the 1912 magma and

which are due the chemical reactions in the hot material after emplacement. In this interpretation, comparison of subsurface compositions with chemical and mineralogical data from fresh surface pumices and consideration of conditions under which minerals form as determined in laboratory experiments will provide guidance.

Bulk composition, that is, the chemical composition of samples large enough (several hundred grams, or about one pound) to represent an entire rock unit, is the most basic of chemical observations. Truly bulk samples of igneous material are not always meaningful, however, as in the mixtures represented by the ash-flow tuff and vent fill that will compose much of the core. These fragmental volcanic units consist of chunks of pristine magmatic material in the form of pumice and abundant pieces of bedrock picked up from the walls of the vent and deep conduit, surrounded by a matrix of much smaller, variably sorted particles of magmatic crystals and glass. Consequently, the relative proportions of each fragment type will be estimated in the core at regular intervals, and representative pumice fragments large enough for analysis will be hand-picked from the fragmental deposits. For the intact intrusions that are intersected by the holes, samples will be taken from the core at intervals that are closely spaced near the intrusion margins and more broadly spaced toward the intrusion centers.

The samples will be analyzed by X-ray fluorescence (XRF) spectrometry. The laboratory at NMIMT is well-equipped for high-precision, high-accuracy analysis of large numbers of samples. The data will serve two important purposes: (1) Establishment of the chemical layering of the vent and adjacent ash-flow sheet, so that the correlation between intra-vent and outflow units can be determined. This correlation will help us interpret how the vent changed over the course of the eruptive sequence. Layering in the ash-flow

sheet will show the chemical sequence of the eruption. Matching, for example, the material adjacent to the wall of the vent with its equivalent layer in the ash-flow sheet will show when during the eruption the vent reached its greatest size. We will also identify the intrusive, unfragmented equivalents of the fragmented erupted units. (2) Determination of the extent of chemical changes associated with the processes of decompression of magma during ascent and subsequent crystallization and hydrothermal alteration.

Understanding chemical and mineralogical changes that have taken place in 1912 igneous material following emplacement and using such information to interpret the changing chemical and thermal environment requires careful comparison of hydrothermally altered and unaltered portions of the system. This can be done by comparing samples from the interior of the ash flow sheet and vent with their quickly cooled equivalents from the surface. Well-defined reactions will indicate, among other things, the movement of gases and interaction with circulating fluids (Ferry, 1984). But definition of the chemical reactions is made difficult by the very small crystal grain size of these rocks. Many of the component minerals cannot be identified with a microscope. X-ray diffraction analysis (reference intensity method) can determine the type and proportions of crystalline phases and glass with acceptable accuracy in very fine-grained materials; such analyses are conducted routinely at SDSM&T. By this method, minerals are identified by their X-ray patterns, even if they are too small to see. Accordingly, a complete survey of the core using the same samples selected for XRF analyses will be conducted using this technique.

X-ray diffraction analysis does not, however, determine the chemical composition of individual grains. Such data contain important information about conditions of crystallization and alteration. In addition, some crystal

grains have within them a chemical zonation (a compositional variation from the center to the edge of the grain) that records changes in conditions during crystal growth. Determination of the composition and zonation of individual grains requires analysis of areas a few millionths of a meter (a ten thousandth of an inch) across and is accomplished by an electron microprobe. This technique will be applied to the core samples in order to interpret conditions of crystallization and alteration and variation in these conditions within the vent and ash-flow sheet. Detailed chemical data on individual mineral phases will also aid in matching intrusions in the vent to their erupted equivalents.

Microprobe analysis will also be used to study how different magmas react when they come into contact. Mingling of chemically contrasting magmas is dramatically shown at Katmai by the banded marble cake-like pumice. This pumice represents material that cooled and solidified almost instantly upon eruption. Drilling will sample mingled magmatic material that stayed very hot for years. By analyzing microscopic points in lines across these bands in the rapidly cooled surface and slowly cooled subsurface samples we can tell what chemical components moved and how fast they moved. We may also be able to estimate how long the different magmas of the 1912 eruption could have been in contact prior to the eruption.

Migration of volatiles* and metals [SNL ; Oak Ridge National Laboratory (ORNL); Southern Methodist University (SMU); Arizona State University (ASU); Stanford University)]

It is clear that dramatic escape of gas and movement of metals occurred during and following emplacement of the 1912 magma. To evaluate the effects of eruptive processes upon volatile (gaseous compounds) and metal migration, it will be necessary to undertake a comprehensive analytical and experimental study of the magmatic and hydrothermal products of the Katmai eruption.

Analytical work will include a detailed chemical (at SNL) and isotopic* (at SMU) characterization of volatiles and trace metals in erupted and unerupted magmatic material and adjacent bedrock.

The distribution of volatiles and trace metals in Katmai samples will be determined using a variety of analytical techniques. For example, water contents of unaltered glasses will be measured down to 0.05 wt.% concentration by Karl Fischer titration, and bulk sulfur, chlorine, and fluorine in glassy and crystalline rocks will be determined at the parts-per-million (ppm) concentration level by X-ray fluorescence and ion chromatography. Bulk analysis for selected trace metals will include XRF and neutron activation techniques, where detection limits vary from parts-per-million to parts-per-billion levels.

We are concerned with understanding how volatiles and metals are released and migrate during three processes, which occur sequentially: decompression (rise of magma), crystallization (cooling of magma), and hydrothermal alteration (circulation of hot water in rock formed from magma). Magma that cooled rapidly to glass records conditions after the first step, fresh crystallized material the second, and altered material the third. To measure the loss of volatiles and metals that occurred during ascent, we will compare the volatile and metals content of glasses from different depths. To measure the loss during crystallization, we will compare the composition of glassy and crystalline samples from near the same depth. To measure changes due to alteration, we will compare altered and unaltered samples.

Because of temperature-dependent sorting of isotopes* and the contrasting isotopic compositions of the different volatile sources, light stable isotopes (naturally occurring, non-decaying isotopes of the light elements H, C, O, and S) provide a powerful method for investigating processes of vapor

separation from erupting magma and the sources of the vapor that permeated the post-eruptive volcanic system. A thorough survey of the core will be conducted to characterize extrusive* and intrusive material in terms of isotope ratios such as $^{13}C/^{12}C$ and $^{18}O/^{16}O$. These ratios are measurably different depending upon whether the volatile components in the rock are of deep-magmatic, shallow-crustal, or atmospheric origin. Moreover, they are changed during loss of gas from the magma during ascent. They are also sorted by prolonged exchange between rock and circulating fluids at elevated temperatures. The resulting data will distinguish regions of the vent and ash-flow sheet that remain pristine, in the sense of showing magmatic isotopic values, from those regions that have undergone high-temperature and low-temperature alteration and contamination with atmospheric water. Detailed analyses of glasses from different depths and different original magmatic compositions will be used to describe evolution of volatiles in the 1912 magmas during decompression and eruption. Careful attention will also be given to the relationship between stable isotope compositions and zones of trace-metal depletion and enrichment in order to identify sources and transport properties of the metal-rich vapors that permeated the tuff.

In order to understand the full history of volatile and trace metal behavior in the 1912 magma, it is important to estimate preeruptive magma compositions with respect to those components. A number of techniques will be used in this task. Glass inclusions trapped within crystals are thought to have been protected from pressure release and hence from gas release during ascent and eruption. Gas release is accompanied by loss of trace metals, as evidenced by analyses of metals-enriched particles in volcanic plumes and of metals-enriched encrustations around volcanic vents. Although inclusions may be different from initial bulk melt compositions, they provide the most direct

approach to estimating pre-eruptive magmatic volatile and trace metal compositions. Trace metals and volatiles in these inclusions will be analyzed using particle microbeam techniques (analogous in concept to the electron microprobe).

Analyses of the glass matrix in surface and core samples will yield post-eruptive volatile and trace metal concentrations in the liquid fraction of the magma. This will show how much of the total metal content of the magma, as revealed by bulk analyses, resided in the liquid portion. We will also characterize the trace metal contents of secondary oxides and sulfides in the fumarolic deposits in order to estimate what proportions of the metals lost from melt were deposited locally in fumarolic vents.

An additional approach to determining initial, pre-eruption conditions and compositions of the 1912 magma will be through an experimental simulation of the eruption. The kinds and proportions of crystals and the composition of liquid that together compose a magma are strongly dependent upon temperature and volatile content. Temperature can be reliably estimated from microanalysis of iron-titanium oxide crystals in the rock. Laboratory experiments using 1912 material will be conducted at appropriate temperatures and at pressures simulating the mid- to upper crust (about 10-20 km, or 6-12 mi. depth). These experiments will be used to check whether the hypothesized volatile contents accurately reproduce the mineralogy and liquid/crystal proportions of the 1912 magma.

Once initial volatile compositions and temperatures are well-constrained, model compositions will be heated and pressurized to inferred 1912 starting conditions and then subjected to rapid decompression corresponding to plausible ascent rates. Decompression will be carried to as low a pressure as practical, and will simulate intrusion of the magma into the lower portion of

the vent funnel. This experiment will improve our knowledge of what happens to magma during ascent. In particular, it will show to what extent loss of gas causes crystallization.

When the analytical and experimental approaches have narrowed down the possible magmatic conditions and gas compositions, additional laboratory experiments will quantify the rates of trace metal transport. They will also evaluate the effects of variable temperature, gas composition, and amount of available oxygen upon transport. These experiments will be conducted by continuously flowing gas of appropriate composition and temperature through a reaction tube containing 1912 volcanic material. The tube will extend well beyond the furnace that maintains magmatic temperature, so that it will be progressively cooler with distance from the volcanic sample. Trace (very small) amounts of metals will be deposited on the cool walls of the reaction tube, simulating fumarolic deposition, and will also be trapped downstream in a filter. We will then determine chemical and mineralogical compositions of the deposits as a function of transport distance and temperature. Metals of particular interest include silver, gold, molybdenum, arsenic, tungsten, and platinum-group metals. By varying conditions in the laboratory, these experiments may reveal why trace metal transport is significant in some volcanic systems, such as Katmai, and not in others.

In summary, the analytical and experimental data will be used to model the migration of volatiles and trace metals during and following the 1912 Katmai eruption. We will attempt to (1) estimate the initial, before 1912, magmatic volatile and trace element composition; (2) determine the volatile and metal loss during magma ascent, crystallization, and alteration; (3) determine the source and types of volatile and metal constituents transported in a gas; and (4) measure the rates at which metals migrated following emplacement.

Patterns and history of fluid circulation [USGS; University of California, Riverside (UCR)]

Investigations will be conducted to describe the birth and decline of the hydrothermal system that developed within the Novarupta vent and associated ash-flow sheet. Studies of rocks exposed at the surface have characterized the chemistry and mineralogy of older, initially high-temperature fumarolic deposits and the low-temperature alteration that is continuing in the vicinity of Novarupta Dome today (Keith, 1984). However, many of the minerals that were present in high-temperature deposits at the surface have been altered or removed by weathering. Fumarolic deposits that will be sampled in core obtained during drilling within the vent and ash-flow sheet are likely to be much closer to the character of the original deposits. Also, analysis of the core will provide an opportunity to determine the effects of increased pressure with depth, and to study the transition from fumarolic (hot gas) to hot-water hydrothermal activity.

Stages of hydrothermal activity will be investigated in core by determining the distribution and orientation of fractures that provided fluid pathways, the mineralogy of the fluid-deposited material that fills them, and the nature and degree of hydrothermal alteration adjacent to these fractures. The sequence of different stages, as represented by different kinds of fracture-fillings, will be established by noting cross-cutting relationships (younger fractures cut older ones). The distribution and orientation of fractures and veins found in the core also provides information about the local stresses on the rocks.

Study of fluids (gas or liquid) trapped as inclusions, each a few millionths of a meter (ten thousandth of an inch) in size, in primary (magmatic) and secondary (hydrothermal) crystal grains in the core can provide

information about the evolution of fluids in the cooling system since 1912. We anticipate that this evolution involved a gradual increase in water from the atmosphere, and decrease in gas from the magma. This kind of information is of great value for interpreting general processes of metal ore deposition in volcanic rocks (Bodnar et al., 1985; Hedenquist and Henley, 1985), and may allow comparisons between the simple Novarupta system and complicated mature volcanic ore deposits such as Comstock, Creede, and Summitville (Hayba et al., 1985). A detailed study will be made of different generations of fluid inclusions found within the various veins and fractures to provide information about spatial and temporal changes in temperature, pressure, and fluid composition.

Sampling and analysis of uncontaminated pore fluids from distinct depth intervals within the drill holes is likely to be an important, but very difficult part of the scientific investigation of the hydrothermal system. If conditions are such that the drill holes can be safely allowed to flow during the drilling operation (fluid would be returned to its source by reinjection in a neighboring hole), fluid samples will be collected at the wellhead for chemical and isotopic analyses. More likely, fluid sampling may be possible only after the hole is completed with casing cemented in place and appropriate wellhead equipment installed. Fluid from specific depths could then be sampled by perforating the casing at successively shallower depths and sealing off previously perforated intervals. Downhole fluid sampling equipment will be available that can operate at temperatures up to about 250^{o}C (480^{o}F). If this procedure is used it will occur in the fourth or fifth project year.

Time constraints from ^{238}U and ^{232}Th decay-series systematics (University of Iowa)

The radioactive decay of unstable isotopes serves as a clock that measures the time since the mineral grains in which the isotopes occur crystallized from magma. Suitable clocks are those isotopes whose half-lives (time required for half the material to decay) are roughly the same as the time span since the crystallization event. Traditionally, very long half-life isotopes have been used to date very old (say, hundreds of millions of years) events, and short half-life isotopes used to date very young events. Members of the ^{238}U and ^{232}Th decay series can be used to date magmatic events ranging from tens to thousands of years in age. This novel approach will be applied to surface and drill core samples from Katmai. Analysis of large crystals (phenocrysts) from rapidly cooled glassy surface samples of the 1912 eruption will date the early crystallization of the 1912 magma when it was deep in the crust, and possibly date the time at which the different magma types chemically evolved from a parent magma.

Analysis of crystalline material from the core may date the gradual inward cooling and crystallization of the material in the vent. The age information obtained on the pre- and post-1912 thermal events will help in modeling the cooling history of the system.

GEOPHYSICAL EXPERIMENTS

In addition to providing samples of the subsurface, the proposed holes permit observations to be made at depth.

Well logging [USGS]

The taking of physical measurements by instruments lowered into a hole, geophysical well logging, has become an important part of geological exploration studies in the past decade. Logs were originally associated with

the oil industry, but other applications have used downhole observations in a variety of geological environments. The primary motivation for logging is the ability to obtain a continuous profile of geophysical properties, which can be related to significant geological properties such as porosity (the proportion of void space in a rock) and permeability (the ease with which liquid or gas can flow through the rock). The continuous profile provided by the log answers many questions about how well the results of tests run on a limited number of core samples represent the layers encountered by the borehole, and permit quantitative application of these values to the entire column.

A second important aspect of well logging is the measurement of properties of relatively large volumes of rock still in place. For some property measurements, the sample of rock contained in recovered cores is too small to be representative. The roughly one-meter diameter area over which the typical geophysical tool measures rock properties may provide more representative measurements than can be performed on small-volume core samples, and includes rock far enough away from the borehole wall to be unchanged by stress caused by drilling. Both of these advantages of well logging - the continuous profile of the geologic column and the in-place measurements of rock properties - mean that geophysical logs should be included in the drilling and sampling project whenever possible.

The remote nature of the proposed project and the anticipated unstable condition, elevated temperature, and slanted orientation of some of the boreholes will pose significant obstacles to geophysical well logging at the site. We propose to conduct the geophysical logging program in two stages: 1) obtaining a baseline set of geophysical logs that are simple and inexpensive to run; and 2) obtaining a set of sophisticated geophysical logs if hole conditions make success likely. The first stage would include a conventional

set of portable logs based on state-of-the art "backpack" equipment. The second stage would include a limited set of logs designed to complement the first, and to provide specific information expected to be of use in the core analysis, and in the interpretation of heat and groundwater flow at the site.

Conventional geophysical logs

These geophysical logs involve equipment that is not expensive to replace, so that the risk of losing the equipment can be taken in relatively unstable boreholes, although the risk of obstructing the hole by a lost tool must be considered in the decision to log. None of these logs would have to be run with the drill rig over the borehole, and all of the equipment can be hand-carried onto the actual site, allowing considerable flexibility in arranging the logging program. The expected order in which the logs would be run and the expected contribution of the resulting geological information are as follows:

1. Temperature logs - The temperature probe, which will provide the most important logging data to the project, is run first. Measurements are made going into the borehole to minimize the effects of disturbances in the borehole fluid. If the log is run shortly after drilling, the disturbed condition of the borehole precludes a good measurement of the natural increase in temperature with depth. However, such a profile yields important information about zones of high permeability by indicating where cold drilling fluid entered the walls of the hole. Repeat measurements made after drilling can be used to identify zones of warm water flow and determine the original, undisturbed temperature profile. These observations are critical to the subsequent modeling of the cooling of the vent and ash-flow sheet.

2. Caliper Logs - The conventional caliper log measures average borehole diameter by recording the extension of a set of spring-loaded arms (usually three, but sometimes one or four). The tool indicates zones of borehole enlargement produced during and after drilling. The arms are usually too large to fit into individual fracture openings but usually indicate fracture zones by means of the enlargement that almost always occurs in such fractured and altered intervals. The mechanical forces imposed by the spring-loaded caliper arms can force sections of rock out of the borehole wall, so that the caliper tool is often run in potentially unstable boreholes prior to obtaining other logs. In the case of slant holes, the tool can be modified to remove two of the three arms yielding a useful single-arm caliper log in which the one remaining arm traverses the "up" side of the borehole as the tool body moves along the "down" side.

3. Natural Gamma Logs - The natural gamma log measures the gamma radiation from the rock associated with the natural decay of radioisotopes of uranium, potassium, and thorium and is therefore related to rock composition. Silicic igneous rocks produce high gamma count rates, as do some products of hydrothermal alteration. A sharp gamma activity difference might, for example, indicate the contact with the sedimentary bedrock, at the bottom or margin of the 1912 igneous rocks.

4. Electrical Resistivity Logging - Electrical properties provide an independent indicator of rock type. Here the natural contrast in electrical conductivity among crystalline rock, porous pumiceous rock saturated with water, and electrically conductive clay minerals

from hydrothermal alteration will provide a readily interpretable profile along the borehole.

5. Fluid Resistivity Logs - The fluid resistivity log contains an electrode set exposed at the bottom of the tool in order to make direct measurements of the electrical conductivity of the fluid in the borehole. This tool would only be of use in cases where flow into or out of the borehole involves fluids of distinctly different conductivities. This is not very likely in general, but we have occasionally found such cases.

If the holes must be cased prior to logging due to unstable conditions, then only the temperature and natural gamma logs can be run.

Advanced Geophysical Logs

Because of the more involved requirements for sophisticated logging, the primary emphasis here will be on flexibility. A number of high-technology logs offer the possibility of collecting important information about rock types and permeability, so that the potential contribution of such logs has to be seriously considered. Yet the expense of preparing to run such logs is much greater than in the case of conventional logs, and could be wasted if borehole conditions prevent their use. Here we seek a compromise between reducing costs and enhancing results. The two most important logs for the Katmai project are:

1. Televiewer Logs - The televiewer produces a "picture" of the inside of the borehole from the reflection of sound waves. The tool is very useful in identifying layers, intrusions, and fractures. It yields the best layer resolution of all the logging tools that could be run on the project it requires an operator with considerable skill in setting up the equipment and in the fine art of tuning the

tool. We almost always find that some kind of field repairs are required. The length of the time needed to run the tool also requires a relatively stable hole. Yet the importance of the televiewer in solving puzzles produced by lost core, locating zones of high permeability, and determining the orientation of intersected veins and fractures makes it valuable.

2. Heat-pulse Flowmeter Logs - The flowmeter provides very sensitive measurements of vertical flow in the borehole. Measurements can be made quickly. We have used the tool to identify individual fractures that produce flow during simple pumping tests. Because of its sensitivity, pumping rates of less than a gallon per minute can be used. Such rates can be achieved by drying part of the borehole, or by adding a small amount of water to the upper casing.

Logging Operations

Tools for both the conventional and sophisticated logs will be kept on site during drilling operations. An experienced 2-person logging team will be on site when the need to case is anticipated, so that logs can be run prior to casing. If hole conditions permit, logs will be run at about the mid-point of the deeper holes, prior to casing, and at final depth (the first cased interval will likely not be logged). The conventional logs will be run first to assess any problems with the hole. We anticipate that the most complete set of logs will be run in holes #1 and #4b, as these holes will be vertical. Some logs may be confined to the upper portion of the holes by high temperature, as only the temperature probe can be used above about 150°C (300°F). However, even at shallow depths data on fluid flow and fracture distribution will be important.

Borehole microseismicity array [University of Southern California (USC)]

The movement of either molten or solid rock produces vibrations that can be measured. Two important aspects of the Katmai system can be investigated by placing seismic sensors at the bottoms of the drillholes for a period of "listening" for seismic waves. First, the amount of remaining activity induced by temperature changes can be measured. Second, if the seismic activity is suitably distributed, the approximate shape of the vent walls can be determined.

With recent developments in volcanic seismology, we are beginning to understand the different types of seismic events associated with volcanoes and geothermal sites. For example, seismic signals may be generated from cracks associated with cooling of intrusions that are still at high or magmatic temperatures. Aki et al. (1978) and Chouet (1979) observed numerous seismic events in the partially frozen lava lake in Kilauea Iki, Hawaii, and found that they are occurring most vigorously above the presumed body of molten rock. In fact, among various geophysical data collected for studying the magma, the location of the seismic event gave the best indication of the extent of the magma body.

The instruments to be emplaced are to be relatively inexpensive, and unless heat deteriorates the sensor, will last for years. If bottomhole temperatures above 125°C to 150°C are encountered, it is simpler to sacrifice the instrument, and if desirable reinstall a new unit above the first, than to deploy a complex heat-proof unit. Placement of the sensors in the wall of the vent is advantageous from the standpoint of temperature, as this should provide the coolest environment at depth (e.g., Fig. 18). It is standard practice to greatly weaken the armored cable at the cable head in order to be able to clear the hole of cable and to reuse the cable. We do not expect to

recover the instruments. The sensors will be installed in phase with the drilling: hole #3 in year 3, hole #4a or 4b in year 4, and hole #1 in year 5, when water is no longer needed.

The channels of seismic data (3 vertical components and 6 horizontal components) will be transmitted via radiotelemetry from Katmai to the Kenai Penninsula where the data will be put on the regional microwave link to the University of Alaska (UA). UA maintains a large seismic data logging facility with the capability of data networking access by USC (and other users in the United States). The existence of the computer data network eliminates potential delays and costly hard-media handling procedures. USC will be responsible for timely processing of the data.

The new element in the data link, the Katmai-Homer radio transmission link, will be installed jointly by USC and UA (by subcontract through USC). USC, which runs an extensive radio-linked seismic net in southern California, will acquire and install the ground equipment (compact environmental packaging, batteries, lightning buffered amplifier-filter-VCO-radio stages). UA will advise on the telemetry set-up (number and location of stages) and will interface the Katmai data stream to the Kenai-Fairbanks dataline. This equipment will be removed at the completion of the project unless its capability for predicting and monitoring eruptions is deemed useful to the Park.

Analysis of geophysical data and refinement of the vent model (University of Alaska)

As the project proceeds, the growing body of data will provide new information about the structure of the vent. It will be important to reevaluate the models for the vent after each field operation in order to guide the next stage of drilling and to arrive at a final view of vent

structure that is consistent with all observations (drilling, geophysics, geology). The initial model of the vent will be based on surface geophysical observations but will involve enlightened guesses as to properties of materials at depth in the vent and geological judgments as to what geometries are reasonable. There will be large uncertainties. For example, the unknown relative proportions of vent-fill material and intact intrusions in the vent make a large range of density and magnetic properties plausible. As soon as drilling has started and core material is available, measurements of the density and the magnetic properties will be made. Gravity and magnetic models will then be recalculated using these more appropriate values. During the second and third phases of drilling, actual intersections of the vent walls and intrusions will further constrain vent geometry and may require additional revision of models.

Also, as part of this investigative task, selected survey points in the Novarupta grid will be reoccupied for both gravity and magnetic measurements. Changes in the magnetic measurements may indicate that temperatures below the surface are changing. Changes in the repeat gravity measurements may reveal changes in the altitude of the grid point or a subsurface redistribution of mass suggestive of movement of magma.

DEVELOPMENT OF ERUPTION AND COOLING MODELS

The project will provide fundamentally new observations for testing and refinement of the chemical and mathematical models that we use to describe volcanic eruptions.

Eruption dynamics [Hawaii Institute of Geophysics (HIG), and Los Alamos National Laboratory (LANL)]

A great deal of progress has been made recently in developing models for explosive eruptions. These models are mathematical descriptions that

treat the erupting material as an expanding dusty gas. The models attempt to show what is happening in and above the vent, and predict relationships among the velocity of erupting material, height of the eruption cloud, size and shape of the vent, and gas content of the magma. Measurement of characteristics of near-vent and vent-fill deposits, and of vent structure are important observations for the further development of models for explosive eruptions.

The Katmai eruption is unique in that only minimal deformation of vent structure appears to have taken place following the event, and the eruption deposits are almost perfectly preserved. Results from drilling of structures and deposits, together with direct chemical observations concerning volatile behavior, will provide the most complete test yet of our understanding of explosive eruptions. A particularly important aspect of this investigation will be the question of what gives rise to the two characteristic styles of explosive eruption: air-fall deposition, and ash-flow deposition (Fig. 13). The former involves the rain of ash and pumice from a towering, highly expanded eruption cloud. The latter is a dense slurry of pumice and ash in gas that races laterally outward from the vent. The 1912 eruption displayed both behaviors in about equal amounts, and is the most important young example of ash-flow volcanism in the world. Of the two, ash-flow behavior is the less energetic but its cause is unclear. It could represent continuous partial collapse of the eruption column that produced the air-fall deposit, decline in gas content of erupting magma, change in geometry of the vent, or some other factor.

Existing theoretical studies make a series of plausible simplifying assumptions: (1) Flow of erupting magmatic material and gas is steady over a time scale of tens of seconds. (2) Rising magma breaks up into a spray of particles and released gas at a well-defined depth. (3) Particles do not

subsequently re-coalesce or become further fragmented. (4) Most of the particles are small enough, as they are formed, to be carried by the stream of released gas. (5) The exit pressure in the vent is either atmospheric or is controlled by choked (constricted) flow.

Models of non-steady eruptions, that is those that do not use assumption #1 but allow the eruption to grow and decline with time, have tended to deal with the emptying of a relatively small reservoir. In this case the entire eruption is over before anything approaching a steady flow is set up. Assumption #4 may be violated when the amount of gas released by the magma is small or when the pressure in the vent is high due to constriction of the flow. In this case, the flow in the vent may resemble that of a slurry rather than a dusty gas. Such a state has been invoked to allow for occasional "throat-clearing" of large fragments in certain kinds of eruptions. There may well be a wide spectrum of conditions in explosively erupting vents.

Drill cores passing through the ash-flow deposits and the vent itself, in combination with ongoing field studies of near- and far-vent surface exposures of the ash-flow sheet and pumice layers, should allow the variation of mass flow and released gas content with time during eruptive phases to be estimated. Given values for both these quantities at any instant, it is possible to develop a theoretical series of corresponding vent and conduit shapes that differ from one another mainly in the extent to which the vent shape has adjusted itself to enable the exit pressure to approximate the atmospheric value. This adjustment may involve either the erosion of the conduit walls or the inward slumping of wall blocks, depending on whether the eruption is increasing or decreasing in violence. The theoretical modeling efforts will therefore be closely tied to geologic interpretation of vent-enlarging and vent-constricting processes based upon observations of drill core from the vent. In

addition, characteristics of the vent-fill will show what kind of mathematical treatment of flow within the vent is most appropriate, and whether the difference between ash-flow and air-fall behavior is to be sought in flow characteristics in the vent or in the eruption column.

Initial computations will be carried out at the Hawaii Institute of Geophysics; these will involve refinements to existing models and will aim to limit the ranges of vent geometries and pressure conditions anticipated on the basis of current ideas. As understanding of the vent becomes more detailed from drilling information concerning vent geometry and history, much more complex computations of pressure and velocity will be made using the facilities at LANL, including the Cray super computer.

Dynamics of cooling and degassing of the 1912 magma [Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), Georgia Institute of Technology]

The intrusions that fed the 1912 eruption were emplaced within and beneath the vent at temperatures of 800-1000°C (1470-1830°F). Magmatic material in the form of ash-flows was deposited on the surface at somewhat reduced temperatures due to expansion and to mixing with cold vent wall material and with air, but much of this material was still above 600°C (1110°F). These high temperatures do not express the full heat content of the system, because a substantial portion of the heat in magma is the heat of crystallization, which is released as the liquid fraction freezes. This intense and voluminous heat source has been cooling for 76 years. It is doing so by two processes: (1) conduction, in which heat flows out of the igneous body and into its cold surroundings through the rocks themselves; and (2) convection, in which cold water flows into the igneous body, is heated, and flows out carrying heat to the cold environment. The first process is slow

because rocks are relatively good insulators. It would have produced incomplete cooling of the ash-flow sheet and only modest cooling of the vent since 1912. The second process, which must also be at work, is fast if there is considerable fluid flow because water can absorb and carry a great deal of heat.

Models for flow of heat and corresponding changes in temperature in and around intrusions have recently reached a high degree of sophistication. They now incorporate both fluid circulation and magma crystallization. To the classical work by Lovering (1935) and Jaeger (1964) on conductive cooling of igneous intrusions have been added studies that treat cooling in the presence of groundwater circulation (e.g., Cathles, 1977; Norton and Knight, 1977) and the penetration of water or steam systems into high temperature zones (e.g., Lister, 1974; Carrigan, 1986). Few observations of temperature and physical properties, and none in the very young intrusive environment, constrain these models. We intend to use drilling observations of the present temperature, permeability, and fluid-flow patterns of the Katmai system, plus geochemical evidence about temperatures and fluid flow in the past, as the basis for modeling the thermal evolution of the cooling system. Rather than construct a single computer program to calculate all aspects of the increase and decrease in temperature, we will use a number of relatively simple models to study the contribution of different processes to the observed results. The specific techniques to be used will depend on the scientific objectives and observations made in each drill hole. Out of this effort we expect to develop an understanding of the processes taking place as this intense heat source cools.

It is clear that the ash-flow sheet and the vent have cooled dramatically since the eruption. One possibility is, of course, that water from rain and snowmelt has largely cooled the entire system. Alternatively, it is reasonable

and perhaps likely that heat has been retained throughout the system. Some interesting possibilities include:

1. The densely-welded parts of the ash-flow may still be warm, with the non-welded top parts cooled as a result of higher permeability.
2. The bedrock underlying the ash-flow and in the vent wall may have retained heat from the eruption.
3. The shallow vent region itself may have scattered regions of mid- to low-temperature hydrothermal activity.
4. The deeper vent region may contain zones with high-temperature gas.
5. The conduit of the Novarupta Dome may still be cooling and degassing.
6. The zone of active downward penetration of the hydrothermal system may be encountered in the vent area.
7. The deeper parts of the vent and conduit could remain at near-magmatic conditions.

Ultimately, the scientific payoff of the thermal modeling effort will depend upon what conditions are encountered.

We describe the tasks involved in the thermal modeling effort in each of three distinct environments. The environments are characterized by heat sources that differ in character, geometry, and surroundings. Each environment provides an opportunity to address a distinct set of scientific objectives. The three environments are the ash-flow sheet in the valley, shallow vent-fill, and intact intrusions in the deep vent region.

Ash-flow sheet

Drill hole #2 will penetrate the ash-flow sheet at a distance from the vent of about five kilometers (Fig. 23). Thermally, the situation is well-

defined. A relatively flat-lying, 200-m (700-ft.)-thick hot layer was laid down essentially instantaneously on cold bedrock at a known time in the past. The surface fumarolic activity has ceased, but the depth of penetration of cold atmospheric water is unknown. Simple 1-dimensional calculations indicate that, depending on this depth of penetration, the ash-flow sheet could still be cooling. The temperature and chemistry of springs near the base of the tuff in the lower valley suggest that this is indeed the case (T.E.C. Keith, personal comm., 1988). Figure 25 shows the present temperature distribution as a function of depth, assuming conductive cooling of a sheet 200 m thick and various initial emplacement temperatures, To. Figure 26 extends the analysis to include the effect of convective cooling to various depths Zo. The principal results of these calculations are that. (1) If the ~200 m-thick sheet had cooled mainly by conduction of heat, the interior temperature could be as high as 350°C (660°F). (2) The actual temperature in the ash-flow sheet will depend primarily on the depth of penetration of atmospheric water into the system. (3) Elevated temperatures could have over reached over 100 m into the country rock by conduction.

The scientific issues related to the cooling of the ash-flow sheet are straightforward. The basic questions are:

1. How significant were the effects of atmospheric water and circulation on the cooling of the ash-flow?
2. What is the relationship between this cooling behavior and the observed physical properties, such as porosity of the sheet?
3. What is the relationship between the cooling behavior and the transport and deposition of metals?

Figure 25: Calculated temperature profiles for conductive cooling of a 200-m-thick ash-flow sheet with an initial uniform emplacement temperature of To.

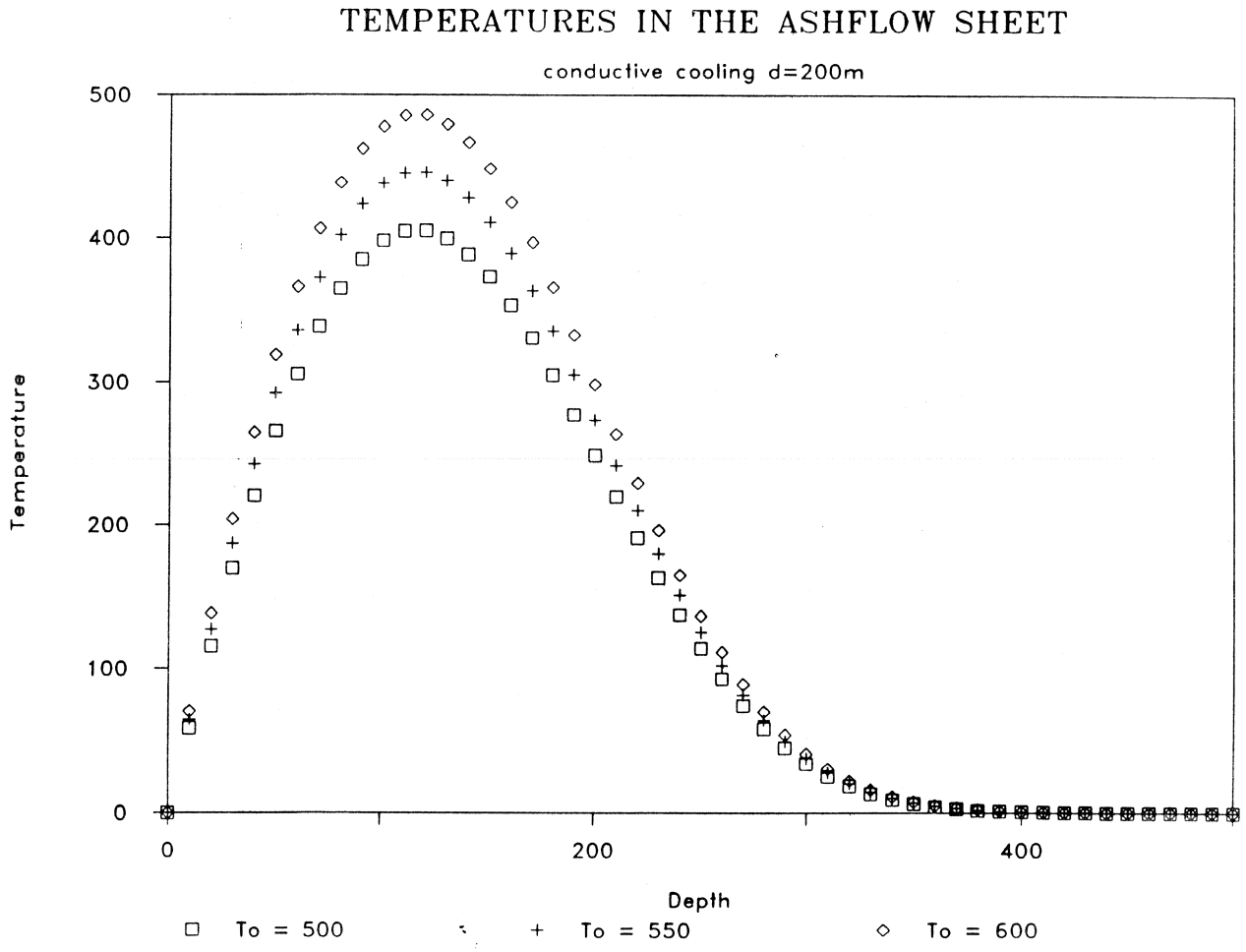
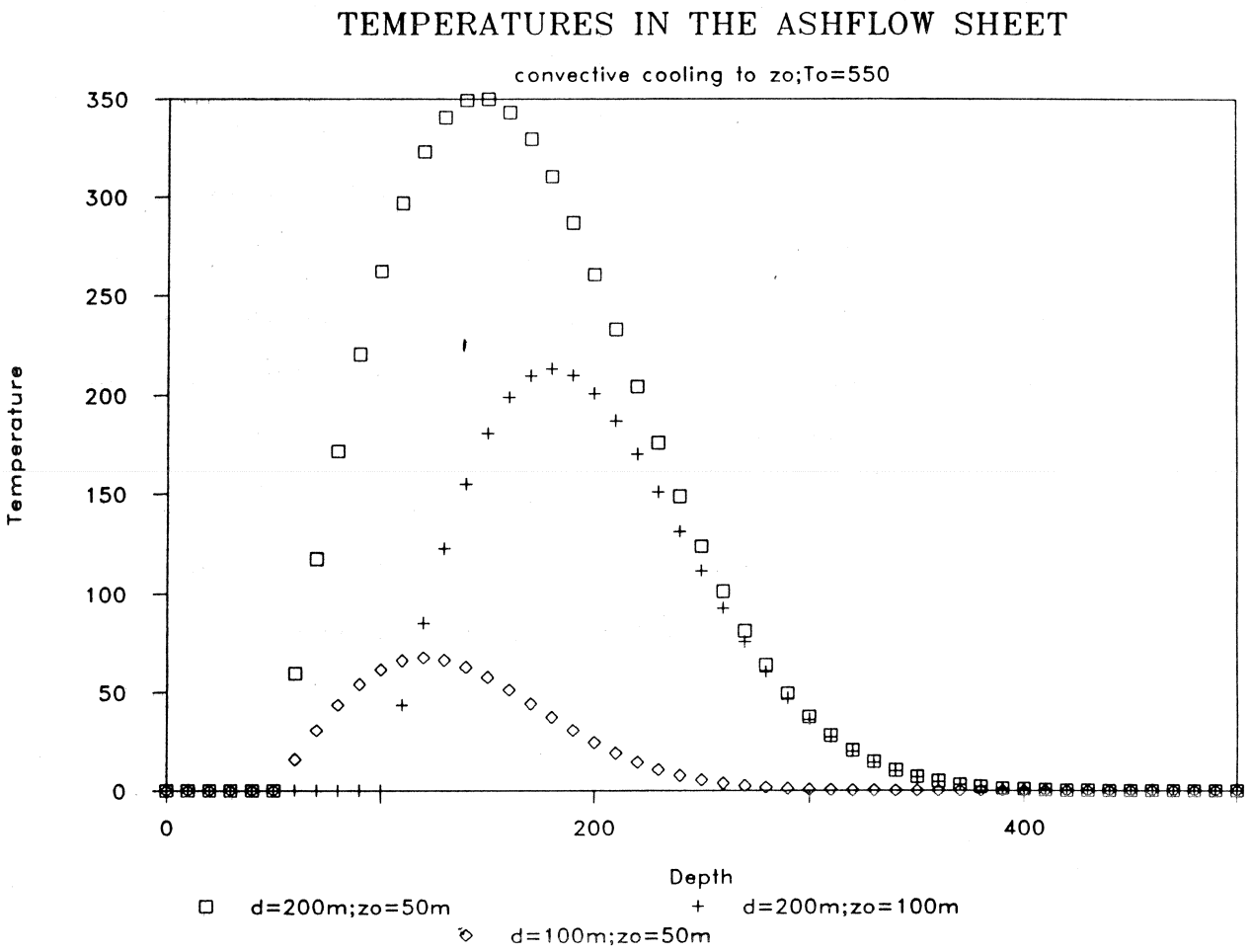


Figure 26: Calculated temperature profiles for cooling of an ash-flow sheet of thickness d with circulation of atmospheric water to depth, Zo. As in Figure 25, To is the emplacement temperature.



The objectives of the data collection include: determination of the changes in temperature with increasing depth from the surface to within the bedrock; assessment of mechanisms of heat loss in the region sampled by the boreholes; measurement of the permeability and thermal conductivity of the materials encountered by the borehole. A hole design and data collection strategy consistent with meeting these objectives will be developed. Existing data, including precipitation levels and runoff estimates, will be compiled (and if necessary, additional measurements will be made) in order to determine the hydrologic conditions to use in thermal models. Physical properties including thermal conductivity, density, porosity and permeability will be measured on samples from the core and in the hole itself as part of the geophysical logging program. Televiewer logs and heat-pulse logs will assess the distribution of fractures in the region penetrated by the borehole.

The above observations will characterize the current thermal and physical conditions in the ash-flow sheet. Other studies will provide insights into the emplacement and early post-emplacement temperature changes in the system. Fluid inclusions in crystals can be used to estimate the post-emplacement temperature history. Fluid migration pathways at various points in time are dependent upon the porosity, permeability, and density of the rocks, and are recognizable on the basis of the hydrothermal minerals produced. Possible migration pathways include those restricted to the ash-flow sheet, those that are confined to ash-flow/bedrock contacts, and those that traverse the bedrock and the ash-flow sheet with little regard to rock type.

A conductive cooling model will initially be used to compare calculated temperatures with those observed in the boreholes. Ultimately, models developed for the cooling and transport of metals by hydrothermal fluids must

take into account the changes in physical properties that occur as the ash-flow sheet is emplaced and cools, and as the hydrothermal circulation patterns develop and change. These changes include welding, compaction, fracturing, and the penetration of surface fluids into the sheet. Refined models will be developed to estimate the complete thermal and physical evolution of the ash-flow sheet.

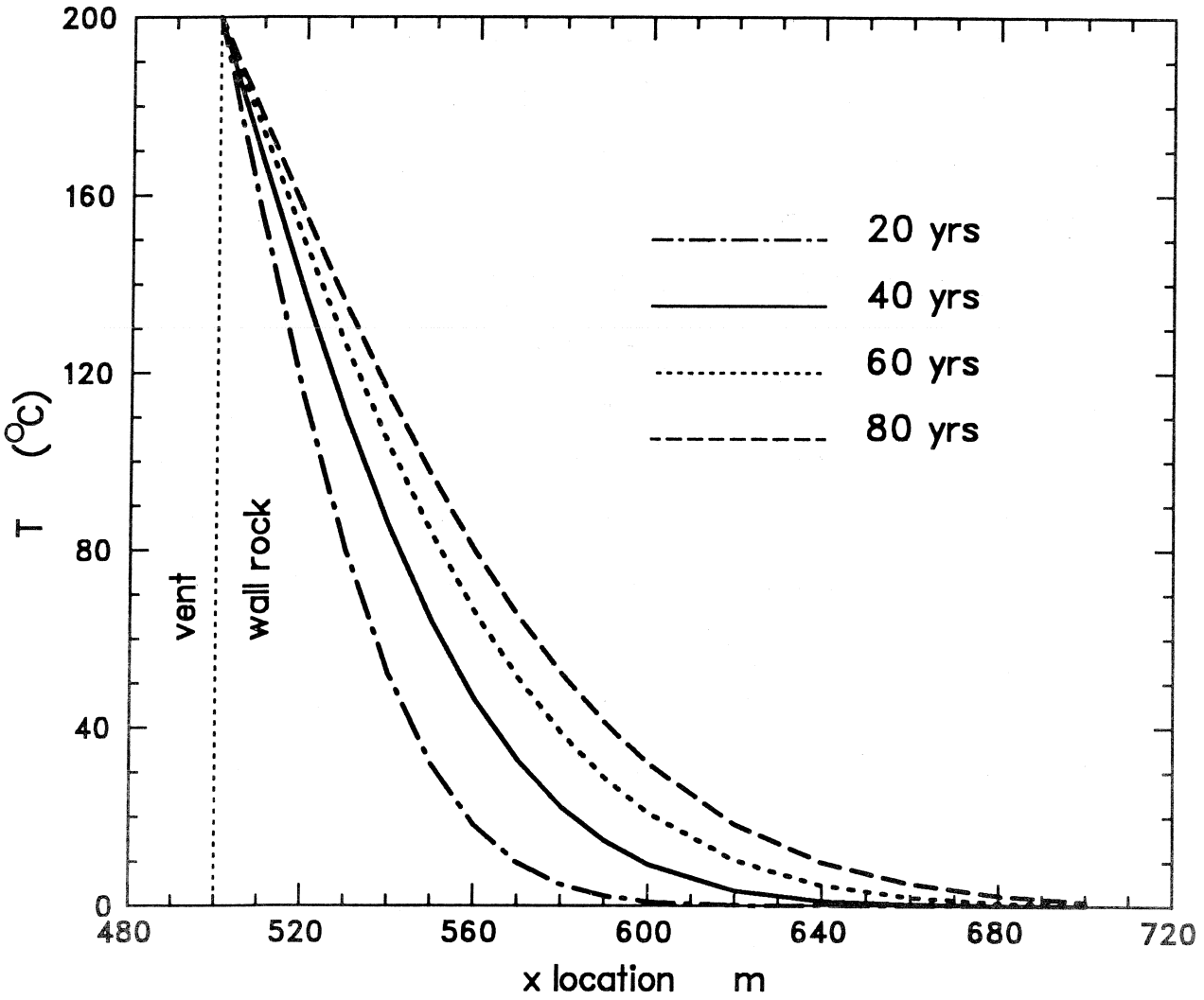
Shallow vent-fill

At shallow depth, material filling the 1912 vent will be fragmental and from three sources. Some fragments and deposits will represent magmatic material that was ejected vertically and fell back into the vent. Some will be magmatic material that never reached the surface, but was lifted upward in the strong flow of gas and small magmatic particles. Still other material will be sedimentary bedrock that slumped or was ripped from the walls of the vent.

Three of the drill holes will sample the shallow vent-fill material (tephra) in the vent region (Fig. 22; holes #1,3,4). The thermal and physical conditions to be encountered are unknown. A very heterogeneous temperature pattern is expected in this region. At present, the warmest thermal discharge in the vent region has a temperature of 86°C (187°F) but large areas are cold. The vent geometry is uncertain and the contact between vent-fill and the underlying bedrock may be the zone of greatest permeability. The vent-fill itself is likely to be a complex mixture of young igneous material and wall rock with a variety of block sizes.

The shallow vent region is likely to have evolved from early magmatic conditions through a high-temperature steam-charged system to a moderate to low-temperature wet hydrothermal system. Simple calculations suggest that the thermal disturbance could extend over 100 m in the wall of the vent (Fig. 27). Portions of the vent could remain in the high-temperature steam stage.

Figure 27: Calculated temperature profiles in the vent wall, for the case in which a rapidly established 200°C hydrothermal system within the vent-fill/vent-wall contact maintains constant temperature at the vent-wall contact, and the wall rock is impermeable to fluid flow. Measurable thermal effects would then extend about 150 m (500 ft) beyond the wall. Cold water toward the vent would suppress this thermal front, while warm water flow out of the vent would extend it.



Factors affecting the current conditions include the rate of downward migration of the hydrothermal system in the center of the vent, as well as the nature of the hydrothermal system developed on the vent margin. One possibility is that a shallow, hydrothermal system exists above a conductively cooling boundary layer. The heterogeneous nature of the vent-fill material, coupled with lack of information on the rate of infiltration of surface water, makes it impossible to predict the detailed thermal conditions to be encountered in the drill holes.

The prime scientific objective is to use calculated thermal histories and observations in the vent drill holes to test alternative models for the initiation and migration of hydrothermal systems into young, hot volcanic formations. Little is known in detail about the mechanisms involved in the development and migration of these systems.

The temperature and physical data needed from the drill holes for this task are essentially identical to those described in the ash-flow sheet section. The drill-hole data will be complemented by heat-flow surveys and surface temperature measurements that define the conditions at the upper boundary and by other geophysical studies of the vent region that help define the 3-dimensional vent structure.

Three progressively more sophisticated models will be developed to calculate the post-emplacement thermal evolution of the vent region: (1) a purely conductive cooling model; (2) a model involving a downward migrating shallow hydrothermal system; and (3) a model combining (2) with a fracture-controlled hydrothermal system located along the vent margins. Current temperature distributions in the vent and wallrock, physical properties of the vent-fill and inferences about the fluid flow and temperature histories will be used in developing these models.

Intrusion within the vent

Two deep holes (Fig. 22; holes #3, and 4a or b) in the center of the vent are expected to intersect intact intrusive rocks representing magma that did not fragment during ascent. There are two reasons for this expectation.

First, the dominant volume of ejected bedrock fragments appears to have come from the upper kilometer (Hildreth, 1987). It is presumed that these fragments were picked up where the erupting magma was behaving as a dusty gas and flowing at high velocity. This presumption is supported by the dramatically different bedrock fragment contents of explosively and non-explosively erupted magma. By contrast with magma that erupts in fragmental form as pumice and ash, magma that does not fragment during ascent and erupts as lava contains much less bedrock debris.

Second, if current ideas (e.g., Sparks, 1978, Wilson, 1980) about fragmentation are correct, then for plausible water contents, the 1912 magma would have fragmented at depths of less than 1 km (0.6 mi.). For example, with 3 wt.% H_2O, fragmentation should have occurred shallower than 0.5 km depth. Some downward movement of the zone of fragmentation is possible if significant strength to the vent wall is assumed, but clearly the fragmentation level rose to the surface by the close of eruptive activity, with the eruption of unfragmented rhyolitic magma as Novarupta Dome lava. Drilling in the center of the vent should, at a minimum, encounter the intrusive feeder of Novarupta Dome, and will probably encounter the intrusive equivalents of the ash-flow sheet as well.

Comparison of the cooling and degassing behavior of fragmental vs. non-fragmental magmatic material is an important aspect of the project. The intrusions were emplaced into the heterogeneous, high-temperature environment of the fragmental vent-fill. Depending on the degree of welding

of the fragments in the vent-fill, the intact intrusives and enclosing fragmental debris may behave thermally as a single very large intrusion, or the intrusions may behave as hot conductive zones within an environment of low-temperature water circulation. Even in the latter case, simple conduction calculations indicate that residual magmatic heat could still be retained in the intrusions.

The 1912 event involved the transport of a vast quantity of heat and gas to the Earth's upper crust and surface. The problems in understanding the movement of heat and gas are related because cooling and degassing both control crystallization and because gas release from magma may influence hydrothermal circulation, and therefore cooling. Specific questions to be addressed in the deep intrusive part of the vent include:

1. How has degassing influenced the cooling of the intrusion and the hydrothermal system?
2. What are the relative roles of cooling and degassing in controlling the crystallization behavior of the magma?
3. Can the transition from explosive to non-explosive activity in the 1912 eruption be attributed to declining magmatic gas content, establishment of a gas-permeable vent funnel, slowing ascent rate, and/or diminishing conduit size?
4. What are the relative roles of conduction and convection in cooling the system, and how are heat and mass transport now occurring in the higher temperature regimes? Is the concept of a hydrothermal circulation system encroaching upon a hot, conductive intrusion valid?

Both in terms of the processes involved in cooling and in decompression of magma, we can view the deep vent environment at Katmai as intermediate between the volcanic regime and the deep crustal regime of granite bodies.

In general, the data collection needs and issues mirror those discussed earlier. Of particular interest will be the residual heat, spatial and size distribution of crystals and bubbles within an intrusion, the distribution and volatile content of glass in the intrusion, and the nature of the permeability that provides pathways between the intrusion and host for magmatic gas and/or hydrothermal fluid.

Modeling approach

Recently developed models for the cooling and degassing of magma will be applied to describe the evolution of the igneous system from inception to its present state. Initially, these models will be separately applied to the questions of cooling and degassing. Depending on the results, a coupled cooling/degassing model may have to be developed to explain the distribution of heat, volatiles, crystals and bubbles in the intrusion.

Summary

Residual heat from the Katmai eruption is retained in the vent (Fig. 17) and possibly in the ash-flow sheet. As a result, the drilling program will evaluate in detail the thermal and mechanical processes that occur in magmatic systems after their emplacement. These processes include the initiation and migration of a hydrothermal system, the cooling, compaction (welding), and fracturing of the eruptive products in the ash-flow and vent regions, and the cooling and degassing of intrusions. We will use observations of the present thermal and physical state of the Katmai system, plus evidence about temperatures and fluid flow in the past obtained from the

geochemical studies as the basis for modeling the thermal and chemical evolution of the cooling system.

PROJECT COORDINATION

The three Principal Investigators (John C. Eichelberger of Sandia National Laboratories, Wes Hildreth of the U.S. Geological Survey, and James J. Papike of the South Dakota School of Mines and Technology) will be responsible for coordination of component investigations and integration of results. They will visit the proposed drill sites at appropriate seasons prior to drilling to assess working conditions and to complete design of the operations. The Principal Investigators will keep apprised of progress in all investigations and will promote exchange and compilation of data, and will guide timely publication of scientific results.

Thomas P. Miller (U.S. Geological Survey) will serve as the point of contact between the project and the National Park Service. In this capacity he will keep the NPS informed of planned activities and will ensure that project personnel are aware of their responsibilities within the Park. He will also issue contracts for, schedule, and coordinate helicopter support of field parties during the predrilling phase.

Engineering, logistical, and safety aspects of the drilling operations will be designed and supervised by the Geoscience Research Drilling Office at Sandia National Laboratories. However, the NPS will retain full authority to terminate field operations at any time that it judges a danger to the Park to exist.

SUMMARY OF EXPECTED RESULTS

In view of the extensive work that has been conducted in understanding volcanoes, it is easy to accept that problems of intrusion, eruption, and cooling of magma are well understood. Cartoons of the unexposed portions of volcanoes seem believable, especially when based on sound consideration of gas-flow and rock-deformation theory. Similarly, the conditions that are generated in the Earth's crust following emplacement of a molten intrusion are readily predicted from knowledge of the properties of typical rocks and application of heat-flow theory. It is likely, however, that these concepts, while sophisticated in approach, are actually very primitive descriptions of nature. Results from drilling at the Inyo Domes Volcanoes in California show how far from reality some carefully considered interpretations of surface observations can be. Yet, we will not progress beyond a cartoon-like understanding of how volcanoes work without the examination of young intact volcanic systems by drilling. Given the complexity of most volcanoes, it is imperative that early drilling investigations probe the simplest possible cases. The 1912 eruption at Katmai is such a case. We can expect that drilling at Katmai will provide an unprecedentedly complete test of widely accepted theories concerning explosive eruptions, will provide the first information on the distribution of metals in an essentially unweathered system where significant vapor-transport has occurred, and will provide the first observations of the distribution of heat and the extent of hydrothermal alteration in a still-cooling system. Although we have well-developed concepts of what to expect, we should not assume that all these concepts will be confirmed. Rather, we should expect that the subsurface investigation of the Valley of Ten Thousand Smokes will have as profound an effect upon volcanology as did the original surface explorations, seventy years ago.

DEVELOPMENT OF THE KATMAI PROJECT

Like most basic research efforts in this country, the Katmai Project is being proposed to the United States Government by working-level scientists through a highly competitive peer-review process. The project is intended to be part of the national Continental Scientific Drilling Program (CSDP), which is based on the premise that future major advances in our fundamental knowledge about the Earth's crust will come through drilling. Although much drilling has been done by industry for specialized commercial reasons, improved knowledge about such important processes as earthquakes and volcanic eruptions will only come from government-funded basic research projects such as this one. Several countries have undertaken ambitious research drilling programs, most notably the Soviet Union and West Germany.

The government agencies that support basic research in the geosciences in the United States are the U.S. Geological Survey, the U.S. Department of Energy, and the National Science Foundation. These are the agencies that collectively fund CSDP. Following favorable peer review of the Katmai Project, representatives of these agencies, acting together as the Interagency Coordinating Group, are applying to the National Park Service for permission to proceed with the project. In considering the request, the NPS will follow existing laws concerning Parks and Wilderness Areas, including procedures specified in the National Environmental Policy Act (NEPA). The NPS will also obtain an independent review of the project by the National Academy of Sciences, to determine whether Katmai is the only site where the research can be properly conducted. An affirmative answer is a necessary condition for approval.

The participants in this project believe that the Katmai locality is uniquely suited for this research because of its combination of size,

youthfulness, simplicity, and perfect state of preservation. We also believe that the proposed work is in the spirit of the original charter that set the Valley of Ten Thousand Smokes aside for federal protection.

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GLOSSARY

(Based on definitions in Bates, R.L. and Jackson, J.A., Dictionary of Geological Terms, 3rd edition, 571 pp., Anchor Press/Doubleday, N.Y., 1983.)

alteration (n.) - Change in the chemical or mineralogical composition of a rock, generally produced by weathering or hot underground water.

andesite (n.) - An intermediate composition volcanic rock, closer to basalt than rhyolite in composition.

ash (n.) - Dust to sand-sized particles formed when magma fragments during an explosive eruption.

ash-flow sheet (n.) - A layer rich in volcanic ash and commonly containing pumice, deposited from a flowing cloud of hot gas and fragmented magma during an explosive eruption.

basalt (n.) - A common, dark, iron-rich, silica-poor rock often erupted as fluid lava flows.

caldera (n.) - A large basin-shaped depression, formed by the collapse of a volcanic vent or vents, or by the explosive removal of material.

casing (n.) - A steel pipe inserted into a drillhole. Casing prevents collapse of the hole.

core (n.) - A continuous cylinder of rock cut by a special kind of drill bit. It is usually extracted from the hole in 5 or 10 ft. segments as drilling proceeds.

dacite (n.) - An intermediate composition volcanic rock, closer to rhyolite than to basalt in composition.

dike (n.) - A planar body of igneous rock that cuts across the trend of adjacent rocks.

dome (n.) - A rounded rock mass that roughly resembles the dome of a

building. Domes may be structural, that is, formed by uplift, or extrusive, formed by eruption of lava.

extrusive (adj.) - Igneous rock that has been erupted onto the Earth's surface. Lava flows and ash are extrusive.

fumarole (fumarolic, adj.) - A hole or vent from which hot gases are emitted.

geodetic (adj.) - Measurement of distances and directions between established points on the surface.

glass inclusion (n.) - Microscopic pockets of glass trapped within crystal grains in a volcanic rock.

hydrothermal (adj.) - Pertaining to hot water, the action, or the products of the action of hot water. Also refers to minerals deposited from such hot waters.

igneous (adj.) - Pertaining to rocks or minerals that solidified from molten material, or the formation of such rocks.

intrusion (n.)(intrusive, adj.) - The process of emplacement of molten rock in pre-existing rock (underground), as opposed to extrusion. Also refers to rocks formed this way.

isotope (n.)(isotopic, adj.) - One of the two or more species of the same chemical element. Different isotopes of an element have slightly different masses and slightly different physical properties, but similar chemical properties because they have the same number of protons and electrons.

magma (magmatic, adj.) - Molten rock generated within the Earth. If it reaches the surface, it is then known as lava, pumice, or ash, depending upon its form. It may be entirely liquid but more generally contains suspended crystals and gas bubbles.

pumice (n.) - Frothy pebble-to boulder-sized clasts that form when magma fragments during an explosive eruption.

quench (n.) - Cooling of magma so rapidly that the liquid portion is preserved as glass, bubbles are preserved as vesicles, and no new crystals form.

rhyolite (rhyolitic, adj.) - A silica-rich, iron-poor volcanic rock often erupted explosively as ash and pumice.

silicic (adj.) - Describes a silica-rich magma or igneous rock (at least 65% silica). Often meant to encompass rhyolite and dacite compositions.

vent (n.) - An opening at the Earth's surface through which volcanic materials are erupted.

vesicle (n.) - A small, usually round cavity in a volcanic rock, representing a gas bubble in the magma.

volatile (n.) - An element or compound that tends to occur as a gas or vapor, or is easily released upon heating. As an adjective, refers to this type of behavior.

welded tuff (n.) - A volcanic rock composed of ash and pumice particles in which the void space has collapsed and the particles have stuck together while the rock was hot.

A copy of the formal, technical version of this proposal can be obtained by writing to:

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