GEOSCIENCE

Drilling Volcanoes

John C. Eichelberger

Introductory geology textbooks always contain a cutaway view of the inside of a volcano. Although eroded volcanic structures provide some factual basis, the primary source for such diagrams is most often the author's merged impressions of similar drawings in other textbooks. But in reality, the only way to look inside an active volcano is to drill into it. Although difficult, such journeys should be made, given the rich rewards for understanding the processes and environment of volcanic conduits.

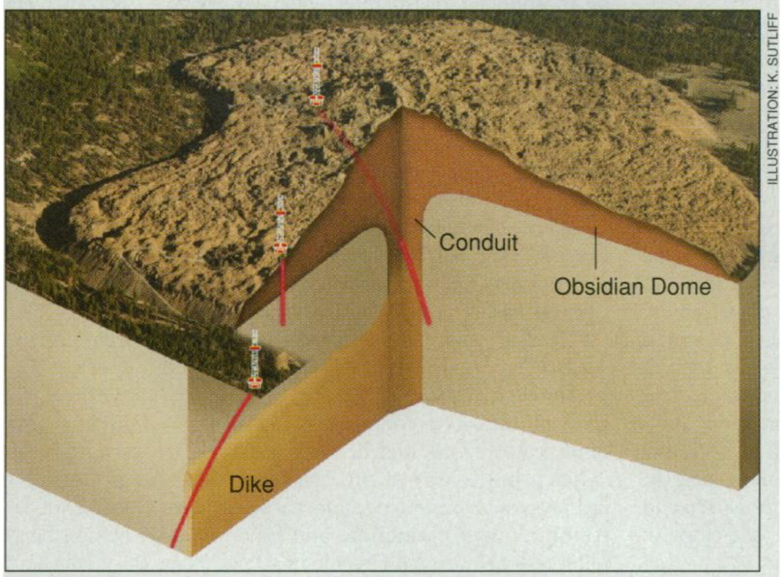
Majestic volcanic mountains exist only because magma is more likely to follow an established path to the surface than to make a new one. If this were not so, there would be many ugly little volcanoes and no towering snow-clad giants. This well-known but little-questioned phenomenon is more remarkable than it might seem. It is not simply that magma rises vertically, because it is well documented that magma can move up inclined paths too. It is not because magma just moves along the path that requires the minimal hydraulic pressure: We know that lofty summit vents are favored over flank vents. It is not because conduits are "open"; they are not, but are instead occupied by igneous rock emplaced during the preceding eruption. Whatever the factors—stress field, structures, chance—that guide magma initially along a particular path, this path is subsequently favored.

Yet, in following a previously used path, a new pulse of magma may encounter a very different environment depending on repose time since the last pulse. For a conduit several meters wide in a water-saturated cone, successive pulses will likely find a soft path occupied by partially molten rock only for weeks or months after the previous eruption. Where repose periods are measured in centuries, as is often the case for andesitic volcanoes, the conduit may present no thermal anomaly at all, and the magma must follow physical discontinuities. Perhaps it "drills" its way upward with magma-heated, abrasive-laden, hydrothermal fluid, guided by a fracture network within or at the margin of the previous intrusion.

Once an active conduit has been established, the magmatic processes that take place within it are no less remarkable. Rise of magma results in exsolution and loss of water, a dominant component in mole-fraction, although not in weight-fraction. Ascending magma inflates to a stiff foam as the combined effects of accumulating bubbles and dehydrating melt increase bulk viscosity by many orders of magnitude. Because most of the viscosity increase occurs during the final few hundreds of meters of ascent, most of the pressure drop is just below the surface (*1*). Fragmentation and explosive expansion, or alternatively degassing and collapse of foam to dense lava, occur in this regime. Lagging far behind is crystallization, which would go to completion in response to water loss even without cooling and would stop most magmas from reaching the surface if the ascent rate did not outrun the crystallization rate.

Researchers have modeled this complex behavior theoretically and have even simulated the conditions of decompression in the laboratory (*2*). However, the nature of the conduit for a real erupting volcano can be obtained only by drilling to observe near-magmatic conditions or by waiting a million years for the "fossil" conduit to be exposed by erosion.

Conduits also provide the geophysical and geochemical signals that are used by volcano observatories to forecast eruptions. Low-frequency seismic events and the hum of tremor apparently arise from fluid flow in the conduit environment (*3*). Deformation of the conduit walls produces high-frequency earthquakes as a result of brittle failure, illuminating the plumbing of the volcano. Magmatic gas may exit the conduit chimney ahead of the magma. Precise surface measurements can detect the swelling of a conduit as magma enters it. All of these signs of impending eruption could be better interpreted if we knew what an active conduit and its immediate environment are really like.



Under the volcano. Oblique aerial photo of the Obsidian Dome volcano with a cutaway drawing of the drill holes intersecting the feeder dike. The width of the field of view is approximately 2 km.

The history of drilling volcanoes is brief but exciting. During repeated penetrations of Kilauea Iki lava lake in Hawaii, temperatures reached over 1100°C, a record high. Spray from a lava fountain had formed a pond in a pre-existing crater that was 100 m deep, so that two decades after the eruption, the melt lens was still tens of meters thick. The molten rock was "cored" with the drill by chilling the lava to glass ahead of the advancing bit with copious cooling water (*4*), producing beautiful columns of black glass studded with green olivines. These, however, were very shallow holes, and the "magma" had already lost its water through eruption. For deep holes, the temperature record is held by the 4-km WD-1 well at Kakkonda, Japan (*5*). This drilling, designed to reach the roots of a producing geothermal field, ended in newly crystallized granite at just over 500°C. A 2-km hole drilled over a suspected granitic magma body near Mammoth Lakes, California, was inexplicably cool, but is scheduled for deepening to 4 km in the near future. Drilling is also being used to read the record of a large span of the life of a volcano, for example in the drilling currently under way near Hilo, Hawaii (*6*).

A few drilling efforts are aimed at the central pipe of a volcano. In 1985, my co-workers and I slant-drilled the 600-year-old Obsidian Dome volcano near Mammoth Lakes, California, reaching its feeder dike at depths of 500 to 700 m (see figure). These results, which included the recovery of fresh intrusive glass from the feeder wall, were important in developing new concepts of effusive eruption (*7*) and flow differentiation (*8*).

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Our attempt to repeat this experiment at the Valley of Ten Thousand Smokes in Alaska, the still-hot site of the largest eruption on Earth in this century, ran afoul when the Department of Interior objected to "mechanized" research in the national park containing the site. (*8*). A bold proposal to drill the seething throat of White Island Volcano in New Zealand failed to surmount obstacles of safety and funding (*9*). Another project is in an early planning stage as a result of an international symposium in Shimabara, Japan, in May of this year: a proposal to drill to the conduit of Unzen Volcano (*10*), active from 1991 to 1995 in an eruption that did $2 billion of damage and took 44 lives.

Successful volcano drilling projects must carefully address issues of safety, funding, environmental protection, property ownership, subsurface targeting, directional drilling in an extreme environment, and public relations. Each of these issues has been overcome at one time or another in other scientific drilling projects, but they have yet to be tackled together in an international project at a single, well-watched, recently active volcano. When they are, the results will permanently change textbook depictions of how volcanoes work and will greatly improve the basis for eruption predictions. Such efforts may ultimately allow drilling into the source chamber itself, sampling live magma quenched in situ. These samples could perhaps answer the age-old question of how the magma "still" works, that is, how magmas as sluggish as molten granite, the key ingredient of continental crust, fractionate so rapidly and cleanly.

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CELL BIOLOGY

Death by Lethal Injection

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Gram-negative bacteria of the genus *Yersinia* cause human diseases that range in severity from distressful gastroenteritis to the horrific Black Death. The success of the Yersiniae in these nefarious endeavors requires that all three of the responsible species overcome the sophisticated defense mechanisms devised by a vigilant host. For example, the Yersiniae must kill macrophages quickly, before these voracious phagocytes devour them. To combat this huge and powerful enemy, these bacteria use a fiendishly clever molecular injection device. When the macrophage contacts these bacteria, a necessary prelude for bacterial engulfment, a specialized secretion channel is opened that allows direct transfer of certain toxic proteins from the bacterial cytoplasm to the cytoplasm of the mammalian cell (see figure, right). These toxic proteins, termed Yops (*Yersinia* outer proteins), effectively paralyze and incapacitate the defender, allowing the bacteria to escape and continue to grow and multiply (*1*). This scenario is analogous to the bite of a poisonous insect or snake inflicted on a predator, except that the contestants are single cells, one prokaryotic and one eukaryotic.

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The discovery of this molecular injection device 4 years ago sparked intense interest, but several key questions remain. One of these is to discover how Yops are marked for injection. On page 1140 of this issue, Anderson and Schneewind (*2*) adapt the logic of a classic experiment in molecular genetics (*3*) to provide compelling evidence for a novel targeting signal or "zip code" within the messenger RNA (mRNA) that specifically tags Yops for secretion.

Most proteins targeted for translocation from the bacterial cytoplasm are made initially in precursor form with a signal sequence of 15 to 30 amino acids located at the amino-terminus. This signal targets the precursor to a complex of Sec (Secretion) proteins that physically moves the precursor across the cytoplasmic membrane. During the translocation reaction a special pro-

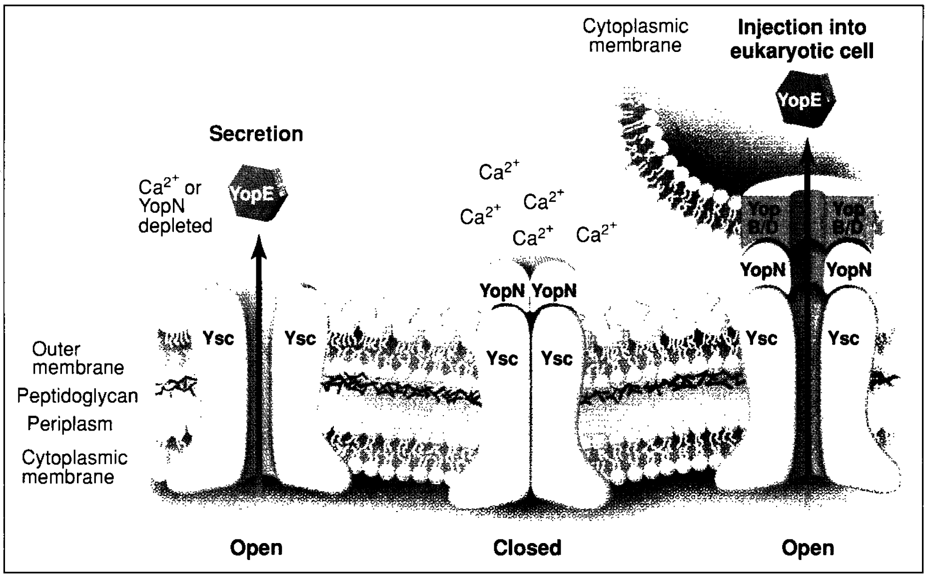

ILLUSTRATION: K. SUTLIFF

The Ysc type III secretion system. The apparatus (**center**) is normally kept closed by YopN, which acts as a cork. The system can be opened either by removing Ca^{2+} or YopN, allowing secretion of Yops (**left**). A microinjection device is formed upon contact of Yops with a eukaryotic cell (**right**). Then Yops pass through the type III system and YopB/D directly into the cytoplasm of the eukaryotic cell. [Adapted from (*1*)]