USGS

A Giant's Troubled Sleep

No one knows when, or if, the Long Valley volcanic system in eastern California will erupt, but recent stirrings have raised scientists' concern and curiosity as magma moves toward the surface

Arrow marks portion of Long Valley where small quakes have struck repeatedly since 1980.

By CHERYL SIMON

MAMMOTH LAKES, CALIF.—The pilot of a 12-seat plane bound from Los Angeles to Mammoth Lakes, Calif., announces that landing is imminent, but the doubtful passenger sees only the jagged, snow-covered peaks of the eastern Sierra Nevada. The plane drops in altitude and follows a curve in its invisible path. Then, a broad, flat expanse of land appears. To the skiers on board, Long Valley, as the flat area is called, is no more than a handy landing strip a few kilometers from the town of Mammoth Lakes, the world's busiest ski resort. But other passengers — scientists en route to a meeting on the geology of the area—view the oval-shaped basin in a different light.

Long Valley is not a true valley, but a caldera, or sunken crater. A volcano erupted here 700,000 years ago, blowing the mountains that filled the area to rocky fragments. An estimated 600 cubic kilometers of the material were strewn from the volcano, and its remains have been found as far east as Washington, D.C. After the eruption the crater caved in, forming the 32-km by 17-km caldera. The frothy mixture of ash and pumice that fills the caldera is called Bishop Tuff. What was left of the volcano's supply of magma, or molten rock, pushed up to form a bulge, or resurgent dome, still visible in the caldera's southern end.

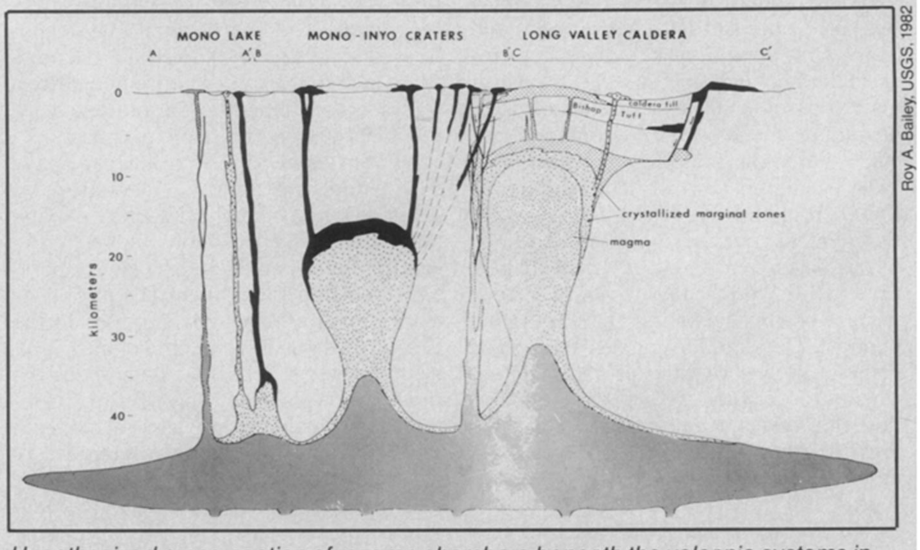
The caldera at Long Valley is of special interest now because abundant signs in the last three years suggest that molten rock is moving once again. The last major eruption here was about 100,000 years ago, though in the last 2,000 years smaller events, such as dome-building and ash flows, have occurred at roughly 200-year intervals. The Mono and Inyo craters 29 km to the north also have been active in the last 200 to 400 years, producing explosive eruptions of ash and rock. There is no sign that these younger volcanoes too are revving up, but based on the intervals at which eruptions recur there, they are due for some action. Volcanic activity at either system, some scientists believe, could jar the other system to life.

While earthquakes often occur without volcanic activity, volcanism — movement of magma and gas in the earth's crust or at the surface — is nearly always accompanied by earthquakes. Quakes are common along the eastern edge of the Sierra Nevada mountain range as the earth responds to stretching of crust over the Basin and Range to the east, and to the grinding of the North American plate and the Pacific plate along the San Andreas fault 300 km to the west. For a while these tectonic earthquakes masked the fact that magma was moving up to shallow depths beneath the caldera. Then, in 1980, four earthquakes of Richter magnitude 6.0 or greater raised fears that an eruption threatened (SN: 6/7/80, p. 356). While there was some chance that these quakes were related only to movement along the fault cutting along the front of the eastern Sierra, the numerous earthquake swarms —clusters of small earthquakes—were all too reminiscent of the swarms that preceded the eruption of Mt. St. Helens in May 1980. Such swarms often are associated with tongues of magma moving up toward the earth's surface.

Something strange was happening at Mammoth Lakes. The seismic data, combined with a total uplift of 40 centimeters in the caldera concentrated over the resurgent dome, suggest that a magma chamber has been replenished. A year ago, the United States Geological Survey (USGS) issued a notice of potential volcanic hazard, the lowest of three levels of formal concern. That notice is still in effect; whether the magma will erupt or cool and harden is anyone's guess. In the meantime, swarms continue. In January of this year thousands of small shocks—and two larger ones—shook the area (SN: 1/15/83, p. 39). Since then the earthquakes have diminished, but still, every few weeks tiny swarms too small to be felt show up on the seismographs that monitor the area.

Critical questions about the magma chamber pervade studies at Mammoth Lakes because such a chamber would be a way-station for magma on its way to the surface. A group of scientists met here recently to discuss the existence and characteristics of such a magma chamber. Has this chamber really been replenished by fresh material from the mantle? Where is the chamber, and what is its shape?

Some of the 50 or so scientists arrived at the meeting skeptical that a magma chamber exists, but by the meeting's end



Hypothesized cross-section of magma chambers beneath the volcanic systems in eastern California. Studies of earthquake waves, and of uplift in the Long Valley caldera, suggest that a magma chamber there has been replenished.

three days later, nearly all were persuaded by several sets of diverse measurements and calculations. Chris Sanders, a graduate student on leave from the California Institute of Technology in Pasadena, has been working with Alan Ryall and Floriana Ryall at the seismological laboratory at the University of Nevada in Reno. He reported that their studies of the pattern of seismic waves travelling through the caldera show a "seismic shadow" cast because the motion of S waves, or shear waves, cannot pass through liquid.

Sanders believes this is strong evidence for a magma chamber, parts of which, he says, rise to within nearly 4.5 kilometers of the earth's surface. According to their measurements, the main chamber is about 10 km long, about 5 km wide, and "appears to be fairly massive," he says. The chamber's bottom reaches to about 13 km deep; from 7 km to 5 km the magma is presumed to be in sheets with some solid rock. From 5.0 km to 4.5 km upward. the S-wave data show magma "fingers" — magma-filled cracks extending toward the surface. David Hill of the USGS in Menlo Park, Calif., described the S-wave analysis as the "best and most compelling evidence for something anomalous happening."

The seismic data are significant in part because the foci, or points of rupture, of the quakes do not correlate with the main faults mapped on the earth's surface. This finding increases the likelihood that the earthquakes are related to movement of magma rather than to tectonic stresses in the area. Alan Ryall has observed that the epicenters, or points on the surface above the foci of the quakes, are scattered in an irregularly shaped area covering about 30 km in a west/northwest, east/southeast direction and about 30 km from north to south. Until 1980, spasmodic tremors (which often are observed in volcanically active areas) in the caldera occurred at 7 km or deeper. Since the end of 1980 some of the tremors have been "quite shallow," he says, and they also have migrated further north into the caldera. During the large swarm in January the epicenters of the quakes were along the caldera's southern boundary.

This boundary of the caldera indicates a zone of weakness dating back to the crater's collapse 700,000 years ago. Jim Savage of USGS in Menlo Park works on studies of land deformation and believes that magma intrusion is a "reasonable interpretation" for the events at Long Valley. He says that the system of fractures that rings the caldera is exactly what one would expect when a crater collapses. Now, he says, "it looks like magma is being introduced below that zone of weakness." Measurements show that between 1979 and 1980 the caldera floor rose about 25 centimeters, with an additional 8 cm rise between 1980 and 1982. Immediately after the January swarm another 7 cm of uplift occurred. Savage thinks this recent swelling is not over the resurgent dome, but along its flank, coinciding nicely with the epicenters of the quakes.

Studies of the electromagnetic field also support the existence of a magma chamber. Fluids — such as water or magma — conduct electrical signals more efficiently than rock does. Conductivity is especially high in a shallow zone 2 km to 3 km below the surface of the caldera, reported Norman Goldstein of Lawrence Berkeley Laboratory and Frank Morrison of the University of California at Berkeley.

At the beginning of the meeting the two researchers were among the most insistent of the scientists doubting the magma chamber's existence. ("If this signals a magma chamber, Nevada would be flooded with melted rock," Morrison cautioned. Parts of Nevada also show zones that efficiently conduct electromagnetic signals.) The high conductivity could be caused by a fluid saturating the system — the extensive hydrothermal fluids, for example — and need not indicate the presence of magma at all, they said. But the zone of high conductivity roughly overlies the area under the caldera where S waves are strongly attenuated, or weakened. After hearing Sanders' presentation of the seismic data, they agreed that a chamber probably exists, but stressed that "interpretation is difficult."

No one disagreed.

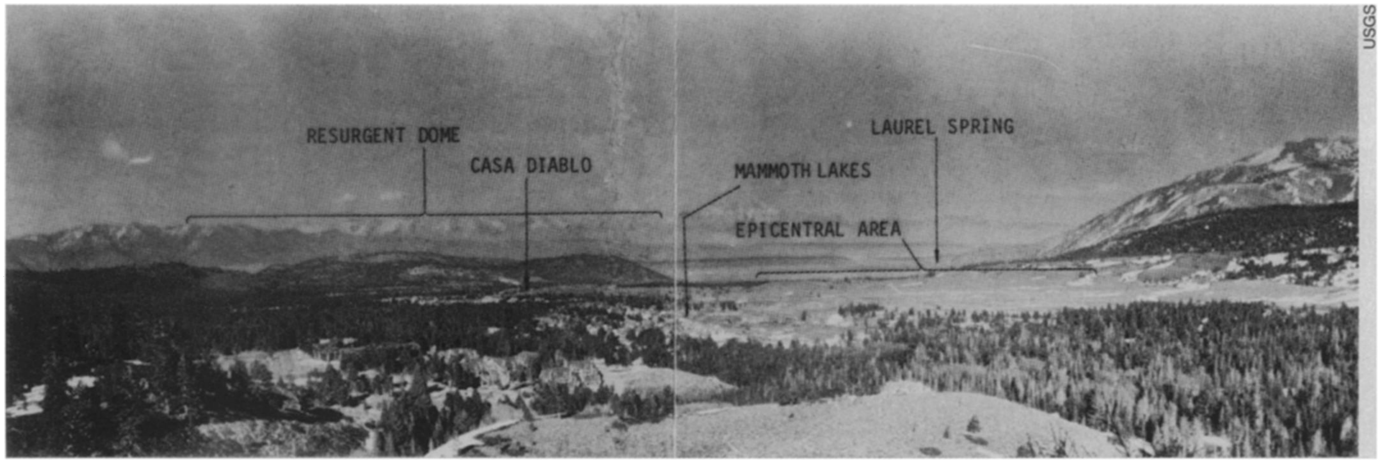
The other researchers noted with enthusiasm the unexpected correspondence between the two sets of data. A hydrothermal system, in which water flowing through the upper crust is heated by fresh magma or residual heat from previous intrusions of molten rock, also would cause the S waves to die out as they pass through the fluid. But, as Roy Bailey of USGS in Reston, Va., explained, "We see S-wave attenuation to greater depth than can be explained by a hydrothermal system." At depth, he says, pore space in the crustal rock is too tight to support circulation of hydrothermal fluids.

Demonstration that a magma chamber exists adds only one piece, albeit a major one, to the geological puzzle that forms Long Valley. The caldera lies within the White Mountain seismic gap, an area about 50 km from east to west, extending about 100 km from Bishop, Calif., north to Luning, Nev. This region has not had a major earthquake (magnitude 7.0 or greater) in historic time, though quakes have occurred in other parts of the north-south belt of earthquake activity.

It has been widely noted that the number and magnitudes of earthquakes have increased in the last few years over a broad area of the western United States. In this part of eastern California, however, quakes are likely to recur at intervals of thousands or tens of thousands of years, compared to about 150 years along the southern stretch of the San Andreas, Ryall says. But other faults have been studied much more thoroughly than those near Mammoth Lakes, and the intervals at which earthquakes are likely to occur along them are better known.

No one knows how a major quake in the area would affect Long Valley. Such a quake could strike independently of any volcanic action, but would it stir the volcano to life by jarring its plumbing system? Conversely, would an eruption, or movement of magma from the shallow chamber toward the surface, trigger a major earthquake?

Most of the uplift at Long Valley has been over the resurgent dome, a remnant of a colossal eruption 700,000 years ago. In the last few years earthquakes have been centered along the caldera's southern boundary.



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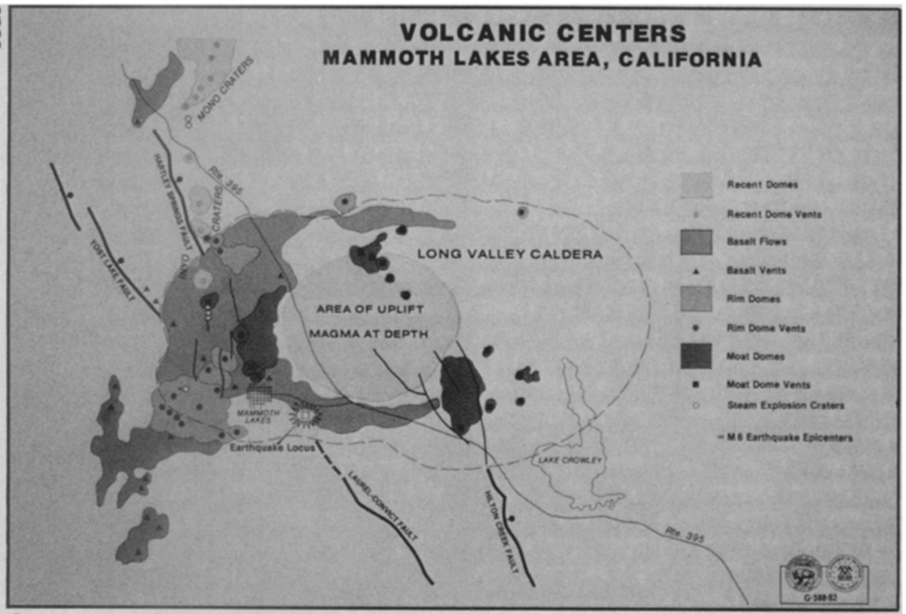

Geologic map of the Mammoth Lakes area and related faults and volcanic systems.

Neither event is impossible. Some scientists would agree with Hill, who says, "If the volcanic system is primed to go by itself, a quake could go through the magma chamber and trigger an eruption," though he says this is unlikely. Other researchers think it also is unlikely that volcanic activity would initiate a major quake, but regardless, the effects of an eruption would be of far graver consequence.

While it may be hundreds or thousands of years until the next eruption at Long Valley, no one can afford to be complacent. One scenario is that the rising magma will heat or encounter the subsurface water, causing a steam explosion like the one that initiated the eruption at Mt. St. Helens. Such an event is called a phreatic explosion, and may or may not be followed by eruptions of lava, as magma is called when it reaches the surface. A phreatic explosion could cause rock to be strewn as far as 10 km from the vent, and would produce billows of ash that could spread for tens of kilometers. A cloud-like "pyroclastic" flow of rock and gas could roar through Long Valley, damaging or destroying everything in its path.

In the popular resort town of Mammoth Lakes, such an event — one of the mildest possible in Long Valley — would not only devastate the community's tourist-based economy, but would block the escape route, the lone highway that runs through the caldera. (Alternate routes are being arranged, at the insistence of USGS.) Avalanches caused by the shaking ground and sudden intense heating would be likely as the heavy snow pack on the surrounding mountains was disturbed and melted.

People may run toward the "gentle" eruptions at Kilauea (SN: 7/9/83, p. 24) on the island of Hawaii to witness the earth in action, but no one would want to be near Long Valley. The magma's high silica content guarantees that the volcano will not be as well-behaved.

Possibilities include heavy ash falls and pyroclastic flows, in which rock and gas stream from the volcanic vent like liquid, travelling at speeds of 50 to 150 km per hour at temperatures of hundreds of degrees Celsius. Lava could build domes, and flow. The danger that a magma-filled dome could lead to a pyroclastic surge increases as it grows, because a dome's flanks are unstable and often collapse. In a special bulletin, USGS scientists estimated that areas within 5 km "could be endangered by such pyroclastic flows, and that this distance would progressively increase as a dome grew higher."

"The odds of seeing something really big are less than something intermediate, but we don't have the kind of data that we can test statistically," Bailey said. He has been studying the composition of lavas in the Mono Crater-Long Valley area, and believes that the magmatic system in Long Valley slowly is returning to its former composition after being perturbed when the Mono Crater system was superimposed 300,000 years ago. The younger systems to the north are at an earlier stage of development than the Long Valley system, and he says that it "will be a long time before either reaches the potential that Bishop Tuff had."

Before an eruption researchers expect to see abundant signs that an explosion is pending. As magma moves toward the surface, thousands of earthquakes will mark its passage through breaking rock, and the ground over the caldera will swell. In January there were thousands of microquakes per hour, but the swarm still was tiny compared to those that have preceded eruptions at other volcanoes, such as Mt. St. Helens. That volcano erupted in May 1980 (SN: 5/24/80, p. 324; 6/7/80, p. 355) in the Cascade Range to the north where the Pacific plate is being subducted beneath the North American continent. Until then, scientists at USGS had had little direct experience with volcanoes at subduction zones.

The system at Long Valley, including the Mono and Inyo craters, also is a new kind of beast as far as the geologists are concerned. At no place on earth, for instance, has an eruption on the scale of the event 700,000 years ago in Long Valley occurred in historic time. That explosion was 600 times as powerful as the biggest eruption at Mt. St. Helens. While such a cataclysm is improbable anywhere, including Long Valley, the precursors and consequences are unknown.

Many of the researchers suspect that the volcanism in eastern California, and in parts of the Basin and Range, is due to stretching of the crust as it is pulled in an east-to-west direction. The Sierra Nevada is rising, and the Owens Valley to the east is dropping down, placing stress on the fault system and perhaps creating space for magma to move up from the mantle. Some scientists, in fact, suggest that Long Valley was once round, and has been elongated as much as 10 km in an east-west direction.

The Long Valley system has been active for at least two million years, based on studies of lavas deposited by an eruption at Glass Mountain, now on the caldera's northeastern boundary, says Arthur Lachenbruch of USGS in Menlo Park. Drawing on measurements of heat flow, seismicity and studies of the composition of lavas in Long Valley, he has proposed a general model for the periodic replenishment of the magma chamber.

If, as it appears, the crust is pulling apart much faster than it is at other locations, fluid, high-temperature magma called basalt is sucked up from the upper mantle through cracks in the lower crust, he explains. This basaltic magma is similar to the magmas that erupt from volcanoes like Kilauea, which form as the crust passes over hot-spots in the earth's mantle (SN: 9/22/79, p. 202). At the Hawaiian volcanoes, however, the magma follows conduits to shallow magma chambers or clear to the surface, its passage unobstructed by the granitic rocks that form the continental crust.

In systems such as Long Valley, basaltic magma, which melts at high temperatures (about 1100°C), rises easily through narrow cracks but then encounters granitic material, which has a much lower melting point (about 800°C). The basalt gives up some of its heat and melts the granite, turning it into a gooey, silica-rich melt called rhyolite. In effect, Lachenbruch says, the basalt cannot rise through the thick rhyolite barrier of its own making; instead, it spreads out horizontally, and acts as a hot-plate that keeps the area warm.

If new hot basalt were not reinjected during the last two million years, the entire system would have cooled and hardened by now, Lachenbruch says. "The fact that we've had almost continuous activity in this area for two million years suggests that there must have been a fairly continuous resupply of heat by basalt from the mantle."

One indication that the magma chamber is being replenished is that the amount of heat being transferred from the hot earth interior via the extensive system of hot springs is quite high. Mike Sorey, a hydrologist with USGS in Menlo Park, reported that 15 heat flow units (a measure of heat flowing through the ground) are being emitted over the whole caldera, with about 75 percent of the heat coming from the resurgent dome. In the Basin and Range to the east, the average is 2 to 2.5 heat flow units, and 1 unit in the Sierra Nevada to the west.

Lachenbruch incorporated this finding into his theoretical analysis of the deep thermal system. He estimates that for an area the size of the caldera, a layer of basalt 10 km to 20 km thick would be required to supply that amount of heat. "To keep this system going and supply the heat that it's losing, you would have to supply enormous amounts of basalt to the crust," he says. "If the hydrothermal system has been going on a long time, say 300,000 years, it means that to be hauling off all of this heat, it must be circulating very deep and very close to the magma chamber." If so, he says, the water is probably reaching to within one km of the molten rock.

The scientists hope that as they increase their knowledge of Long Valley and of the earthquake regime in the area, their ability to assess the possibility of eruptions will improve. Changes in seismicity and uplift are obvious precursors; concentrations of gases, such as radon, emitted at steam vents may indicate adjustments in crustal strain.

John Eichelberger of Sandia Laboratories in Albuquerque, N.M., has found that volcanic glasses less than 1,000 years old from the area contain much higher percentages of water than have been seen before in fresh glass. The water content is 2 percent to 3 percent by weight, rather than a few tenths of a percent. These glasses are not, as previously believed, fragments from varied flows but are themselves quickly cooled, gas-rich magmas.

With colleagues, Eichelberger has found that within individual eruption sequences the glasses start out with high water content, and that the water declines to about two tenths of a percent by weight as an eruption continues. One possible explanation is that the magma bodies are chemically zoned, and that the wet magmas erupt first. A second possibility, and one that Eichelberger thinks is more likely, is that the most gaseous magmas are erupted first, and that as the eruption continues, so does degassing. The least gaseous magmas are those involved in building the dome in the late stages of an eruption.

The gas studies may be useful in tracking the progress of an eruption. The isotopic content of the gases may change during the event, and it may be possible to determine the state of degassing in the magma by sampling gases emitted at steam vents. Still, Eichelberger says, "It's really unclear whether any of these geochemical techniques will be useful in a predictive sense."

The scientists at the meeting said repeatedly that they were not here to discuss the potential hazards. The purpose of this meeting, they stressed, was to establish the geometry of the magma chamber and to discuss the possibility of drilling a hole into a yet-to-be specified location in the area. A drill hole could reveal valuable information about the composition and gas content of the magma and frozen rock, about the hydrothermal system, and about the amount and location of basaltic and rhyolytic magma. Nearly all of the researchers agreed, though, that much more must be learned about Long Valley before a costly drilling project can be justified.

This month dozens of researchers will stream through Long Valley and the nearby mountains to emplace still more instruments. The least that will come of the activity at Long Valley is that the scientists will learn more about this kind of volcanic system as it develops. No one knows which way events will go. Long Valley may slip docilely back into its dormant state, with no eruption to mark this episode in its history. But then again, it may not. □