Volcanism of Long Valley, California:
The Bishop Tuff Eruption

The west coast of North America has been tectonically and volcanically active for billions of years. The Sierra Nevada Mountains in eastern California were born of volcanoes, and magma has been erupting in the Long Valley to the east of the mountains for over three million years (Bailey, et. al., 1989). However, the climactic eruption of the region occurred relatively recently in the region's geologic history. About 760,000 years ago, a huge explosion of magma warped the Eastern Sierra into the landscape that exists today. The eruption depleted a massive magma chamber below the earth's surface so that the ceiling of the chamber imploded, forming what is now known as the Long Valley caldera. The caldera is at the eastern base of the Sierra Nevada Mountains, about 50 km northwest of the town of Bishop, and 30 km south of Mono Lake (Bailey, 1976).

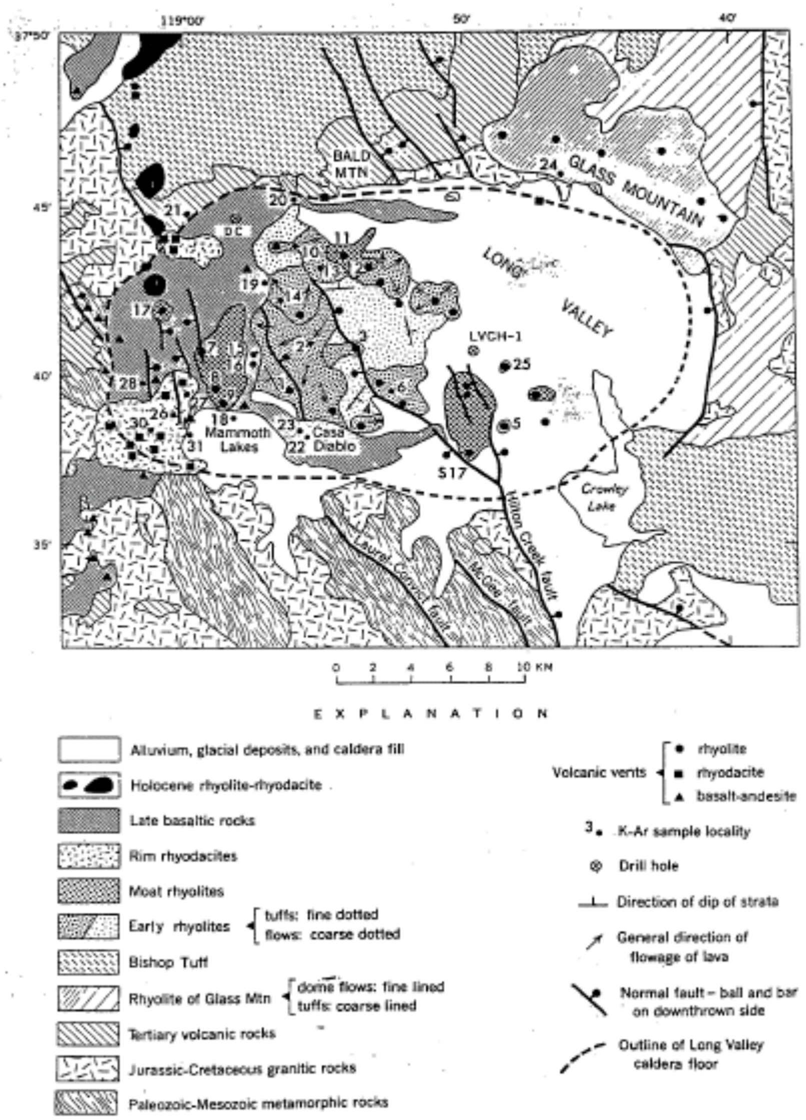


Fig. 3. Generalized geologic map of Long Valley caldera.

A geologic map of the Long Valley Caldera, including both pre- and post-caldera rock (Bailey, 1976).

The ejecta from the eruption moved over land and through the air: the ash that fired out of the volcano was blown as far east as Nebraska in a huge, dark cloud of plinian ash. A nuee ardente billowed over the rim of the volcano and spread lava to the south, east and north, forming a volcanic outcrop now called the Bishop Tuff. Today, an expanding resurgent dome in the center of the depression indicates current magmatic activity beneath the caldera, and earthquake swarms in the last 25 years could also be linked to subsurface magma movement. Clearly, the Long Valley caldera is not dormant, so understanding the eruption that formed the caldera and surrounding features is essential to assessing the region's current and, more importantly, possible future activity.

Volcanic activity existed prior to the Bishop Tuff eruption 760,000 years ago. Precaldera eruptions began 360,000 years ago with wide-spread trachybasalts and trachyandesites. The youngest of these rocks are dated at about 220,000 years ago. Rhyodacties and quartz latites in the modern caldera area extruded from about 320,000 years ago to 260,000 years ago, and then silica-rich rhyolites at Glass Mountain northeast of the caldera erupted from about 210,000 years ago to 80,000 years ago. The scattered distribution of the initial mafic eruptions indicates that they were erupted from the mantle, while the slightly younger domes and flows were from a deep-crustal source. The youngest rhyolite eruptions erupted at the northeast rim of the caldera at Glass Mountain and were the first activity of the silicic Long Valley magma chamber (Bailey, et. al., 1989).

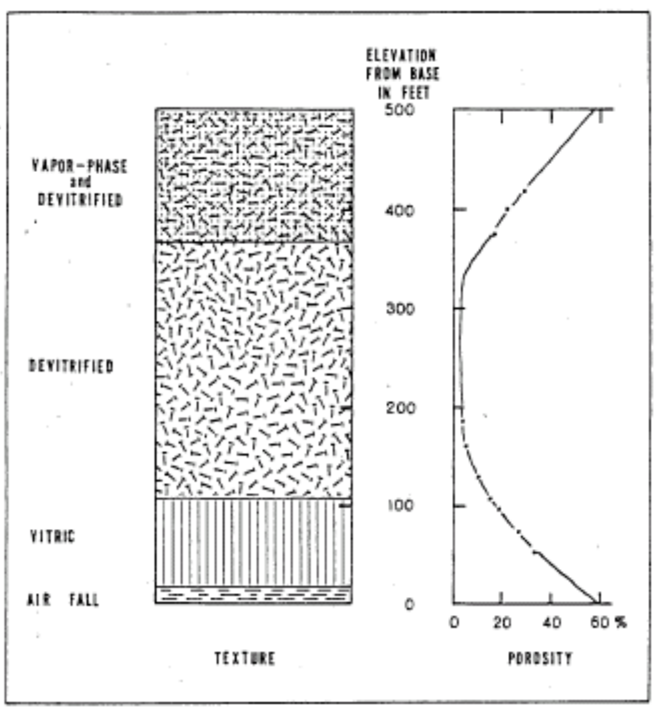
This chamber gave birth to the cataclysmic eruption of 760,000 years ago, and is connected to the magma which erupted from the chain of rhyolite domes that stretch up to the northwest. Eruptions crept sequentially along this line, beginning with the Bishop Tuff eruption and most recently displaying activity in the middle of Mono Lake at the island Negit. This most recent volcanism of the Inyo-Mono crater eruptions occurred as late as 1850 A.D (Bailey, et. al., 1989).

The cataclysmic eruption which caused the collapse of the caldera and the deposition of the Bishop Tuff was an explosive, fast event. It ejected coarsely porphyritic biotite rhyolitic ash and viscous lava with an approximate silica content of 76 percent. The total ejecta came to about 600 km^3, which emerged mainly as ash flows (Bailey and

Hill, 1999). The sequence began with air-fall ash eruptions that lasted for four days or more. Beginning 10-15 hours after the air-fall eruption, southeast-directed ash flows erupted simultaneously. Then the latest, thickest, north-directed flow began 3-4 days after the ash flow eruptions began, and lasted about 1.5 days (Lipshie, 2001). The magma chamber emptied in just a week or less, an unusual speed which greatly affected the landforms that the eruption left behind.

Shortly after the eruption, the caldera subsided into an elliptical depression 32 km long by 17 km wide, and 2-3 km deep. Collapse perhaps occurred along ring faults which have since been covered by younger pyroclastic material (Bailey, et. al., 1999). The eruption began in the south central area of the caldera near the Hilton Creek fault. Judging by the lithic content of this area compared to others in the caldera, a succession of ring-faults erupted ash flows in sheets. The change from single-vent Plinian mode to multiple vents along ring faults occurred when just 20 percent of the total ejecta was out (Hildreth and Mahood, 1986). According to Charles Bacon of the USGS, this two-phase eruption process is due to "withdrawal of magmatic support from below." The roof of the magma chamber is left unsupported after the single-vent eruption, so the column collapses, forming multiple ring fractures with vents all around them from which pyroclastic flows continued (Francis, 1992).

What came spilling out of the fiery vents was an ignimbrite, a hot cloud of material deposited in a pyroclastic flow, such as a nuee ardente. This material spread quickly in at least two pulses of volcanic activity and perhaps as many as seven. The deposition from these flows cooled and formed the Bishop Tuff. Ignimbrites are fluidized, meaning the solid and liquid particles are suspended in expanding, hot gaseous particles (Williams and McBirney, 1979). This begins the process of sorting clasts by size and density and forming "segregation structures." These structures then provide direct escape routes for gas. Joints and welding are evidence of the speed of the emplacement of the deposit: the flow units all cooled together in a "compound cooling unit." A typical ignimbrite is well-graded by size and density of clasts. The fine-grained basal layer is material ground up when the flow shears against the ground surface. The grain size increases upwards in this layer because of dispersive forces. Above this layer, clasts are stratified by density, so pumice floats to the top while lithic clasts sink downwards. The top layer is fine-grained ash deposit, which is the result of gas escaping the ignimbrite (Francis, 1992).



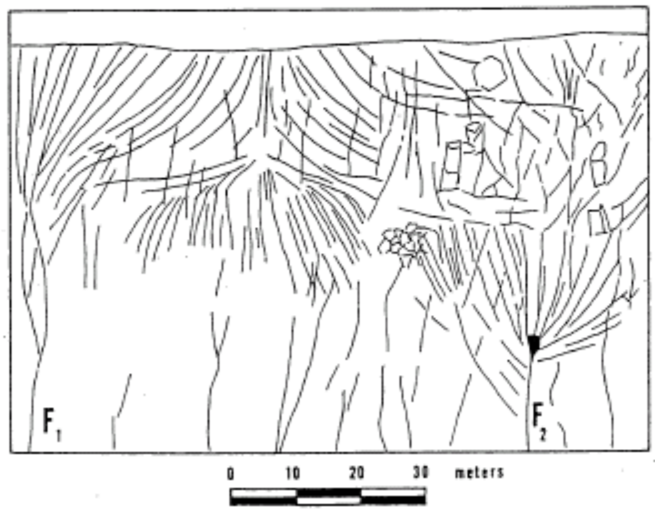
A profile of the Bishop Tuff by texture and density (NASA, 1987).

The Bishop Tuff can be divided into such strata in a cross section such as the Owens River Gorge. The zonal pattern, according to a 1987 NASA guide, is basically defined by four identifiable sections: at the bottom is a white, well-bedded air fall unit, overlaid by non-welded vitric ash. Then a partially-welded vitric tuff unit with porosity ranging from 10 to 45 percent grades upward to a densely-welded devitrified tuff with less than 10 percent porosity. The top is a partially-welded to non-welded unit. The gradual superposition of vapor-phase alteration on devitrification is noted by the change from cliff-forming to slope-forming units at this point. The cliff-forming unit is the densely-welded, devitrified zone, and the overlying partially-welded devitrified zone with 10 to 20 percent porosity is the slope-forming unit. Welding controls the type crystallization that occurs (NASA, 1987).

A cross-section of the Owens River Gorge reveals the geologic history before and after the tuff was deposited. The base is a Triassic Wheeler Crest quartz monzonite. Twenty meters of precaldera trachybasalt rest on top of that, which erupted from a vent 1 km north of the gorge about 320,000 years ago. That layer is overlain by outwash gravel from the Sherwin glaciation, with the Bishop Tuff ash flows on top of that.

The colors of the tuff fade from pink at the top, to brown in the middle, to dark grey at the bottom (Bailey, et. al. 1989). There are greys and pinks, ranging from salmon to dark brown, and including blacks, purples and oranges. Phenocrysts and xenoliths of basalt, hornfels, quartzite and granite can be found in the tuff (Lipshie, 2001).

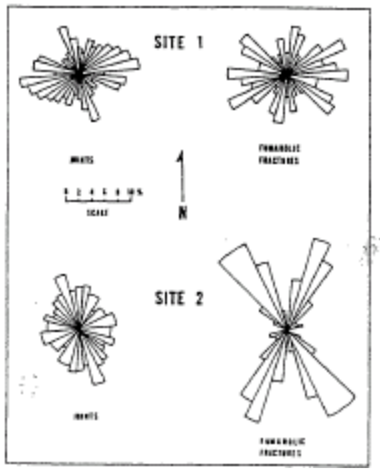
Joints in the tuff are often vertical, but inclined and radial jointing is common. In the densely vitrified zone, joints are widely spaced at about 6 to 12 m apart. These joints are encrusted with tridymite and fayalite at the top. These abruptly give way to close, columnar joints at the 10 percent porosity level. Fumerolic mounds are at the center of columnar joint roses, and they are most common in the partially welded zone where there is vapor phase crystallization. At the Owens River Gorge, the roses are spaced 90-150 m apart (NASA, 1987).



A sketch of the joint pattern between fumerolic ridges at the Owens River Gorge (NASA, 1987).

The jointing patterns in the Tuff are arranged by gas movement. The temperature of the nuee ardente is estimated to have been between 500 and 750 degrees Celsius, which is 930 to 1,380 degrees Fahrenheit (Lipshie, 2001). As the hot ash compacted, joints formed during welding. Water and volatiles were released during devitrification in the zone of dense welding. Because the flow – or multiple flows on top of each other – cooled so quickly into one cooling unit, gas escaped in unique patterns (Sheridan, 1970). At the fumerolic fractures, heat rose faster with escaping vapors than by conduction, which controlled crystallization: because larger volumes of gas were escaping through fumaroles, vapor phase zone formed (NASA, 1987). Early conjugate joint sets controlled the distribution of fumaroles after welding but before vapors escaped. Then, after vapor phase activity, as heat was escaping, random orthogonal joints formed, which developed into fumaroles.

Fumaroles have left mound shapes on the surface of the volcanic tableland and irregularities in the jointing of the tuff. The mounds are durable relative to the surrounding tuff, so they are positive topographic features. They are .5 to 5 m above the terrain, and they appear in two types: domical mounds are 60 m in diameter, and straight or curved vertical joint ridges are 1.5 to 5 m high and up to 600 m long (Sheridan, 1970).



Diagrams of rose joints and fumerolic fractures created by gas movements through the tuff as it quickly cooled (Sheridan, 1970).

The general mineralogy of fumerolic areas and the vapor-phase zone are similar, with a zone of hydrothermal alteration around fumerolic vents. These inner zones contain hydrobiotite and marialite, and they have less SiO_2, and more Al_2O_3, K_20, and H_2O (Sheridan, 1970).

The southeast tableland, including Owens River Gorge, is the most extensive exposure of the Bishop Tuff (Bailey and Hill, 1999), yet it is only a fraction of the total ignimbrite deposited by the nuee ardente. Two-thirds of the tuff is buried in the caldera (Hildreth and Mahood, 1986) under younger volcanic rock. After the cataclysmic eruption of 760,000 years ago, eruptions at 12 vents near the center of the caldera continued for 40,000 to 100,000 years, accumulating about 500 m of material in the caldera. These rhyolites are generally aphyric to sparsely porphyritic with about 75 percent silica content (Bailey, et. al., 1999), but they erupted in two phases.

First came eruptions which deposited rock known as early rhyolite. Pyroclastic debris erupted, and then hot, fluid flows of rhyolite, forming volcanic rocks that distinctly contrast with the Bishop Tuff: they are aphyric, sometimes sparsely porphyritic, and contain less than 5 percent crystals. The phenocrysts include plagioclase, hypersthene, biotite, and Fe-Ti oxides. This contrast with the tuff marks a change in magmatic conditions after the collapse of the caldera (Bailey, et. al., 1989). Also, the concentric zonation of post-caldera material perhaps indicates the progressive downward crystallization of the magma chamber. This implies that the silica content decreased in the post-caldera eruptions because the chamber was being tapped deeper and deeper (Bailey, et. al., 1999).

After a quiescent period of about 100,000 years, intracaldera volcanism was active again. Rhyolite erupted mainly in the moat of the caldera, likely from ring fractures peripheral to the resurgent dome. The eruptions of so-called moat rhyolite occurred in clockwise succession around the resurgent dome in 200,000-year intervals. An eruption in the northern sector of the moat occurred at 500,000 years ago, and one occurred at the southeastern sector 300,000 years ago. Finally an eruption at the western sector occurred 100,000 years ago. Moat rhyolite is crystal-rich, containing 20 percent phenocrysts of plagioclase, quartz, sandidine, biotite, hornblend, and Fe-Ti oxides. It is coarsely porphyritic and its thick, steep-sided domes suggest higher viscosity and lower temperature than the early rhyolite (Bailey, et. al., 1989).

Soon after the moat rhyolite eruptions, a lake filled the depression. Evidence of Pleistocene Lake, as it is known, is preserved in strand lines and terraces that run along the eastern caldera wall. It was water from this lake that carved the Owens River Gorge when resurgent doming uplifted the lake bottom. The resurgent dome was an island in the middle of the lake when it was full about 600,000 years ago and 100,000 to 50,000 years ago. Glacial erratics of granite are lodged in the terraces, indicating that icebergs from glaciers were floating across the lake from the mountains at the west. The water was eventually drained by the downcutting of the Owens River. Crowley Lake, which sits in the South Moat today, is a man-made water reserve, not a remnant of Pleistocene Long Valley Lake (Bailey, et. al., 1989).

The resurgent dome is evidence of magma resurging toward the surface of the earth. In the past year, USGS researchers have observed increased temperatures on the resurgent dome, indicating and increase in the magma's proximity to the surface. Carbon dioxide accompanies magma to the surface, and gas emissions have begun to kill trees on the resurgent dome, and at the base of Mammoth Mountain on the southwest rim of the caldera.

Hydrothermal activity is also evidence of present magma activity below the surface. Magma is heating the ground as high as the water table, so that fumaroles are steaming all over the caldera floor. But magma is heating the ground as high as the surface! Hot springs are abundant in the caldera, and the surface water in these locations is being heated by magma as it rises up again.

It is unpredictable whether a cataclysmic explosion like the Bishop Tuff eruption will happen again. It is staggering to imagine an event of that magnitude occurring today, when humans are sprawled inside, outside and around the caldera. Thousands of skiers fly to the Long Valley Caldera for Mammoth Mountain's slopes every winter, and the millions who populate Los Angeles to the south drive up to recreate in the summer.

An ash cloud that reached over more than half of the United States, as the Bishop ash cloud did, would stop life in its tracks by covering everything in ash. Cars wouldn't start, plants and animals would be choked, the sun would be blocked, and the agricultural economy would be devastated.

What is known, though, is that something is happening down there which is slowly but surely transforming life up here. By keeping track of resurgence in the caldera, carbon dioxide emissions, earthquakes and fumaroles, we have a better chance of assessing when the next eruption is coming, and if it can possibly compare to the volcano which left in its wake the Bishop Tuff.

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