EVOLUTION OF THE MONO-INYO CRATERS VOLCANIC CHAIN, LONG VALLEY VOLCANIC FIELD, EASTERN CALIFORNIA

By

Bissett E. Young

Volcanoes of the Eastern Sierra Nevada

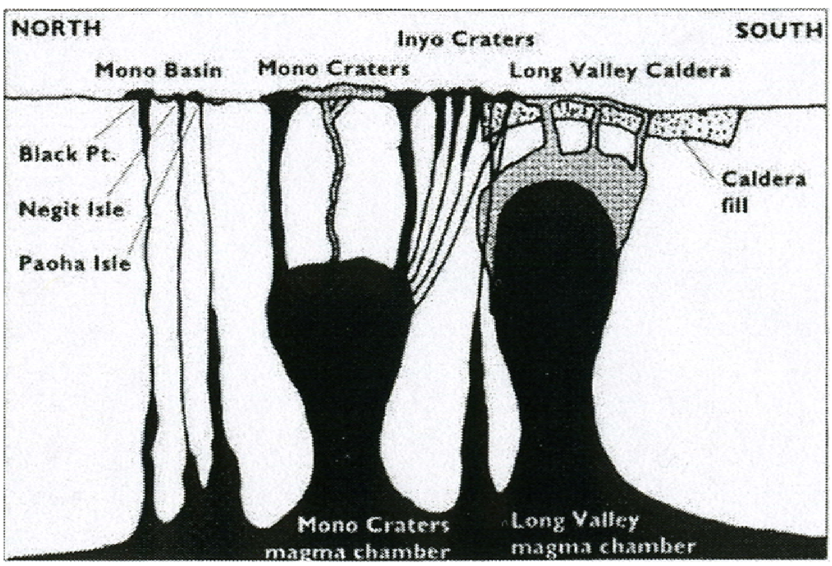
June 2008

Abstract

Volcanism began in Long Valley volcanic field 4 Ma, and regional volcanism continues today. East-west extensional forces have produced widespread normal faulting in this area. Subsequent thinning of the crust allows decompression melting of the mantle and provides molten material with pathways to the surface. The Mono-Inyo Craters are the youngest volcanic features in the Long Valley volcanic field, ranging in age between 40,000 and 250 years old. They occur along a fissure system trending north from the west moat of Long Valley Caldera to Black Point fissures, north of Mono Lake. Eruptions along the Mono-Inyo Craters fissure system have at times range from phreatic to magmatic, explosive to effusive, and mafic to rhyolitic. The variety of volcanic activity can be observed as an abundance of domes, craters, fissures, and tephra deposits covering the area.

Introduction

The Long Valley volcanic field is situated above the East Sierran frontal fault zone, east of the Sierra Nevada, in the westernmost reaches of the Basin and Range province. The volcanic field is located at the northern end of the Owens Valley Rift and covers an area of ~4,000km^2 (Bailey, 2004). Rifting in the Owens Valley began 4.5 Ma, coincides with the uplift of the Sierra Nevada (Huber, 1981 as referenced in Bailey, 2004), and is associated to global trend of increased plate motion (Bailey, 2004). Extensional forces are acting in the region are responsible for decompression melting of the asthenospheric mantle. This, in turn, has caused melting and thinning of the overriding lithosphere (Bailey, 2004). Molten material moves toward the surface due to the relative force of gravity, which exerts a greater force on the denser surrounding and overlying rock than on the magma body. If the magma reaches a point of buoyant equilibrium it may form a chamber underground. As the magma body loses heat to the surrounding rock, the change in its' chemical composition due to processes of fractional crystallization and assimilation may allow it to continue to rise. The new body of magma will have a higher silica content and a greater percentage of dissolved gas. This change combined with decreasing pressure from overlying rock may result in an extremely explosive eruption. As magma moves up, it is often provided access through fractures in the surrounding rock. Basin and range rifting has produced extensive normal faulting east of the Sierra Nevada. Many of the volcanic features along the Mono-Inyo Craters fissure system have been directly tied to the presence of local grabens (Miller, 1985).



Volcanoes of the Long Valley volcanic field (adapted from Tierney,…)

Volcanism in this area began around 4 Ma and continues to present day. Volcanic activity over this expanse of time has been both explosive and effusive, creating a wide variety of landforms and volcanic products. Long Valley volcanism is separated by Bailey [2004] into two phases: a pre-caldera phase beginning 4 Ma leading up to and including the Long Valley eruption and caldera collapse, followed by a post-caldera phase including intra-caldera extrusions of the Early and Moat Rhyolites an the commencement of activity along the Mono-Inyo Craters volcanic chain. Both phases of volcanism are generally defined by a mafic-to-silicic evolution, but the sources are most likely unrelated (Bailey, 1989). Chemical and mineralogical analyses of the different volcanic products from both the pre- and post-caldera sequences gives evidence to the notion that the two phases relate to separate magmatic sources (Bailey, 2004). Pre-caldera volcanism including eruption of the Bishop Tuff 760ka, as well as post-eruption intra-caldera extrusions of rhyolite, are associated with the Long Valley magma chamber, whereas the post-caldera volcanism along the Mono-Inyo Craters chain is related to a separate elongate chamber along the Mono-Inyo Craters fissure system (Bailey, 1989; Tierney, 1995)

The main focus of this paper is the latter phase of volcanism, related to the Mono-Inyo Craters volcanic chain. The chain exists along a 45km line from Mammoth Mountain in the south to Mono Lake in the north (Bailey, 1989). Eruptions along this line began between 300 and 200ka and the chain continues to be active today, its' most recent eruption having occurred 250 years ago, on Paoha Island in Mono Lake.

Pre-caldera Volcanism

Volcanism began in the Long Valley volcanic field with the eruption of mafic lavas (basaltic-andesitic) over a wide swath of land (~4,000km^2), which is an indication of an extensive mantle source region (Bailey et al., 1989). This was followed by period (~3.2-2.6ma) of Rhyodacite dome formation around the north-northwest perimeter of the present day caldera (Bailey et al., 1989). The shift of volcanic composition from mafic to intermediate is an indication that molten material accumulated within a magma chamber, resulting in increased silica content of the magma due to fractional crystallization (Bailey et al., 1989).

Further accumulation and differentiation eventually led to the development of the Long Valley magma chamber, an enormous body of highly silicic magma at shallow depth. The Glass Mountain rhyolite domes, flows and tuffs erupted between 2.1 and 0.8ma were the first features produced from this new magmatic body (Metz and Mahood, 1985 as referenced in Bailey, 1989). The extremely explosive Long Valley eruption took place around 760 ka, during which $600km^3$ of material was ejected from the magma chamber in the form of ash falls and pyroclastic flows. This eruption was responsible for creating the Bishop Tuff and for the formation of the enormous Long Valley Caldera, an oval shaped depression with an approximate area of $450km^2$ (Bailey, 1976). The collapse is thought by Bailey [1976] to have occurred along arced ring fractures, few of which are visible today. The Bishop Tuff is the name given to the welded rock produced by pyroclastic flows (Gilbert, 1938; Hildreth, 1979; referenced by Bailey et al., 1989) during the eruption deposited around and within the caldera, covering an area of $1500km^2$ up to depths of 200m (Bailey et al., 1989).

Post-caldera Early and Moat Rhyolites

The catastrophic eruption was followed by a new dome-building phase within the caldera, around 750-650 ka (Bailey, 1976; Mankinen et al., 1986). This phase was initiated by eruptions of pyroclastic tephra and followed up with aphyric rhyolite flows, collectively known as the Early Rhyolite (Bailey, 2004). These successive events built up the caldera floor to heights of 500 m (Bailey et al., 1989). A resurgent dome developed in the center of the caldera over the next 100,000 or less years. The Moat Rhyolite was erupted following dome resurgence in three events: 500,000 years ago in the north, 300,000 years ago in the southeast, and 100,000 years ago in the west moat (Bailey, 1989). The west moat eruption could be the most recent to issue from the Long Valley magma chamber (Bailey, 1989).

Mono-Inyo Craters Volcanic Chain

Post-caldera mafic volcanism relating to the Mono-Inyo sequence began in the west moat of Long Valley Caldera, around 415 ka (Bailey, 2004). Some flows reached a depth of up to 250 m, pooling in the west moat and overflowing into the north and south moat around the resurgent dome (Bailey, 1989). Extensive mafic lava flows also took place southwest of the caldera from 250 to 100 ka, and include Devil's Postpile (Bailey, 2004). Further north, eruptions of mafic lava took place near June Lake between 40,000 and 20,000 years ago and at Black Point fissures 13,300 years ago (Bailey, 1989).

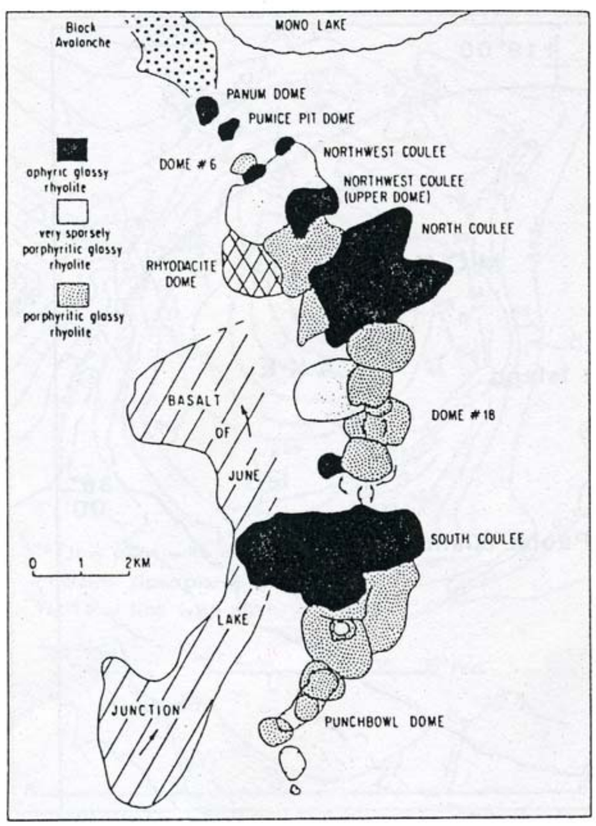
Rhyolitic eruptions occurred at intervals with these mafic episodes at other locations along the Mono-Inyo chain (Bailey, 1989). The largest accumulations of material were at points of intersection between the Mono-Inyo Craters fissure system and the ring fractures on the circumference of the caldera. The intersection at the southwest rim of the caldera is where Mammoth Mountain sits, a culmination of 12 or more silica rich domes and flows erupted between 200 and 50 ka (Bailey, 1989).

The Mono-Inyo Craters chain began to take shape with the eruption of rhyolites at the Mono Craters around 40,000 years ago (Bailey, 1989). The Mono Craters chain is a 17-km long arc trending north, from the northwestern end of the Long Valley Caldera (Sieh, 1984). The chain sits above a ring fracture, Bailey et al. [1989] refers to it as a "structural zone of weakness," where the rounded edge of an ancient magma chamber meets country rock. It is this relationship that is responsible for the bow shape of the Mono Craters chain. The chain includes at least 30 intersecting domes, coulees and craters, joined together to create a ridge up to 610 meters higher than the local topography (Bailey, 1989). Volcanic activity extends north from the ridge of the Mono Craters chain, along the Mono-Inyo Craters fissure system, to produce the volcanoes of Mono Lake and Black Point Fissures.

According to seismological data (Achauer and others, 1986; referenced by Bailey, USGS), these eruptions were derived from a magma chamber underlying the chain at a depth of 10-20km. However, Hill [2006] states that the Mono Craters magma chamber sits at a depth of only 6-10km. Older eruptions along the Mono Craters chain produced mainly porphyritic rhyolites while younger eruptions produced aphyric rhyolites (Bailey et al., 1989). This implies that the temperature of the magma increased over time, and/or that the depth of the chamber decreased (Bailey et al., 1989). Increased fluidity of erupted material allowed a greater quantity to be erupted. Studies by Wood [1984] show that temperatures of the erupted material are positively correlated with volumes produced.

The most recent eruptions of the Mono Craters, in the 8th century and in the late14th to early15th century, likely issued from a 6-km-long rhyolite dike beneath the chain (Sieh, 1984). These eruptions were preceded by the development of a graben along the range crest with a length of 1-2 km; Plinian tephras then erupted from vents within the graben (Sieh, 1984). These air-fall deposits were followed by pyroclastic flows and surges, and subsequent phases built tephra rings around the vents; in the final eruptive phases, domes and coulees oozed out and formed rhyolitic plugs over the vents (Sieh, 1984).

The youngest of the Mono Craters is Panum Crater, with eruptions dated between 1345 and 1445 CE (Hill, 2006). Stratigraphic layering provides evidence of two explosive events at this site; each was followed by a separate dome-building phase (Bailey et al., 1989). Initial phreatic eruptions blasted away overlying rock and produced a crater and tephra ring around the vent; this was followed by pyroclastic flows and surges (Bailey et al. 1989). A first dome began to form within the crater, but was destroyed and produced an avalanche that compromised the northwest side of the tephra ring (Bailey et al., 1989). Subsequent pyroclastic flows and surges traveled through this breach, into Rush Creek and Mono Lake (Sieh, 1984). The eruptive phase proceeded with more air-fall deposits, building upon the tephra ring. Finally, glassy rhyolitic extrusions produced a new composite dome (Bailey et al., 1989).



The Mono Craters chain (adapted from Wood, 1977a)

The dome within Panum Crater contains three (Bailey et al., 1989) or four (Sieh, 1984) distinct subunits with unique textures and structures. North dome is the youngest feature and is composed of a mix of banded and pumiceous rhyolite (Bailey et al., 1989; Sieh, 1984). A north-trending fissure crosscuts north dome. South dome is slightly older than north dome and is built of banded rhyolite, foliated pumice and obsidian (Sieh, 1984). Southwest and east domes are the oldest sections and are likely related to the early explosive phases (Sieh, 1984; Bailey et al., 1989).

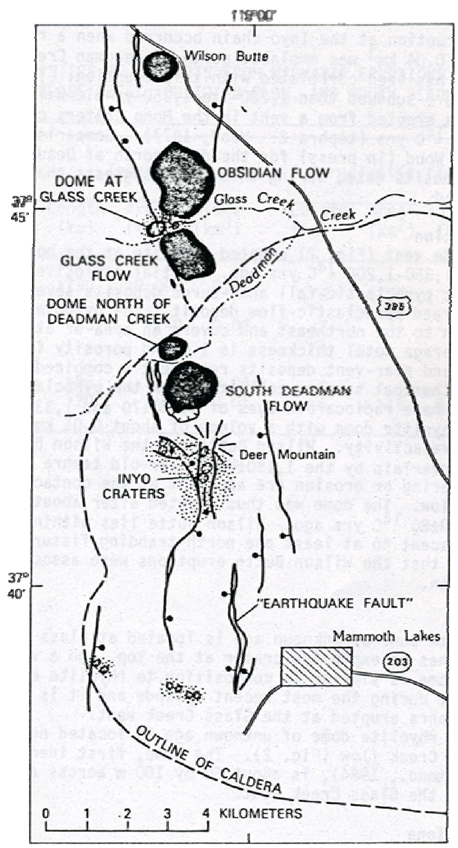
Eruptions of Inyo Craters

Inyo Craters chain is an 11km long linear stretch of domes and craters, extending from Mono Craters to the western rim of Long Valley Caldera. The chain sits within a 2-3 km-wide graben related to the regional extensional forces (Miller, 1985). The region is riddled with north-south fissures, implying that crustal extension is directly related to volcanic eruptions along the chain (Miller, 1985).

The earliest eruptions along the chain produced north Deadman Creek Dome around 6,000 years ago and Wilson's Butte between 1,200-1,350 years ago (Miller, 1985). Wilson's Butte sits at the northern end of the Inyo chain, inside a graben. Dome building at the site was preceded by explosive activity (Miller, 1985). A layer of pyroclastic flow covers layers of air-fall and pyroclastic surge deposits. The rhyolitic dome was then extruded atop these deposits (Miller, 1985). Volcanic products of these earlier eruptions on the Inyo chain bear chemical resemblance to those of the Mono Craters (Bailey, 1989).

Eruptions at Obsidian Dome, Glass Creek Dome, and South Deadman Creek Dome took place within months to a few years of each other, dated to between 550 and

650 years ago (Bailey, 1989; Miller, 1985). At all three vents, explosions of air-fall tephra were followed by base surges and pyroclastic flows (Miller, 1985) A number of phreatic eruptions contemporaneously produced the Inyo Craters on Deer Mountain, several craters on the north face of Mammoth Mountain and at other locations along the chain (Bailey, 1989; Miller, 1985). After conclusion of the explosive phenomena, effusive rhyolitic extrusions built domes over the vents (Bailey, 1989).



Inyo Craters chain (Adapted from Miller, 1985)

Early eruptions of tephra at South Deadman Creek, near the center of the Inyo chain on the northeast margin of Long Valley Caldera, spread out in a tongue to the northeast of the vent. This basal tephra layer is covered by interbedded pyroclastic flow and surge deposits with overall thickness of up to 10m. A second, larger tephra deposition followed and extends to the south-southwest of the vent. Eruptions soon commenced at Obsidian vent, 5km north of the South Deadman Creek vent. Tephra deposits stretching northeast of the vent for distances up to 25km are covered by low volume pyroclastic surge and flow deposits. These deposits overlap deposits from the South Deadman Creek eruption, indicating that they are younger (above description from Miller, 1985).

Glass Creek vent, situated north of Deadman Creek and 1.5km south of Obsidian vent, began erupting tephras soon afterward (Miller, 1985). The volume of erupted material from Glass Creek during this phase was greater than the combined tephra deposits at South Deadman Creek and Obsidian vents (Miller, 1985). Miller [1985] infers that thick poorly sorted beds of pumice, some welded, present at Glass Creek are the result of a landslide of accumulated material around the vent. Bursik and Reid [2004] attributed some deposits in Glass Creek canyon to lahars relating to the Inyo eruptions. Emplacement of a feeder dike is likely responsible for these eruptions (Miller, 1985).

Concurrent steam-driven explosions, the result of rising magma heating groundwater, blasted craters along the north-south Inyo chain (Miller, 1985; USGS Long Valley website, 2004). These phreatic craters include the Inyo Craters on the summit and south face of Deer Mountain, several craters that span the length between Obsidian and South Deadman Creek vents (Miller, 1985), as well as six craters on the north face of Mammoth Mountain in a line along the caldera rim (Bailey et al., 1989).

Phreatic eruptions were followed by massive rhyolitic extrusions at South Deadman Creek, Obsidian, and Glass Creek vents (Miller, 1985; Bailey et al.,1989). The rocks at these locations exhibit what Bailey et al. [1989] refers to as a “marble-cake” patterned mixing of light and dark rhyolite. The light-colored rhyolite, containing pumice and abundant phenocrysts, appears to be similar to the moat rhyolite of the Long Valley caldera (Bailey, 1989). In contrast, the darker colored rhyolite has higher silica content and few or no crystals, resembling later extrusion along the Mono Craters chain (Bailey, 1989). The implications of these observations are that during eruption, magmas from these two magma chambers were mixed during simultaneous extrusion through a single conduit (Bailey, 1989).

Volcanoes of Mono Lake

Mono Lake lies at the northernmost end of the Mono-Inyo Craters volcanic chain. Black Point, on the northern shore of the lake, formed 13,300 years ago under the waters of a much deeper Mono Lake (Tierney, 1995). Basaltic rock from underwater eruptions is interbedded with lake sediments and glacial depositions from the Sierra Nevada (Tierney, 1995). While still underwater, enormous northeast-southwest trending fissures opened within the volcano (Tierney, 1995). Negit Island in Mono Lake is a cinder cone built by several dacitic eruptions over the past 1,600 or more years, with the most recent eruption 270 years ago (Bailey, 1989; Tierney, **).** Paoha Island is composed mainly of uplifted lake sediments, with some andesitic eruptions on its' north shore. According to Tierney [1995], uplift of the island has occurred within the last 310 years. Bailey [1989] suggests that the uplift is attributed to a rhyolitic intrusion, while Tierney [1995] believes that it could be due to submerged fault movement. Rhyolitic eruptions produced a number of small islands northeast of Negit, as well as a dome-like intrusion on northern Paoha (Bailey, 1989). Other volcanic phenomena include underwater phreatic craters, steam vents and hot springs in and around the lake (Bailey, 1989; Tierney, 1995).

Hazards Associated with Future Volcanic Activity

Seismic unrest in the Long Valley caldera combined with uplift on the resurgent dome, has, in recent times, caused many to worry about the possibility of future eruptions in Long Valley. A future eruption along the Mono-Inyo chain appears more likely; the chain is geologically young and involves multiple eruptions occurring within a short time span (Bailey, 1989; Tierney, 1995). Miller [1985] postulates that future eruptions will be similar to the most recent eruptions at the Inyo domes. Associated hazards of a future eruption could therefore include tephra-fall, lahars (Bursik and Reid, 2004), and pyroclastic flows and surges. Future eruptions are speculated to be on the same scale as previous eruptions along the chain, which are considered relatively small events. However, Tierney [1995] warns that, similar to the development of the Long Valley magma chamber, a large silicic body could eventually accumulate beneath the Mono-Inyo chain and greatly increase the risk.

The USGS closely monitors seismic activity, ground deformation, and volcanic gases in an effort to predict a future eruption and mitigate the associated hazards. Most scientists who have studied the area agree that a future eruption is inevitable, but not necessarily imminent (USGS Long Valley Observatory website).

REFERENCES CITED

Bailey, Roy A. Volcanism, Structure, and Geochronology of the Long Valley Caldera, Mono County, California: Journal of Geophysical Research, v. 81, no. 5, p. 104-122, 1976.

Bailey, Roy A. Geologic Map of Long Valley Caldera, Mono-Inyo Craters Volcanic Chain and Vicinity, Eastern California: U.S. Geological Survey, to Accompany Map I-1933, 1989.

Bailey, Roy A., Miller, C.D., Sieh, Kerry. Excursion 13B: Long Valley caldera and Mono-Inyo Craters volcanic chain, eastern California: New Mexico Bureau of Mines & Mineral Resources, Memoir 47, 1989.

Bursik, M., Reid, J. Lahar in Glass Creek and Owens River during the Inyo Eruption, Mono-Inyo Craters, California: Journal of Volcanology and Geothermal Research, vol. 131, no. 3-4, pp. 321-331, 2004.

Hill, Mary. Geology of the Sierra Nevada: California Natural History Guides. University of California Press, 2006.

Miller, C.D. Holocene Eruptions at the Inyo Volcanic Chain, California—Implications for Possible Eruptions in Long Valley Caldera: Geology, v. 13, p. 14-17, 1985.

Sieh, Kerry. Most Recent Eruptions of the Mono Craters, Eastern Central California: Holocene Paleoclimatology and Tephrochronology, East and West of the Central Sierran Crest, Field Trip Guidebook for the Friends of the Pleistocene Pacific Cell, 1984.

Tierney, T. Geology of the Mono Basin. Kutsavi Press: Lee Vining, CA, 1995.

USGS Long Valley Observatory website. Explosive volcanic activity associated with the Inyo eruptions: http://lvo.wr.usgs.gov.InyoEruption/InyoExplosions.html.