This perspective is based largely on my study of the Long Valley Caldera (California, USA) over the past 40 years. Here, I’ll examine the “knowns” and the “known unknowns” of the complex tectonic–magmatic system of the Long Valley Caldera volcanic complex. I will also offer a few brief thoughts on the “unknown unknowns” of this system.

THE KNOWNs

The Long Valley Caldera, located along the eastern escarpment of the Sierra Nevada mountain range, formed 760 ky ago with the eruption of ~600 km³ of rhyolite we now call the Bishop Tuff. The caldera sits between two range-front normal faults: the Hilton Creek Fault to the south and the Hartley Springs Fault to the north (Fig. 1). The 1,300–650-year-old silicic vents forming the Inyo Domes extend into the west moat of the caldera. Mammoth Mountain is a 100–50 ka dacitic, cumulo-volcano surrounded by mafic volcanic vents as young as 8 ka that lies on the southwest rim of Long Valley Caldera (Hildreth 2004). Mammoth Mountain at 11,000 feet and the town of Mammoth Lakes at its base serve as a year-round resort and one of the largest ski areas in the USA.

No notable volcanic activity was documented in the caldera from the time of the early settlers in the mid-1800s through to early 1980. The onset of current caldera unrest occurred in May 1980, just a week after the May 18 eruption of Mount St. Helens (Washington, USA), with four magnitude 6 (M 6) earthquakes. Three were located beneath the Sierra Nevada just south of the caldera and the third was located beneath the southern margin of the caldera. A leveling survey later that summer revealed that the resurgent dome in the center of the caldera had bowed upward by 25 cm since the late 1970s, implying magmatic, rather than tectonic, processes were at work (Savage and Clark 1982).

Attempts by US Geological Survey (USGS) geologists to explain the implications of the ongoing unrest were initially greeted with outrage and denial in the resort community of Mammoth Lakes—a population largely unaware of the long history of volcanism in the area. Antagonism toward Earth scientists gradually waned through the 1980s and early 1990s as the caldera’s unrest continued to produce many locally felt earthquakes. The community began to accept the message presented by scientists through frequent public lectures and geological field trips open to the public. Outreach has included USGS support for civil authorities from Mammoth Lakes and Mono County to attend the 10th anniversary meeting on the eruption of Mount St. Helens.

Seismic unrest of the Long Valley Caldera has continued with recurring earthquake swarms in the south moat seismic zone (SMSZ), accompanied by elevated seismicity in the Sierra Nevada block to the south. Inflation of the resurgent dome has continued at rates as high as 20 cm/y since the late 1970s, implying magmatic, rather than tectonic, processes were at work (Savage and Clark 1982).

Mammoth Mountain has a magmatic system that is distinct from that of the Long Valley Caldera. But it, too, joined in the regional unrest with a nine-month earthquake swarm in 1989–1990. Mid-way through this sequence, long-period “volcanic” earthquakes began occurring at mid-crustal depths (10–20 km). By early 1990, diffuse emissions of magmatic CO₂ began killing trees in several areas around the mountain, and elevated levels of ³⁷Ar/³⁶Ar were detected from a fumarole on the upper flank of the mountain. The CO₂ emissions have since resulted in four fatalities when skiers fell into CO₂-rich snow pits. Swarms of lower-crustal, brittle-failure earthquakes, centered at depths of 20–30 km, occurred from June 2006 to September 2009, each followed by a seismic increase in the upper 10 km of the crust beneath Mammoth Mountain. There was a doubling in uptake of magmatic CO₂ in the 2009–2012 tree-rings in a large tree near the CO₂ tree-kill area (Lewicki et al. 2014). This post-1989 seismicity illuminates the crustal roots of the magmatic system and the path of CO₂-rich magmatic fluids from the base of the crust (depth ~30 km). This seismicity stands in contrast to the Long Valley Caldera, which has produced no earthquakes deeper than 10 km. Both findings limit our ability to access the state of the magmatic system beneath the caldera.

Included with the knowns are the surface geology and structure of the upper 5 km of the crust.

THE KNOWN UNKNOWNS

Geophysical studies of the area have sometimes produced conflicting results. Just how the results of these studies relate to one another and to the actual physical properties of the crust beneath the caldera are the known unknowns. Without a clear image of the deep structure beneath the caldera, a critical known unknown is the process inflating the resurgent dome. Two views prevail. One holds that inflation is dominated by the actual physical properties of the crust beneath the caldera are the known unknowns. Without a clear image of the deep structure beneath the caldera, a critical known unknown is the process inflating the resurgent dome. Two views prevail. One holds that inflation is dominated...
by activation of hydrothermal fluids, while the other involves renewed intrusion of magma and associated volatiles into the upper crust. Careful mapping and analysis of the eruptive history of the Long Valley Caldera led Hildreth (2004) to suggest that current inflation is driven by hydrous volatiles from secondary boiling of the final stages of a moribund, 760 ka Bishop magma chamber. Others suggest that inflation is driven by advection of a melt-fraction into the upper crust. The simplest model providing a good fit to the deformation data is a volume increase in a compact magma body centered at a depth of 7 km beneath the center of the resurgent dome (Montgomery-Brown et al. 2015).

The difference between these two views carries important implications for hazard assessment. If the volume of low seismic wave-speeds 10–15 km beneath the caldera inferred by Weiland et al. (1995) and Seccia et al. (2011) holds up to further testing, does it correspond to a zone of secondary boiling in a moribund Bishop magma chamber or to recent (last ~10,000 years) emplacement of a melt fraction at mid-crustal depths resulting from, say, basal underplating and collapse of a lower-crustal crystal mush?

Geothermal fluids upwelling beneath the Inyo Domes flow eastward down the hydrologic gradient within the postcaldera fill (2–3 km deep). Magma CO2 carried by this thermal water is apparently derived from a basaltic reservoir somewhere beneath the Inyo Domes (Brown et al. 2013). The elevated 3He/4He ratios in thermal springs in the east moat have been attributed to fluids ascending from upper-mantle sources along an extension of the Hilton Creek Fault into the caldera (Suemnicht et al. 2015). At issue here is lack of evidence for postcaldera (760 ka) displacement along the Hilton Creek Fault into the caldera (Hildreth 2004; Hill and Montgomery-Brown 2015). This leaves a question of whether the magmatic CO2 and the elevated 3He/4He in the thermal water in the east moat might be, in part, derived from a recent melt intrusion beneath the resurgent dome.

The temporal correlation between the onset of seismicity in the Sierra Nevada south of the caldera and caldera unrest suggests a tectonic–magmatic interaction. A related issue is the possibility of a local tectonic earthquake triggering the onset of eruptive activity in a magmatic system that has reached a tipping point in its evolution. Indeed, Hildreth (2004) points to the possibility that a major earthquake on the Hilton Creek Fault may have triggered the onset of the 760 ka caldera-forming eruption of Bishop Tuff. In mapping eruptive deposits of the Bishop Tuff, he found that the onset of the eruption began near the point where the Hilton Creek Fault intersects the southeastern margin of the ring fracture system. Modern examples of proximal triggering include the summit eruption of Kilauea volcano (Hawaii, USA), which began half an hour after the 29 November 1975, M 7.5 Kalapana earthquake, and the M 5 earthquake that triggered the onset of the catastrophic 18 May 1980 eruption of Mount St. Helens. In many cases, seismic waves (dynamic stresses) from large regional earthquakes and major (M > 7.5) earthquakes at global distances have triggered increased seismicity at volcanic and geothermal sites around the globe, including Long Valley Caldera and Mammoth Mountain. In a few cases, this remote dynamic triggering may have accelerated onset of eruptive activity in magmatic systems already in a near-critical state (Hill and Prejean 2015).

These examples underscore the importance of considering tectonic–magmatic interactions in parallel with processes within an internally evolving magmatic system when forecasting eruptions or making volcanic hazard assessments. A recent report on earthquake hazards in the Long Valley–Mono Lake region (Chen et al. 2014) represents one step in this direction. The above known unknowns illustrate the limits of current understanding of the state of magmatic systems for both the caldera and Mammoth Mountain and their proximity to criticality or tipping points. Moreover, these known unknowns present a challenge in communicating to the local residents and authorities the significance of the ongoing unrest, potential volcanic hazards, and reliable eruption forecasts.

**The Unknown Unknowns**

Unknown unknowns further complicate the challenge of making socially useful eruption forecasts. Even the most successful models developed for Earth’s structure and active processes are simplified versions of reality. The gap between models and reality is potentially a rich source of unknown unknowns. Similarly, unrecognized regional strain perturbations in an evolving tectonic–magmatic environment can compromise long-to-intermediate-term eruption forecasts based either on models or on probabilistic analysis of the recurrence history of past eruptions. Earthquake-triggered eruptions represent an extreme example of the challenge in making short-term eruption forecasts. On a more positive note, a number of successful short-term (days to weeks) eruption forecasts have been based on on-site experience and pattern recognition during accelerating unrest episodes leading to eruptions (White and Mc McLusclad 2016).

**REFERENCES**


Contamination makes aluminum oxide a priceless gem

Aluminum oxide or corundum is a commonly available material. However, trace levels of contaminants in the crystal structure of aluminum oxide can result in priceless gems, such as rubies, sapphires, and emeralds. Rubies are corundum with chromium contaminates. It’s the chromium that produces the deep red color. Next to diamonds, rubies are the most precious gems. Sapphires come in many different colors: yellow, red, pink, and the more traditional color, blue. The blue color is only possible when titanium and iron are both present in the structure. The gem shown in Figure 1 was labeled a ruby at a gem show. However, the X-ray diffraction pattern collected on the Rigaku MiniFlex, shown in Figure 2, matches corundum and the two additional phases that can be found in sapphires, mainly, rutile [TiO₂] and Cronstedtide [Fe₂⁺Fe³⁺(SiFe³⁺)O₃(OH)₂].

This gem would be more appropriately called a red sapphire.