Volcanic Unrest and Hazard Communication in Long Valley Volcanic Region, California

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Abstract

The onset of volcanic unrest in Long Valley Caldera, California, in 1980 and the subsequent fluctuations in unrest levels through May 2016 illustrate: (1) the evolving relations between scientists monitoring the unrest and studying the underlying tectonic/magmatic processes and their implications for geologic hazards, and (2) the challenges in communicating the significance of the hazards to the public and civil authorities in a mountain resort setting. Circumstances special to this case include (1) the sensitivity of an isolated resort area to media hype of potential high-impact volcanic and earthquake hazards and its impact on potential recreational visitors and the local economy, (2) a small permanent population ($\sim$8000), which facilitates face-to-face communication between scientists monitoring the hazard, civil authorities, and the public, and (3) the relatively frequent turnover of people in positions of civil authority, which requires a continuing education effort on the nature of caldera unrest and related hazards. Because of delays associated with communication protocols between the State and Federal governments during the onset of unrest, local civil authorities and the public first learned that the U.S. Geological Survey was about to release a notice of potential volcanic hazards associated with earthquake activity and 25-cm uplift of the resurgent dome in the center of the caldera through an article in the Los Angeles Times published in May 1982. The immediate reaction was outrage and denial. Gradual acceptance that the hazard was real required over a decade of frequent meetings between scientists and civil authorities together with

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public presentations underscored by frequently felt earthquakes and the onset of magmatic CO_2 emissions in 1990 following a 11-month long earthquake swarm beneath Mammoth Mountain on the southwest rim of the caldera. Four fatalities, one on 24 May 1998 and three on 6 April 2006, underscored the hazard posed by the CO_2 emissions. Initial response plans developed by county and state agencies in response to the volcanic unrest began with “The Mono County Volcano Contingency Plan” and “Plan Caldera” by the California Office of Emergency Services in 1982–84. They subsequently became integrated in the regularly updated County Emergency Operation Plan. The alert level system employed by the USGS also evolved from the three-level “Notice-Watch-Warning” system of the early 1980s through a five level color-code to the current “Normal-Advisory-Watch-Warning” ground-based system in conjunction with the international 4-level aviation color-code for volcanic ash hazards. Field trips led by the scientists proved to be a particularly effective means of acquainting local residents and officials with the geologically active environment in which they reside. Relative caldera quiescence from 2000 through 2011 required continued efforts to remind an evolving population that the hazards posed by the 1980–2000 unrest persisted. Renewed uplift of the resurgent dome from 2011 to 2014 was accompanied by an increase in low-level earthquake activity in the caldera and beneath Mammoth Mountain and continues through May 2016. As unrest levels continue to wax and wane, so will the communication challenges.

1 Geologic Setting and Background

Long Valley caldera is a 15- by 30-km oval-shaped topographic depression located midway between Mono Lake and the town of Bishop in east-central California (Fig. 1). It is nestled against the western escarpment of the large graben formed by the Sierra Nevada on the west and the White Mountains on the east. This impressive eastern Sierra landscape has developed over the past three million years as a result of repeated slip on the range-front normal faults and persistent volcanism. The dominant volcanic event in the area was the massive eruption of the Bishop Tuff during the collapse of Long Valley caldera 760,000 years ago. This caldera-forming eruption spewed some 600 km^3 of rhyolitic ash across much of the western United States. Frequent, smaller eruptions have continued within the caldera and along the adjacent Mono-Inyo volcanic chain right up to the recent past, the most recent of which was a small eruption from the north side of Paoha Island in the middle of Mono Lake some 250 years ago (Bailey 2004; Hildreth 2004).

From a purely scientific viewpoint, the Long Valley Caldera-Mono Craters volcanic field is a natural laboratory for studying the interaction between active tectonic and magmatic processes in a transtensional continental regime. In the presence of people and their societal accoutrements, however, active geologic processes pose geologic hazards. The earthquake hazard in this area is emphasized by range-front faults with Holocene offsets (Chen et al. 2014), the great, ($M_W \sim 7.8$) Owens Valley earthquake of 1872, together with the series of $M > 7$ earthquakes this century that ruptured much the Eastern California-Central Nevada Seismic Belt (Wallace 1981). The volcanic hazard is reflected in the recurrence of small to moderate volcanic

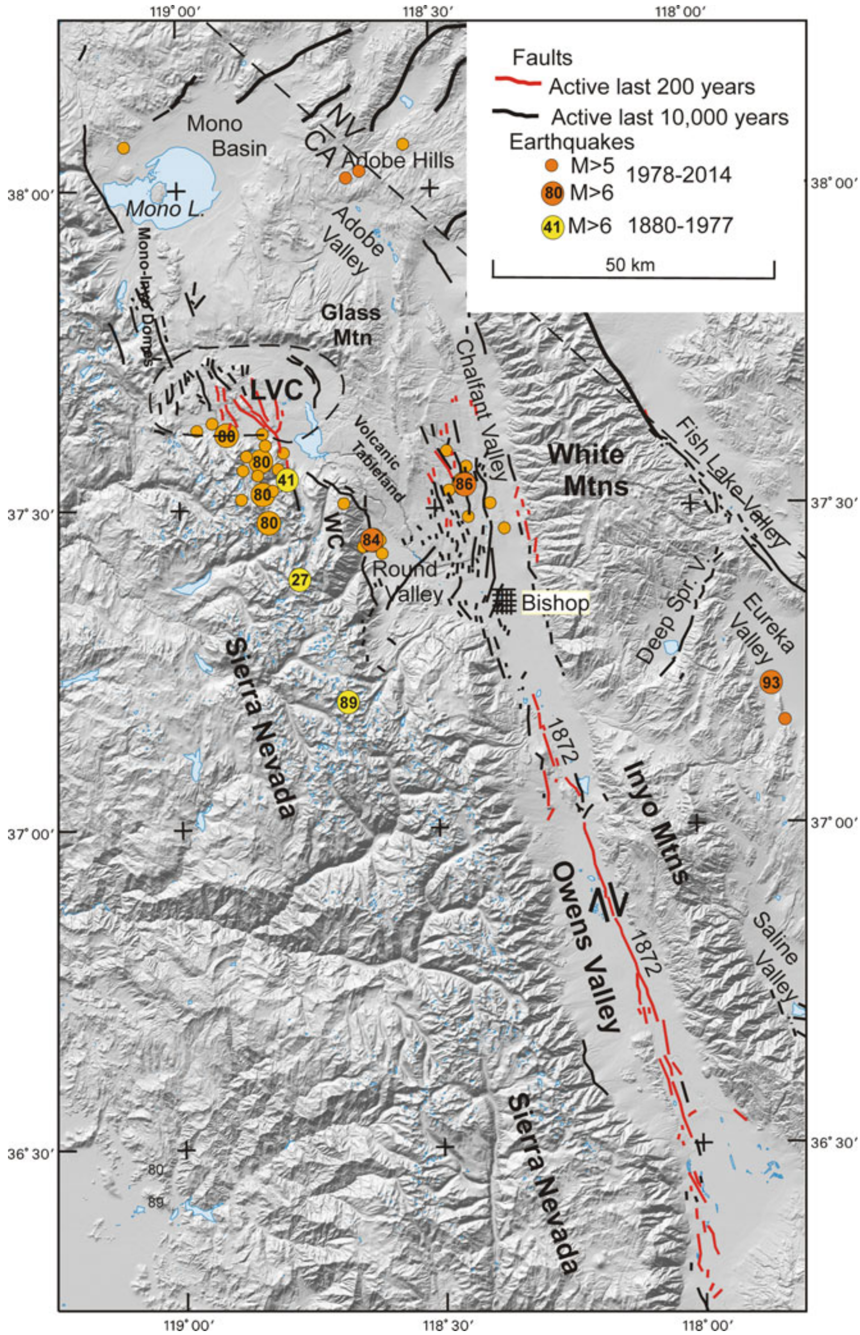

Fig. 1 Shaded relief map showing regional setting of Long Valley Caldera (LVC) along the eastern escarpment of the Sierra Nevada with M $\geq$ 6 earthquake epicenters (*yellow circles* for 1880–1977 and *orange circles* for 1978–2014) and M $\geq$ 5 earthquake epicenters for 1978–2014 (*small orange circles*) where numbers are last two digits of the year. *Black lines* are faults with Holocene offset, *red lines* are faults with offsets in the last 200 years. Note the surface rupture of the M 7.8, 1872 Owens Valley earthquake, which was dominantly right-lateral, strike-slip. Updated from Fig. 3 in Hill (2006) (courtesy of The Geological Society, London)

eruptions along the Mono-Inyo volcanic chain over the past 50,000 years. Over the past 5000 years, for example, some 20 small to moderate eruptions have occurred from vents scattered along the Mono-Inyo volcanic chain at intervals of 200–700 years. Most were explosive, rhyolitic eruptions accompanied by ash clouds and occasional pyroclastic flows; a few were effusive basaltic eruptions. On the basis of this 5000-year record, the background (unconditional) probability of an eruption from somewhere along the Mono-Inyo chain is roughly 0.5% per year. For perspective, this is comparable to the probability of a M $\sim$ 8 earthquake along the San Andreas fault or an eruption from some of the major Cascade volcanoes. It is thus typical of the background probability for geologic hazards throughout much of the active margin of the North American Plate. The particular challenge in the case of Long Valley caldera lies in (1) making a meaningful assessment of the probability gain (conditional probability) for an eruption as this large magmatic complex displays varying levels of seismicity, ground deformation, and magmatic gas emissions, and (2) effectively communicating this and associated uncertainties to civil authorities, the public, and the media. The problem is one of reliable eruption forecasting and real-time, probabilistic hazard assessment.

Eastern California is an important recreation area heavily used by much of urban California as well as visitors from elsewhere in the country and the world. Mammoth Mountain volcano, which last erupted $\sim$55,000 ybp, stands on the southwestern rim of Long Valley caldera (Hildreth et al. 2014). It hosts one of the largest ski areas in the country. The resort town of Mammoth Lakes at the base of Mammoth Mountain sits within the southwestern corner of the caldera (Figs. 2 and 3). Mammoth Lakes, with a permanent population of $\sim$8000 and a temporary population that swells to over 40,000 during major ski weekends, is a year-round, destination resort providing ready access to the adjacent high Sierra as well as mountain biking, fishing, and golf during summer months. This does not mix easily with talk of geologic hazards, particularly high-profile hazards posed by volcanoes and earthquakes (Hill 1998).

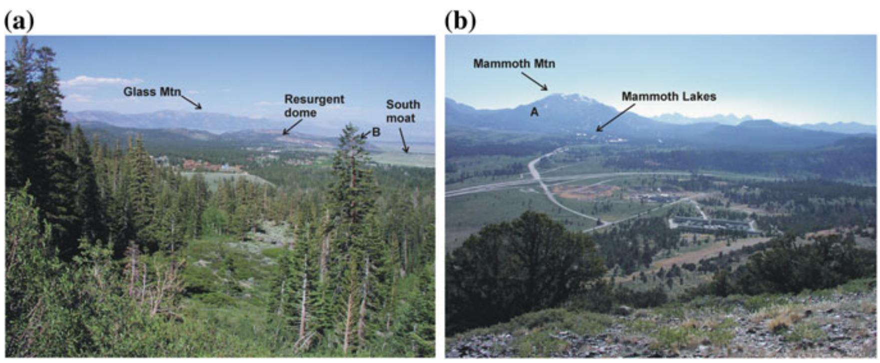

Fig. 2 Photographic views across Long Valley Caldera. **a** View to NE across Long Valley Caldera from Lake Mary Rd on the SE flank of Mammoth Mountain (taken from point "A" in photo **b**). Mammoth Lakes is in the middle-left foreground, the resurgent dome in the middle distance and the South moat to the right. Glass Mountain forming the NE rim of the caldera in on the horizon behind the resurgent dome (USGS photo). **b** View from the resurgent dome westward to Mammoth Mountain (taken from point "B" in photo **a**). The 40 MW geothermal plant is in the foreground, Hwy 395 cuts across the middle distance, and Hwy 203 extends toward Mammoth Lakes at the base of Mammoth Mountain. High peaks of the Sierra Nevada form the distant horizon to the right of Mammoth Mountain (USGS photo)

2 Hazard Communication (and Miscommunication) During Two Decades of Strong Volcanic Unrest (1978–2000)

A $M_L = 5.8$ earthquake on October 4, 1978, located beneath Wheeler Crest 14 km southeast of Long Valley caldera (roughly midway between Bishop and Mammoth Lakes) marked the onset of the extended episode of unrest in the caldera and vicinity that continues today (Figs. 3 and 4; Hill 2006; Shelly and Hill 2011; Lewicki et al. 2014). Over the following year and a half, seismic activity in the form of $M > 3$ and occasional $M > 4$ earthquakes gradually migrated northwestward and the southern margin of the caldera. Then, on May 25, 1980, just seven days after the catastrophic eruption of Mount St. Helens, three $M \sim 6$ earthquakes shook the southern margin of the caldera accompanied by a rich aftershock sequence. By the morning of May 27, the Director of the U.S. Geological Survey (USGS) had released a formal "Hazard Watch" (Table 2a) noting the possibility of additional $M \sim 6$ earthquakes in the area. Just hours later, a fourth $M \sim 6$ earthquake shook the area—a successful "short-term" forecast!

That summer, Savage and Clark (1982) re-leveled a section of Highway 395 through the

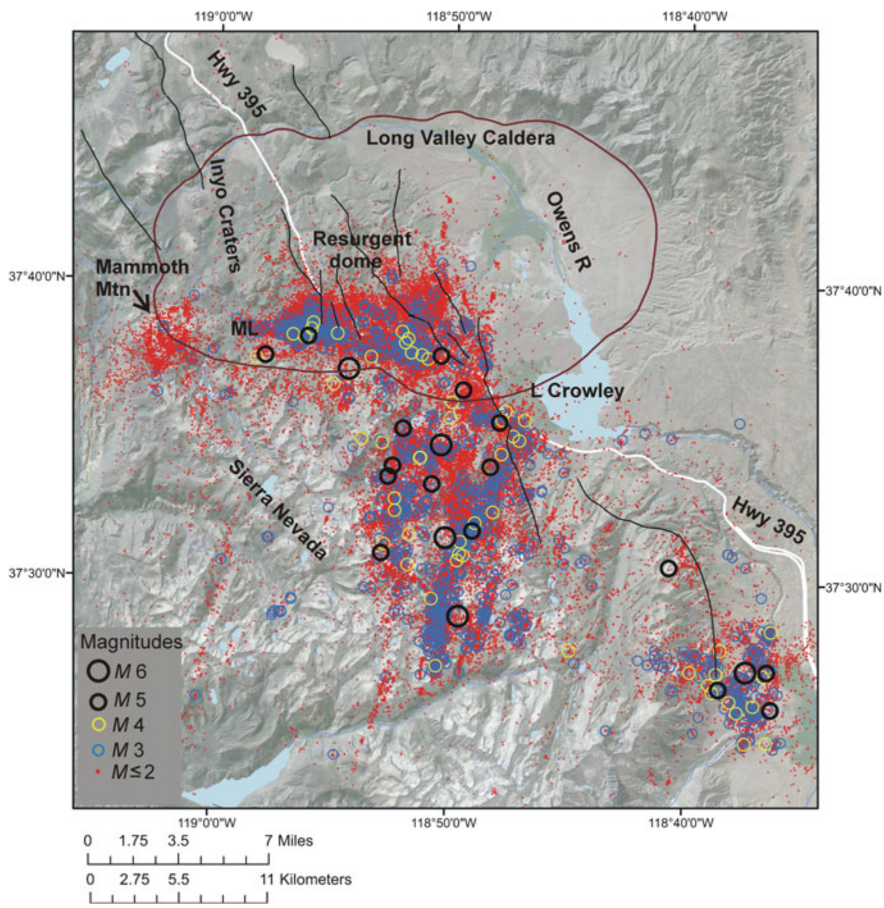

Fig. 3 Map of epicenters for earthquakes with magnitudes $1.5 \geq M \leq 6.5$ from 1987 to 2014 scaled by symbol size. Epicenters for the 1978–1983 interval (prior to installation of the locally dense seismic network in 1984) are from the standard NCSN catalog and include only $M \geq 3$ earthquakes. Epicenters for $M \geq 1$ earthquakes the 1984–2014 interval are from the double-difference catalog of Waldhauser (2009). *ML* indicates the town of Mammoth Lakes. Background shaded relief and seismicity thanks to Stuart Wilkinson

area affected to document the co-seismic displacement expected from this series of four M ~ 6 earthquakes. What they found instead, was a broad, dome-shaped uplift of the caldera floor (the resurgent dome). Monuments near the center of the resurgent dome were 25 cm higher in the summer of 1980 than they had been in 1975. Measurements of a trilateration network spanning the area made in 1979 suggested that most, if not all of this deformation developed sometime between the summer of 1979 and the summer of 1980. With fresh images of Mount St. Helens in mind, it required no great leap to recognize a volcanic signature in this combination of strong earthquake swarm activity and ground deformation. Still, if the activity had died away as with most aftershock sequences, attention would have soon focused elsewhere.

Earthquake activity continued, however, with frequent swarms that included locally felt earthquakes (M ~ 3–5 events), rapid-fire bursts of small earthquakes (spasmodic bursts), which are often associated with active volcanoes, and evidence that focal depths appeared to be getting shallower with time (Ryall and Ryall 1983). Roy Bailey of the USGS, who produced the Long Valley Caldera geologic map (Bailey 1989) and was Volcano Hazards Program Coordinator, had initial responsibility for communicating the significance of this activity to local authorities. In discussions between scientists in the USGS, the California Division of Mines and Geology (CDMG), and Alan Ryall at the University of Nevada, Reno over the winter of 1981 and a meeting in early May 1982, a consensus developed that we had an obligation to inform local civil authorities of our concerns about the volcanic nature of this activity. The result was a memo to the Chief Geologist in USGS headquarters dated May 17 recommending a volcanic Hazard Watch (the middle level of the three-level hazard terminology in use by the USGS at the time; see Table 2a). Hazard notification was top-down at the time, passing from the Federal government (USGS) to the State of California Governer's Office of Emergency Services (CalOES) and from there, on to the counties and cities affected. A dialogue between USGS headquarters and CalOES on the precise wording of the alert ensued. Meanwhile, a science reporter for the Los Angeles Times got wind that something was up. An article announcing that the USGS was about to release a "Notice of Potential Volcanic Hazards" appeared in the Los Angeles Times on the morning of May 25, 1982, just two days before the Memorial Day weekend and short circuiting the official release of the "Notice of Potential Volcanic Hazards" (the lowest level in the Notice/Watch/Warning hazard terminology) scheduled for the next day: The local response was one of outrage, anger, and disbelief (what volcano?!) exacerbated by inflammatory headlines and news stories about "brewing lava eruptions" and a town in denial. Geologists, and USGS geologists in particular, immediately became persona non grata in Mammoth Lakes and Mono County—an attitude that only gradually mellowed over the years. Under the best of circumstances, communicating information on a newly recognized hazard is tricky—this serves as an outstanding example of the wrong way to start such a dialogue.

Roy Bailey, Coordinator of the Volcano Hazards Program, oversaw USGS monitoring efforts in the caldera through the summer and fall. In December 1982 the USGS instituted the Long Valley Monitoring Project with David Hill as Chief Scientist in charge of coordinating research, monitoring, and hazard communication efforts in Long Valley Caldera. The California Division of Mines and Geology (CDMG) assumed a comparable responsibility in 1982, and purchased an automatic earthquake recording system and eventually hired a volcano seismologist, Stephen McNutt in spring 1984. In an effort to clarify the significance of the Notice of Potential Volcanic Hazards, Miller et al. (1982) published USGS circular 877 describing the nature of the potential hazards from future volcanic eruptions, and CDMG prepared a series of eruption scenarios as the basis for response planning. These documents together with the persistence of ongoing unrest stimulated disaster preparedness efforts by State, County, and Federal land management agencies in the area that included establishing Incident Command

Table 1 Key to events noted in Fig. 4

Number	Date	Event
1	4 Oct. 1978	Wheeler Crest M 5.8 earthquake
2	25–27 May 1980	Three M 6 earthquakes on 25th. USGS releases Hazard Watch for possible additional M ∼6 earthquakes on the 27th; a fourth M 6 earthquake four hours later (a “successful” forecast)
3	1980–1981	Savage and Clark (1982) re-level Hwy 395 to discover a 25-cm uplift of the resurgent dome. Ongoing swarm activity in the caldera
4	25–26 May 1982	L.A. Times article announcing planned release of USGS Notice of Potential Volcanic Hazards on 25th. Official release of USGS Notice of Potential Volcanic Hazard on the 26th
5	December 1982	D. Hill appointed USGS Scientist-in Charge (SIC) of the Long Valley project (LVO). CDMG established comparable role
6	7–14 Jan. 1983	Strong south moat swarm including two M 5 earthquakes
7	31 Aug. 1983	Hill and Filson attend “1000-year lunch” with business leaders
8	Oct 1983	Dedication of the “Mammoth Scenic Loop”, a 2nd road into town
9	Sept. 1983	USGS Director replaces Notice-Watch-Warning alert system by a single-level Hazard-Warning system
10	Aug. 1984 Oct. 1984	The Town of Mammoth Lakes incorporates S. McNutt joins CDMG as volcano seismologist
11	23 Nov. 1984	A M 6.1 earthquake in Round Valley
12	21 July 1986	A M 5.9 foreshock followed 12 h later by the M 6.4 Chalfant Valley earthquake
13	Aug. 1987	Hill and Bailey LVC field trip for Dr. Graham and Andrea Lawrence
14	May 1989 to March 1990	11-month long earthquake swarm beneath Mammoth Mtn. Onset of deep LP (volcanic) earthquakes and magmatic CO_2 emissions from flanks of Mammoth Mtn
15	17–19 May 1990	Town and County officials attend USGS workshop on the 10th anniversary of the May 1990 Mount St. Helens eruption
16	1991	LVO adopts alphabetic A-E, alert-level system
17	1991–1997	Recurring earthquake swarms and continued resurgent dome inflation
18	June 1997	LVO replaces alphabetic alert-level system with a 5-level color code
19	Nov. 1997–Jan. 1998	Earthquake swarm activity including M 4.8 and 4.9 earthquakes accompanied by elevated resurgent dome inflation
20	28 June–4 July 1998	Mammoth Lakes City Manager accompanies Hill to 1st IAVCEI Cities on Volcanoes meeting in Rome and Naples, Italy.
21	1998–1999	M 5.1 earthquakes on 8/6/98 and 14/7/98 near the south-east margin of the caldera and a M 5.6 earthquake on 15/5/99 in Sierra Nevada block 5 km S. of caldera
22	Oct. 2006	USGS adopts a uniform ground/aircraft hazard warning system for all five volcano observatories
23	March 2008	Mammoth Mountain Ski Area opens the “Top of the Mountain” display illustrating the geologic and volcanic history of the area
24	Jan. 2009	M. Mangan becomes LVO SIC
25	2011–2014	Inflation of the resurgent dome resumes and continues at a rate of 2 cm/year through 2014 accompanied by low-level swarm activity under Mammoth Mountain, the caldera, and the Sierra Nevada block to the south
26	Feb. 2012	The California Volcano Observatory (CalVO) is established with responsibility for all California volcanoes including Long Valley
27	July 2014	Joint USGS-CGS Earthquake Hazard Scenarios report released (Chen et al. 2014)

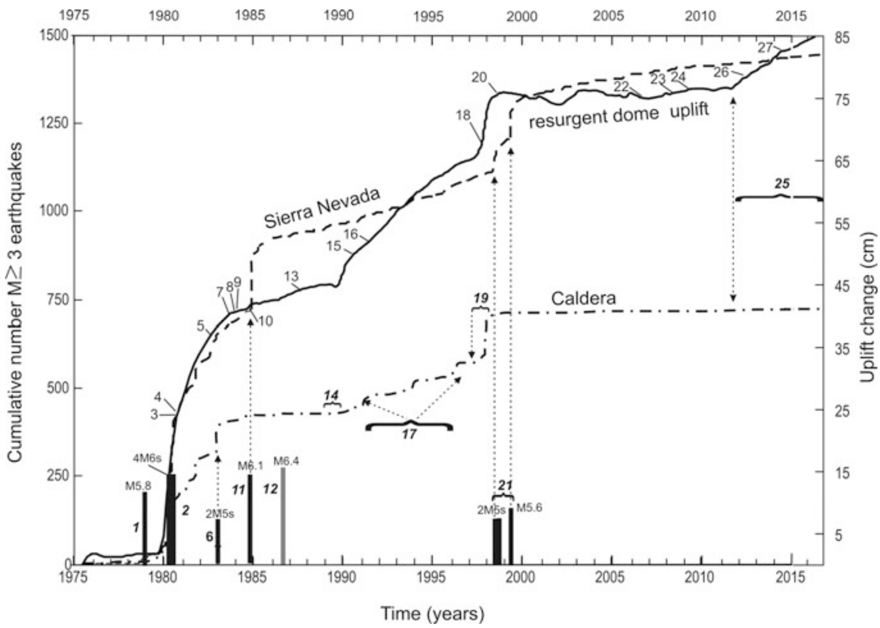

Fig. 4 Time history of resurgent dome uplift (*solid line*) and the cumulative number of M $\geq$ 3 earthquakes in Long Valley Caldera (*dot-dashed line*) and the Sierra Nevada block (*dashed line*) from 1978 through May 2016. *Solid line* represents uplift of the center of the resurgent dome with numbers tied to numbered events in Table 1. Heavy vertical bars mark occurrences of M $\geq$ 6 earthquakes (including their M $\leq$ 5 aftershocks) with length proportional to magnitude. *Horizontal brackets* indicate periods of earthquake swarm activity. *Dashed arrows* point to associated rate changes in cumulative number of earthquakes The *grey bar* is the M = 6.4 Chalfant Valley earthquake and its aftershocks (see Fig. 1), which do not contribute to the cumulative number count for Sierra Nevada earthquakes. *Bold italic* numbers are linked to numbered events in Table 1

(ICS) and Unified Command (UCS) systems as well as emergency response plans including “Plan Caldera” of the California OES and the “Basic Emergency Plan” of Mono County (Mader et al. 1987).

As low-level earthquake swarm activity continued through the summer and fall of 1982, however, a series of public meetings did little to mitigate the simmering anger of much of the public and business community. Then, on the afternoon January 7, 1983, activity abruptly resumed with an intense earthquake swarm in the south moat of the caldera that included two M = 5.3 earthquakes accompanied by nearly constant felt shaking from frequent M3 to 4 earthquakes over the next several weeks (Fig. 4). This was an El Nino winter and the snow was piled high along the roads within Mammoth Lakes and along the only paved road connecting the town to Highway 395. At his own initiative, the Chairman of the Mono County Board of Supervisors, ordered second (dirt) road plowed. He also initiated steps to have this road widened and paved to provide an alternate way out of town. This was not a popular decision, in part, because it carried an implicit acknowledgment that there might actually be a volcanic hazard. Setting some sort of record from inception to completion, the newly paved “escape route” was formally dedicated in October of 1983 as the “Mammoth Scenic Loop”. The Chairman and a second member of the board who had been pro-active in support of the new road and other mitigation issues (including monthly public updates by the USGS on the evolving caldera unrest) were voted out of office in a special recall election over the following summer.

Re-leveling of the deformation network along Highway 395 during the summer of 1983 showed that the resurgent dome had been uplifted by an additional 7 cm over the winter. Following the intense January 1983 swarm, both the earthquake activity and deformation rates within the caldera activity began a gradual decline that persisted through the remainder of the 1980s.

Resentment of the media attention attracted by the "Notice of Potential Volcanic Hazards" was most acutely expressed by the real estate and business communities. Other agencies with responsibilities in the area, including the U.S. Forest Service, the Bureau of Land Management, National Park Service, and Mammoth Mountain Ski Area together with a number of residents were supportive of efforts to monitor the activity and communicate its significance. The Ski Area, for example, instigated a series of day-long geology field trips for the public and local officials led by Hill and Bailey that proved to be an especially effective means of explaining the active geologic setting of Long Valley caldera and Mono Craters area, and Hill provided a series of invited public lectures on the significance of the ongoing activity in the early 1980s.

On August 31, 1983, John Filson (then Chief of the USGS Office of Earthquakes, Volcanoes, and Engineering) and Hill attended a luncheon meeting in Mammoth Lakes with local business leaders that was organized by the president of the Chamber of Commerce. John Filson recalls that occasion as the "1000-year lunch." One of the people at the 1000-year lunch was an influential resident rumored to have drafted several critical letters to the USGS Director on behalf of the local business community. He had earned BS and Ph.D. degrees in electrical engineering from prestigious universities, and at the time was working as a consultant for the aerospace industry from his home in Mammoth Lakes. As it turns out, this same individual, Dr. William Graham, became President Ronald Reagan's Science Advisor from 1986 to 1989. Needless to say, scientists monitoring Long Valley caldera developed a bit of angst when they learned that the President's science advisor and the resident from the 1000-year-lunch were one and the same person! In August 1987, Bailey and Hill had the opportunity to take the Science Advisor and Andrea Mead Lawrence, an influential member of the Mono County Board of Supervisors (also a 1952 Olympic gold medalist in Alpine skiing), on a field trip around the caldera. In the end, both were instrumental in easing relations between scientists and the local business community as they came to understand the nature of hazard.

The continued existence of the "Notice of Potential Volcanic Hazards" was a thorn in the side of the Mammoth Lakes business community. The Federal Register (v. 24, no. 7, 1977) defined this notice as "*Information on the location and possible magnitude of a potentially hazardous geologic condition. However, available evidence is insufficient to suggest that a hazardous event is imminent or evidence has not been developed to determine the time of occurrence*". Given this definition and the geologic history of the caldera and its unrest, USGS scientists had no basis for rescinding the notice. In September, 1983, the Director of the USGS announced that the three-level Notice/Watch/Warning hazard notification system was being replaced by a one-level "hazard warning" system, which would be used only when the situation required a "near-term" (hours to days) public response (Table 2a). This change in hazard communication terminology became official on 24 January 1984 (Federal Register, v. 49, no. 21, pp. 3838–3839, January 31, 1984). By default, this change removed the "Notice of Potential Volcanic Hazard" for Long Valley caldera. In August 1984, the town of Mammoth Lakes was formally incorporated, thereby requiring the scientific community to interact with a new civil authority. While activity remained low within the caldera following the January 1983 swarm, this was not the case for seismic activity outside the caldera. On November 23, 1984, the $M_L = 6.1$ Round Valley earthquake and its many aftershocks (located midway between the southeastern caldera boundary and Bishop) shook the region (Figs. 1 and 4). The area again was repeatedly shaken from late July through mid August, 1986, by the rich foreshock and aftershock sequence associated with the $M_W = 6.4$ Chalfant Valley mainshock of July 21, 1986 located 20 km southeast of the caldera. Each of these earthquake sequences generated a

Table 2 Evolution of USGS hazard warning systems (HWS) in abbreviated form

(**a**) USGS-wide systems for hazard statements released by the Director

1977–1983, *Federal Register*, v. 42, no. 70, 1977

Terminology	Significance[a]
NOTICE OF POTENTIAL HAZARD	Info on potential hazard but insufficient data to time of occurrence
HAZARD WATCH	Info on potentially catastrophic event within months to years
HAZARD WARNING	Info on time, location, and magnitude of a potentially disastrous geologic event
11 October 1983, *Federal Register*, v. 48, n. 197, 1983	
HAZARD WARNING	Info on a potential geologic hazard posing a significant threat requiring a timely response

(**b**) Local hazard level systems for the Long Valley Caldera volcanic field with authority for releasing hazard statements delegated to the LVO Scientist-in-Charge

17 April 1991 Alphabetic system[b] (Hill et al. 1991)

STATUS	USGS RESPONSE	ACTIVITY LEVEL	RECURRENCE
N	Normal monitoring	Background	–
E STATUS	Notify responsible personal as appropriate	Weak unrest	Weeks
D STATUS	Notify mid-level USGS personnel, OES, CDMG, USFS	Moderate unrest	Weeks–months
C STATUS	Notify USGS Office Chief, OES headquarters, State Geologist	Strong unrest	Months–years
B ALERT	Alert USGS Director, trigger an EVENT RESPONSE	Intense unrest	Years–decades
A ALERT	Issue HAZARD WARNING	Eruption likely	Decades–centuries

(**c**) June 1997 LVO Color-code system[c] (Hill et al. 2002)

GREEN (NORMAL)	Normal operations with information calls as appropriate	Background to	Most of the time
		Strong unrest	Months to years
YELLOW (WATCH)	Full call-down Event response	Intense unrest	Years to decades
ORANGE (WARNING)	Full call-down Event response (if not in place)	Accelerating unrest eruption likely	Decades to centuries
RED (ERUPTION)	Full call-down Event response (if not in place)	Minor to moderate eruption with possible increase in intensity	Centuries to millennia

Table 2 (continued)

(**d**) 2006 A uniform ground-based and aviation warning system adopted for all USGS volcano observatories (Gardner and Guffanti 2006). Authority for releasing hazard statements delegated to the respective Observatory Scientists-in-Charge	
Ground-based system for USGS Volcano Observatories[d]	
Terminology	Description
NORMAL	Non-eruptive, background activity levels
ADVISORY	Activity levels above background, or ongoing eruptive activity declining
WATCH	Heightened or escalating unrest, or ongoing eruption poses limited hazard
WARNING	Hazardous eruption imminent or underway
Aviation color code used by USGS Volcano Observatories[d]	
Color	Description
GREEN	Volcano is in a non-eruptive state
YELLOW	Volcano is showing elevated unrest levels
ORANGE	Volcano is exhibiting escalating unrest: potential eruption time-frame uncertain, or minor eruption underway with no or minor ash emissions
RED	Eruption is imminent or underway with significant ash emissions high into the atmosphere

[a]No stand-down criteria specified
[b]Stand-down criteria based on current ACTIVITY LEVEL
[c]Stand-down criteria based on current ACTIVITY LEVEL
[d]Stand-down criteria based on current activity levels noted under DESCRIPTION

flurry of news stories on seismic activity and volcanic unrest in the Mammoth Lakes area, further aggravating the local business leaders over negative publicity.

Activity returned to the vicinity of the caldera with the onset of a persistent earthquake swarm beneath Mammoth Mountain that began in early May and continued into March 1990 (Hill et al. 1990; Langbein et al. 1993; Cramer and McNutt 1997). Only a handful of earthquakes in this swarm had magnitudes as large as $M = 3$, but the activity included numerous spasmodic bursts, which are commonly associated with active volcanic systems. The swarm was accompanied by the onset of magmatic CO_2 emissions around the flank of the mountain and a marked increase of magmatic Helium ratios to values as high as $R/R_A \sim 7$, where $R = (^3He/^4He)$ is the ratio of light to heavy Helium isotopes measured in fumarole gasses and R_A is the isotope ratio in the atmosphere. Taken together, these observations suggest an intrusion of magmatic fluids into the shallow crust beneath Mammoth Mountain (Hill and Prejean 2005). In an effort to keep local civil authorities apprised of the situation, Hill called the City Manager for Mammoth Lakes several times a week with updates on evolving activity. At one point in a conversation with Steve McNutt, the City Manager asked in apparent exasperation if we couldn't provide him with some sort of written criteria for how seriously he should regard the varying levels of activity. His request led to development a response plan that included an alphabetic scheme of five "alert levels" (E through A in ascending order of concern) modeled after that used for the Parkfield earthquake prediction experiment (Table 2b; Hill et al. 1991). This alphabetic system included criteria for stepping down from an elevated alert level—an element that was absent in the old "Notice-Watch-Warning" system. With an important addition, the USGS Director ceded local authority to the Chief Scientist of the Long Valley monitoring project to communicate changes in alert level directly to local officials thus avoiding delays associated with high-level, inter-agency discussions.

In an effort to help local civil authorities better appreciate the issues involved with volcanic hazards, the USGS invited Mono County and Mammoth Lakes civil authorities to attend a conference commemorating the tenth anniversary of the May 1980 Mount St. Helens eruption. This conference, which was held adjacent to Mount St. Helens in Kelso Washington on May 17–19, 1990, included presentations by local civil authorities as well as scientists who were directly involved in responding to this catastrophic eruption. The occasion turned out to be enormously informative for all concerned.

Meanwhile, frequent trilateration measurements with the 2-color geodimeter showed that deformation rates across the resurgent dome began to increase substantially in October of 1989 (Langbein et al. 1993). Three months later, earthquake swarm activity resumed in the south moat of caldera and continued to wax and wane through mid-1997, accompanied by relatively steady uplift of the resurgent dome at a rate of 2- to 3-cm/year (Fig. 4; Langbein et al. 1993). Other developments that persisted through the 1990s involved high concentrations of magmatic CO_2 in the soil around Mammoth Mountain and growing number of long-period (LP) volcanic earthquakes occurring at depths of 10–20 km beneath the southwest flank of Mammoth Mountain (Pitt and Hill 1994). In May 28, 1998, a cross-country skier died of CO_2 asphyxiation after falling into a collapsed snow cave filled with 70% CO_2 at the base of Mammoth Mountain (Hill 2000) Both the CO_2 emissions and LP earthquakes were coincident with the 1989 Mammoth Mountain swarm, and together they serve as a reminder that this 11,000-foot high volcano, which last erupted 55,000 years ago, is not extinct.

The increased activity within the caldera provided ample opportunity to exercise the "alert-level" system. For a while, it seemed to work just fine as we moved back and forth between the lower "status levels" from E through C. The new system included a matrix, rather than top-down, system for information flow in which alerts are passed to State, County, and City authorities simultaneously. Flaws in this alphabetic scheme began to emerge, however, as the media added their own twist on the status levels. On a slow news day, for example, a swarm including a couple of M $\sim$ 3, locally felt earthquakes corresponding to a "D-status" under this scheme would get reported in headlines as a "D-level volcano alert" (the latter two words added by the reporter or headline writer). Of course, most of the public didn't understand what a "D-level alert" meant—except that is sounded serious. The result was exaggerated concern in the public (should I cancel my planned vacation to Mammoth?), and renewed frustration in the business community over negative "volcano" publicity (see Mader et al. 1987).

The USGS in consultation with Mono County, Mammoth Lakes, the California State Geologist and head of CDMG, the California Earthquake Prediction Evaluation Council (CEPEC), and the California Office of Emergency Services (CalOES), began discussing ways to improve this system by making it less susceptible to misinterpretation by both the media and the public at large. The result was a four-level color scheme, with the three lower status levels (E, D, and C) grouped under "condition GREEN" (no immediate risk), replaced level B by "condition YELLOW" (watch), and replaced level A by "condition ORANGE" (warning). A final color, "condition RED" was added to indicate an eruption was actually under way. Mono County suggested that we incorporate shapes with this scheme. The result associated GREEN with a circle, YELLOW with a square, and ORANGE with a diamond (skiers will recognize these as the shapes indicating beginner through advanced slopes). A triangle (the shape of a volcano) was chosen to represent RED. This new system was formally adopted in

June 1997, shortly before the onset of a sustained period of escalating unrest in the caldera (Table 2c; Fig. 4; Hill et al. 2002).

In April–May of 1997, the two-color geodimeter data again showed hints of an increasing horizontal deformation rate across the resurgent dome (Langbein 2003). By early July, earthquake swarm activity in the caldera picked up with an increasing frequency and intensity that persisted through the remainder of the year and into January 1998 (Fig. 4). The peak in this activity from mid-November through early January 1998 included nine earthquakes with magnitudes of M = 4.0 or greater accompanied by thousands of smaller events. The three largest earthquakes had magnitudes of M = 4.8–4.9. Resurgent dome deformation escalated through the second half of 1997, reaching a peak uplift rate of over 2 cm/month in mid-November. By the end of the year, the center of the resurgent dome was approximately 10 cm higher than in early May. Mammoth Mountain earthquake swarm activity also increased in September through December 1997. Under the new color-code notification system, the condition remained GREEN through this extended period of elevated activity. During particularly strong swarm sequences on November 22 and 30, however, activity came extremely close to meeting the guidelines for a condition YELLOW (it would have been level C under the old system—see Table 2). The Long Valley caldera web page, on which most of the monitoring data are available in real-time together with frequent written updates on the current condition and its significance, was receiving tens of thousands of "hits" a day. It also attracted lots of email with messages ranging from "why aren't we at YELLOW yet?", "you're a pawn of the Realtors", "what are you covering up?", "I'm moving to Maine!" to "thanks for an excellent job of keeping us informed and keeping things in perspective". Both the seismicity and deformation rates within the caldera gradually slowed through the first half of 1998. Six months later, however, Mammoth Lakes and vicinity was again shaken by three M 5 earthquakes in the Sierra Nevada just south of the caldera—a pair of M 5.1 events on 8 June and 14 July 1998, respectively, and a M 5.6 event on 15 May 1999. The abundant aftershocks to these earthquakes included a number of M > 3 earthquakes, which were felt locally. On August 6, 1999, the Long Valley monitoring project was officially established as the Long Valley Observatory (LVO) with Hill as Scientist-in-Charge (SIC).

After nearly two decades of intense, episodic unrest, the Mammoth Lakes Town Council agreed to support travel for the Town Manager to attend the first Cities on Volcanoes (COV) meeting held in Naples and Rome from 28 June to 4 July 1998. This was the first of an ongoing series of international meetings under the IAVCEI (International Association of Volcanology and Chemistry of the Earth's Interior) umbrella bringing together scientists and civil authorities for discussion on volcanic hazards and mitigation. Having the Mammoth Lakes Town Manager at the COV marked an important milestone in the efforts of scientists to grow community awareness.

3 Maintaining Community Awareness and Preparedness During Low-Level Volcanic Unrest (2001–May 2016)

Since the turn of the century, unrest has diminished in Long Valley Caldera (Fig. 4; Wilkinson et al. 2014). The communication challenge has thus become one of maintaining public awareness and preparedness when there are few signs of volcanic unrest recognized by the public. Two notable exceptions during the relative quiescence from 2000 to 2011 included: (1) the tragic death of three skiers on April 6, 2006, as they fell into a CO_2—filled snow cave that had developed over the fumarole on the upper flank of Mammoth Mountain, and (2) the temporary onset of geyser activity in Hot Creek (a popular bathing area) in 2006. Instrumentally detected low-level unrest between 2000 and 2011 included additional inflation of the resurgent dome by 3–4 cm in 2002 accompanied by minor seismicity (Feng and Newman 2009). In 2006, 2008, and 2009 short-lived swarms of earthquakes, all too small to be felt, occurred at depths at 25–30 km below Mammoth Mountain (Shelly and Hill 2011). An increase in shallower earthquakes, again too small to be felt, followed within a few months of each swarm and magmatic CO_2 emission increased in tandem at the surface (Lewicki et al. 2014). Scientists relate these phenomena to deep intrusion and degassing of basaltic magma in the lower crust followed by upward migration of CO_2-rich fluids through fracture development. To the non-scientist, however, the significance of "stealth" magma supply events is hard to appreciate. Few earthquakes were felt, and the uptick in magmatic gas could be measured, but not seen. Years of low-level volcanic unrest require a sustained effort to educate a growing population base and a changing cast of elected officials, land managers, and civil authorities.

Effective hazard education requires persistence and strategic networking within at-risk communities. From the beginning, USGS scientists have demonstrated their commitment to hazard mitigation in the Long Valley region by attending quarterly meetings of the Mono and Inyo County Office of Emergency Services, Unified Command System (UCS). Through participation in the UCS scientists have learned to speak the language of emergency response teams and have become integral members. The standalone "Plan Caldera" developed in the 1980s during the height of caldera unrest has evolved into the Mono and Inyo county Emergency Operations Plan, which includes regularly updated contributions written by scientists. USGS scientists have provided face-to-face volcano hazard training to citizens in the local Community Emergency Response Team (CERT), a volunteer disaster response organization sponsored by the Mammoth Lakes Police Department, Mammoth Fire District and Mono County Public Health, as well as, specialized trainings for civil authorities through a partnership with the Federal Emergency Management Agency—National Disaster Preparedness Training Center and the University of Hawaii. In collaboration with USGS scientists, the USFS Ranger Districts in Mammoth Lakes and Mono Lake visitors centers established an information display on the active geology of the region, and Mammoth Mountain Ski Area developed a "Top of the Mountain" display taking advantage of a spectacular overview of regional geology.

Sustaining a proactive hazard education program in the Long Valley region is time-consuming and costly, but necessary. In 2009 this responsibility fell to Margaret Mangan as the newly appointed LVO SIC as Hill stepped aside to become Scientist Emeritus. The necessity of continuing education is underscored by renewal of caldera inflation, which began in early 2011, and has continued through early 2017 (Montgomery-Brown et al. 2015). The time-averaged uplift rate from 2011 through 2014 was about 2 cm/year, comparable to that of the mid-1990s. Seismicity within the caldera increased as well with modest earthquake swarms in the caldera in June and July 2014 followed by the most energetic swarm since 1999 in September 2014 with eight earthquakes of magnitudes M $\sim$ 3.0–3.8 that were felt in the town of Mammoth Lakes. Just prior to this swarm, USGS and CGS scientists had briefed the Mono and Inyo County Unified Commands on earthquake hazards in the region in preparation for release of a joint report describing scenario earthquake hazards for the Long Valley—Mono Lake area (Chen et al. 2014). Meanwhile, Mammoth Mountain has continued to produce episodic, low-level swarm activity (Shelly et al. 2015).

Periodic evaluation of the effectiveness of hazard communication is also necessary, and new methodologies must be developed to meet modern needs. Several years after the introduction of Long Valley's four-level color-code warning system, for example, the USGS Volcano Hazards Program recognized the need to establish a national alert-notification system, one that covers all US volcanoes and that distinguishes between ground-based and atmospheric hazards (Gardner and Guffanti 2006; Fearnley et al. 2012). By 2006, two new communication vehicles where in use—Volcano Alert Notifications (VANs) and Volcano Observatory Notices for Aviation (VONAs), both of which use four-tiered threat level systems (Table 2d).

VANs use Normal-Advisory-Watch-Warning to specify increasing threat on the ground (e.g., lahars, lava flows) and VONAs use Green-Yellow-Orange-Red to specify increasing threat to aviation (ash clouds and volcanic aerosols). The dual ground-level and aircraft-ash systems recognize that a low-level effusive eruption might pose a serious local hazard (Warning) without posing a serious ash hazard for aircraft at 30,000 feet. In keeping with communications in the digital age, an email-based Volcano Notification Service (VNS) automatically delivers VANs, VONAs, and other volcano information to all subscribers who register online at http://volcanoes.usgs.gov/vns (Accessed 13 February 2017).

In 2012, the USGS Director announced establishment of the California Volcano Observatory (CalVO), giving the former LVO the responsibility to monitor Long Valley caldera, as well as the other young and restless volcanoes in the state (Stovall et al. 2014). As the director explained "By uniting the research, monitoring, and hazard assessment for all of the volcanoes that pose a threat to the residents of California, CalVO will provide improved hazard information products to the public and decision makers alike."

4 Conclusions

Applying scientific research to understand the processes driving magmatic unrest in a large caldera and communicating the significance of this research in terms of volcanic hazards represents a microcosm of the challenges that much of science faces today as we grapple with the societal relevance of scientific research. Long Valley caldera unrest has provided a rich experience in terms of both scientific return and the challenges in trying to effectively communicate socially useful information on natural hazards to the public.

We have come a long way since the highly charged relations between geologists and the business community of the early 1980s. Those involved on the scientific side learned to be much more effective at presenting messages on activity levels and their significance in terms that can be understood by the general public, and the residents of Mono County and eastern California have gained a much better appreciation for the geologically active environment in which they live. The following three points are important in this regard:

1. We must continue to do the best science possible as we track the ongoing activity. Understanding the processes driving the unrest is key to understanding the nature of the hazards posed by the unrest and their likely evolution in terms of long-term forecasts and short-term predictions. This is similar to medicine, for which understanding the processes that cause disease provides the best guidance for treatment. Ultimately, our credibility with the public rests on a foundation of sound science.
2. Establishing and maintaining an effective and credible working relation with civil authorities and the public requires constant attention and a major commitment in time. Long-term continuity with scientific personnel and a stable policy with clearly defined lines of responsibility are important elements in this process. The tenures of Hill as LVO SIC from 1982 to 2009, Mangan as LVO SIC from 2009 to 2011 and CalVO SIC from 2012 to present have provided continuity of scientific and hazard information spanning 4 Mammoth Lakes Town Managers, 3 Mono County Sheriffs, 5 State Geologists, and 6 California Office of Emergency Services Directors.
3. Finally, although the "geologists not welcome" signs have long since disappeared from motel and restaurant windows in Mammoth Lakes, it's important to keep in mind that a protracted crisis and an evolving resort population will severely test the good will and trust scientists worked so hard to establish since the early 1980s. The threat of an impending volcanic eruption inevitably presents a narrow path and an element of uncertainty to a successful response. On one side, an over-anxious response will exacerbate the "false alarm" problem (one, or at most

two, "needless" evacuations, for example, may well destroy our credibility and effectiveness as scientists). On the other side, an overly conservative response (no need to worry yet) may lead to serious casualties and fatalities if an explosive eruption does develop. The 1991 eruption of Mount Pinatubo in the Philippines stands as an example of the narrow path to success in this business with timely evacuations implemented less than a week in advance of the most hazardous, explosive phase of the eruption. This places a premium on good science, experience "under fire", cool heads, and, yes, a little luck.

Additional information sources

Those not familiar with Long Valley caldera and its activity can find maps, background information, diagrams, and plots summarizing current activity under Long Valley caldera on the California Volcano Observatory web site at: http://volcanoes.usgs.gov/volcanoes/long_valley/ (Accessed on 15 January 2015)

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