Mathews, W.H., 1952b, Ice-dammed lavas from Clinker Mountain, southwestern British Columbia: American Journal of Science, v. 250, p. 553-565.
Mathews, W.H., 1958, Geology of the Mount Garibaldi map area, southwestern British Columbia — II. Geomorphology and Quaternary volcanic rocks: Geological Society of America, Bulletin, v. 69, p. 179-198.
Mathews, W.H., 1972, Geology of the Vancouver area of British Columbia: 24th International Geological Congress, Guidebook 24, pt. A05-C05, 47 p.
Sivertz, G.W.G., 1976, Geology, petrology and petrogenesis of Opal Cone and the Ring Creek lava flow, southern Garibaldi Park, B.C., B.Sc. Thesis, University of British Columbia, Vancouver, 74 p.
Souther, J.G., 1977, Volcanism and tectonic environments in the Canadian Cordillera — a second look, *in* Baragar, W.R.A., Coleman, L. and Keen, C.E., eds., Volcanic Regimes in Canada: Geological Association of Canada, Special Paper 16, 3-24.
Thompson, P.H., 1968, Remnant magnetism in the Garibaldi volcanics near Squamish, British Columbia, B.Sc. Thesis, University of British Columbia, Vancouver, 19 p.
Woodsworth, G.J., 1977, Pemberton (92J) map area: Geological Survey of Canada, Open File 482.

Magmatic Unrest at Long Valley Caldera, California, 1980-1990

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Summary
On May 25, 1980, the resort town of Mammoth Lakes, California, was shaken by a remarkable 48-hour-long earthquake sequence that included four M=6, two M=5 and 300 M=3 quakes. The nature of the precursory seismicity plus the unusual character of the May 25-27 sequence itself suggested that it was not typical of tectonic earthquakes in the region. Discovery of 25 cm of domical uplift centred on the resurgent dome within Long Valley caldera strongly implied that this activity was accompanied, if not caused, by influx of magma into the Long Valley magma chamber.

Prologue

On May 25, 1980, one week after the May 18 eruption of Mount St. Helens and following by only a few hours its second major explosive eruption, the resort town of Mammoth Lakes, California, was shaken by a remarkable 48-hour-long earthquake sequence that included four M=6, two M=5, and 300 M=3 quakes (Sherburne, 1980). The largest of these quakes were located on the southern margin of Long Valley caldera and in the High Sierra immediately to the south. The known recurrence interval of tectonic earthquakes in this region, M=5.5 to 6 quakes every decade or two, suggested that this sequence was essentially tectonic in origin, yet the nature of the precursory seismicity along the entire length of the Sierra Nevada front during the preceding three years, plus the unusual character of the May 25-27 sequence itself, suggested that it was not typical of tectonic earthquakes in the region (Ryall and Ryall, 1980). Discovery of 25 cm of domical uplift centred on the resurgent dome within Long Valley caldera during a levelling survey in the summer of 1980 (Savage and Clark, 1982), together with the recognition of seismic P- and S-wave attenuation at depths of 7-8 km beneath the resurgent dome (Ryall and Ryall, 1981), strongly implied that this activity was accompanied, if not caused, by influx of magma into the Long Valley magma chamber. This interpretation was strengthened by continuing unusual seismicity in 1980-82, wherein seismic swarms characterized as spasmodic bursts were localized in a 4-km-diameter epicentral area in the south moat of the caldera at depths from 8 to 5 km (Ryall and Ryall, 1983). Spasmodic bursts are commonly recognized in active volcanic areas and are thought to be the result of rapid-fire brittle rock fracture driven by transient increases in local fluid (either magma or water) pressure. One of the strongest of these swarms, including a M=4.1 and several M=3 quakes, occurred on May 7, 1982, with hypocentres as shallow as 2 km. This activity suggested the upward injection of magma or the expulsion of vapour under high pressure from the magma chamber (Ryall and Ryall, 1983), and it prompted the United States Geological Survey to issue a "Notice of Potential Volcanic Hazard" and to mobilize an intensive monitoring effort in the Long Valley area (Bailey, 1982; Hill, 1984). The Notice, issued when visions of the devastation of Mount St. Helens were still fresh in the public's mind, evoked from the media and the public, particularly locally, the same range of emotional responses previously encountered at Mount St. Helens (Peterson, 1990), varying from disbelief to anger, and scientists were forced to learn anew some difficult lessons in public relations and tactful information dissemination.

Nature and Chronology of Continuing Activity

Since this initial 1980-82 activity, seismicity and ground deformation in the vicinity of Long Valley have waxed and waned to the present time. After several months of relative quiescence in late 1982, the area was again shaken on January 6, 1983, by an intense earthquake sequence, which this time included two quakes of M=5.3 and thousands of lesser magnitude. This sequence, beginning in the south moat of the caldera at the 1982 main epicentral area, spread rapidly eastward along an 8-km-long, steeply dipping, planar zone, with hypocentres extending from 10 km depth nearly to the surface. It was accompanied by 7 cm additional rise of the resurgent dome and 22 cm right lateral slip along a rupture surface beneath the south moat. Modelling of the seismicity and ground deformation suggested that, in addition to influx of additional magma beneath the resurgent dome, magma also may have been injected as a dyke along the caldera ring fracture (Savage and Cockerham, 1983). This possibility increased concern for an eruption of greater magnitude and extent than was previously considered likely, and appropriate emergency-response plans were formulated by the California Office of Emergency Services, in co-operation with the California Division of Mines and Geology, the US Geological Survey and local officials.

Throughout 1983, '84, '85 and '86, sporadic earthquakes and occasional small swarms continued in the south moat of the caldera, as well as in the Sierran block to the south (Figure 1); and deformation, both uplift on the resurgent dome and extension across it, continued, but at the relatively slow rate of 1 ppm/yr (Figure 2). During this time, two major tectonic earthquake sequences occurred southeast of the caldera at the margins of the Owens Valley rift: one in November 1984 on the west side of the rift near Round Valley, and another in July 1986 on the east side of the rift near Chalfant. Both of these sequences included two or more quakes exceeding M=5 and hundreds of lesser aftershocks that continued for several months, following patterns typical of tectonic sequences in the region. They tended to confirm the notion that the intracaldera activity, although apparently magma-induced, was part of a more regional tectonic disturbance.

In the weeks following the Chalfant earthquake, seismicity in the caldera and in the Sierran block to the south dropped to an anomalously low level, but it returned to 1985 levels through 1987 and 1988; deformation within the caldera also continued at approximately the same 1 ppm/yr strain rate. In early 1989, seismicity within the caldera again decreased noticeably, but, in May 1989, earthquakes began occurring beneath Mammoth Mountain, a dormant rhyodacite cumulodome on the southwest rim of the caldera (Hill *et al.*, 1990). Although sporadic small swarms had been recorded beneath Mammoth Mountain since 1982, this activity was unusual in its initial exponential-like increase and in its persistence, peaking in June and slowly declining toward the end of the year. It was also unusual in including numerous spasmodic bursts and occasional low-frequency events. The hypocentres of these swarms defined a vertically oriented, NNE-trending, planar zone at depths of 9 to 6 km. Focal mechanisms for many of the quakes indicated NNW-SSE extension, consistent with dyke injection parallel to the trend of the 600-year-old Inyo Craters and to the dykes that fed eruptions from them (Miller, 1985; Eichelberger *et al.*, 1985).

In September 1989, coinciding with a decline in seismic activity beneath Mammoth Mountain, extension across the resurgent

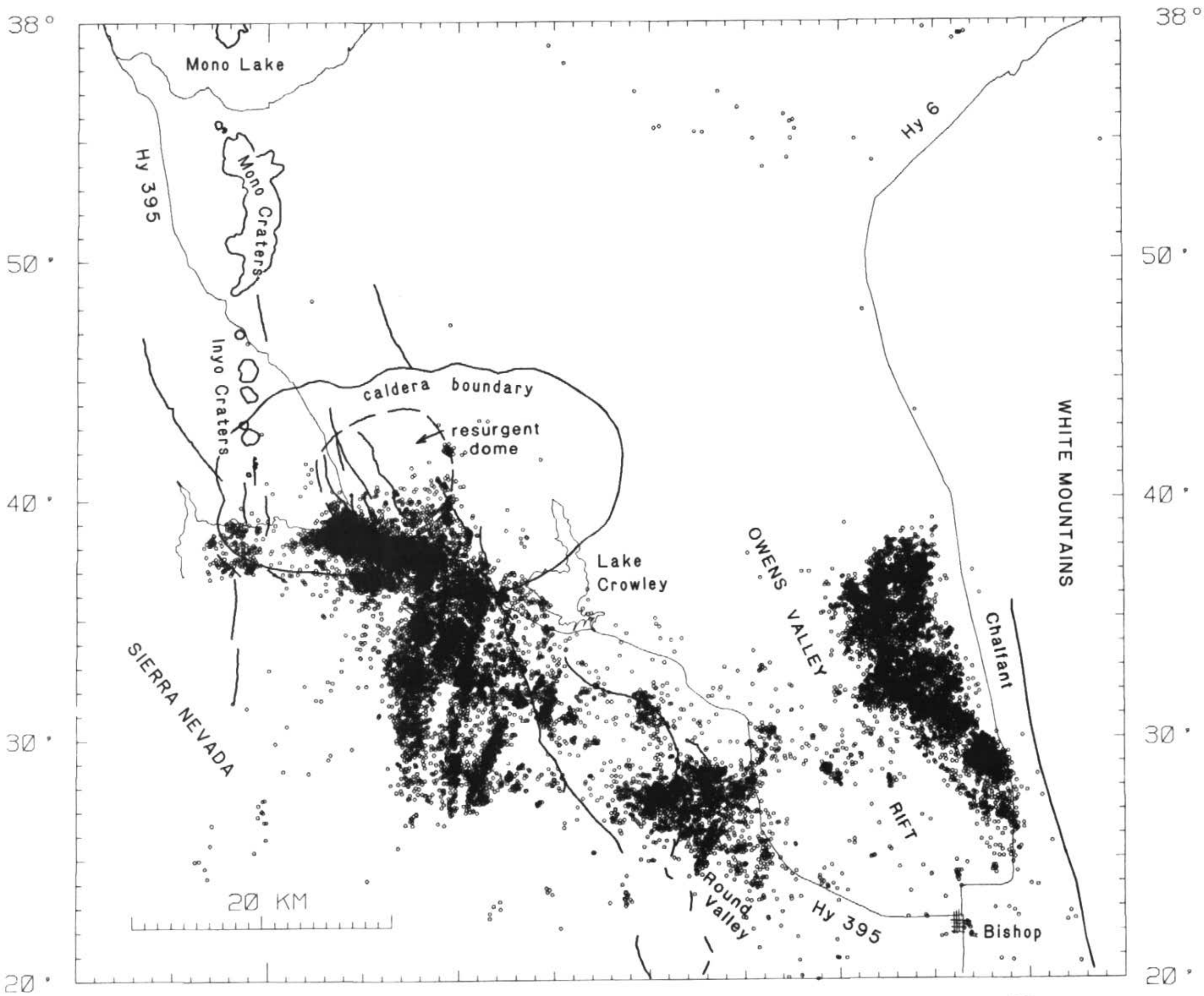

Figure 1 *Distribution of earthquake epicentres in vicinity of Long Valley caldera, 1978-1986. (Plot courtesy of R.S. Cockerham).*

dome, as measured by two-colour laser surveys, began increasing dramatically (5 times the rate of the previous year) and, in November and December, this was accompanied by increasing seismicity in the south moat, peripheral to the resurgent dome. The course of these recent changes, both on Mammoth Mountain and in the caldera, is being carefully monitored, as both suggest an increased rate of magma influx at depth.

Geology

The geologic and geophysical basis for understanding the current activity at the Long Valley and Mono-Inyo Craters chain was developed between 1972 and 1980 as a result of efforts by the USGS Geothermal Research Program to determine the origin and characteristics of the hot-water geothermal system within the Long Valley-Mono Basin KGRA (Known Geothermal Resource Area) (Muffler and Williams, 1976). Within the Long Valley-Mono Basin area (Figure 3), there are two distinct, but probably interrelated, active volcanic-magmatic systems (Bailey *et al.*, 1976; Bailey, 1989). The older system, centred on Long Valley caldera, covers a 4000 km² area straddling the eastern Sierra Nevada frontal fault zone at the northern end of the Owens Valley rift; it has evolved from basaltic through rhyolitic magma compositions over the past 3.6 m.y. The younger system, the Mono-Inyo Craters volcanic chain, is localized along a narrow, 50-km-long, north-trending fissure system that transects the western part of Long Valley caldera and extends to Mono Lake; it has evolved through similar compositions over the past 0.3 m.y. Both systems appear to be involved in the current unrest.

Long Valley caldera. The Long Valley system evolved through a precaldera stage which included successive extrusion of (1) widespread basalts and andesites (3.6-2.2 Ma), (2) rhyodacites and quartz latites localized in the vicinity of the later site of Long Valley caldera (3.1-2.5 Ma), and (3) high-silica rhyolites at Glass Mountain northeast of the site of the later caldera (2.1-0.8 Ma). This sequence culminated in (4) cataclysmic eruption of 600-750 km³ of high-silica rhyolite magma, resulting in deposition of the widespread 730-ka Bishop Tuff and collapse of the roof of its source chamber to form the 2-3 km deep, 17×32 km oval depression of Long Valley caldera. Subsequent volcanism was confined to the caldera with successive eruption of two distinct lava types: (5) aphyric to sparsely porphyritic ***early rhyolite*** extruded concomitantly with resurgence of the caldera floor (700-600 ka), and (6) coarsely porphyritic hornblende-biotite ***moat rhyolite*** extruded at 200,000-year intervals at 500, 300, and 100 ka in clockwise succession around the resurgent dome. The 100-ka lavas appear to be the youngest that can be related petrologically to the Long Valley magma chamber (Bailey, 1984).

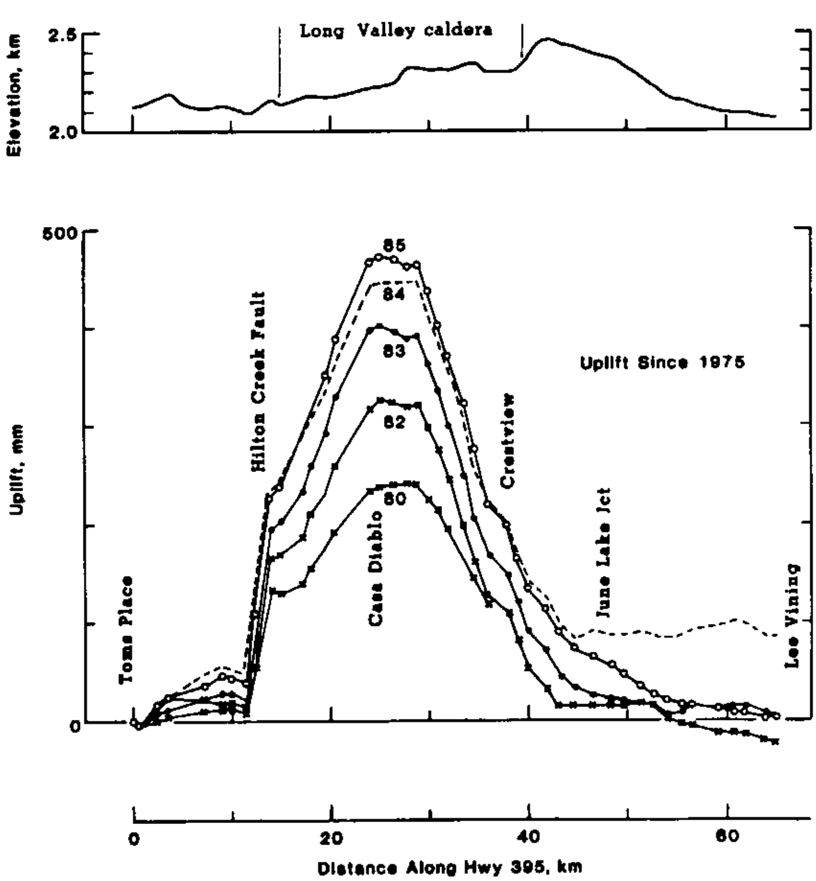

Figure 2 *Uplift profiles based on levelling surveys along Hwy 395 across Long Valley caldera between 1980 and 1985 relative to 1975 datum. Upper diagram shows topographic profile along Hwy 395; for location see* Savage et al. *(1987, figure 2). (From Savage* et al.*, 1987).*

Mono-Inyo Craters. The north-trending Mono-Inyo Craters volcanic chain has evolved through stages resembling those of the precaldera sequence at Long Valley, erupting (1) basalts and andesites mainly in the west moat of Long Valley (300-60 ka) and later in Mono Basin (40-13.3 ka), (2) rhyodacites and quartz latites at Mammoth Mountain (200-50 ka) and later in Mono Basin (100? ka), and (3) high-silica rhyolites at Mono Craters (40-0.6 ka) and low-silica rhyolites at Inyo domes (5-0.6 ka). During the last 3,000 years the Mono-Inyo rhyolites have erupted at about 500-year intervals. Petrologic evidence (Kelleher and Cameron, 1990) and teleseismic data (Achauer *et al.*, 1986) indicate that these rhyolites probably originated from small discrete magma bodies located directly beneath the vents rather than from a large subcaldera magma chamber.

Geophysics

There is abundant evidence that a sizeable thermally anomalous body underlies Long Valley caldera. The existence of the Long Valley geothermal field itself is indicative, but S-wave attenuation studies, teleseismic P-delay studies, and gravity studies all identify approximately coincident anomalous bodies of low-density material at 7 to 15 km depth that can reasonably be interpreted as partly molten; see Hill *et al.* (1985) and Rundle and Hill (1988) for summaries containing additional references; see also Hill (in press), outlining the subcaldera brittle-ductile transition.

Probable Causes of Unrest

The Long Valley and Mono-Inyo magmatic systems have been alternately and occasionally simultaneously active, suggesting that the two are intimately related. A major thermal and geochemical rejuvenation of the Long Valley system coincided with the basaltic episode that initiated the Mono-Inyo system at about 300 ka (Bailey, 1984). Geologic evidence indicates that significant additional uplift of the resurgent dome preceded or accompanied eruption of the 300-ka rhyolite in the southeast moat (Bailey *et al.*, 1989), but the exact timing, magnitude, rate, and duration of uplift are not known. Little or nothing is known of the precursory seismicity and ground deformation that preceded other, more recent prehistoric rhyolitic eruptions at Long Valley, but it is likely that most episodes were preceded by seismicity and deformation not unlike that underway at present.

Evidence in the form of fluid basaltic inclusions in a number of the Long Valley and

Mono-Inyo rhyolites (Bailey, 1984; Varga *et al.*, 1988; Kelleher and Cameron, 1990) suggests that some of the rhyolitic eruptive episodes were accompanied and possibly triggered by injection of mafic magma into the roots of the rhyolitic chambers (see Sparks *et al.*, 1977). This accords with thermal calculations by Lachenbruch *et al.* (1976) indicating that the residual Long Valley magma chamber must have been repeatedly rejuvenated thermally in order to have remained volcanically active over the past 500,000 years. Given the regional tectonic setting and the local structural and petrologic history, it is likely that the current seismicity and ground deformation reflect a new episode of thermal rejuvenation brought about by accelerated regional extension accompanied by influx of mafic magma from the mantle into the roots of the Long Valley chamber (Figure 4), in a manner similar to that suggested by Lachenbruch and Sass (1978) for the Basin and Range province.

Based on the 200,000-year periodicity of the Long Valley moat-rhyolite episodes and on the 100-ka age of the youngest episode, an eruption from the Long Valley magma chamber would seem remote, not to be expected for another 100,000 years. Statistically, the more likely site for future eruptions is along the Mono-Inyo Craters chain, where eruptions have occurred every 500 years or so and the most recent occurred only 500-600 years ago. The 1989 seismicity and evidence for dyking beneath Mammoth Mountain, at the southern end of the Mono-Inyo chain, would tend to favour eruptions from the Inyo source, but with the recent acceleration of uplift on the resurgent dome, possible eruptions from the Long Valley source cannot be ignored. However, ***an eruption from either source is not necessarily inevitable*** in the near future; a survey of historical unrest at calderas worldwide shows that most such episodes of unrest do not culminate in eruptions (Newhall and Dzurisin, 1988).

Nature of Possible Eruptions

Over the past 700,000 years, only rhyolite has erupted from the Long Valley source, hence rhyolite eruptions would seem most likely in the future. These eruptions would probably consist of pyroclastic showers followed by dome extrusion. Eruptions from the seismically active southern end of the Mono-Inyo chain have been dominantly phreatic, basaltic, or rhyodacitic. Past basaltic eruptions have produced large cinder cones and extensive lava flows; Mammoth Mountain

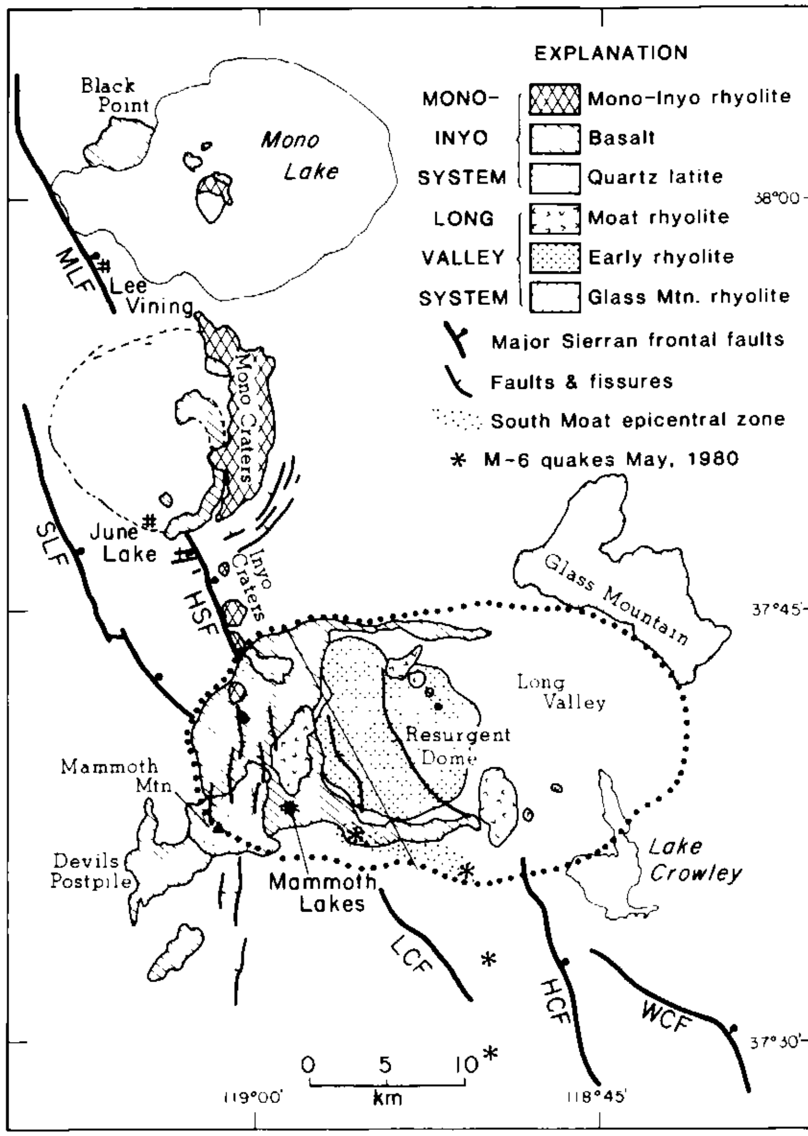

Figure 3 ***(right, upper)*** *Generalized geologic map of Long Valley caldera and Mono-Inyo Craters volcanic chain. (From Hill* et al., *1985).*
***MLF**, Mono Lake fault; **HSF**, Hartley Springs fault; **SLF**, Silver Lake fault; **LCF**, Laurel-Convict fault; **HCF**, Hilton Creek fault; **WCF**, Wheeler Crest fault.*

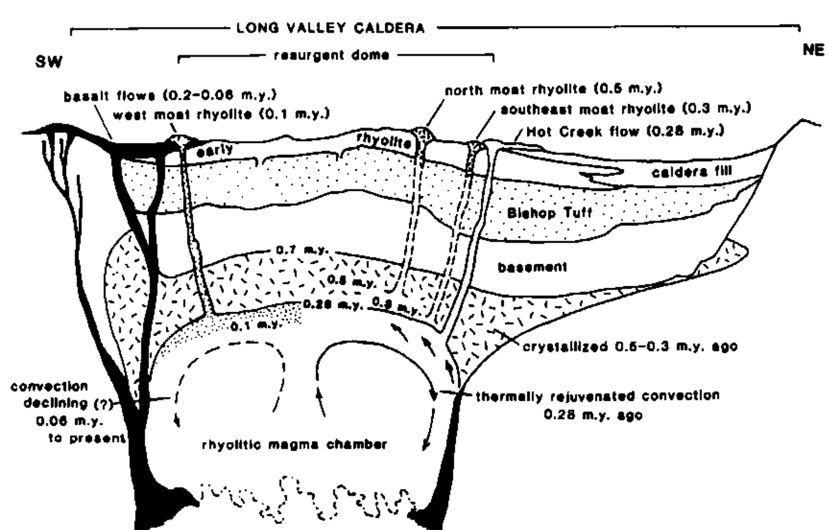

Figure 4 *Cross-section through Long Valley caldera and inferred subjacent magma chamber depicting thermal magmatic rejuvenation at 0.28 Ma and 0.1 Ma as a model for current unrest. Influx of basalt into root zone produces uplift of resurgent dome, followed by eruption of basalt and/or rhyolite in caldera moat and on rim. (From Bailey, 1984).*

was built by repeated extrusion of thick, steep-sided lava domes and flows, preceded by minor phreatic and pyroclastic activity. Debris-avalanches and block-and-ash flows have sometimes accompanied dome extrusion. More detailed summaries of the kinds of eruptive activities to be expected are presented by Miller *et al.* (1982).

References

Achauer, U.L., Green, J.R., Evans, J.R. and Iyer, H.M., 1986, Nature of the magma chamber under Mono Craters area, eastern California, as determined from teleseismic travel time residuals: Journal of Geophysical Research, v. 91, p. 13,873-13,891.

Bailey, R.A., 1982, Mammoth Lakes earthquakes and ground uplift: precursor to possible volcanic activity?: United States Geological Survey, Yearbook 1982, p. 4-13.

Bailey, R.A., 1984, Chemical evolution and current state of the Long Valley magma chamber, *in* Hill, D.P., Bailey, R.A. and Ryall, A.S., eds., Active Tectonic and Magmatic Processes Beneath Long Valley Caldera, Eastern California: United States Geological Survey, Open-file Report 84-939, p. 25-40.

Bailey, R.A., 1989, Geologic map of Long Valley caldera, Mono-Inyo Craters volcanic chain, and vicinity, Mono County, California: United States Geological Survey, Miscellaneous Investigations Map I-1933, scale 1:62,500.

Bailey, R.A., Dalrymple, G.B. and Lanphere, M.A., 1976, Volcanism, structure, and geochronology of Long Valley caldera, Mono County, California: Journal of Geophysical Research, v. 81, p. 725-744.

Bailey, R.A., Miller, C.D. and Sieh, K., 1989, Excursion 13B: Long Valley caldera and Mono-Inyo Craters volcanic chain, eastern California, *in* Chapin, C.E. and Zidek, J., eds., Field Excursions to Volcanic Terranes in the Western United States, Volume II: Cascades and Intermountain West: New Mexico Bureau of Mines & Mineral Resources, Memoir 47, p. 227-254.

Eichelberger, J.C., Lysne, P.C., Miller, C.D. and Younker, L.W., 1985, Research drilling at Inyo domes, 1984 results: EOS, v. 66, p. 186-187.

Hill, D.P., 1984, Monitoring unrest in a large silicic caldera, the Long Valley — Inyo-Craters volcanic complex in east-central California: Bulletin Volcanologique, v. 47, n. 2, p. 371-395.

Hill, D.P., in press, Temperatures at the base of the seismogenic crust beneath Long Valley caldera, California, and Phlegrean Fields caldera, Italy, *in* Volcanic Seismology, Springer-Verlag.

Hill, D.P., Bailey, R.A. and Ryall, A.S., 1985, Active tectonic and magmatic processes beneath Long Valley caldera: an overview: Journal of Geophysical Research, v. 90, p. 11,111-11,120.

Hill, D.P., Ellsworth, W.L., Johnston, M.J.S., Langbein, J.O., Oppenheimer, D.H., Pitt, A.M., Reasenberg, P.A., Sorey, M.L. and McNutt, S.R., 1990, The 1989 earthquake swarm beneath Mammoth Mountain, California: an initial look at the 4 May through 30 September activity: Seismological Society of America, Bulletin, v. 80, p. 325-339.

Kelleher, P.C. and Cameron, K.L., 1990, The geochemistry of the Mono Craters-Mono Lake volcanic islands complex, eastern California: Journal of Geophysical Research, v. 95, p. 17,643-17,659.

Lachenbruch, A.H. and Sass, J.H., 1978, Models of an extending lithosphere and heat flow in the Basin and Range province, *in* Smith, R.B. and Eaton, G.P., eds., Cenozoic Tectonics and Regional Geophysics of the Western Cordillera: Geological Society of America, Memoir 152, p. 207-250.

Lachenbruch, A.H., Sass, J.H., Munroe, R.J. and Moses, T.H., Jr., 1976, Geothermal setting and simple heat conduction models for Long Valley caldera: Journal of Geothermal Research, v. 81, p. 769-784.

Miller, C.D., 1985, Holocene eruptions at the Inyo volcanic chain, California: implications for possible eruptions in Long Valley caldera: Geology, v. 13, p. 14-17.

Miller, C.D., Mullineaux, D.R., Crandell, D.R. and Bailey, R.A., 1982, Potential hazards from future volcanic eruptions in the Long Valley-Mono Lake area, east-central California and southwest Nevada — a preliminary assessment: United States Geological Survey, Circular 877, 10 p.

Muffler, L.J.P. and Williams, D.L., 1976, Geothermal investigations of the U.S. Geological Survey in Long Valley, California, 1972-1973: Journal of Geophysical Research, v. 81, p. 721-724.

Newhall, C.G. and Dzurisin, D., 1988, Historical unrest at large calderas of the world: United States Geological Survey, Bulletin 1855, 1108 p.

Peterson, D.W., 1990, Overview of the effects and influence of the activity of Mount St. Helens in the 1980s: Geoscience Canada, v. 17, p. 163-166.

Rundle, J.B. and Hill, D.P., 1988, The geophysics of a restless caldera — Long Valley, California: Annual Review of Earth and Planetary Science, v. 16, p. 251-271.

Ryall, A. and Ryall, F., 1980, Spatial-temporal variations in seismicity preceding the May 1980 Mammoth Lakes, California, earthquakes, *in* Sherburne, R.W., ed., Mammoth Lakes, California, Earthquakes of May 1980: California Division of Mines and Geology, Special Report 150, p. 27-39.

Ryall, A. and Ryall, F., 1983, Spasmodic tremor and possible magma injection in Long Valley caldera, eastern California: Science, v. 219, p. 1432-1433.

Ryall, F. and Ryall, A., 1981, Attenuation of P and S waves in a magma chamber in Long Valley, California: Geophysical Research Letters, v. 8, p. 557-560.

Savage, J.C. and Clark, M.M., 1982, Magmatic resurgence in Long Valley caldera, California: possible cause for the 1980 Mammoth Lakes earthquakes: Science, v. 217, p. 531-533.

Savage, J.C. and Cockerham, R.S., 1983, Earthquake swarm in Long Valley, California, January 1983: evidence for dike intrusion: Journal of Geophysical Research, v. 89, p. 8315-8324.

Savage, J.C., Cockerham, R.S., Estrem, J.E. and Moore, L.R., 1987, Deformation near Long Valley caldera, eastern California, 1882-1986: Journal of Geophysical Research, v. 92, p. 2721-2746.

Sherburne, R.W., 1980, ed., Mammoth Lakes, California, Earthquakes of May 1980: California Division of Mines and Geology, Special Report 150, p. 91-130.

Sparks, R.S.J., Sigurdsson, H. and Wilson, L., 1977, Magma mixing: a mechanism for triggering acid explosive eruptions: Nature, v. 267, p. 315-317.

Varga, R.J., Bailey, R.A. and Sumnicht, G.A., 1988, Evidence for 600-year-old basalt and magma mixing at Inyo Craters volcanic chain, eastern California: Abstract, EOS, v. 69, p. 1491.

Patterns of Volcanism in the Cascade Arc During the Past 15,000 Years

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Summary

About 110 well-dated and 70 poorly dated eruptive periods less than 15,000 years old at individual volcanoes in the Cascade arc constitute a data set for identifying spatial and temporal patterns of eruptive activity. Key features of the record include: (1) the mean frequency of eruptive periods during the past 4,000 years is approximately two per century; however, the variance about the mean may be large; (2) at most major centres, episodes of activity lasting several thousand years are defined by groups of eruptive periods separated by apparent dormant intervals of roughly similar duration, (3) arc-wide clustering of eruptive activity may exist at 0-4 ka, 6-8 ka, and 10-14 ka. Such clustering would be remarkable in light of significant along-arc changes in crustal structure, stress field, and subduction-zone geometry.

Introduction

Studies of the eruptive history of individual volcanic centres provide important information about patterns of activity and repose, variations in magma-extrusion rate, petrologic evolution, and changes in eruptive behaviour. With sufficient details about the eruptive history of the centres in an arc, one can look for arc-wide patterns that might reflect arc segmentation, changing tectonic conditions, or differing processes of magma genesis. Of course, the length of time for which activity is reconstructed governs the degree of detail obtainable and the types of questions that can be addressed. Thus, eruptive patterns over time scales of millions of years are needed to discern the effects of major changes in plate convergence rates (*e.g.*, Verplanck and Duncan, 1987) or shifts in vent distribution (*e.g.*, Guffanti and Weaver, 1988).