Midcrustal, Long-period Earthquakes beneath Northern California Volcanic Areas

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INTRODUCTION

Long-period (LP) volcanic earthquakes are commonly associated with magma migration and magmatic interactions with hydrothermal systems in the shallow crust. Swarms of shallow (depths < 5 km) LP earthquakes serve as one of the more robust seismic precursors to volcanic eruptions (Chouet, 1996). LP earthquakes also occur at mid- to lower crustal depths beneath young volcanic systems (Hasegawa *et al.*, 1991; Koyanagi *et al.*, 1987; White, 1996). In this paper, we document the occurrence of LP earthquakes at midcrustal focal depths beneath each of the major volcanic centers in northern California that have produced late-Quaternary to recent eruptions. These volcanic centers include the Mount Shasta-Medicine Lake complex, Lassen Peak, Clear Lake, and the Mammoth Mountain-Mono Craters complex (Figure 1). In addition, we find a small cluster of LP's beneath the central Sierra Nevada 30 km west-southwest of Mammoth Mountain.

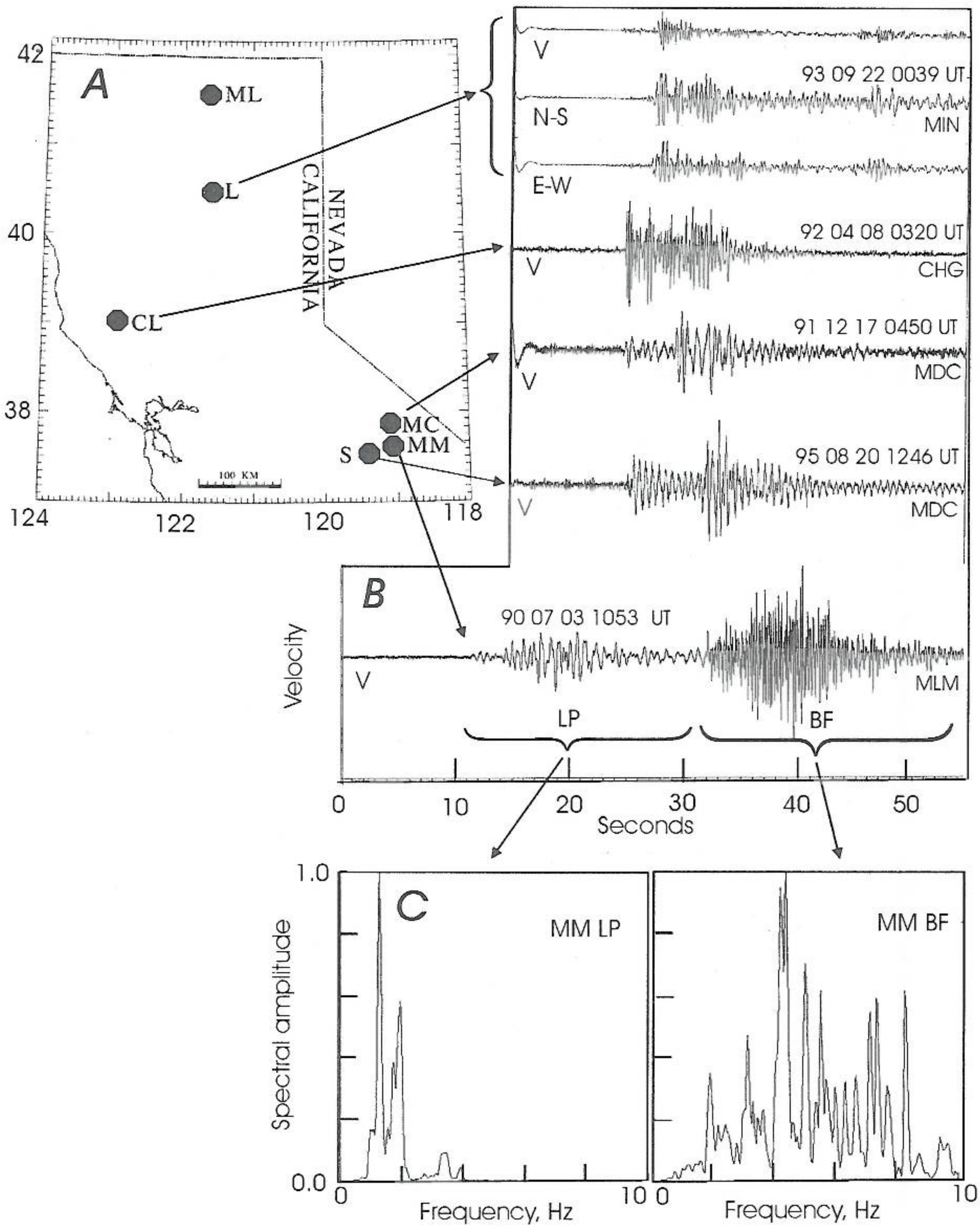
Seismograms of LP earthquakes differ from the much more common broadband signature of brittle-failure (BF) earthquakes in that they are relatively deficient in energy at frequencies above 5 Hz and have an extended, ringing coda (Figure 1). Their onsets are sometimes impulsive with relatively clear *P* and *S* phases but are more commonly rather emergent. They have comblike spectra with dominant peaks generally from 1–5 Hz and often (but not always) in a harmonic relation to one another. The LP earthquakes described in this paper were all detected and located using stations within the Northern California Seismic Network (NCSN). They have focal depths ranging from 10–35 km and are systematically located near or below the base of the seismogenic crust as defined by the maximum focal depth of nearby and much more numerous BF earthquakes. The LP earthquakes are small, with amplitude magnitudes of M ~2.5 or less. Their dominant spectral peaks are typically in the range of 1–2 Hz.

Throughout this paper, we report earthquake focal depths with respect to the mean elevation of the local seismic network (approximately the local mean surface elevation) rather than sea level. For the areas considered here, the mean surface elevation ranges from ~0.6 km above sea level (asl) around Clear Lake, ~2.0 km asl in the vicinity of both Medicine Lake and Lassen Peak, and ~2.5 km asl in the vicinity of Mammoth Mountain.

SEISMIC NETWORK AND EVENT DETECTION

Our ability to reliably detect and locate LP earthquakes occurring within NCSN has an uneven history, and it continues to be spatially uneven within the network today. The RTP and CUSP (Oppenheimer *et al.*, 1993) algorithms that proved so successful in automatically timing and locating BF earthquakes within the network commonly failed to recognize the more emergent onsets of the LP events. Prior to 1993 we relied almost entirely on systematic scanning of seismic traces recorded on 16 mm film to identify LP earthquakes occurring within the NCSN network. From 1967 through 1985, all stations within the NCSN were recorded on both 16 mm film and magnetic tape, and earthquakes were timed using the film or playbacks from the magnetic tape. By 1980, the analog seismic signals were being digitized in real time and passed to the online RTP system for automatic detection and hypocentral location. In 1984, the CUSP system, which detects events and saves the digital seismograms for off-line, interactive analysis, came into use (Oppenheimer *et al.*, 1993). The number of stations recorded on 16 mm film was systematically reduced after 1985, and film recording was finally terminated in 1994. The *Earthworm* system, the current, real-time, online processing system for NCSN, replaced the original RTP system in 1997 (see http://www.cnss.org/EWAB/toc.html for additional information on the *Earthworm* system).

Because of the emergent character of LP earthquakes and the distribution of stations recorded on the 16 mm films through 1994, the level of LP activity at most locations remains uncertain. At Lassen Peak, for example, the local stations were originally recorded on 16 mm film that was analyzed separately from the rest of the NCSN data. Under these circumstances, an LP earthquake recorded on the Lassen stations could have been mistaken for the *S*-wave arrivals from a regional event located somewhere beyond the cluster of Lassen stations. Indeed, LP earthquakes occurring near Lassen Peak were not recognized as such until after the Lassen Peak stations were integrated into the rest of the network around 1985.



▲ **Figure 1.** (A) Map showing sites of deep LP earthquakes in northern California. ML = Medicine Lake Volcano, L = Lassen Peak, CL = Clear Lake, S = Sierra Nevada, MC = Mono Craters, MM = Mammoth Mountain. (B) Representative seismograms for LP earthquakes from Lassen Peak (L), Clear Lake (CL), Mono Craters (MC), Sierra Nevada (S), and Mammoth Mountain (MM). The Universal Time (UT) for each earthquake is given in the respective traces as yr, mo, hr, min-sec. Three-letter code below each trace at the right is local station name. The Lassen Peak seismograms are from the 3-component, STS-1 seismometer at station MIN operated by U.C. Berkeley and recorded at 20 samples/second; CL, MC, S, and MM seismograms are from 1 Hz, vertical-component seismometers recorded at 100 samples/sec. MM seismogram shows an LP earthquake at Mammoth Mountain preceding a BF earthquake south of Long Valley Caldera as recorded at station MLM (location on Figure 3). (C) Normalized velocity spectral amplitudes for the LP and BF earthquakes, respectively, from the MM seismogram.

In late 1992, a PC-based detection system (Evans and Pitt, 1995) began to detect and successfully save LP earthquakes occurring beneath the Mammoth Mountain-Devils Postpile area along the western margin of Long Valley caldera (LVC) in eastern California. During the 2.5 years of overlapping operations, all LP earthquakes recognized on the 16 mm film were captured by the PC system and located using *Hypoinverse*. The detection algorithm, which requires a network of ten to fifteen stations, has not been implemented elsewhere within the NCSN. Thus, with the exception of the LVC region (see Pitt and Hill, 1994), our ability to detect LP earthquakes in northern California after 1994 remains limited.

LP EARTHQUAKE OCCURRENCES

Below, we describe the occurrences of LP earthquakes detected within the following regions of the Northern California Seismic Network dating from 1976: (1) the Mount Shasta-Medicine Lake volcanic field, (2) Lassen Peak, (3) Clear Lake, (4) the central Sierra Nevada, and (5) the Mammoth Mountain-Devils Postpile-Mono Craters area of eastern California. See Table 1 for a list of the LP earthquakes plotted in Figure 2.

Mount Shasta-Medicine Lake Volcanic Field

We have detected two LP earthquakes beneath the Mount Shasta-Medicine Lake volcanic field along the axis of the Cascade Range in northern California. Both occurred beneath Medicine Lake Volcano (Figure 2A), which is located 40 km east-northeast of Mount Shasta and last erupted about 900 ybp (Donnelly-Nolan *et al.*, 1990). Medicine Lake Volcano is a large shieldlike structure with a central caldera roughly 10 km in diameter.

The earlier of the two LP earthquakes detected beneath Medicine Lake Volcano occurred on 14 October 1986. Only one seismograph station was located within 35 km of this first event (Δ = 7 km), and the hypocenter of this event is poorly constrained and not plotted in Figure 2. Five additional seismograph stations, including one three-component station, were installed in the area during a swarm of BF earthquakes that began on 29 September 1988 (Dzurisin *et al.*, 1991). This earthquake swarm, which lasted through 1989, was concentrated at depths of less than 4 km beneath the 7 × 12 km Medicine Lake caldera. The second LP earthquake occurred toward the end of this swarm (on 1 December 1989) at a focal depth of 15 km beneath the western edge of the swarm epicentral area (Figures 2A, B). No other LP earthquakes were detected through the end of 1994, when the 16 mm film recording was terminated. If any LP earthquakes have occurred in the area since1994, they were not detected. Dzurisin *et al.* (1991) report no evidence for a direct relation between the two Medicine Lake LP events and the shallow BF earthquake swarm.

Lassen Peak

Lassen Peak, the southernmost Cascade volcano, is a large dacitic dome formed about 27,000 ybp. It is the largest edifice within the cluster of dacitic domes and basaltic flows forming the Lassen volcanic field, which developed with multiple eruptions over the past 0.6 ma. Lassen Peak itself last erupted in 1914–1915 with a series of phreatic blasts and small to moderate explosive eruptions of dacitic lava (Clynne *et al.*, 2000).

TABLE 1
Event List for LP Earthquakes Plotted in Figure 2

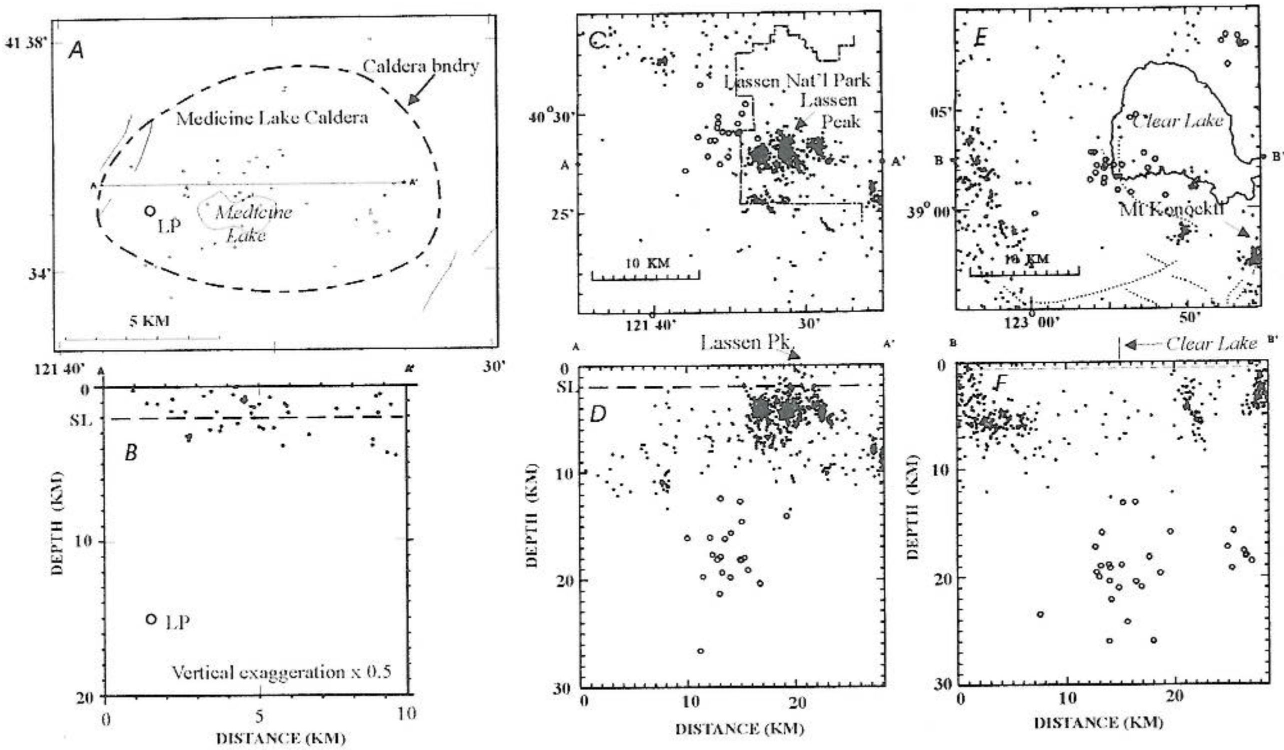
YMD	Time	Latitude	Longitude	Depth	N	RMS	ERH	ERZ	CODA	AZ	MIN
Medicine Lake											
19891201	10:30:4.46	41°35.02′	121°37.91′	15.22	10	0.21	2.1	1.6	2.9	99	14
Lassen											
19820415	15:56:55.72	40°27.8′	121°35.08′	19.81	8	0.05	0.7	1	1.9	111	6
19831216	04:59:42.39	40°28.97′	121°34.43′	18.16	8	0.05	0.6	1.5	1.5	78	4
19840730	06:33:52.46	40°29.52′	121°35.71′	12.42	6	0.04	0.7	1.5	1.6	135	7
19840730	10:48:27.24	40°29.84′	121°35.71′	17.86	6	0.03	0.9	1.2	1.5	140	6
19850117	06:47:41.45	40°28.81′	121°37.06′	26.62	9	0.16	1.6	1.7	1.3	141	8
19851020	11:19:33	40°28.17′	121°31.37′	14.08	5	0	1.9	0.8	1.4	131	5
19860831	14:10:41.83	40°29.03′	121°34.37′	18.15	11	0.08	0.5	0.8	1.7	80	4
19870806	20:47:3.66	40°28.64′	121°35.93′	18.12	12	0.11	0.6	0.8	2.2	120	6
19871029	15:31:26.81	40°27.11′	121°37.91′	16.11	9	0.23	1.1	1.5	1	105	2
19880502	07:14:0.61	40°28.62′	121°36.25′	17.66	9	0.07	0.6	0.8	127	2	

YMD = year, month, day; N = number of stations; RMS = root mean square error for travel-time residuals; ERH = horizontal location error (km); ERZ = vertical location error (km); CODA = coda magnitude; AZ = maximum azimuthal gap in station coverage; MIN = distance (km) to nearest station.

TABLE 1 (CONTINUED)
Event List for LP Earthquakes Plotted in Figure 2

YMD	Time	Latitude	Longitude	Depth	N	RMS	ERH	ERZ	CODA	AZ	MIN
19880910	19:15:27.93	40°30.46′	121°33.91′	19.11	12	0.24	0.9	1.6	1.2	113	4
19881014	22:43:34.23	40°29.28′	121°35.79′	21.34	8	0.08	1.1	1.2	1.3	134	3
19881015	01:26:43.57	40°27.42′	121°35.62′	19.36	7	0.06	0.5	0.5	1.3	151	3
19881024	08:28:20.2	40°27.83′	121°36.41′	16.06	8	0.06	0.5	0.9	1	166	1
19890117	23:50:34.66	40°29.07′	121°34.32′	14.57	9	0.06	0.6	0.8	1.7	124	4
19890509	16:25:32.75	40°31.47′	121°36.89′	19.74	8	0.07	1	0.6	1.5	184	7
19900724	04:04:11.32	40°29.48′	121°34.41′	12.69	9	0.09	0.6	0.6	1.1	113	4
19901104	12:23:43.62	40°29.05′	121°35.43′	16.19	7	0.04	0.8	2	1	125	4
19920827	02:51:23.21	40°29′	121°35.03′	15.63	11	0.08	0.6	0.6	1.9	76	4
19930922	00:39:39.09	40°28.71′	121°33.12′	20.37	10	0.15	1	1	2.2	118	3
19931031	05:54:42.82	40°29.99′	121°34.14′	17.96	14	0.14	0.8	0.9	1.7	112	4
Clear Lake											
19820713	05:38:17.12	39°4.71′	122°53.26′	20.94	12	0.24	0.8	1.6	2	66	8
19820816	15:57:4.23	39°2.01′	122°52.51′	25.95	6	0.09	1.6	2.8	1.4	111	10
19820821	10:31:23.24	39°1.8′	122°55.88′	18.96	19	0.19	0.6	1.1	2	43	8
19820821	10:31:43.57	39°1.46′	122°56.23′	17.2	13	0.17	0.6	1.5	2.7	71	7
19840718	13:33:7.71	39°2.45′	122°55.22′	22.11	10	0.12	0.8	1.4	2.5	93	8
19850603	05:24:13.26	39°2.18′	122°55.8′	15.88	10	0.07	0.5	2.6	1.5	91	8
19851108	04:08:58.39	39°2.18′	122°55.26′	19.17	14	0.17	0.8	1.1	1.7	75	8
19851210	10:24:5.28	39°1.28′	122°55.36′	18.85	9	0.04	0.6	1.2	2	133	9
19861213	22:39:26.85	39°0.8′	122°53.61′	20.44	9	0.06	0.5	1.2	1.5	96	10
19890203	03:50:17.18	39°2.19′	122°54.19′	24.19	10	0.08	0.6	1.1	123	10	
19890203	03:50:24.87	39°2.04′	122°55.34′	25.96	10	0.08	0.9	0.6	88	8	
19890203	03:50:42.51	39°2.84′	122°55.96′	20.01	17	0.1	0.4	0.8	2	97	7
19890203	03:51:4.25	39°2.78′	122°52.76′	18.16	10	0.04	0.5	1	1.8	132	12
19900605	07:38:22.5	39°4.57′	122°53.64′	13.05	8	0.07	0.5	1.1	1.7	111	8
19900804	04:21:49.6	38°59.8′	122°59.77′	23.47	7	0.15	1.1	2.3	1.9	176	17
19920408	03:20:21.75	39°8.24′	122°46.1′	18.58	7	0.05	0.7	1.2	1.5	127	5
19921107	11:27:2.6	39°8.16′	122°46.44′	18.04	7	0.06	0.9	1.2	1.7	128	4
19930927	19:52:33.82	39°0.63′	122°51.38′	15.84	11	0.05	0.5	0.7	2.3	128	8
19931028	10:15:54.6	39°0.93′	122°54.45′	13.09	10	0.13	0.5	2	0.1	83	10
19931028	10:16:12.11	39°2.19′	122°54.72′	21.02	16	0.12	0.5	0.8	47	9	
19931028	10:16:32.61	39°1.6′	122°54.54′	18.87	8	0.1	1.1	2.8	83	10	
19940813	17:12:44.28	39°7.21′	122°47.27′	15.75	7	0.04	0.7	1.4	1.3	158	3
19941120	08:34:12.86	39°8.64′	122°47.39′	19.2	6	0.06	0.8	1.4	1.6	160	3
19950217	14:56:34.57	39°2.47′	122°52.03′	19.65	7	0.08	0.8	1.2	1.3	131	10
19950811	20:54:51.07	39°1.53′	122°55.31′	20.4	18	0.09	0.4	0.7	2.1	84	9
19950812	10:38:0.54	39°8.35′	122°47.67′	17.25	11	0.15	0.7	1.5	1.6	75	3
19951020	15:20:2.02	39°8.6′	122°46.61′	17.61	6	0.01	0.7	1.6	1.6	150	4
19951022	13:08:48.07	39°8.28′	122°46.5′	18.11	7	0.04	0.6	1.3	1.5	128	4

YMD = year, month, day; N = number of stations; RMS = root mean square error for travel-time residuals; ERH = horizontal location error (km); ERZ = vertical location error (km); CODA = coda magnitude; AZ = maximum azimuthal gap in station coverage; MIN = distance (km) to nearest station.



▲ **Figure 2.** (A) Seismicity map and (B) east-west cross-section for Medicine Lake caldera (adapted from Dzurisin *et al.*, 1991). (C) Seismicity maps and (D) cross-section for Lassen Peak. (E) Seismicity map and (F) cross-section for the Clear Lake region. Small circles indicate BF earthquakes; large circles indicate LP earthquakes. Cross-section planes show projection of all events in their respective maps. Dashed line labeled SL indicates sea level.

The USGS began monitoring seismicity in the Lassen Peak area in 1977. The earliest identified LP earthquake occurred on 15 April 1982. During the next twelve years, 34 LP earthquakes were sufficiently well recorded to resolve hypocentral locations. These events have focal depths ranging from 13–27 km. LP events near Lassen Peak generally occur singly but sometimes in sequences of two or three events that are separated in time by minutes to hours. The annual occurrence rate varied from none in 1991 to eight in 1988. LP epicenters are offset 5–8 km west of the centers of recent volcanic activity at Lassen Peak, and they are spatially isolated from nearby areas of shallow BF seismicity (Figures 2C, D), which appear to correlate with the areas of geothermal activity in the region. The horizontal offset of the LP earthquakes from either Lassen Peak and associated volcanic vents or BF seismicity, however, is less than half of the focal depth of the LP events. An intriguing temporal coincidence occurred when the first LP earthquake in over a year followed the M 5 Klamath Falls, Oregon earthquake of 22 September 1993, by just a few hours. This temporal coincidence raises (but does not answer!) the question of whether this earthquake might have been triggered by the Klamath Falls earthquake just 200 km to the north.

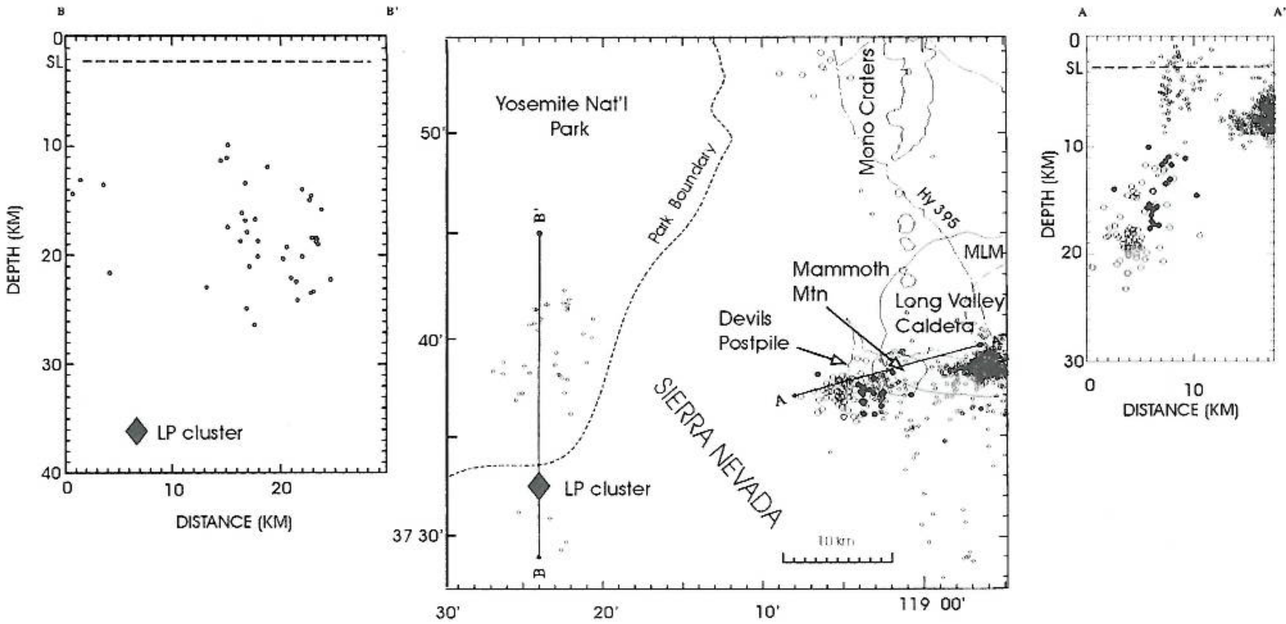
Clear Lake

The Clear Lake volcanic field lies within the Coast Ranges north of San Francisco Bay. It is associated with a right-stepping offset between the Maacama and Bartlett Springs Faults within the eastern branch of the San Andreas Fault system. The Geysers geothermal steam field is adjacent to the southwest margin of the Clear Lake volcanic field. This volcanic field has developed with multiple eruptions over the past 1 Ma. The most recent eruptions of basaltic lava occurred roughly 11,000 ybp from vents near Mount Konocti along the southwestern shore of Clear Lake (Donnelly-Nolan *et al.*, 1993; Sims *et al.*, 1988).

In 1975 a dense seismograph network began to monitor the seismicity associated with development of the Geysers geothermal field. The first LP event to be recognized within the NCSN occurred beneath the Clear Lake area on 15 January 1976. No additional LP earthquakes were identified until 1982. Since 1982, we have determined hypocentral locations for an additional 29 LP earthquakes in the area with focal depths ranging from 12–27 km. Some Clear Lake LP earthquakes have a relatively higher frequency onset (Figure 1) and trigger the CUSP system, where they are timed along with the many nearby BF earthquakes. Others, however, were identified only on the 16 mm film. The Clear Lake LP events occur in two clusters, one near the west side of Clear Lake and the other just northeast of the lake (Figures 2E, F). Both clusters are within 10–15 km of the Mount Konocti basaltic vents.

Sierra Nevada

The LVC LP detection algorithm identifies occasional mid-crustal LP earthquakes located at depths around 35 km



▲ **Figure 3.** Seismicity map and cross-sections for the Mammoth Mountain-Mono Craters-Sierra Nevada region. Small circles indicate BF earthquakes. Larger circles indicate LP earthquakes. Solid large circles represent LP earthquakes recorded by a temporary deployment of 3-component seismograph stations around Mammoth Mountain (Foulger *et al.*, 1998). Cross-sections A-A′ through Mammoth Mountain and B-B′ through the central Sierra Nevada include earthquake hypocenters projected from 5 km on either side of the cross-section line. Filled diamond indicates LP cluster beneath the Sierra Nevada. MLM is the station location for the Mammoth Mountain (MM) seismogram in Figure 1B. Dashed line labeled SL indicates sea level.

beneath an area immediately south of Yosemite National Park in the central Sierra Nevada (Figure 3). The only volcanic rocks in this section of the central Sierra Nevada are isolated patches of 3.5 Ma basaltic andacites (Moore and Dodge, 1980). The late-Quaternary and Holocene volcanic vents associated with Mammoth Mountain, Devils Postpile, and Red Cones, however, lie 30 km to the east-northeast of these LP earthquakes and thus within a source depth of their hypocenters (see next section).

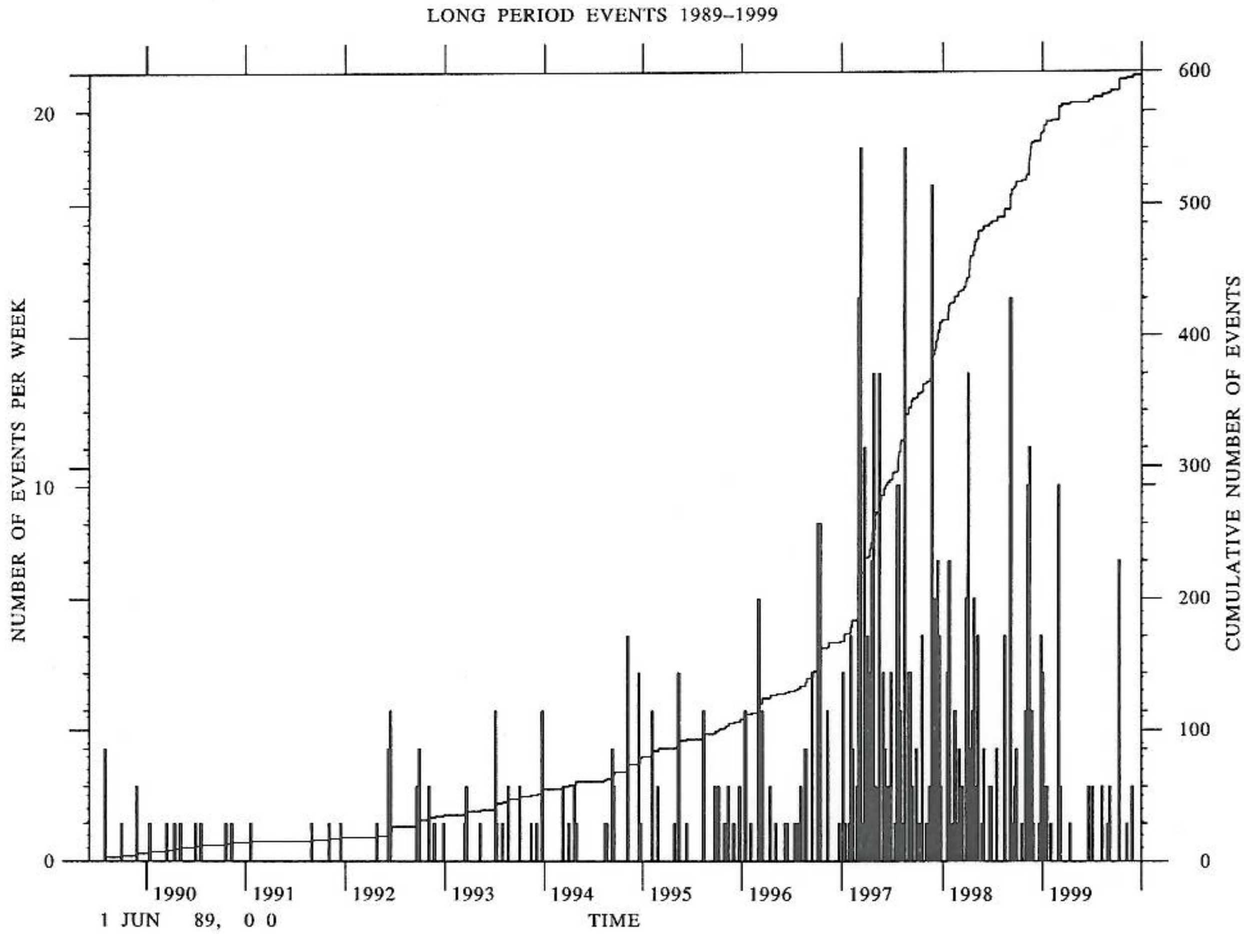
The central Sierra LP earthquakes may occur as isolated events or in clusters of three to ten events over a period of several minutes. The earliest identified cluster of LP events beneath the central Sierra Nevada occurred on 4 December 1994. Subsequent episodes occurred in 1995 on 15 and 20 August, and 21 November, and on 21 January 2000. The LP hypocenters are located between two shallower, more diffuse clusters of BF earthquakes (Profile B-B′ in Figure 3). Because the 1994 LP earthquakes are clearly visible on the 16 mm film, we are reasonably certain that no previous LP earthquakes occurred in this area between 1982, when stations in the eastern Sierra Nevada were added to the network, and 1994.

Mammoth Mountain-Devils Postpile and Mono Craters

The highest rate of LP earthquake activity in northern California occurs beneath Mammoth Mountain, which stands at the southern end of the Mono-Inyo volcanic chain and along the southwest margin of Long Valley caldera in east-central California (see Figure 3, Bailey, 1989; Pitt and Hill, 1994). The Mono-Inyo chain has produced multiple eruptions of both basaltic and rhyolitic lavas over the past 200,000 years, including the basaltic Devils Postpile flows (~75,000–50,000 ybp) and the postglacial Red Cones (~5,000 ybp) basalts. Mammoth Mountain itself developed with a series of dome-building dacitic eruptions between 100,000 and 50,000 ybp. The most recent eruptions along the Mono-Inyo volcanic chain occurred just 250 ybp on Paoha Island in Mono Lake and 500–600 ybp from a series of vents along the northern end of the Mono Craters and the southern end of the Inyo Craters (Bursik and Sieh, 1989; Miller, 1985). Here we update an earlier paper (Pitt and Hill, 1994) on deep LP earthquakes beneath Mammoth Mountain-Mono Craters.

The locally dense seismic network in Long Valley caldera and vicinity was installed in 1982 as part of an intensive effort to monitor unrest that began in 1980 (Hill, 1984). Most of the earthquakes associated with this unrest have occurred in swarms of BF earthquakes located within the upper 10 km of the crust beneath the south half of the caldera and Mammoth Mountain, and the upper 18 km of the crust beneath the Sierra Nevada block to the south (Figure 3). Note that mean surface elevation in this area is ~2.5 km above sea level. LP earthquake activity in the region occurs in two clusters: one at depths of 10–25 km beneath the west flank of Mammoth Mountain and the other, smaller cluster (just ten events to date) at depths of 20–35 km beneath an area centered 5–10 km west of the Mono Craters (Figure 4, Pitt and Hill, 1994). Aside from this small cluster of deep LP earthquakes, the Mono Craters area has been seismically quiet since at least 1982.

As described by Pitt and Hill (1994), the first LP earthquake detected beneath the southwest flank of Mammoth



▲ **Figure 4.** Time history of LP earthquake activity at Mammoth Mountain-Devils Postpile showing the number of timed events per week and cumulative number of events.

Mountain occurred at a depth of 17 km on 27 July 1989, during the 1989 Mammoth Mountain earthquake swarm (a single LP event on 31 July 1982 has subsequently been identified). This Mammoth Mountain swarm, which persisted from May through December 1989 and involved hundreds of small (M ≤ 3) BF earthquakes at depths shallower than 10 km, appears to have been associated with magma injection into a north-northeast-trending dike beneath Mammoth Mountain (Hill *et al.*, 1990). The onset of deep LP earthquake activity during this 1989 swarm also corresponds with the onset of carbon dioxide out-gassing from several locations on the flanks of Mammoth Mountain (Farrar *et al.*, 1995; Hill, 1996) and with an increase in magmatic helium in the form of a pronounced rise in the He^3/He^4 ratio from a fumarole on the north side of the mountain (Sorey *et al.*, 1998, 1993). Deep LP earthquake activity continued at a relatively low rate following the Mammoth Mountain swarm through 1995. This rate increased progressively through mid-1997 as illustrated in Figure 4 (the location threshold for deep LP earthquakes beneath Mammoth Mountain has remained at about M ~0.5 throughout). The cumulative number of detected and located LP events exceeded 100 by mid-1995 and exceeded 400 by the end of 1997. The LP activity rate decreased abruptly at the end of April 1998, at which point the cumulative number of located events was nearly 500.

Locations for 72 of the deep LP earthquakes with the highest quality solutions are plotted in Figure 3 (*Hypoinverse* solution parameters: RMS ≤ 0.3 sec, ERH and ERZ ≤ 1 km, and azimuthal gap ≤ 150 degrees). Deep LP activity peaked in mid-1997, two to three months after the onset of accelerated uplift of the resurgent dome began in conjunction with escalating BF earthquake swarms in the south moat of the caldera. The rates of resurgent dome uplift and south-moat swarm activity peaked in November-December 1997 (Hill, 1998). The hypocenters of the LP earthquakes located with NCSN stations define a diffuse cloud in map view and an elongated pattern in depth that appears to dip to the southwest (Figure 3). The extent of this depth range is supported by the spread in *S-P* readings for individual earthquakes. The apparent southwest dip, however, may be an artifact of the station distribution, which is concentrated in the caldera. During the summer of 1997, the NCSN stations were supplemented with a temporary network of three-component digital stations deployed around Mammoth Mountain (Foulger *et al.*, 1998). Solid circles in Figure 3 indicate LP earthquakes located with this augmented network. These hypocenters were determined using a three-dimensional inversion algorithm rather than *Hypoinverse*. They define a narrow, north-trending, nearly vertical pattern that may correlate with the inferred dike intrusion in 1989.

DISCUSSION

With the exception of Mount Shasta, midcrustal LP volcanic earthquakes occur beneath each of the major volcanic centers in northern California. In each case, the horizontal offset of the LP earthquake epicenters from late Quaternary to recent volcanic vents is less than their average focal depths. Interestingly, the direction of offset is generally to the west or southwest of the recent volcanic vents. This westward offset applies as well to the occasional, 35-km-deep LP events beneath the central Sierra Nevada, which are offset 30 km to the west-southwest of Mammoth Mountain. Whether these Sierra Nevada LP events are somehow related to the current Mammoth Mountain-Inyo Domes magmatic system, however, is not clear. These earthquakes could reflect a recent invasion of basaltic magma to midcrustal depths beneath the central Sierra Nevada; they all occur beneath the seismogenic crust as defined by maximum focal depths of nearby BF earthquakes.

Two generally accepted source models for LP earthquakes involve the resonance of fluid-filled cracks (Chouet, 1992) and unsteady, nonlinear fluid flow along conduits with irregular geometry (Julian, 1994). The former requires a high fluid-rock impedance contrast for efficient seismic wave radiation, a condition met by bubbly or frothy fluids. At shallow depths the bubbly fluid may be vesiculating magma or boiling hydrothermal fluids. Under the relatively high confining pressures at midcrustal depths, however, the most plausible candidate for a bubbly fluid is basaltic magma supersaturated with carbon dioxide gas (Gerlach *et al.*, 1996). The nonlinear fluid flow model of Julian (1994) does not require a high fluid-rock impedance contrast, although it does require a relatively invicid fluid. It is still not clear from available data which of these models best explains the source processes for the midcrustal LP earthquakes. In either case, we believe basaltic magma is the most likely active fluid because (1) it has a relatively low viscosity, (2) it is a rich source of CO_2, and (3) CO_2 as a gas phase remains in equilibrium with CO_2-saturated basaltic magma under midcrustal confining pressures. Certainly the onset of CO_2 flux from the flanks of Mammoth Mountain coincident with the onset of midcrustal LP activity beneath the mountain is consistent with this possibility (Hill, 1996).

The growing evidence that silicic volcanic eruptions may be "triggered" by injections of basaltic magma into existing silicic magma bodies (Pallister *et al.*, 1996) gives added importance to recognizing the occurrence of midcrustal LP earthquakes beneath young volcanic systems. The sudden onset or significant increase in the rate of midcrustal LP earthquake activity, for example, may provide an early indication that a volcanic system previously in repose has become reactivated and is evolving toward an eruption. This may be especially important in basaltic or bimodal volcanic fields, in which basaltic magma is capable of moving from midcrustal depths to the surface in a matter of hours to days.

Mid- to lower-crustal LP earthquakes have been recognized beneath a number of young volcanic systems elsewhere (Hasegawa *et al.*, 1991), and it seems likely that they may be more common than generally thought. Indeed, our experience in northern California suggests that standard network processing techniques are likely to overlook LP earthquake activity. Most automatic detection algorithms, which are well tuned to detect and time local (Hill *et al.*, 1985) BF earthquakes, do poorly in recognizing the emergent onsets and low-frequency coda typical of LP earthquakes. For networks that depend exclusively on event detection for archiving seismic data, any record of LP activity may thus be lost. As the continuous recording and scanning of analog seismic channels becomes a vanishing practice, it is important that specially tuned detection algorithms of the sort described by Evans and Pitt (1995) be implemented in local seismic networks that encompass young volcanic systems to ensure recognition of midcrustal LP earthquake activity and the spatial-temporal variations thereof.

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