drainage, preserved beneath spoil cast up when the ditch was dug, was recovered and represents the surface from which the core was taken. Location is on Map N.2618, Laguna de Tagua Tagua, Departamento de Cachapoal, Instituto Geográfico Militar, scale 1:25,000 (1930).
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Spasmodic Tremor and Possible Magma Injection in Long Valley Caldera, Eastern California

Abstract. *Intensive microearthquake swarms with the appearance of volcanic tremor have been observed in the southwest part of Long Valley caldera, southeastern California. This activity, possibly associated with magma injection, began 6 weeks after several strong (magnitude 6+) earthquakes in an area south of the caldera and has continued sporadically to the present time. The earthquake sequence and magmatic activity are part of a broad increase in tectonic activity in a 15,000-square-kilometer region surrounding the "White Mountains seismic gap," an area with high potential for the next major earthquake in the western Great Basin.*

On 25 May 1982, 2 years after the occurrence of four earthquakes of local magnitude (M_L) 6.0 to 6.3, the U.S. Geological Survey (USGS) issued a "Notice of Potential Volcanic Hazard . . ." for the Mammoth Lakes area, eastern California (*1*). Events cited as having heightened the concern of USGS scientists included uplift of the floor of Long Valley caldera by about 10 inches (*2*), observation of spasmodic tremor at a single site in the southwestern part of the caldera, progressive movement of earthquakes toward the surface at this same site, and formation of a new group of fumaroles. This report describes the last three of these observations.

Figure 1a shows the location of 386 earthquakes of the Mammoth Lakes sequence for the period 4 October 1978 to 24 May 1980, and Fig. 1b shows 1088 events from 25 May 1980 to 1 October 1982. The epicenters shown in Fig. 1 were determined by using the HYPO71 algorithm (*3*) and are accurate to within about 1 km; location of the events changed only slightly in test runs with a range of reasonable crustal models. Similarly, we estimate that the accuracy of focal depth determinations is of the order of ±1 to 2 km for events in the southwest part of the caldera, the only area for which event depth is discussed in this report.

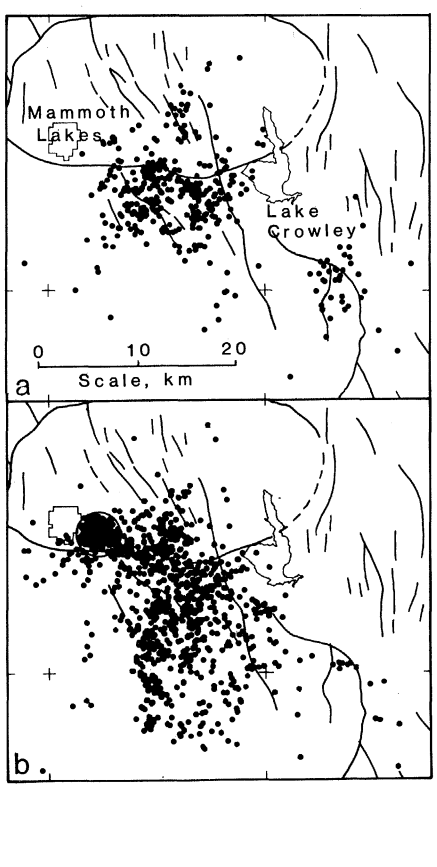

Fig. 1. Seismicity in the Mammoth Lakes area before and after 25 May 1980. Outline of Long Valley caldera and prominent faults are shown by heavy lines. (a) The 386 earthquakes in the period 4 October 1978 to 24 May 1980. Sequence began with an M_L 5.7 event in the cluster southeast of Lake Crowley, and gradually moved northwest over the next 18 months. (b) The 1088 earthquakes in the period 25 May 1980 to 1 October 1982. Swarms with the appearance of spasmodic tremor were located in the circle just east of the town of Mammoth Lakes in (b). Only events with location quality C or better are shown.

As illustrated by Fig. 1b, this sequence was not associated with a single fault, but involved complex brecciation of an irregular-shaped crustal block extending 30 km in a northwest-southeast direction and 25 km from north to south. As noted earlier (*4*), the sequence began with an M_L 5.7 shock on 4 October 1978, 15 km southeast of the caldera; over the next 18 months the epicentral zone grew toward the northwest, and activity gradually concentrated in an area just south of the caldera (Fig. 1a). On 25 and 27 May 1980, six events occurred with M_L 5.7 to 6.2, and the epicentral zone extended to the south and west. During 1981 seismicity was concentrated along the southern caldera boundary and in a north-south zone extending 7 km into the caldera and 15 km south of it. The largest shock in 1981, on 30 September, had M_L 5.7.

Primary (P) wave fault-plane solutions for 44 events of this sequence show strike-slip mechanisms for all events shallower than 9 km, and oblique- to dip-slip (normal faulting) for those deeper than 9 km (*5*). Orientation of the axis of minimum compressive stress for all of the solutions is consistent with crustal extension along the north-northwest–trending Sierra Nevada frontal fault system—deeper shocks resulting from normal or oblique movement on faults striking north-northwest and dipping east, and shallow events reflecting conjugate right- and left-lateral shear on nearly vertical fractures striking, respectively, west-northwest and north-northeast. Hill (*6*) proposed a model in which conjugate shear failures of this type accompany the formation of magma-filled dikes, to explain the predominance of strike-slip mechanisms in volcanic regions prone to earthquake swarms. Comparison of his model with focal mechanisms for the Mammoth Lakes sequence suggests that events with strike-slip mechanisms may be associated with the formation of clusters of magma-filled dikes at depths less than 9 km. The existence of magma at shallow depth in the caldera is indicated by a relative delay of about 0.3 second for teleseismic P waves recorded in the west-central part of the caldera (*7*), by secondary arrivals on a refraction profile, tentatively identified as reflections from a low-velocity horizon (*8*), and by the lack of secondary (S) waves for earthquakes around the southwest boundary of the caldera recorded by regional seismic stations to the north (*9*).

Following the strong shocks in May 1980, earthquakes in one small area in the southwest part of the caldera began to occur as intensive swarms, with a typical swarm lasting for 1 to 2 hours, producing hundreds of microearthquakes and having the appearance of spasmodic tremor observed in volcanic regions (*10*). To date, eight such bursts of activity have occurred, and all of them were located within a circle 4 km in diameter, just east of the town of Mammoth Lakes (Fig. 1b). Swarms with the appearance of spasmodic tremor were not observed at other locations within the active area, nor did such swarms occur in this sequence before 3 July 1980.

Over the last 2 years, events in the swarm area have moved progressively to the north, farther into the caldera (Fig. 2a). Depth of the activity has also changed, but not in a strictly progressive sense: the minimum depth for events in the swarm area prior to 1981 was 7 km, while numerous events have had a depth less than 5 km since then (Fig. 2b). In the most recent swarm on 7 and 8 May 1982, many events had relatively low-frequency P- and S-wave arrivals that were too emergent for analysis—similar to the so-called B-type earthquakes observed at depths less than 1 to 2 km in volcanic regions (*11*).

In January 1982, residents of Mammoth Lakes noticed new fumarole activity near Casa Diablo Hot Springs, just northeast of the swarm area shown in Fig. 1b.

Taken together, these observations confirm the suggestion by Lachenbruch and Sass (*12*) that lithospheric extension in the Basin and Range province results in a combination of normal faulting and magmatic intrusion of the brittle crust. According to those authors, bimodal silicic volcanic centers like Long Valley caldera exist "because they are at places where the lithosphere is pulling apart rapidly, drawing up basalt from below to fill the void." In the case under consideration, a major earthquake swarm in the Mammoth Lakes area appears to have started with a complex pattern of strike-slip faulting, possibly associated with the formation of northwest-trending dikes, at shallow depth in a broad area south of Long Valley caldera. This activity reached a maximum level in the spring and summer of 1980, with uplift of the resurgent dome within the caldera (*2*) and the occurrence of several strong earthquakes involving normal or oblique faulting along the caldera boundary and in the crustal block south of it. Following this maximum activity, brecciation and possibly associated intrusion of the shallow crust spread rapidly to the south, north, and west, with occasional bursts of spasmodic tremor marking an area of rapid crack formation just east of the town of Mammoth Lakes, due either to the injection of a small tongue of magma in the southwest part of the caldera or to gas expelled under high pressure from the magma chamber.

It is interesting to note that the Mammoth Lakes earthquake sequence and associated volcanic activity were part of a broader increase in tectonic activity affecting much of the western United States. As noted earlier (*4*), the flurry of moderate earthquakes starting in the fall of 1978 affected the entire Sierra Nevada frontal fault zone—from Doyle in the north to Inyokern at the southern end of the Owens Valley. At the same time, according to Raleigh *et al.* (*13*), the pattern of strain accumulation in southern California changed from slow north-south compression to rapid dilatation, and seismicity throughout California has risen dramatically, "returning to levels that in the past have been associated with earthquakes of $M > 7$." In the region around Long Valley caldera, since 4 October 1978, 47 earthquakes with M_L 4.0 to 5.3 have occurred in the following zones: northeast-trending zone between Mono Lake, California, and Luning, Nevada; northeast side of the White Mountains, in Fish Lake Valley, Nevada; and in the area around Bishop, California. Another 104 shocks with M_L 4.0 to 6.3 have occurred in the Mammoth Lakes area. In comparison, only 19 events with M_L 4.0 or greater were observed in this entire region during the previous 9-year period.

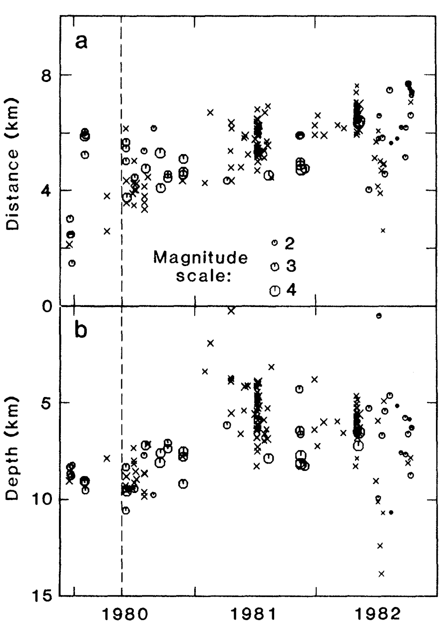

Fig. 2. (a) Migration of activity in the swarm area toward the north. Southern boundary of caldera would be at a distance of about 3 km. (b) Plot of focal depth with time for events in the swarm area. In (a) and (b), circles correspond to events with location quality A or B and symbol size is proportional to magnitude. Dashed line indicates time of large earthquakes on 25 May 1980.

Noting that this increase in seismicity has taken place in and around the so-called "White Mountains seismic gap" (area between the north end of faulting associated with the 1872 Owens Valley earthquake and the south end of the 1932 Cedar Mountains ruptures), we suggest that the potential for a major earthquake in this gap is substantially higher now than it has been for at least the last two decades. Such an event could involve rupturing on fault segments within the zones mentioned in the preceding paragraph, and it could lead to further adjustments within Long Valley caldera in response to stress changes generated by the earthquake itself. To investigate this question further, the University of Nevada, in cooperation with other university, state, and federal groups, is carrying out an intensive program of seismic monitoring in the southern Sierra Nevada region.

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