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RESPONSE PLANS FOR VOLCANIC HAZARDS IN THE LONG VALLEY CALDERA AND MONO CRATERS AREA, CALIFORNIA

by

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SUMMARY

Recurring earthquake swarms in Long Valley caldera through the 1980's and associated inflation of the resurgent dome in the caldera emphasize that this geologically youthful volcanic system is capable of further volcanic activity. This document describes the U.S. Geological Survey's response plan for future episodes of unrest that might precede the onset of renewed volcanism in the caldera or along the Inyo-Mono Craters chain to the north.

Specific response actions under this plan are keyed to a five-level status ranking with successive levels, E through A, triggered by progressively more intense levels of seismic activity and ground deformation as summarized in Table 1.

TABLE 1. STATUS RANKING AND ACTIVITY LEVELS

STATUS[1]	USGS RESPONSE[2]	ACTIVITY LEVEL	RECURRENCE INTERVALS[3]
A ALERT	Issue GEOLOGIC HAZARD WARNING	ERUPTION LIKELY within hours to days	decades to centuries
B ALERT	Alert Director, Trigger EVENT RESPONSE	intense unrest	years to decades
C STATUS	Notify Office Chief, OES Hdqtrs. State Geologist	strong unrest	months to years
D STATUS	Notify Team Leaders, Branch Chiefs, OES comm., USFS, CDMG, & UNR	moderate unrest	weeks to months
E STATUS	Notify Chief Scientist personnel. Information call to OES communications and local authorities as appropriate (ie. a locally felt earthquake)	weak unrest or possible instrument problems	weeks
N	Normal monitoring activities	background activity	---

[1] Derived by combining the status of each monitoring network according to Table 8.

[2] USGS RESPONSE for a given status will include the responses specified for all lower statuses.

[3] estimated RECURRENCE INTERVALS for a given status are based primarily on the recurrence of unrest episodes in Long Valley since 1980, the record of M > 4 earthquake activity in the regions since the 1930's, and the geologic record of volcanic eruptions in the region over the last 50,000 years.

The USGS continuously monitors activity in Long Valley caldera and vicinity by means of a seismic network (18 stations within and immediately adjacent to the caldera and 38 stations within 50 km of the caldera) and deformation monitoring networks that include two borehole dilatometers, 7 borehole tiltmeters, one long-base

tiltmeter, and three differential magnetometers. Data from each of these networks are telemetered to computers in USGS headquarters in Menlo Park, California for automatic, real-time processing and immediate analysis. In addition, horizontal deformation within the caldera is monitored several times a week using a two-color geodimeter to measure a network of geodetic lines.

The nature and intensity of activity triggering a given status are based on examples of precursory activity to volcanic eruptions elsewhere in the world and on activity within Long Valley caldera recorded during the last decade. We have no record of the nature of the activity that preceded previous eruptions from the Long Valley-Mono Craters (LVC/MC) system (the most recent of which occurred 500-600 years ago) and have not attempted to calculate probabilities that the activity associated with a given STATUS will lead to an eruption.

Under this plan, response activities for STATUS E (weak unrest), STATUS D (moderate unrest), and STATUS C (strong unrest) involve information calls to scientists and officials within the USGS and to the California Office of Emergency Services (OES) and U.S. Forest Service regarding the nature of the activity and the associated STATUS. OES will in turn relay this information to officials in Mono and Inyo counties and the town of Mammoth Lakes. Response activities for STATUS B (intense unrest) and STATUS A (eruption likely) require the commitment of resources and personell, and we will use the term ALERT with these two levels. A B-LEVEL ALERT (intense unrest) will trigger an EVENT RESPONSE, which includes 1) an expanded call-down to all agencies affected, 2) establishment of a field center at the Fire Station in Mammoth Lakes for intensified local monitoring and observation, and 3) assignment of authority to the USGS Chief Scientist for LVC/MC to direct all USGS personnel engaged in the response. An A-LEVEL ALERT will be triggered when the geophysical activity indicates that an eruption may break out within a few hours to days. Notification of an A-LEVEL ALERT will be communicated to affected agencies through the expanded call-down used for the B-LEVEL ALERT, and an A-LEVEL ALERT will initiate the process for a formal GEOLOGIC HAZARD WARNING from the Director of the USGS. Stand-down criteria for each status specify a schedule for terminating an status after activity in the area has fallen below the status threshold.

I. INTRODUCTION

Long Valley caldera and the Mono-Inyo volcanic chain in eastern California form one of several geologically youthful volcanic systems in California that pose potential hazards to nearby population centers from future volcanic eruptions (Miller, 1989). The recurring earthquake swarms and episodes of ground uplift that dominated the geologic unrest in Long Valley caldera through the 1980's emphasize that the magmatic system beneath this large silicic system is still active and capable of producing renewed volcanic eruptions (Hill and others, 1985a,b; Rundle and Hill, 1989: Bailey and Hill, 1990). This document describes the U.S. Geological Survey's response plans to future episodes of unrest and onset of possible volcanic activity in the vicinity of the caldera and the Mono-Inyo volcanic chain based on results from geophysical monitoring networks in the region since 1980 and on premonitory activity observed before volcanic eruptions elsewhere in the world. It updates and supersedes Open-File Report 84-500 (U.S. Geological Survey, 1984).

Sections III and IV form the core of this document. Section III defines five response statuses tied to successively more intense levels of geologic unrest detected on networks that monitor seismic activity, ground deformation, and stress-induced variations in the magnetic field intensity. Section IV describes the U.S. Geological Survey's response to these activity levels. The five-level STATUS ranking (Table 1) is modeled after that developed for the Parkfield earthquake prediction experiment (Bakun and others, 1987). This system has the advantage that it has been in use for several years and its basic structure is familiar to both USGS officials and the California Office of Emergency Services (OES).

The status ranking is based on the sort of activity that we expect to see PRIOR TO THE ONSET OF A VOLCANIC ERUPTION. Once initiated, volcanic eruptions commonly show a wide range of behaviors with multiple eruptive phases that may play out over months to years. Should an eruption eventually develop in the Long Valley caldera region, it will almost certainly be necessary to adjust the STATUS criteria (or establish a new set of criteria) tailored to the location and nature of the eruption as it evolves in time (and perhaps location).

A principal objective of this document is to improve communication of the significance of scientific information derived from monitoring measurements to local, state, and federal officials. Specifically, the status ranking described in Section IV provides a graded measure of our concern about the possibility that a given level of unrest might threaten local communities with a volcanic eruption. This status ranking thus offers civil authorities a framework they can use to gauge and coordinate their response to a developing geologic crisis. Effective communication and coordination are particularly important because the U.S. Geological Survey has neither the authority nor the expertise to determine the civil response to an evolving crisis.

Note: Readers wishing to skip the technical and scientific details in this document can focus on the SUMMARY, the first four paragraphs and the final paragraph under STATUS THRESHOLDS (SECTION III), and SECTION IV on ORGANIZATION AND RESPONSE.

II. BACKGROUND

GEOLOGIC SETTING

Long Valley caldera, located in east-central California, is a 15- by 30- km elliptically-shaped depression at the base of a left-stepping offset in the eastern escarpment of the Sierra Nevada range. The Mono-Inyo Craters form a 40-km long chain of rhyolitic volcanic centers that extends northward from the west central section of the caldera to the south shore of Mono Lake. The adjacent eastern escarpment of the Sierra Nevada, which is dominated by large, east-dipping normal faults, forms the western margin of the extensional Basin and Range province (Figure 1).

The region of eastern California that includes Long Valley caldera has been a persistent source of volcanic activity throughout much of its geologic history. As described by Bailey and others (1976), the most recent episode of volcanism began about 3 million years (my) ago with wide-spread eruptions of intermediate and basaltic lavas accompanying the onset of large-scale normal faulting and formation of the eastern front of the Sierra Nevada. Beginning about 2 my ago, multiple rhyolitic eruptions from vents along the northeast rim of the present-day caldera formed the Glass Mountain complex. Long Valley caldera was formed about 730,000 years ago with the catastrophic eruption of more than 600 km^3 of rhyolitic lavas (the Bishop tuff) accompanied by subsidence of an elliptically-shaped crustal block 1 to 2 km into the partially evacuated magma chamber. Smaller eruptions from the residual magma chamber accompanied uplift of the west-central section of the caldera over the next 100,000 yrs to form the resurgent dome. Subsequent eruptions of rhyolite lavas from the residual magma chamber occurred around the margin of the resurgent dome at 500,000, 300,000, and 100,000 years ago (Bailey and others, 1976; Bailey, 1989: Bailey and Hill, 1990).

Between about 220,000 and 50,000 years ago, basaltic and rhyodacitic lavas erupted from widespread vents in the west moat of the caldera. During this same interval, repeated rhyodacitic eruptions from a tightly clustered group of vents on the southwestern rim of the caldera produced the domes and flows that form Mammoth Mountain (Bailey, 1989).

The latest eruptions in the region occurred along the Mono-Inyo Craters volcanic chain. Rhyolitic eruptions began along this chain about 40,000 years ago and have continued through recent times with eruptions along the north end of the Mono Craters about 600 years ago (Bursik and Sieh, 1989) and along the south end of the Inyo Craters (Miller, 1985) about 550 years ago. In both cases, the eruptions resulted from the intrusion of an 8-10 km-long, north-striking feeder dike into the shallow crust that vented several places along strike. Intrusion of a shallow crypto-dome beneath Mono Lake 100 to 200 years ago uplifted the lake bottom-sediments to form Pahoa Island (Lajoie, 1968; Stine, 1989).

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RECENT UNREST

Historically, the crust immediately south of Long Valley caldera has been one of the most persistent sources of moderate (magnitude 5-6) earthquakes in California (Ryall and Ryall, 1980; Hill and others, 1990). From 1910 through 1970, for example, some 20 magnitude (M) = 5-6 earthquakes occurred within 40 km of the south margin of Long Valley caldera including a cluster of four $M \geq 5$ events and one $M = 6$ event in 1941 near Tom's Place approximately 10 km southeast of the caldera (Cramer and Toppazada, 1980). None of the earthquakes during the 1910-1970 interval were located within the caldera, however.

Figure 2 shows earthquake epicenters in the region associated with the episode of heightened seismic activity from 1978 through 1986. Earthquakes of $M = 3–4$ began occurring intermittently within the south moat of the caldera in the months following a M=5.8 earthquake on October 4, 1978, located beneath Wheeler Crest midway between Mammoth Lakes and Bishop (15 km southeast of the caldera). This activity culminated in three $M \approx 6$ earthquakes on May 25, 1980. The first of these events was located just inside the south margin of the caldera, the second beneath the south moat (near Casa Diablo Hot Springs), and the third within the Sierra Nevada block about 5 km south of the caldera. Aftershocks continued to shake the region, and on May 27 the Director of the U.S. Geological Survey announced a Hazard Watch (see Appendix A) for additional potentially damaging earthquakes in the region. A fourth $M = 6$ earthquake struck an area about 10 km south of the caldera later that day (Hill and others, 1985).

Leveling and trilateration measurements completed in 1980 showed that the central section of the caldera (the resurgent dome) had been uplifted by 25 cm between the fall of 1979 and the summer of 1980 (Savage and Clark, 1982). Swarms of $M = 3–4$ earthquakes continued to occur in the south moat of the caldera through 1982. Concerns raised by these persistent earthquake swarms and inflation of the resurgent dome, together with new fumarolic activity in the Casa Diablo area at the southwestern margin of the resurgent dome in January 1982, prompted the Director of the U.S. Geological Survey to issue a Notice of Potential Volcanic Hazards (Appendix A) on May 25, 1982. Strong reaction to this Hazards Notice within the local community, the news media, federal, state, and local agencies overshadowed the relatively modest earthquake swarm activity that persisted within the caldera through remainder of 1982 (Hill and others, 1985; Mader and others, 1987).

On January 7, 1983, an intense earthquake swarm that included two $M = 5.3$ earthquakes and a multitude of smaller events began in the south moat. This swarm was accompanied by an additional 7 cm uplift of the resurgent dome and the possible intrusion of a thin dike to within 4 km of the surface beneath the south moat (Savage and Cockerham, 1984). The January 1983 swarm gradually subsided over the next several months and was followed by occasional smaller swarms through the remainder of 1983 and the next half of 1984. The Notice of Potential Volcanic Hazard issued in May 1982 was withdrawn de facto on September 30, 1983, when the U.S. Geological Survey changed its formal hazard notification terminology from the three-level Notice-Watch-Warning system to a single-level Hazard Warning system (Appendix A; Mader and others, 1987).

Following a swarm just west of the Highway 203-395 junction during the last half of July 1984, which included a $M = 3.6$ and $M = 3.2$ earthquake plus hundreds of smaller events, activity within the caldera declined to a relatively low level that persisted through 1989 with only a few $M \approx 3$ events and minor swarms. Regional activity continued, however, with a $M = 5.8$ earthquake in Round Valley 20 km southeast of the caldera on November 23, 1984, and a $M = 6.4$ earthquake in Chalfant Valley 30 km east of the caldera on July 21, 1986. Both earthquakes were followed by prolonged aftershock sequences. The Chalfant earthquake sequence was particularly intense (Cockerham and Corbet, 1987; Smith and Priestly, 1988); it was preceded by pronounced foreshock activity and included three $M \approx 6$ earthquakes.

Frequent laser-ranging measurements using the two-color geodimeter within the caldera and annual leveling and trilateration surveys showed that the resurgent dome continued to inflate at a relatively slow but steady strain rate of about 1 microstrain per year from 1984 through late 1989. The cumulative uplift over the central part of the resurgent dome from 1980 through mid-1989 exceeded 50 cm (Langbein, 1989; Savage, 1989).

In early May 1989, a swarm of small earthquakes began under Mammoth Mountain on the southwest rim of the caldera and persisted to the end of the year. This swarm appears to have been associated with a dike-like (tabular shape with a vertical orientation) intrusion at depths between 6 to 10 km beneath Mammoth Mountain (Hill and others, 1990). It was accompanied by minor deformation (approximately 1 cm of uplift) and included four $M = 3$ earthquakes in addition to thousands of smaller earthquakes and frequent spasmodic bursts (see Appendix B).

Beginning in late September 1989, measurements with the two-color geodimeter showed that the extension rate across the resurgent dome increased rather abruptly to between 2-5 cm per year. The initial ten-fold increase in strain rate (to 5-10 microstrain per year) has gradually slowed to less than 3 microstrain per year as we complete this document in early 1991. Swarm activity began picking up in the south moat in mid-December 1989 as the Mammoth Mountain activity waned. This renewed south moat activity had much the same spatial distribution as the 1981-84 swarms, although only a handful of events have exceeded $M = 3$ through mid-1990. The swarms centered just west of the Highway 203-395 junction in late February and early March 1990 reached 100 to 300 $M \geq 0.5$ events per day. These are the highest seismicity rates within the caldera since the swarms of 1983-84.

CHARACTER OF POSSIBLE ERUPTIVE ACTIVITY

Future eruptions are most likely to consist of the types and scales of eruptive activities that have occurred in the past in the Long Valley-Mono Craters region. Eruptions within the last 50,000 years in the region include explosive eruptions of rhyolitic and rhyodacitc (silicic) lavas like those that formed the Mono Craters and Inyo Domes 500 to 600 years ago (Bailey, 1989; Miller, 1985). Such eruptions produced ashfalls, pyroclastic flows and surges of small to large volume, and relatively nonexplosive eruption of silicic lava domes and flows (Miller and others, 1982; Miller, 1989). Some eruptions within the last 50,000 years have also been relatively nonexplosive and produced lava flows and cinder cones of basaltic (mafic) composition such as the several-thousand-year-old Red Cones south of Mammoth Mountain. If magmatic eruptions were to occur, we should expect to see one or the other of these eruptive types but not both. The geologic record suggests that silicic eruptions are somewhat more likely than mafic ones. Both silicic and mafic eruptions are likely to be preceded by phreatic eruptions similar to those that formed the Inyo Craters. Such eruptions often occur when magma comes sufficiently close to the surface to produce steam blasts in the shallow ground water without the magma itself actually reaching the surface.

Specific effects of future eruptions in the Long Valley-Mono Craters area will depend upon the composition and volume of magma erupted as well as the location(s) of eruptive vent(s). Although patterns of seismic activity and ground deformation may provide clues to the locations of the eruptive vents shortly before magma reaches the surface, monitoring data will provide no information on either the composition or volume of an impending eruption.

Eruptions of Ryrolitic (Silicic) Magma

Explosive eruptions of rhyolitic lava could range in volume from small to moderate like those that formed the Inyo and Mono Domes (Miller, 1982, p. 7,8), to much larger (but less likely) volumes like those that formed Mammoth Mountain and the Mammoth Knolls north of Mammoth Lakes. During their initial explosive phases, the larger of these eruptions typically produced large volumes of coarse pumice deposited as a thick blanket of tephra over a wide region as well as destructive pyroclastic flows and surges capable of causing severe damage to distances of at least 20 km from a vent. The late phases of such eruptions produced steep-sided lava flows and domes.

Eruptions of Basaltic (Mafic) Magma

Lava fountains typical of basaltic eruptions would scatter ash and coarser material over the region and spawn lava flows that would flow downhill from the vent at relatively slow speeds (tens of meters/hr to a few km/hr). Significant accumulations of tephra could develop within 10 km of the vent. These accumulations would be thickest near and directly downwind from the vent. Basaltic flows could extend several km downslope from their vents.

Miller and others (1982) and Miller (1989) provide a more extensive discussion of potential hazards from future eruptions, details about the nature and effects of hazardous volcanic processes, and volcanic-hazard zonation maps for the Long Valley-Mono Craters region.

III. STATUS THRESHOLDS

The status thresholds specified here for activity in Long Valley caldera follow the five-level, lettered system developed for the Parkfield earthquake prediction experiment (Bakun and others, 1987). N is the "normal", or background level, and an increase in status from E through A correspond to an increasing threat that activity will culminate in an eruption. STATUS A (an A-LEVEL ALERT) indicates the strong possibility that the activity will culminate in an eruption within hours to a week or so and will initiate a GEOLOGIC HAZARD WARNING (see Appendix A).

Because the most recent eruptions in the region occurred 500 to 600 yrs ago, no historic or instrumental records exist for the specific patterns of precursory activity that preceded previous eruptions in Long Valley caldera or along the Mono-Inyo volcanic chain. Accordingly, the activity level specified below for each status is based on a combination of patterns for premonitory activity to eruptions of well-monitored volcanoes elsewhere in the world (see Decker, 1989; Newhall and Dzurisin, 1989; McClelland and others, 1989) and on the multiple episodes of unrest in Long Valley caldera that followed the four $M = 6$ earthquakes in May 1980. Although we lack the statistical basis for calculating reliable probabilities that a specific activity level will culminate in an eruption within a specified time interval, we recognize the importance of establishing meaningful probability estimates for each status and will attempt to make them as sufficient data are available. In the meantime, the USGS will use the status ranking listed in Table 1 to guide its response to future episodes of unrest within Long Valley caldera and along the Mono-Inyo volcanic chain.

Prompt recognition of changes in activity and rapid assessment of these changes in terms of status requires a continuous stream of reliable data that is available in real time. The instrumentation networks currently operating in Long Valley caldera that fulfills this monitoring requirement are summarized in Appendix C. They include a telemetered seismic network, four telemetered strain-monitoring networks, and a geodetic network that is measured several times a week. Regional geodetic networks (leveling, trilateration, and GPS) are normally measured just once a year, and they will generally not contribute to the assessment of rapidly developing activity in terms of a specific status. In the case of intense activity, however, field crews may be mobilized to measure critical parts of these networks on a frequent basis to help better define the areal extent, magnitude, and rate of the associated ground deformation. (See Hill, 1984, and Sorey and others, 1989, for a description of more experimental monitoring networks for gravity, hydrological, and geochemical data that are measured at infrequent or irregular intervals.)

The following sections describe minimum geophysical activity levels that will trigger a specific status for the monitoring networks described in Tables 2, 5, and 6 as well as rules in Table 8 for combining individual statuses (lower case letters) to obtain a summary STATUS (upper case letters). (See Appendix C for a summary of the monitoring networks.)

It is important to realize that the activity specified for each status in the following tables serves as a guideline only. In particular, these tables should not be viewed as a rigid, infallible recipe (algorithm) that invariably leads to the appropriate response. PERSONAL JUDGMENT WILL INEVITABLY PLAY A CRITICAL ROLE IN DECIDING OR CHANGING STATUS. Two issues deserve special emphasis in this regard:

1) Because we have yet to witness an eruption in Long Valley caldera or along the Mono-Inyo volcanic chain, we probably have not anticipated all significant variations in activity patterns that might precede an eruption. We must be prepared to incorporate unexpected variations in activity within the status ranking in the future.

2) Numbers for activity rates, magnitudes, etc. associated with each status suggest only approximate activity levels. Initial estimates of earthquake magnitudes, for example, may be uncertain by a quarter of a magnitude unit, and adverse conditions (high winds, noisy telemetry, dead stations, etc.) may reduce the activity rate reported by the real-time processor by 10-20% or more. Furthermore, instrument problems may cause drift, which could initially be interpreted as deformation.

The final paragraph of this section defines the nominal stand-down criteria for each STATUS.

SEISMICITY

In its current configuration (Appendix C), the seismic network operating in the Long Valley region detects and locates essentially all magnitude 1 and greater ($M \geq 1$) earthquakes occurring within and adjacent to the caldera and a large fraction of the $M \geq 0.5$ earthquakes. It does somewhat more poorly, however, along the Inyo-Mono Craters chain as the network is less dense to the north (see Figures C1 and C2). The signals from the seismometers in the field are telemetered to computers at USGS headquarters in Menlo Park that are programmed to automatically identify and locate the earthquakes within minutes of their occurrence. This Real Time Processing (RTP) system rings a paging system alerting seismologist on duty when the seismicity rate in the Long Valley caldera region exceeds 20 events per hour and/or when a $M \geq 3$ earthquake occurs in the region (a seismic *status e;* see Table 2).

During particularly intense swarm activity, the RTP system cannot discriminate all individual events and thus underestimates the seismicity rate for all magnitude intervals. In this case, we will look to the average amplitude levels calculated by the RSAM (Real-time Seismic Amplitude Measurement) system (plus the records from more distant stations) to help judge changes in swarm intensity. The RSAM system provides a continuous measure of the signal level for selected seismic stations averaged over a ten-minute window (Murray and Endo, 1989).

Table 2 specifies the minimum seismic activity levels that will trigger a specific seismic status. Had this status ranking been in effect during the 1980's, we would have reached *c status* several times between mid 1980 and mid 1982 during the swarms in the south moat that included at least one $M \approx 4$ earthquake. We would also have reached a *c status* during the May-December, 1989 Mammoth Mountain swarm (Hill and others, 1990) and the January-March 1990 swarm beneath the south moat, both of which had high seismicity rates that persisted for days at a time. In retrospect, the sequence of four $M = 6$ earthquakes on May 25-27, 1980 would have triggered a *b-alert* as would the January 1983 swarm, which included two $M = 5.3$ earthquakes (Savage and Cockerham, 1983). No level of seismicity in the caldera through early 1990, however, would have placed us at an *a-alert* for seismicity.

An *a-level alert* for seismicity requires persistent harmonic tremor or swarms of earthquakes with a distinctly "volcanic" appearance characterized by a pronounced absence of high-frequency energy (see Appendix B for examples of "volcanic" and "tectonic" earthquakes). High rates of tectonic or volcano-tectonic earthquakes alone are not sufficient for an *a alert* Although seismicity rates typically exceed hundreds of detected events per hour (and commonly tens of $M \geq 3$ events per day) in the hours to days prior to an eruption, activity at volcanoes elsewhere in the world with comparable or even greater rates has occurred in swarms not followed by eruptions (see Table 3).

Swarms of earthquakes resembling LP (long period) volcanic earthquakes and harmonic tremor (see Appendix B) appear to be the most robust *seismic* indicator of impending volcanic activity. The onset of swarms of LP volcanic earthquakes, for example, preceded the eruptions of Mount St. Helens, Nevado del Ruiz, and Mount Redoubt by 10 to 36 hours (Chouet and others, 1990; Swanson and others, 1983; Harlow, 1986; Gil Cruz and others, 1987).

We have recorded a number of isolated earthquakes in Long Valley caldera that are deficient in high-frequency energy compared to tectonic earthquakes, but we have yet to find any events that closely resemble the LP volcanic earthquakes illustrated in Appendix B. Nor have such events been identified in either the Phlegrean Fields (Italy) or Rabaul (Papua New Guinea) calderas. Each of these calderas has shown strong earthquake swarm activity and ground uplift (tumescence) ranging from 0.5 to 3 m during the last decade but, to date, none of this activity has culminated in volcanic eruption.

DEFORMATION

Most volcanic eruptions are preceded by pronounced ground deformation in response to increasing pressures within shallow crustal magma chambers or subsurface displacements produced by the upward intrusion of magma into the shallow crust. The deformation may be minimal for volcanoes that erupt frequently from an established conduit system. In most well-documented cases of eruptions from volcanic systems that have been in repose for several decades or more, however, ground deformation prior to the eruption is pronounced and generally increases in both rate and magnitude prior to the outbreak of an eruption (Newhall and Dzurisin, 1989).

Documented surface displacements prior to volcanic eruptions commonly range from tens of cm to several m, and the associated strains may range from tens to several hundred ppm (see Table 4). As with other precursory phenomena, however, pronounced ground deformation does not inevitably lead to a volcanic eruption. Many magmatic intrusions into the shallow crust, for example, stop short of reaching the surface. The dramatic uplifts of 2-3 m within the last decade documented for both Rabaul caldera in Papua New Guinea and the Phlegrean Fields caldera in Italy emphasize this point (Table 4). Unfortunately, it is extremely difficult to determine whether a magmatic intrusion in progress has sufficient energy to reach the surface.

The status ranking for deformation in Tables 5 and 6 is based on both deformation (or strain) rates and total deformation. We rely principally on telemetered data from the continuous strain instruments (Table 5) for information on short-term (1 week or less) strain rates and on geodetic measurements with the two-color geodimeter (Table 6) for long-term strain rates and cumulative deformation.

Continuous Strain

Continuous strain status ranking in Table 5 is keyed to strain rates on the basis that: 1) the more rapid the pressure build-up or intrusion rate, the shorter the time to a critical strain state and possible eruption, and 2) surface deformation rates increase as an intrusion approaches the surface at a constant rate. Documented strain rates prior to eruptions vary considerably (Table 4), and we have rather arbitrarily set the threshold for an *a-level alert* at the relatively high strain rate of 10 ppm/day for the Long Valley caldera region. In addition, we require that this high strain rate be corroborated on several instruments to minimize the chances of being misled by an instrument malfunction. Because the borehole tiltmeters operate against a higher background noise level than either the dilatometers or the long base tiltmeter, they are not reliable for strain rates below about 5 ppm/week (or roughly 1 ppm/day) and thus are not included in the criteria for statuses *e* through *c* in Table 5.

Short-term strain changes of 0.05 ppm/hour *(status e)* or 0.1 ppm/day *(status d)* detected by either the POPA or PLV1 dilatometers will trigger a paging system to alert scientists of the possibility of a rapidly developing deformation crisis or instrument problems. Had the status criteria in Table 5 been in effect from the time the dilatometer (POPA) became operational in mid-1984, *status d* for strain would have been triggered only twice. The first occurred about a month before the July 21, 1986, Chalfant Valley earthquake ($M = 6.4$ and located 50 km east of POPA), and the second occurred during the last week in April, 1989, just prior to the Mammoth Mountain earthquake swarm (Hill and others, 1990). Theoretical calculations by Mortensen and Hopkins (1987) indicate that deformation associated with the January 1983 earthquake swarm would have resulted in a *b-level alert* for strain had the tiltmeter network been operational at the time.

Geodetic Strain

The status ranking for geodetic strain in Table 6a is based primarily on measurements of the CASA two-color geodimeter network, which, weather permitting, are repeated two to three times a week. In the case of intense activity and a B- or A-LEVEL ALERT, we will consider mobilizing field crews to measure sections of the regional geodetic networks (Appendix C) on a frequent basis and incorporating these results in Table 6a as well. The strain changes in Table 6a are given in 10-day intervals, the minimum interval for which strain rates are meaningful for the routine measurement schedule of the two-color geodimeter. Note that the 10-day geodetic strain changes for a given status in Table 6a correspond to the 1-day rates for the dilatometers in Table 5. The geodetic criteria also include the possibility that modest strain rates sustained for a sufficiently long time can result in large cumulative strains and a higher status than appropriate for the underlying strain rate (rocks commonly fail at cumulative strains on the order of 100 ppm, or 1×10^{-4}).

If strain rates exceed 1 ppm per day and a B-LEVEL ALERT (EVENT RESPONSE in Table 1) is in effect, we will consider substituting a standard (one-color) geodimeter for the two-color instrument to track the higher strain rates. Under these circumstances, the 0.1 ppm precision of the two-color instrument becomes less important than the ability of standard geodimeters to continuously track line length changes that exceed 2.5 cm between successive measurements.

Strain measured on three lines of the CASA two-color network averaged just over 0.5 ppm/10 day during the episode of accelerated inflation of the resurgent dome from late September 1989 through early March 1990. Had these criteria been in effect, we would have had a *status d* for geodetic strain sustained for nearly 5 months. As indicated in the following section, however, a *status d* for geodetic strain by itself is not sufficient to trigger a combined STATUS D.

DIFFERENTIAL MAGNETIC FIELD

The differential magnetic field network (Appendix C) is designed to detect small changes in the local magnetic field induced by stress changes in the shallow crust (a change of 1 nT roughly corresponds to a stress change of several bars). Accordingly, changes in the magnetic field detected by this network should show a general correlation with local deformation of the crust. A change in the magnetic field greater than 1 nT over times ranging from a day to several months detected on at least one instrument will trigger a *status d* for the differential magnetic field (Table 7). We have observed only one such change since the network became operational in 1984. The station SBFM (Figure 4) showed a 2 nT change from mid-1989 to mid-1990 generally coincident with an increase in the extension rate across the caldera measured by the two-color geodimenter network and an increase in earthquake swarm activity in the south moat of the caldera during the first quarter of 1990.

ADDITIONAL PHENOMENA

Additional phenomena not monitored by existing networks or instrument systems may influence decisions on appropriate STATUS, particularly at the B- and A-LEVEL during episodes of intense activity. The most important of these include:

[1] Pronounced ground cracking with displacements across individual cracks of a few cm or more and increasing. Distributed sets of tension cracks and/or slip on opposing sets of normal faults bounding a graben commonly develop as magma approaches the surface prior to volcanic eruption.

[2] Development of new fumaroles and/or hot springs or a vigorous increase in the output from several existing fumaroles and/or hot springs.

[3] Pronounced increase or onset of SO_2 (sulfer dioxide) from existing fumaroles or newly developed cracks. Magma releases a variety of gasses as it approaches the surface; SO_2 is the easiest to detect of these diagnostic gasses. Increases in helium isotope ratios ($^3He/^4He$) may also accompany magmatic intrusion.

Confirmed observations of these phenomena could well prove decisive in moving to an A-LEVEL ALERT in cases when the criteria from the monitoring networks (Tables 2, 5, 6, 7, and 8) indicate the upper range of a B-LEVEL ALERT or a marginal A-LEVEL ALERT. Clear, well-documented changes in gravity, hot spring chemistry, gas chemistry, or other parameters for which sparse but reliable baseline data exist (see Hill, 1984), may also influence a decision on moving to the next higher STATUS in cases when criteria for the monitoring networks indicate only marginal support for the higher STATUS. Coherent changes in several of these parameters would carry considerably more weight than would a strong change in a single parameter.

COMBINED STATUS

Table 8 specifies the way in which we will combine the statuses for individual monitoring networks (lower-case letters) to arrive at a COMBINED STATUS (upper-case letters in Table 1). Table 8 provides a means of weighting the relative significance of the activity detected by individual monitoring networks in judging the overall significance of an episode of unrest in the caldera or along the Mono-Inyo volcanic chain. A dash (-) in this table means any level a through e.

Using the combination rules in Table 8, for example, we could in principle reach combined LEVEL-A ALERT on the basis of seismic activity alone. While it seems unlikely that we would reach an *a-level alert* for seismicity without strong, local deformation (comparable to at least a *b-level alert* for either continuous strain or the geodetic network), we have explicitly included this possibility for two reasons: 1) intense swarms of LP events and/or sustained harmonic tremor are strong indicators of an impending eruption, and 2) most of the Mono-Inyo crater chain lies beyond the range of the closely monitored deformation networks. We can also reach an A-LEVEL ALERT with clear *b-level alerts* on the seismic, continuous strain, and geodetic networks, or *a-level alerts* on either the continuous strain or the geodetic networks plus an *a-level alert* on the magnetic network. Similar patterns apply for lower statuses.

STAND-DOWN CRITERIA

Since the onset of episodic activity in Long Valley caldera in 1980, each of the unrest episodes has eventually declined to a "normal" (N) level of background activity. We expect that most future episodes of unrest will do the same. Table 9 specifies the criteria for standing down from a given status after the activity triggering the STATUS has fallen below the STATUS threshold.

These stand-down criteria specify a minimum time interval that a given STATUS will remain in effect after activity triggering the STATUS has fallen below the threshold for the STATUS. At the end of this time interval, the STATUS will automatically drop to the next lower level consistent with any ongoing activity unless explicitly extended by the Chief Scientist for Long Valley monitoring. Thus, a C STATUS would remain in effect for 3 days after the activity triggering the STATUS fell below the C STATUS threshold. At the end of 3 days, the STATUS would drop to whatever level was appropriate for any ongoing activity (including an N STATUS in the case of normal or background activity).

The stand down criteria for A- and B-LEVEL ALERTS deserve special comment. The intense activity that triggers a B-LEVEL ALERT also triggers an EVENT RESPONSE and an intensive field monitoring effort within the caldera (Section V). We will continue intensive field monitoring for two weeks after the activity falls below the B-ALERT criteria to insure continuity of field data and to minimize remobilization costs in case the drop in activity is only a temporary lull. In many cases, a temporary quiescence interrupts the unrest leading to an eruption just prior to the initial outbreak of the eruption. This premonitory quiescence, when it occurs, commonly lasts a few hours to a few days (Shimozuru and Kagiyama, 1989). Accordingly we will normally extend an A-LEVEL ALERT for one week beyond the time activity drops below the A-level threshold and then drop to a B-LEVEL ALERT and continue intensive field monitoring for a second week. If the activity has remained at a level consistently below the B-LEVEL threshold for the entire two-week period, we will drop the STATUS to that appropriate for any continuing activity.

IV. ORGANIZATION AND RESPONSE

This section describes the U.S. Geological Survey organizational structure for response to activity in the Long Valley caldera-Mono Craters (LVC/MC) region as initially specified in USGS Open-File Report 84-500 (1984) and modified to incorporate the STATUS RANKING defined in Table 1.

Figure 3 illustrates the organizational structure for USGS response to activity in the Long Valley-Mono Craters area. The role of this organization depends on the STATUS in effect. Under B- or A-LEVEL ALERTS and an EVENT RESPONSE (see Figure 4), this organization derives authority from the USGS Director through the Chief of the Office of Earthquakes, Volcanoes, and Engineering (OEVE) to direct all USGS activities concerning the response. During periods of normal activity or STATUS E through C, the organization has the role of coordinating monitoring, hazard assessment, and public information activities in the Long Valley caldera-Mono Craters area as they are carried out under normal USGS management channels.

ORGANIZATIONAL STRUCTURE

Chief, Office of Earthquakes, Volcanoes, and Engineering

The Chief, Office of Earthquakes, Volcanoes, and Engineering (OEVE) has overall responsibility under both routine and EVENT RESPONSE conditions for monitoring, hazards assessment, and all operations relating to volcanic and earthquake hazards in the LVC/MC area (Figure 1). The Office Chief is responsible for ensuring that accurate summaries of geologic, monitoring, and hazards information are prepared and transmitted as frequently as conditions require to the Chief Geologist, the Assistant Director for Engineering Geology, and the Director, as well as to the California Division of Mines and Geology and the California Office of Emergency Services. He is also responsible for ensuring that policies and instructions of the Chief Geologist and Director are transmitted to, and followed by, personnel under his direction. He or she is assisted, as necessary, by the Coordinator of the Volcano Hazards Program.

Chief Scientist, LVC/MC

During periods of routine activity, the Chief Scientist for LVC/MC acts as a coordinator and works through the appropriate line managers to coordinate monitoring, hazards assessment, and information dissemination for the LVC/MC area. He or she ensures that the USGS is in an appropriate state of readiness for a timely response at LVC/MC. He or she ensures that monitoring and hazards assessment are conducted efficiently, effectively, and thoroughly, and that USGS activities in the LVC/MC area are summarized in the form of monthly or other periodic and interim reports and distributed in a timely manner. The Chief Scientist also ensures that the monitoring and hazards data are adequately analyzed and periodically reviewed. This review process should include periodic meetings of all monitoring and hazards assessment personnel, as well as meetings and discussions with the Scientific Advisory Team, relevant USGS managers, and the three Team leaders (see Figure 3), as appropriate. The Chief

Scientist is responsible for ensuring that accurate and timely hazards assessments and supporting scientific information are issued to all concerned parties, including local, state, and Federal officials and the public.

When activity at LVC/MC becomes sufficiently intense to prompt the declaration of EVENT RESPONSE conditions by the Chief of OEVE, the Chief Scientist initiates establishment of a field center and ensures that all relevant monitoring, hazards, and support personnel are rapidly mobilized and dispatched to that field center. Under these Event Response Conditions, the Chief Scientist has full authority to direct all USGS personnel engaged in the response, wherever physically or organizationally located, and to call upon the resources of all USGS units assigned to and necessary for monitoring, hazards assessment, and support activities (see Response and General Operational Procedures below).

Team Leaders

To assist the Chief Scientist are three Team Leaders: Monitoring Team Leader, Hazards Assessment Team Leader, and Support Team Leader. During routine activity, these Team Leaders act as coordinators for their respective functions and work through normal management channels while assisting the Chief Scientist to accomplish his or her goals. Under EVENT RESPONSE conditions, however, these Team Leaders report directly to the Chief Scientist and, through him or her, have full authority to issue instructions to their respective team members, determine team strategy, and assign necessary personnel to specific tasks.

[1] *Monitoring Team Leader:* The Monitoring Team Leader serves as a consultant and advisor to the Chief Scientist in determining monitoring requirements and in analyzing and interpreting monitoring results. During periods of routine activity, the Monitoring Team Leader maintains an overview of all monitoring activities, in order to ensure that all monitoring networks are maintained and that measurements are carried out thoroughly and with adequate frequency. Under EVENT RESPONSE conditions, the Monitoring Team Leader directs monitoring activities carried out at the LVC/MC area and ensures that the results of all monitoring activities are collected, integrated, analyzed, and made available promptly to the Chief Scientist and the Hazards Assessment Team Leader.

[2] *Hazards Assessment Team Leader:* Under both routine conditions and EVENT RESPONSE conditions, the Hazards Assessment Team Leader prepares hazard assessments based on monitoring and other scientific data. He or she ensures that these assessments are accurate, are based on thorough integration of the current monitoring data, and are prepared in a timely manner. He or she presents and explains these hazards assessments and their scientific basis to local, state, and Federal officials and to the public. Should the Chief Scientist be absent from the field center under EVENT RESPONSE conditions, the Hazards Assessment Team Leader has full authority to act in his behalf.

[3] *Support Team Leader:* Under routine conditions, the Support Team Leader is responsible for ensuring that the support that may be required under EVENT RESPONSE conditions is maintained in an appropriate state of readiness. Under Event Response Conditions, the primary function of the Support Team Leader is to relieve, a much as possible, the Chief Scientist, the Monitoring Team Leader,

the Hazards Assessment Team Leader, and their respective team members of the burdens associated with logistics, liaison with other agencies, and contact with public and press. The Support Team Leader ensures that all resources necessary for monitoring, hazards assessment, and information dissemination are available or are acquired and emplaced as quickly as possible. Such resources include those relating to transportation, communications, procurement, clerical and administrative support, space, accommodations, and public relations. He acts as liason between the Chief Scientist and the California Division of Mines and Geology, the California Office of Emergency Services, local, state, and Federal agencies, and other USGS divisions. He is responsible for the release of information to the public. The Support Team Leader also serves the Chief Scientist as a consultant and advisor, particularly concerning agency and interagency policy and regulations and public relations. The Assistant Chief Geologist, Western Region, normally functions as the Support Team Leader.

Scientific Advisory Team:

This team, selected from recommendations by the Chief Scientist and in consultation with the Chief, OEVE, and appropriate Branch Chiefs, consists of several scientists within and outside the USGS with broad volcanological or geophysical knowledge, or with other special expertise or insight, who individually or collectively can develop an overview of the Long Valley activity and operations. The advisory team provides the Chief Scientist with background information and advice on the interpretation of monitoring, hazards assessment, and other scientific data, on the possible long- or short-term course of the activity, and on monitoring strategy. The team need not be formally assembled during periods of increased activity. When assembled, however, it does not participate directly in the monitoring, hazards assessment, or support activities. Thus the team members are free to provide a calm, objective analysis of an evolving situation without being caught up in the operational responsibilities of the USGS response.

Assistant Chief Scientist, LVC/MC:

When the Chief Scientist is away from Menlo Park, he or she will be represented in Menlo Park by an Assistant Chief Scientist. During periods of routine activity, the Assistant Chief Scientist will act for the Chief Scientist in all matters concerning the LVC/MC area. During periods of increased activity when the Chief Scientist is at the LVC/MC field center, the Assistant Chief Scientist will have full authority, through the Chief Scientist, to direct the monitoring and other activities at Menlo Park and the other permanent USGS centers.

RESPONSE AND GENERAL OPERATIONAL PROCEDURES

The following outlines the general operational procedures and activities for implementation of the USGS LVC/MC Response Plan. The Event Response Structure is diagramed in Figure 3 and 4.

[1] *STATUS C, D, and E. Advisory Calls:* Initial communication of any change in geologic conditions that might possibly increase the level of volcanic hazard will be by a telephone call-down. At the onset of any unusual activity, the seismologist on duty at Menlo Park or the person noting the change in activity will call

the Chief Scientist (or the Assistant Chief Scientist if the Chief Scientist is absent from Menlo Park), who is responsible for the decision to activate the call-down procedure. The Chief Scientist will evaluate the activity and, for STATUS C, D, or E make the appropriate advisory calls (Figure 5).

[2] *ALERT LEVEL B. Declaration of EVENT RESPONSE:* If, upon evaluation of the data and consultation with USGS scientific and management personnel, the Chief Scientist concludes that the activity warrants a B-LEVEL ALERT, he or she will recommend that the Chief, OEVE (or designated deputy), declare EVENT RESPONSE conditions. Such a declaration will activate the establishment of a field center. USGS, local, state, and federal officials will be notified of this decision through the B-level call-down procedure (see Figure 5).

[3] *ALERT LEVEL A AND GEOLOGIC HAZARD WARNING:* If, upon evaluation of the data and consultation with USGS scientific and management personnel, the Chief Scientist concludes that the activity indicates that an eruption is likely to occur within hours to a few days, he or she will, with the concurrence of the Chief of OEVE (or designated deputy), declare an A-LEVEL ALERT and recommend that the Director issue a GEOLOGIC HAZARD WARNING for an imminent volcanic eruption. If a B-LEVEL ALERT is not already in effect, the A-LEVEL ALERT will also trigger an EVENT RESPONSE. Depending on the location of activity and the likely site for the eruption outbreak, the Chief Scientist may, in the interest of personnel safety and continuity of monitoring activities, move the field-operations center from Mammoth Lakes to Bridegport (see [7] below).

[4] *Assignment of EVENT RESPONSE Personnel:* Either in advance of or upon declaration of EVENT RESPONSE Conditions, the Chief, OEVE, or the Chief Scientist, will make arrangements for the assignment of appropriate personnel and other resources from all USGS units. Once these resources are secured, the Chief Scientist has the full authority for assignment of LVC/MC EVENT RESPONSE personnel. Normally, his or her requests for personnel or equipment will be discussed with and relayed through the appropriate supervisor, who must make every effort to supply the resources requested. In the event that a supervisor is not available, the Chief Scientist may contact and assign individuals directly. Should a LVC/MC EVENT RESPONSE situation occur simultaneously with heightened activity elsewhere, conflicting demands for personnel and resources will be resolved, if necessary, by the Chief, OEVE. Once assigned to a LVC/MC EVENT RESPONSE Team, all personnel and equipment fall under the authority of the EVENT RESPONSE structure until released by the Chief Scientist or the Chief of OEVE.

[5] *Establishment of a Field Center:* One or more field centers will be established by the Chief Scientist on declaration of EVENT RESPONSE conditions by the Chief, OEVE. Deployment of personnel and material to the field centers will be on instructions of the Chief Scientist to project personnel, either directly or through appropriate managers. By prearrangement, the Mammoth Lakes Fire Station is the primary field center for USGS operations and communications. Should conditions be deemed too hazardous to establish or maintain a field center at Mammoth Lakes, a secondary Field Center at Bridgeport will be activated. The

field center will serve as (1) a communications center for USGS field operations, (2) a staging center for all monitoring, scientific, hazards assessment, and support activities, and (3) an information center for local, state, and Federal officials. The field center will include at a minimum a radio base station, telephone and telefax communications, a seismograph, a computer terminal, and auxiliary power.

[6] *Field Operations and Communications:* Once EVENT RESPONSE conditions have been established, each person or field party must contact the appropriate Team Leader prior to beginning field activities in the Long Valley region to (1) inform him/her of their field plans, where they will be staying, etc., and (2) receive last minute information on logistics and special arrangements. When operating under EVENT RESPONSE conditions, radio contact is to be maintained with the field center at all times while in the field, and field personnel must be prepared to respond directly to requests and instructions from either the Team Leaders or the Chief Scientist concerning monitoring efforts, hazard assessment, data reporting, safety precautions, and other matters. In addition, one or more representatives from each field party must participate in any coordination or data evaluation meetings called by the Chief Scientist or the respective Team Leaders.

The short-term hazard assessment of an impending volcanic eruption will depend almost exclusively on the quality and timeliness of data generated by the various monitoring efforts and on the ability of personnel to review promptly all monitoring results as they are generated. Therefore, it is essential that the data from each monitoring activity be transmitted through the Monitoring Team Leader to the Chief Scientist and the Hazards Assessment Team Leader as quickly and accurately as possible. While responding to heightened activity, the focus of all monitoring activities must be on the current situation and how it is changing. Everyone involved in monitoring efforts should bear in mind that their own personal safety, as well as that of their colleagues and the public, may depend on how quickly their data are collected, processed, transmitted, and analyzed in conjunction with the data produced by their coworkers.

[7] *Change of Field Centers:* If intense unrest or volcanic activity makes it wise to abandon the Mammoth Lakes Fire Station as a field center, the secondary center will be in Bridgeport at the District Ranger Station, U.S. Forest Service, Toiyabe National Forest, about 50 miles north of Mammoth Lakes. The decision to change field centers is the responsibility of the Chief Scientist; time permitting, the Chief Scientist will consult with the Chief, OEVE. Specific instructions for change of centers will be issued by radio to all field parties at that time.

If possible, duplicate facilities will be established at the Bridgeport field center prior to a change in field centers in order to avoid loss of communications and monitoring capabilities during the changeover.

[8] *Deactivation:* Deactivation of the USGS LVC/MC field center will be determined and announced by the Chief Scientist in consultation with the Chief, OEVE, and the three Team Leaders. Normally, deactivation will coincide with the termination of a B-LEVEL ALERT status (see Table 9). Personnel are not to cease operating from the field center without first notifying their Team Leader of their intentions and receiving his or her permission.

COORDINATION BETWEEN GEOLOGIC AND WATER RESOURCES DIVISION

In the case of an EVENT RESPONSE condition, the Regional Hydrologist, Western Region, will arrange to have members of the Water Resources Division, along with the necessary equipment, assigned to the Event Response Team. Once assigned to the Event Response Team, they will be under the supervision of the Chief Scientist.

In a situation in which assessment of hydrologic hazards becomes a significant component of the Event Response, the Regional Hydrologist, Western Region, will arrange to have a high-level scientist assigned to the Chief Scientist's immediate staff. This individual will have the responsibility for advising the Chief Scientist on potential hydrologic hazards of the situation and the appropriate response. This individual will work with the Chief Scientist and assume supervision of the hydrologic group within the Event Response Team as delegated by the Chief Scientist.

In either situation, the final responsibility for the Survey's response will rest with the Chief Scientist.

APPENDIX A. U.S. Geological Survey Terminology for Geologic Hazard Warnings.

Current Hazard Warning System

An official HAZARD WARNING by the U.S. Geological Survey is defined as follows in the October 11, 1983, issue of the Federal Register (v. 48, n. 197):

GEOLOGIC HAZARD WARNING -- a formal statement by the Director of the U.S. Geological Survey that discusses a specific geologic condition, process, or potential event that poses a significant threat to the public, and for which some timely response would be expected.

This issue of the Federal Register further states that "The term Hazard Warning is reserved for those situations posing a risk greater than normal and warranting considerations of a timely response in order to provide for public safety. Information regarding hazardous conditions that do not meet the criteria for a Hazard Warning may, however, also be sent to public officials as it becomes available. Transmittal of such information would not constitute a Hazard Warning." The criteria for a Geologic Hazard Warning are:

[1] A degree of risk greater than normal for the area; or a hazardous condition that has recently developed or has only been recently recognized; and

[2] A threat that warrants consideration of a near-term public response.

Hazard Warning System Prior to 1983

Prior to October 1983, official statements by the U.S. Geological Survey on geologic hazards were based on the three-level system described in the April 12, 1977, issue of the Federal Register (v. 42., no. 70). The three levels (from lowest to highest) were defined as follows:

NOTICE OF POTENTIAL HAZARD -- 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.

HAZARD WATCH -- information, as it develops from a monitoring program or from observed precursors, that a potentially catastrophic event of a generally predictable magnitude may occur within an indefinite time (possibly months to years).

HAZARD WARNING -- information (prediction) as to the time, location, and magnitude of a potentially disastrous geologic event.

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Official statements by the U.S. Geological Survey on geologic hazards in the Long Valley caldera region issued in May 1980 (HAZARD WATCH for potentially damaging earthquakes) and May 1982 (NOTICE OF POTENTIAL VOLCANIC HAZARD) were based on this three-level system.

APPENDIX B. Definitions and Examples of Seismic Events.

A consensus has yet to be reached in the scientific literature on the classification of seismic events occurring in areas of current or recent volcanism (Crosson, 1987; Chouet, 1988; McNutt, 1989). In this document, we distinguish between 1) events that have the appearance of ordinary tectonic earthquakes with significant energy across the entire 1- to 30 Hz band covered by the local seismograph stations, and 2) events that have a distinctly "low-frequency" appearance characterized by a marked deficiency in energy at frequencies above 5-10 Hz. Earthquakes in the first group result from dominantly brittle processes (ie. shear or tensile failure in solid rock). A number of processes may produce events in the second group, including vigorous movement or vesculation (degassing) of magma or the close interaction of magma with a shallow hydrothermal system (Chouet, 1988).

Events resembling tectonic earthquakes

The vast majority of earthquakes recorded in volcanic areas fall in this category. They result from brittle failure due to differential stresses in solid rock, which radiates seismic energy over a broad frequency range. Whether differential stresses that lead to brittle failure are due to regional tectonic processes (tectonic earthquakes), local magmatic/volcanic processes, or some combination thereof (volcano-tectonic earthquakes), the result is the same: abrupt slip of rock surfaces past one another along a fault plane producing the classic double-couple radiation pattern. In some cases, particularly in volcanic and geothermal areas, brittle failure may involve the abrupt opening of tensile cracks to produce non-double-couple radiation patterns (Julian, 1983; Foulger, 1988). Fluids may trigger brittle failure by, for example, reducing the effective frictional strength across a fault plane through increasing pore pressure, but the fluid phase does not directly contribute to the radiated seismic energy.

Tectonic or volcano-tectonic earthquakes: These earthquakes typically have clear P and S waves with substantial energy at frequencies above 10 Hz (Figure B1a). The source mechanics and elastic radiation from volcano-tectonic earthquakes are indistinguishable from those occurring in purely tectonic regimes.

Spasmodic bursts: Rapid-fire burst of small earthquakes (generally $M < 2$) with overlapping coda (Figure B1b). Spasmodic bursts with durations ranging from tens of seconds to 30 minutes or more accompanied earthquake swarms beneath the south moat in 1982 (Ryall and Ryall, 1983) and the 1989 swarm beneath Mammoth Mountain (Hill and others, 1990). Individual events within a spasmodic burst commonly have the appearance of tectonic earthquakes although the signal level between events may remain above background noise levels well beyond the coda decay times for tectonic earthquakes. Spasmodic bursts rarely, if ever, occur in purely tectonic regimes. Although the process producing spasmodic bursts remains speculative, a likely mechanism involves rapid-fire brittle failure along sub-adjacent fault surfaces driven by a transient increase in fluid pressure (Hill and others, 1990).

Events clearly deficient in high-frequency energy

Earthquakes clearly deficient in high-frequency energy ($f > 5\text{–}10\ Hz$) with respect to tectonic earthquakes of comparable magnitude and location often precede and commonly accompany volcanic eruptions. Unfortunately, the processes responsible for their anomalous "low-frequency" appearance may not always be clear without careful, time-consuming analysis. Here we emphasize two examples of "low-frequency" seismic events that show strong evidence of being closely tied to vigorous magma movement or shallow boiling and degassing: LP (Long Period) volcanic earthquakes and harmonic tremor.

LP (long-period) volcanic earthquakes: LP events form a distinctive class of volcanic earthquakes recognizable by their nearly monochromatic, relatively low-frequency (1-5 Hz) wave-forms that "ring" for many cycles (Figure B2). LP events appear to be closely related to harmonic tremor and presumably result from resonances associated with vigorous fluid motion, which at depths less than 4-5 km, may involve degassing or boiling (Chouet, 1989). We have identified no LP earthquakes in Long Valley caldera to date.

Harmonic (volcanic) tremor: Nearly monochromatic wave-trains with dominant frequencies typically ranging from 1-5 HZ that may persist with relatively steady to strongly fluctuating amplitude levels for minutes to hours (Figure B2). Harmonic tremor accompanies nearly all eruptive activity and commonly precedes it by hours to days. In some cases, harmonic tremor evolves from a sequence of overlapping LP earthquakes pointing to a common source process. We have identified no harmonic tremor in Long Valley caldera to date.

Events intermediate in character.

Earthquakes intermediate in character between broad-band tectonic earthquakes at one extreme and narrow-band LP volcanic earthquakes at the other are common on active volcanoes, and they result from a number of processes. In some cases, for example, tectonic earthquakes produce seismograms with a low-frequency appearance because the high-frequency energy generated at the source is scattered by strong heterogeneities in the crust (commonly true for extremely shallow earthquakes) or attenuated by propagation through a "soft" volume such as a magma body. In other cases, the low-frequency appearance of the seismogram accurately reflects the absence of high-frequency energy in the earthquake source. Such sources may involve failure in relatively soft (hot) rock or perhaps turbulent flow or resonance of fluids within cracks or dikes. We have recorded a number of isolated earthquakes in Long Valley caldera that fall in this intermediate category (Figure B3).

Application to seismic status

A swarm of earthquakes clearly resembling the LP events illustrated in Figure B3 will pose little problem for using the criteria in Table 5 to arrive at a seismic status. The difficulties will arise with the occurrence of a swarm of earthquakes that fall in the grey area with a character somewhere between tectonic and LP events. A degree of personal judgement will inevitably come into play in this case. Isolated occurrences of such events, as we have seen in the past, seem to pose no immediate threat. A swarm of such events, however, may indicate a more vigorous magmatic event than recorded to date. Certainly a high priority must be placed on a prompt and careful analysis of swarm events for their significance. To make an initial assessment of the significance of such a swarm that begins at 3 AM or on a weekend, however, may require a rather subjective judgement on whether the swarm earthquakes more closely resemble tectonic events (Figure B1a) or LP events (Figure B2).

APPENDIX C. Current Monitoring Networks and Instrumentation

This appendix summarizes the instrumentation currently operating in Long Valley caldera that fulfills the monitoring requirement for prompt identification of changes in activity. The telemetered networks provide continuous data on seismicity and deformation for real-time computer processing and analysis. Routine measurements of the two-color geodimeter network provide data on deformation changes on time scales of a week or more. The regional geodetic networks (leveling and GPS) are normally measured just once a year, and they will generally not contribute to rapid evaluation of activity levels. In the case of B- or A-LEVEL ALERTS, however, field crews may be mobilized to measure critical parts of these networks on a frequent basis to help define the areal extent, magnitude, and rate of the associated ground deformation. Each of these networks are summarized below. (See Hill, 1984, and Sorey and others, 1989, for a description of more experimental monitoring networks for gravity, hydrological, and geochemical data that are measured at infrequent or irregular intervals.)

TELEMETERED NETWORKS

Data from the following networks are telemetered to computers in Menlo Park and are available for review and analysis in real time.

SEISMIC NETWORK

Locations of the 18 telemetered seismic stations currently operating in the immediate vicinity of Long Valley caldera are shown in Figure C1, and locations of the 35 stations within 50 km of the caldera with signals telemetered to Menlo Park are shown in Figure C2 and listed in Table C1. Twenty eight of these stations are operated by the U.S. Geological Survey in Menlo Park as part of the central California network, and seven are operated by the University of Nevada at Reno as part of the northern Nevada seismic network.

Seismic stations in this Long Valley network use the same high-gain, short-period instrumentation used in the central California Network (Eaton, 1977). Most of the stations consist of a vertical component seismometer with a free period of 1 s; two (MDPM and MSLM) are two component stations (one vertical and one horizontal seismometers with a N-S orientation). The FM analog signals generated by each station in the network are telemetered by radio or telephone line to both Menlo Park and Reno.

At the USGS headquarters in Menlo Park, the FM data are fed into a dedicated microprocessor-based "Real Time Processing" (RTP) system programmed to discriminate earthquakes from common noise sources (electronic transients, cultural noise, etc.) and to extract P-wave arrival times, first motion polarities, as well as P-wave amplitudes and coda duration information for magnitude estimates (Allen, 1978). This system routinely detects earthquakes as small as $M = 0.0$–0.5 in the caldera and nearly all earthquakes of $M \geq 1.0$. Hypocentral locations and initial magnitude estimates for earthquakes detected by the RTP system are automatically computed and available in an on-line computer file within two to three minutes of an earthquake occurrence.

STRAINMETER (DILATOMETER) NETWORK

Two Sacks-Evertson borehole volumetric strainmeters (dilatometers) are operated in the Long Valley caldera region in a cooperative effort with the Carnegie Institution of Washington. These two dilatometers (POPA and PLV1 in Figure C3) are sampled automatically every 10 minutes and the data are transmitted to Menlo Park via the Geostationary Operational Environmental Satellite (GEOS). Every 10 minutes, the dilatational strain averaged over the last 60 minutes is automatically computed and updated every 10 minutes by an on-line computer in Menlo Park. The raw on-line data are then corrected for earth tides and atmospheric pressure loading, determined from a theoretical earth tide model and an on-site pressure transducer co-located at POPA. Provided the instruments and telemetry are operating properly, changes in strain of 0.2 ppm over several days (long-term) or 0.1 ppm at periods less than a day (short-term) can clearly be detected. Short-term strain changes are detected by an algorithm that identifies strain changes of more than 0.05 ppm in a one-hour period. Long-term strain changes are detected by an algorithm that identifies changes in strain changes greater than 0.1 ppm above estimated background noise in 24-hour period.

WATER WELL

Fluctuations in ground-water level in the water well just south of Lookout Mountain (LKT) in Long Valley caldera (Figure C3, Table C2) are measured every 15 minutes and the data are transmitted every 4 hours via the GOES satellite to computers in Menlo Park. Water-level variations in this well with periods of two weeks or less closely reflect local volume strain in the crust, and thus the information from this well is comparable with that from the dilatometers (Rojstaczer, 1989). The earth tides show up clearly in the well indicating that its sensitivity at periods on the order of days is 0.01 ppm or better.

TILTMETER NETWORK

Data from seven shallow (2-10 m deep) borehole tiltmeter sites and a long-base Michaelson tiltmeter (Figure C3, Table C2) are sampled every 10 minutes and telemetered to Menlo Park at 10 minute intervals via the GEOS satellite. The borehole tiltmeter array is capable of discriminating rapid changes in tilt at the level of 5 to 10 microradians (ppm) occurring within a period of a few days to one week (Mortensen and Hopkins, 1987). The Michaelson long-base tiltmeter, which is operated by Roger Bilham at the University of Colorado, is an L-shaped, water-tube instrument 0.5 km on a side. It has both greater accuracy and stability than the shallow borehole instruments, and is capable of resolving tilt changes on the order of 0.1 microradian over periods of a week. In principal, it has the capability of resolving tilt changes of 1 microradian over a period of years or more (Behr and others, 1989).

Four stills installed around the margin of Lake Crowley to monitor relative variations in lake level permit us to use Lake Crowley as a natural, long-base tiltmeter in the southeast corner of the caldera (Figure C3). Measurements at each of the sites include water pressure at a depth of 35 feet below the 1987 lake level, water temperature at the base of the still, air temperature, wind velocity, and assorted electronic parameters for trouble shooting and data checking. The data are sampled once every 20 minutes and transmitted with satellite digital telemetry through the GEOS weather satellite to USGS headquarters in Menlo Park. This system is capable of resolving differential uplift across the lake as small as 3 mm. Data collected from April 1987 through September 1988 showed a tilt to the southeast of about 0.3 ppm/y consistent with gradual inflation of the resurgent dome documented by the two-color geodimeter and leveling data. Unfortunately, the lake level dropped below the bottom of the stills in late 1988 rendering this system unusable until precipitation in the region returns to pre-1988 levels.

DIFFERENTIAL MAGNETIC FIELD

Stress changes imposed on a rock induce small changes in the magnetic susceptibility and remanence of the rock, which in turn produces small variations in the local magnetic field. The local magnetic field in Long Valley caldera is monitored with absolute, total field magnetometers (Mueller et al., 1981) at three sites to detect such changes (Figure C3, Table C2). Magnetic field data from these three stations are sampled automatically every 10 minutes and transmitted to Menlo Park where they are processed and checked to determine whether changes exceeding the background noise have occurred during the previous 24 hours. To isolate local magnetic field variations, data from adjacent stations are automatically differenced and smoothed with a 3-day smoothing window. The result is monitored daily and plotted weekly. We consider changes greater than 1 nT at periods greater than one day to be anomalous (a change of 1 nT roughly corresponds to a stress change of several bars). We have not yet observed such changes in Long Valley caldera, although they have been documented prior to and during recent eruptions from Mount St. Helens; Mt. Mihara, Japan; Mt. Ruapehu, New Zealand; and Reunion Island (Johnston and Stacey, 1964; Johnston and others, 1981; Davis and others, 1984; Yukutake et al., 1986; Zlotnicki and LeMouel, 1985).

TWO-COLOR GEODIMETER NETWORK

Distance measurements for 7 to 10 lines extending from the CASA monument using a two-color geodimeter are collected 2-3 times a week, weather conditions permitting (Figure C4). Accordingly, a week to 10 days is the minimum time interval for which meaningful strain changes can be resolved under normal circumstances. The other baselines are measured infrequently with sampling intervals between one month to one year as conditions warrant. These lines will not be used in the short-term evaluation of a status unless the center of activity shifts. Table 6b summarizes the 95% (two sigma) confidence intervals for significant strain changes along lines in the CASA network for time intervals ranging from 10 to 200 days. These statistics are based on data accumulated since routine measurements of the CASA network began in mid 1983 through 1988.

REGIONAL GEODETIC NETWORKS

The regional geodetic networks involve arrays of monuments that are normally surveyed on an annual basis using leveling, and GPS (Global Positioning System) techniques. These regional networks provide long-term definition of the regional deformation field and a regional context for more localized deformation within the caldera or along the Mono-Inyo volcanic chain. Because these networks are measured infrequently, they will not normally contribute to the determination of the status for short-term fluctuations in moderate to strong unrest (status e through c). In the case of intense unrest and an EVENT RESPONSE, however, we may initiate frequent surveys of appropriate sections of these regional networks and incorporate the results with the two-color network in Table 6 to evaluate the geodetic status.

LEVELING NETWORK

The level lines used to track vertical deformation in the region are shown in Figure C4. The earliest leveling measurements in the Long Valley region date back to a 1905 survey along Highway 395 (line 1). Subsequent surveys along this section of the highway were completed in 1914, 1932, 1957, 1975, 1980, 1982, and annually thereafter (Castle and others, 1984; Savage, 1989). Lines 3 and 6 within the caldera were established in 1975 and the remaining lines in the summer of 1982. All of these lines have been surveyed annually since 1982 according to second-order specifications, which yield a precision given by $s = aL^{1/2}$ where s is the standard deviation, $a = 1.4$ mm and L is line length in km (Castle and others, 1984).

GPS NETWORKS

Deformation in the region around Long Valley caldera from 1980 through 1989 was monitored with annual trilateration surveys using a Geodolite laser-ranging instrument (Savage, 1989). These annual Geodolite trilateration surveys were phased out in 1989 and replaced with an expanded network of monuments surveyed by the Global Positioning System (GPS). The squares in Figure C5 indicate the locations of monuments in the Long Valley GPS network. Four of these sites (Mammoth, Casa, Convict, and Lookout) and all of the sites marked with an open square were surveyed in 1989 by both Geodolite and GPS techniques to provide continuity in the deformation history of the region and to compare results from the two measurement systems. Sites marked with open squares will not be part of future GPS surveys because of difficult access. The solid diamonds in Figure C5 indicate the locations of monuments in the Mono Chain GPS network, which was first surveyed in the summer of 1990.

The GPS technique uses coded signals from multiple satellites with known orbits to resolve the precise location of a receiver on the ground (Davis and others, 1989; Prescott and others, 1989). GPS offers several advantages over trilateration; line-of-sight is not required between receiver sites (monuments), surveys can be completed in poor weather, and measurements resolve changes in both horizontal and vertical position. A complete survey of a 15-station network using five GPS receivers takes four to eight days depending on the desired precision. Under normal circumstances, the data from a completed survey are returned to Menlo Park for processing and final results are available in about two weeks. If necessary, however, the data can be reduced in a field office and processed to obtain preliminary estimates of relative monument positions within a matter of hours. With current technology and normal procedures, a GPS survey is capable of resolving horizontal distances to within about 10 mm and elevations to within about 30 mm. These uncertainties in position will be about 50% larger for preliminary estimates under field-office conditions.

APPENDIX D. Sample Messages Accompanying B- and A-LEVEL ALERTS

The Chief Scientist LVC/MC will inform by telephone the duty officer of the OES communication center in Sacramento that a specific ALERT LEVEL is in force according to the procedures outlined in Figures 4 and 5. In the case of a B- or A-LEVEL ALERT, the Chief Scientist, with consent of the Chief of OEVE, will telefax one of the following messages to the Director of OES. The Office of Emergency Services is responsible for relaying the message to county and city officials within twenty minutes of receipt from the USGS. After appropriate civil officials have been notified, the message will be released to the media and the public.

B-LEVEL ALERT MESSAGE

The U.S. Geological Survey has initiated an field operation centered in Mammoth Lakes to closely monitor the [specify activity: earthquakes swarm activity; ground deformation; etc.] currently centered in [specify place: south moat of Long Valley caldera, the Mono Craters, etc.] approximately [x] miles [direction] from [nearby towns]. Activity of this sort is symptomatic of magma movement in the crust beneath volcanic areas throughout the world. Most likely the activity will decay to normal background levels over the next few weeks or months as has been the case with previous episodes of heightened activity in region. There remains a small possibility, however, that the current activity may evolve toward a volcanic eruption. In this case we would expect to see the earthquake activity and ground deformation intensify as as magma moves upward to shallow depths in the crust. Our expanded monitoring efforts will focus on the early identification of any changes in the activity pattern that may be diagnostic of an impending eruption. We will establish direct contact with OES and local civil authorities from the temporary USGS field center in Mammoth Lakes and will keep them informed of significant changes in activity and an assessment of its implication for possible volcanic hazards.

A-LEVEL ALERT MESSAGE

The intense activity [specify type] currently centered in [specify place] indicates that a volume of magma is being injected into the shallow crust with a strong possibility that the magma will reach the surface to produce a volcanic eruption in the comming hours to days. We cannot say precisely when magma might reach the surface, nor can we specify the precise size, duration, or type of the eruption should one actually develop. Indeed, it is still possible that the magma may yet stop short of the surface and an eruption.

Intensified U.S. Geological Survey monitoring efforts from a temporary field center in Mammoth Lakes [or Bridgeport] will focus on the prompt identification of any changes in the activity pattern that may help specify the time and place magma may reach the surface to produce an eruption. We will maintain direct contact with OES and local civil authorities from the temporary USGS field center in Mammoth Lakes [or Bridgeport] and will keep them informed of significant changes in activity and an assessment of its implication for possible volcanic hazards.

SUPPLEMENT TO A-LEVEL MESSAGE

If an eruption does develop from this activity, it will most likely produce small to moderate volumes of silicic lava similar the eruptions that occurred 650 years ago at the north end of Mono Craters and 550 years ago at the Inyo Domes. In this case we may expect to see: 1) phreatic eruptions as the magma interacts with the shallow ground water producing steam blasts that can throw large blocks of rock several hundred meters from the vent (the "eruption" could stop at this point as it did with the phreatic blasts that formed the Inyo Craters); 2) explosive magmatic phase during which hot pumice and ash would be ejected thousands of feet into the air producing thick pumice accumulations near the vent, extensive deposits of fine ash hundreds of km down-wind, and destructive pyroclastic flows that may reach distances as great as 5 to 10 km from the vent; and 3) a final phase that involves the slow extrusion of lava to form steep-sided flows and domes. As with the eruptions 550 and 650 years ago, eruptions may occur from several separate vents in succession with the vents spaced over a distance of 5 to 10 km. Individual eruptions may be separated in time by days to perhaps weeks. Larger, more destructive eruptions following the same basic pattern are possible but less likely.

Also possible, but less likely, is a small to moderate eruption of basaltic lava similar to the eruptions that produced the Red Cones several thousand years ago. In this case, we may expect to see: 1) an initial series of phreatic eruptions as described above for the silicic eruption sequence; 2) the onset of magmatic eruptions with fluid basaltic lava fountaining several hundred meters into the air from a line of vents that may extend several km across the country. These eruptions would scatter ash and tephra over the region and feed the beginnings of slow-moving lava flows; 3) consolidation of lava fountaining into a few vents feeding lava flows that move downslope at speeds ranging from a few meters/hr to several km/hr. The resulting lava flows may extend 10 km or more from the vents depending on the vigor and duration of eruption.

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TABLE 1. STATUS RANKING AND ACTIVITY LEVELS

STATUS[1]	USGS RESPONSE[2]	ACTIVITY LEVEL	RECURRENCE INTERVALS[3]
A ALERT	Issue GEOLOGIC HAZARD WARNING	ERUPTION LIKELY within hours to days	decades to centuries
B ALERT	Alert Director, Trigger EVENT RESPONSE	intense unrest	years to decades
C STATUS	Notify Office Chief, OES Hdqtrs. State Geologist	strong unrest	months to years
D STATUS	Notify Team Leaders, Branch Chiefs, OES comm., USFS, CDMG, & UNR	moderate unrest	weeks to months
E STATUS	Notify Chief Scientist, project personnel. Information call to OES communications and local authorities as appropriate (ie. a locally felt earthquake)	weak unrest or possible instrument problems	weeks
N	Normal monitoring activities	background activity	---

[1] Derived from combining the status of each monitoring network according to Table 8.

[2] USGS RESPONSE for a given status will include the responses specified for all lower statuses.

[3] estimated RECURRENCE INTERVALS for a given status are based primarily on the recurrence of unrest episodes in Long Valley since 1980, the record of M > 4 earthquake activity in the regions since the 1930's, and the geologic record of volcanic eruptions in the region over the last 50,000 years.

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TABLE 2. SEISMIC STATUS[1].

Seismic Status	Minimum Seismic Activity
a	Harmonic tremor with duration > 1 hr and RSAM[2] amplitudes > 100 on two or more stations with confirming evidence that the signal is not due to an instrumental or telemetry problem.
	OR ≥10 long-period (LP) earthquakes/hr sustained for 3 or more hrs.
b	A swarm with ≥1 M≥5 events, ≥ 5 M≥4 events/day, ≥ 25 M≥3 events/day.
	OR >60 RTP[3] events events/hr sustained for 6 or more hrs.
	OR >1000 RTP events/day.
	OR ≥ 3 spasmodic bursts/day with durations > 30 min AND a c-status on at least one of the deformation networks.
	OR Harmonic tremor with duration >10 min and RSAM amplitudes > 50 on two or more stations with confirming evidence that the signal is not due to instrumental or telemetry problems.
	OR ≥ 5 long-period (LP) earthquakes/hr for 4 or more hrs.
c	≥ 1 M≥4 event, ≥ 5 M≥3 events/day, or ≥ 25 M≥2 events/day.
	OR >30 RTP events/hr sustained for 4 or more hrs, or >300 RTP events/day.
	OR >10 M≥1 events/day sustained for 3 or more days.
	OR Mean focal depths of events become systematically shallower during a swarm sustained for hrs to days.
	OR ≥ 3 spasmodic bursts /day with duration > 10 min AND a d-level on at least one of the defromation networks.
	OR Harmonic tremor with duration < 5 min and/or RSAM amplitudes > 50 on two or more stations with confirming evidence that the signal is not due to instrumental or telemetry problems.
	OR Three or more long-period events/day.
d	≥ 2 M≥3 events/day, or >5 M≥2.5 events/day.
	OR >20 RTP events/hour sustained for 3 or more hours.
	OR >100 RTP events/day.
	OR One or more spasmodic bursts with duration < 10 min.
e	≥ 1 M≥3 events/day (may be locally felt).
	OR >20 or more RTP events/hour.
	OR >5 M ≥ 2 events/day.
	OR >10 RTP events/hr for 3 or more hours.
	OR A sudden shift in seismicity to new area.

[1] Applies to earthquakes located within Long Valley caldera, 5 km beyond the caldera boundary, and within a 10-km-wide band centered along the Mono-Inyo volcanic chain extending northward through the center of Mono Lake.

[2] RSAM: Real-time Seismic Amplitude Measurement

[3] RTP: Real Time Processor

OR carries its inclusive meaning (ie. x or y or both).

TABLE 3. Seismicity rates for selected earthquake swarms

Location	Detected[1]	M > 1	M > 2	M > 3	M > 4	Mmax	LP[2]/ tremor	eruption	ref.
Long Valley									
May 80					≈ 15/day	M=6 (4)	no	no	14
May 82				7/3 days		M=4.1	no	no	
Jul 82				4/10 days		M=3.4	no	no	
Nov 82	≈ 100/day		≈ 9/day			M=2.8	no	no	
Jan 83	≈ 800/day			25/hour	≈ 10/day	M=5.3 (2)	no	no	13
Jun 89	≈ 40/day	≈ 25/day	2/day			M=3	no	no	6
Mar 90	>300/day					M=3	no	no	
Campi Flegri									
Oct 83	>300/day					M=4	no	no	9
Mar 84	≈ 500/day		5/day			M=4	no	no	9
Rabaul									
Apr 84	≈ 1700/day					M=4.8	no	no	10
Mt St. Helens									
Mar 80	≈ 600/day		>70/day	≈ 50/day	1-4/day	M=4	yes	yes	2
Matsushiro									
Nov 65	≈ 2000/day			>200/day		M=5.0	no	no	4
Off-Ito									
July 89	≈ 400/hour			40/day		M=5.5	yes	yes	5
Redoubt									
Dec 89	≈ 150/hour					M<2	yes	yes	1
Fuego									
Jan 77	2000/day	70/day	≈ 5/day			M=2.8	no	no	17
Augustine									
Feb 86	>5000/day					M=2.5	no	yes	7
Usu									
Aug 77	200/hour			5/hour		M=3.8	yes	yes	16
Pavlof									
Apr 86	800/day	400/day				M=2.1	yes	yes	11
Galapagos									
Jun 68				90/day	33/day	M=5.2	?	no	3
Kilauea									
Jan 83	>1100/day	92/day	18/day	1/day		M=3.3	yes	yes	8
Mt. Hood									
Jul 80	20/hour		14/hour			M=2.8	no	no	12
Medicine Lake									
Sep 88	80/hour			2/hour		M=4.2	no	no	15

[1] Minimum magnitude not specified but generally M<1

[2] LP: Long period earthquake (see Appendix A).

References: 1) Alaskan Volcano Observatory Staff (1990); 2) Endo et al. (1981); 3) Filson et al. (1973); 4) Hagiwara and Iwata (1968); 5) JMA (1989); 6) Hill et al. (1990); 7) Kienle et al. (1986); 8) Koyanagi et al. (1988); 9) Lirer et al. (1987); 10) Mori et al. (1989); 11) McNutt et al. (1989b); 12) Rite and Iyer (1981); 13) Savage and Cockerham (1984); 14) Smith and Ryall (1982); 15) Walter and Dzurisin (1989), McNutt (1989c); 16) Yokoyama et al. (1981); 17) Yuan et al. (1984)

--

TABLE 4. Deformation at Selected Volcanoes Prior to Eruptions or During Unrest

Volcano	Strain rate	Duration	Maximum displacement	Monitoring technique	Eruption	Ref
Long Valley						
1979-80	>25 ppm/yr	<1 yr	25 cm	leveling	no	8
1983-88	≈ 1 ppm/yr	≈ 5 yr	5 cm	leveling/geod	no	9
1989-90	≈5 ppm/yr	> 6 mo	>4 cm	geod	no	4
Campi Flegrei						
1538	> m/day	≈ 1 day	≈ 500 cm	visual est.	yes	3
1970-72	≈ 20 ppm/yr	2 yr	> 70 cm	leveling/geod	no	2
1982-84	≈ 20 ppm/yr	2 yr	150 cm	leveling/geod	no	2
Rabaul						
1937	> m/day	≈ 1 day	> 200 cm	visual est.	yes	7
1983-84	≈ 300 ppm/yr	1 yr	>160 cm	tilt/geod	no	6
Mount St. Helens						
April 10, 1980	>30 ppm/hr	≈ 1 hr		tilt	yes	5
Krafla						
1976	≈ 800 ppm/yr	≈ 9 mo	140 cm	tilt/leveling	no[1]	11
Izu-Oshima						
Nov 1986	≈ −0.5 ppm/yr	several yrs	≈ −5 cm	level/geod	yes[2]	1
Off-Ito						
July 1989	≈ 5 ppm/day	7 days	> 20 cm	tilt/geod/GPS	yes	10

[1] This was one of many episodes of sustained inflation followed by abrupt deflation and shallow intrusion between 1976 and 1978. A small eruption accompanied abrupt deflation on April 27, 1977, three episodes later (Johnsen et al., 1980).

[2] Deformation preceding the initial summit eruption on November 15, 1986, involved slight deflation (indicated by negative strain and displacement) of the caldera (Ida, 1988).

References: 1) Ida (1988); 2) Berrino et al. (1984), Bianchi et al. (1987); 3) Dvorak (1990); 4) Langbein (personal communication, 1990); 5) Lipman et al. (1981); 6) McKee et al. (1989); 7) Newhall and Dzurisin (1988), Fisher (1934); 8) Savage and Clark (1980); 9) Savage (1989), Langbein (1989); 10) Thatcher (1990); 10) Tryggvason (1980), Johnsen et al. (1980).

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TABLE 5. CONTINUOUS STRAIN STATUS.

Strain Status	MINIMUM STRAIN CHANGES
a	Changes > 10 ppm/day and accelerating on multiple instruments (both dilatometers, the long-base tiltmeter, at least 3 of the borehole tiltmeters, and the water well).
b	Changes > 1 ppm/day on 1 dilatometer AND a simultaneous change > 0.2 ppm/day on the second dilatometer AND/OR the long-base tiltmeter AND/OR a simultaneous areal strain change of at least 1 ppm/day on the water well. OR Changes > 10 ppm/week on two or more tiltmeters with a simultaneous rate of at least 5 ppm/week on the long-base tiltmeter and two additonal borehole instruments.
c	Changes > 0.5 ppm/day on 1 dilatometer with a simultaneous change of at least 0.1 ppm/day on the second dilatometer AND/OR the long-base tiltmeter AND/OR a simultaneous areal strain rate of at least 0.5 ppm/day on the water well.
d	Changes > 0.1 ppm/day on 1 dilatometer with a simultaneous change of at least 0.05 ppm/day on the second dilatometer AND/OR the long-base tiltmeter AND/OR a simultaneous areal strain rate of at least 0.1 ppm/week on at least one of the water wells.
e	Changes > 0.05 ppm/hr on 1 dilatometer (calls pager) OR Changes > 0.05 ppm/day on the long-base tiltmeter. OR Changes > 0.05 ppm/day on the water well.

TABLE 6a. GEODETIC STRAIN ALERT

Geodetic Status	Minimum Deformation
a	Displacements >10 cm/day on three or more baselines.
b	Changes from background[1] strain rate of >10 ppm over 10 days on at least 3 baselines. OR Cumulative strain that exceeds background by 100 ppm over one year (corresponds to a > ≈ 3 ppm/10 day extensional strain rate sustained for months or > 100 cm cumulative displacement).
c	Changes from background strain rate of >5 ppm over 10 days on at least 3 baselines. OR Cumulative extensional strain that exceeds background by 10 ppm over one year or less (corresponds to an extensional strain rate of at least 0.3 ppm/10 day sustained for months or > 10 cm cumulative displacement).
d	Changes from background strain rate of >0.5 ppm over 10 days on at least 3 baselines.
e	Changes from background of >0.5 ppm over 10 days on at least 1 baseline.

[1] For the two-color geodimeter network, background is twice the standard deviation (2σ) of measurements made from late 1984 through mid 1989 for each baseline (see Table 9b).

TABLE 6b. CUMULATIVE STRAINS EXCEEDING 2σ WITH 95% CONFIDENCE FOR TWO-COLOR GEODIMETER LINES FROM CASA.

Line	τ=10	τ=20	τ=50	τ=100	τ=200
			2σ strain change in ppm		
Krakatau	0.40	0.39	0.44	0.54	0.71
Knolls	0.44	0.45	0.54	0.69	0.92
Hot	0.35	0.31	0.32	0.36	0.46
Sherwin	0.43	0.43	0.50	0.62	0.82
Tilla	0.42	0.40	0.46	0.56	0.74
Miner	0.52	0.54	0.67	0.86	1.16
Shark	0.47	0.45	0.52	0.64	0.84
Convict	-	-	0.67	0.72	0.85
Taxi	-	0.59	0.50	0.50	0.56
JMC	-	0.58	0.49	0.49	0.55
Lomike	-	0.93	0.98	1.16	1.47

τ is the time interval in days over which the 2σ strain changes are estimated for each line.

TABLE 7. MAGNETIC FIELD STATUS

Magnetic Status	Minimum Changes in Magnetic Field
a	A cumulative change of >10 nT [1] in 10 days or less on more than one instrument.
b	A cumulative change of >5 nT in 10 days or less on more than one instrument.
c	Changes >1 nT over one day to several months on two independent instruments. OR A rate of change > 0.3 nT/mo sustained for six months or more on at least one instrument.
d	Changes >1 nT over one day to several months on at least one instrument.
e	Changes >1 nT between station pairs in less than 24 hours rings pager. This may occur because of instrument malfunction and/or clock syncronization failure and usually indicates that maintainance is necessary.

[1] nT: nanoTessla

TABLE 8. COMBINED STATUS

COMBINED STATUS (Table 1)	SEISMIC (Table 2)		CONTINUOUS STRAIN (Table 5)		GEODETIC STRAIN (Table 6)		MAGNETIC (Table 7)
	a		-		-		-
A	b	and	b	and	b		-
	-		a	and	a		-
	-		a	or	a	and	a
	b		-		-		-
B	c	and	c	and	c		-
	-		b	and	b		-
	-		b	or	b	and	b
	c		-		-		-
C	d	and	d	and	d		-
	-		c	and	c		-
	-		c	or	c	and	c
	d		-		-		-
D	e	and	e	and	e		-
	-		d	and	d		-
	-		d	or	d	and	d
E	e	or	e	or	e	or	e

Note: "or" carries its inclusive meaning (ie. x or y or both).
Lower-case letters a through e indicate minimum status for the respective monitoring networks.
"-" (a dash) indicates any level, a through e.

TABLE 9. STAND-DOWN RULES. Schedule for terminating a given STATUS after activity falls below the trigger threshold for that STATUS.

STATUS	Time* (days) 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
A	A	-	-	-	-	-	-	>	B	-	--	--	--	--	->	C, D, E, or N
B	B	-	-	-	-	-	-	-	-	-	--	--	--	--	->	C, D, E, or N
C	C	-	-	>	D,	E,	or	N								
D	D	-	>	E	or	N										
E	E	>	N													

* Days after activity falls below the threshold for a given STATUS.

TABLE C1. Seismic stations in Long Valley caldera and vicinity telemetered to USGS headquarters in Menlo Park

Name	Latitude	Longitude	Elevation (m)	Component	Institution
MSKM	37°39.18′	119°01.44′	2660	V	GSM
MMLM	37°39.36′	118°58.68′	794	V	GSM
MCDM	37°32.89′	118°26.50′	1430	V	GSM
MCMM	37°36.59′	118°52.40′	2260	V	GSM
MLHM	37°40.78′	118°48.75′	2122	V	GSM
MCSM	37°39.30′	118°54.27′	2420	V	GSM
MOGM	37°28.75′	118°29.05′	1463	V	GSM
ORCR	37°38.12′	118°39.36′	2301	V	UNR
MDCM	37°42.60′	119°02.50′	2520	V	GSM
CASR	37°34.49′	118°33.09′	2107	V	UNR
HTCR	37°31.79′	118°46.26′	3012	V	UNR
RCCR	37°29.26′	118°43.30′	2804	V	UNR
SCHR	37°21.95′	118°41.22′	2365	V	UNR
SLKR	37°50.04′	119°07.72′	2438	V	UNR
WMDR	37°26.61′	118°38.22′	1683	V	UNR
MATM	37°52.40′	119°52.00′	1353	V	GSM
MCLM	37°35.41′	118°49.45′	2630	V	GSM
MDPM	37°37.94′	119°04.74′	2340	V + 1 H	GSM
MDRM	37°38.32′	118°50.13′	2220	V	GSM
MEMM	37°39.98′	118°56.35′	2495	V	GSM
MFBM	37°25.77′	118°25.70′	1366	V	GSM
MGPM	37°37.59′	118°54.08′	2208	V	GSM
MMSM	37°37.83′	119°01.84′	2500	V	GSM
MRDM	37°35.88′	119°03.40′	2500	V	GSM
MMIM	37°25.20′	119°44.56′	200	V + 1 H	GSM
MMTM	37°22.55′	119°10.68′	2751	V	GSM
MHDM	37°07.36′	119°53.60′	117	V + Z	GSM
MLCM	37°36.63′	118°54.95′	2550	V	GSM
MLMM	37°43.70′	118°56.79′	2540	V	GSM
MMPM	37°36.60′	119°01.68′	2870	V	GSM
MRCM	37°40.41′	118°30.39′	2040	V	GSM
MSLM	37°37.00′	118°57.30′	2530	V + 1 H	GSM
MTCM	37°37.90′	118°57.90′	2398	Z	GSM
MTUM	37°21.20′	118°33.81′	1810	V	GSM
MWBM	37°10.13′	118°20.19′	1560	V	GSM

GSM = U.S.G.S, Menlo Park; UNR = University of Nevada, Reno

V = vertical component, Z = low-gain vertical component, H = horizontal component.

TABLE C2. Coordinates for deformation monitoring instruments in Long Valley caldera and vicinity telemetered to USGS headquarters in Menlo Park.

BOREHOLE DILATOMETERS (STRAINMETERS)

Name	Latitude	Longitude	Sensor depth (m)
POPS	37°37.93′	119°04.73′	162
PLV1	37°40.15′	118°58.53′	178

WATER WELL

Name	Latitude	Longitude	Well depth (m)
LKT	37°43.00′	118°55.44′	916

DIFFERENTIAL MAGNETOMETERS

Name	Latitude	Longitude
HCRM	37°38.76′	118°50.28′
SBFM	37°40.80′	118°56.58′
MGSM	37°28.74′	118°34.38′

BOREHOLE TILTMETERS

Name	Latitude	Longitude	Sensor depth (m)
CA1	37°38.65′	118°54.98′	6
ES1	37°42.46′	118°57.15′	6
FO1	37°40.64′	118°49.20′	6
LA1	37°40.63′	118°52.50′	6
HC1	37°38.66′	118°50.25′	2
SH1	37°38.17′	118°53.55′	6
VA2	37°37.80′	118°55.35′	5

TABLE C2 (continued).

MICHAELSON LONGBASE TILTMETER, CENTRAL VAULT

Name	Latitude	Longitude	Depth (m)
MTB	37°37.97′	118°50.02′	3

LAKE CROWLEY TILTMETER STILLS

Name	Latitude	Longitude
CRS	37°34.98′	118°43.85′
CRE	37°37.94′	118°43.69′
CRN	37°39.28′	118°44.87′
CRW	37°37.06′	118°45.32′

FIGURE CAPTIONS

FIGURE 1. Simplified geologic map of the Long Valley region showing distribution of volcanic rocks related to Long Valley caldera magmatic system and the younger Inyo-Mono craters magmatic system. HSF, Hartly Springs fault; HCF, Hilton Creek fault; MLF, Mono Lake fault, SLF, Silver Lake fault; WCF, Wheeler Crest fault; CD, Casa Diablo; HC, Hot Creek (after Hill et al., 1985).

FIGURE 2. Map showing distribution of epicenters for earthquakes recorded in the Long Valley region from 1978 through 1986.

FIGURE 3. Structure for U.S. Geological Survey monitoring and response activities in the Long Valley caldera - Mono Craters region, California.

FIGURE 4. Flow diagram for deciding STATUS in response to geologic unrest in the Long Valley caldera - Mono Craters region.

FIGURE 5. STATUS Call-Down Trees. Heavy lines indicate calls to be made on a 24-hour basis (this includes all calls under B- or A-LEVEL ALERTS). Remaining calls to be made promptly during normal working hours.

Key to abbreviations:

ADMIN, Administrative Division (USGS);
FEMA, Federal Emergency Management Agency;
IGP, Branch of Igneous and Geothermal Processes (USGS);
NMD, National Mapping Division (USGS);
OES, California Office of Emergency Services;
OEVE, Office of Earthquakes, Volcanoes, and Engineering (USGS);
PIO, Public Information Office (USGS);
SEIS, Branch of Seismology (USGS);
TECT, Branch of Tectonophysics (USGS);
UNR, University of Nevada, Reno;
USFS, U.S. Forest Service.

FIGURE B1. Examples of seismograms for (a) a tectonic (volcano-tectonic) earthquake, and (b) the onset of a spasmodic burst (total duration about 30 minutes). Both occurred beneath Mammoth Mountain at the southwestern margin of Long Valley caldera (from Hill et al., 1989).

FIGURE B2. Seismogram showing LP earthquakes, Harmonic Tremor, and a Volcano-Tectonic earthquake recorded on Nevada del Ruis Volcano, Columbia, on September 9, 1985 (from Chouet, 1991).

FIGURE B3. Examples of seismograms for (1) a typical swarm earthquake (volcano-tectonic) and (2) an earthquake intermediate in character with enhanced low-frequency energy recorded in Long Valley caldera (from Hill et al., 1989).

FIGURE C1. Map showing locations of seismograph stations in the Long Valley caldera region that are telemetered to USGS headquarters in Menlo Park. Station names ending in M are operated by the USGS; those ending in R are operated by the University of Nevada at Reno.

FIGURE C2. Detail of Figure C1 showing telemetered seismograph stations located within and immediately adjacent to Long Valley caldera.

FIGURE C3. Map showing locations of telemetered deformation instruments in Long Valley caldera.

FIGURE C4. Map showing two-color geodimeter network in Long Valley caldera. Line lengths are measured from instrument monuments CASA, LOOKOUT, MILL, MINER, and WHITMORE to reflector sites identified with names in smaller capital letters.

FIGURE C5. Map showing GPS (Global Positioning Satelite) stations in the greater Long Valley region. Open squares indicate GPS stations tied to lines in the regional Geodolite network (see Savage, 1988).

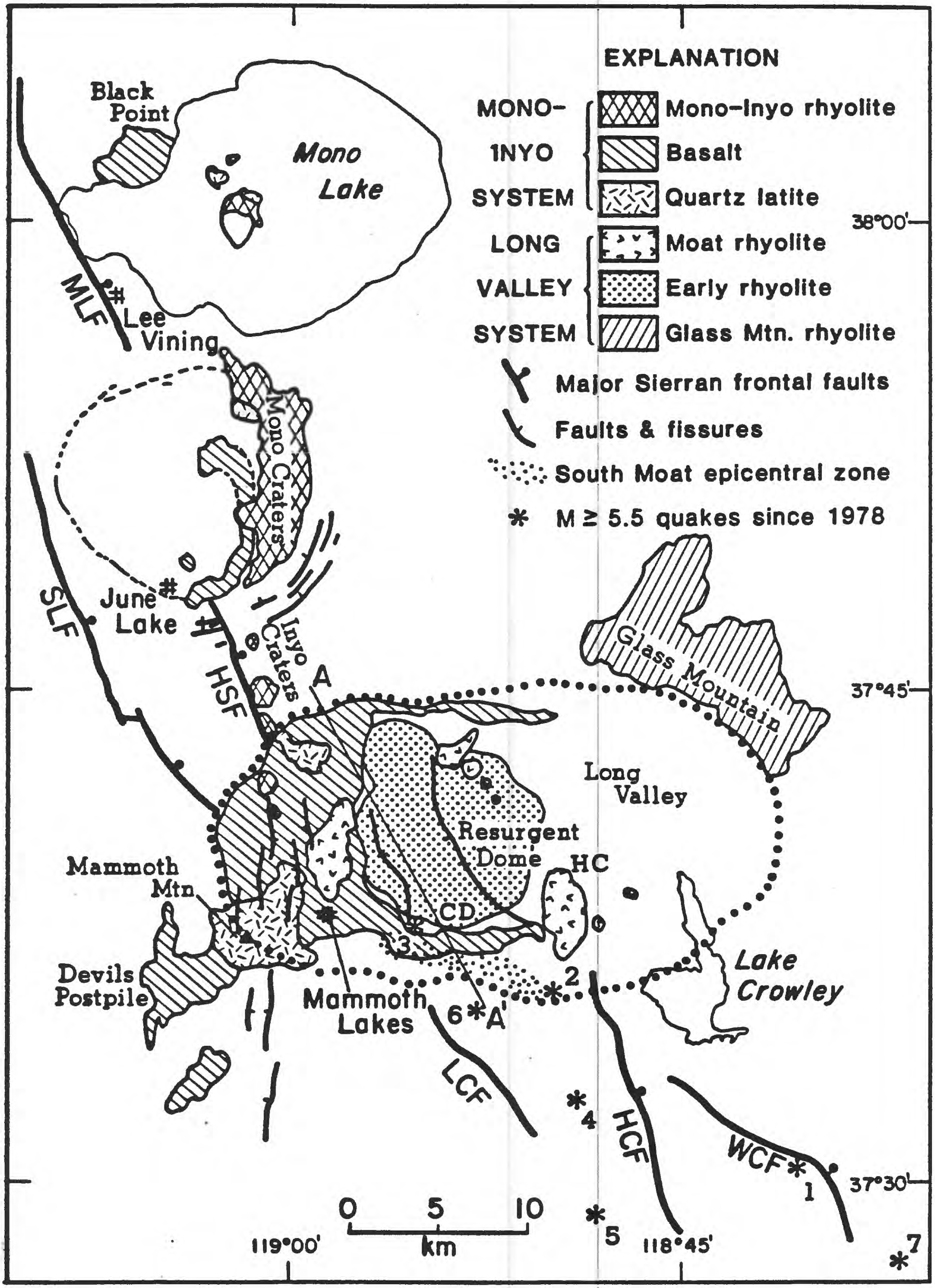

EXPLANATION
MONO-INYO SYSTEM
Mono-Inyo rhyolite
Basalt
Quartz latite
LONG VALLEY SYSTEM
Moat rhyolite
Early rhyolite
Glass Mtn. rhyolite
Major Sierran frontal faults
Faults & fissures
South Moat epicentral zone
M ≥ 5.5 quakes since 1978
Black Point
Mono Lake
MLF
Lee Vining
Mono Craters
SLF
June Lake
HSF
Inyo Craters
A
Glass Mountain
Long Valley
Resurgent Dome
HC
CD
Mammoth Mtn
Devils Postpile
Mammoth Lakes
A'
Lake Crowley
LCF
HCF
WCF
1
2
3
4
5
6
7
38°00'
37°45'
37°30'
119°00'
118°45'
0
5
10
km

FIGURE 1

1978 - 1986

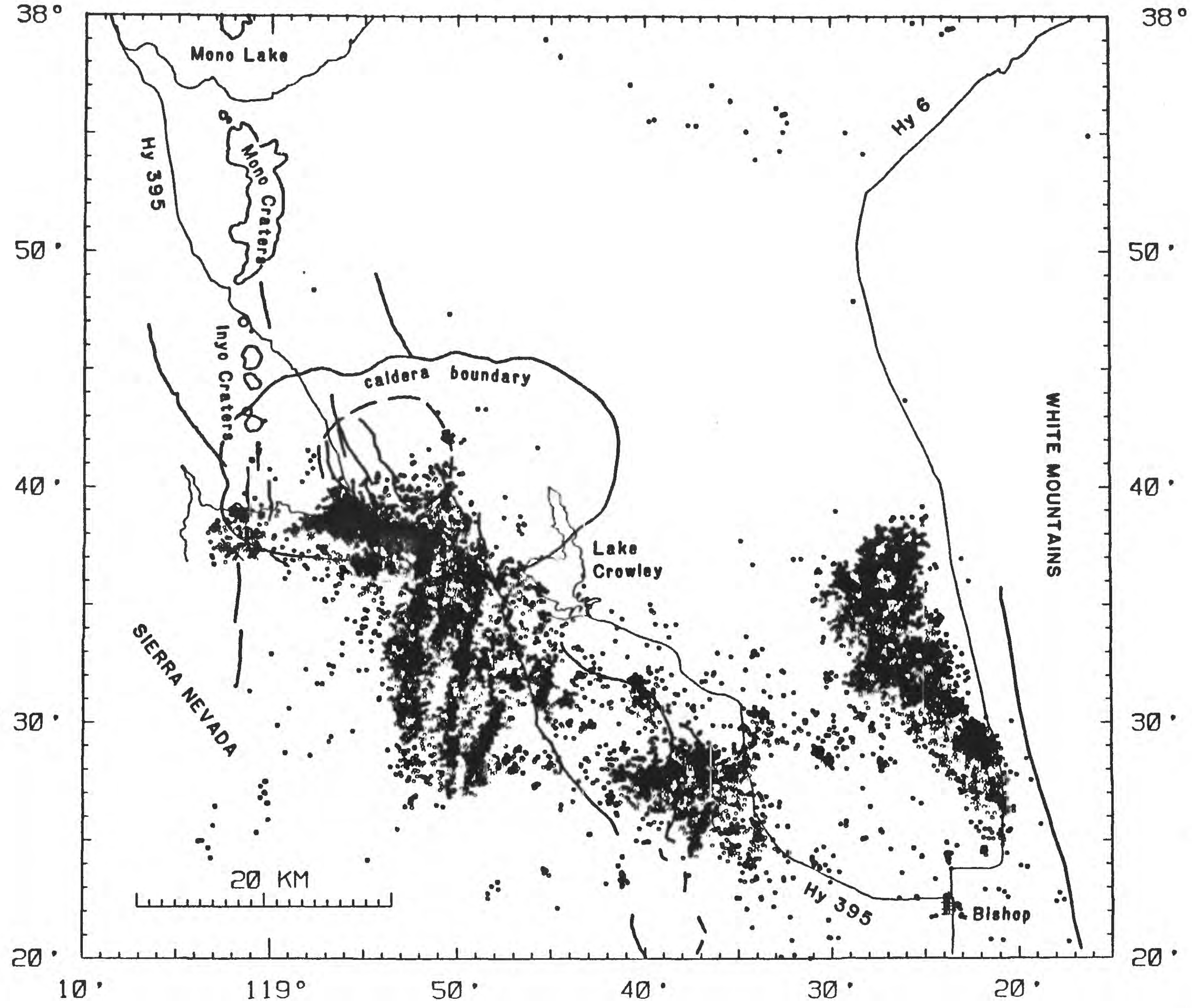


FIGURE 2

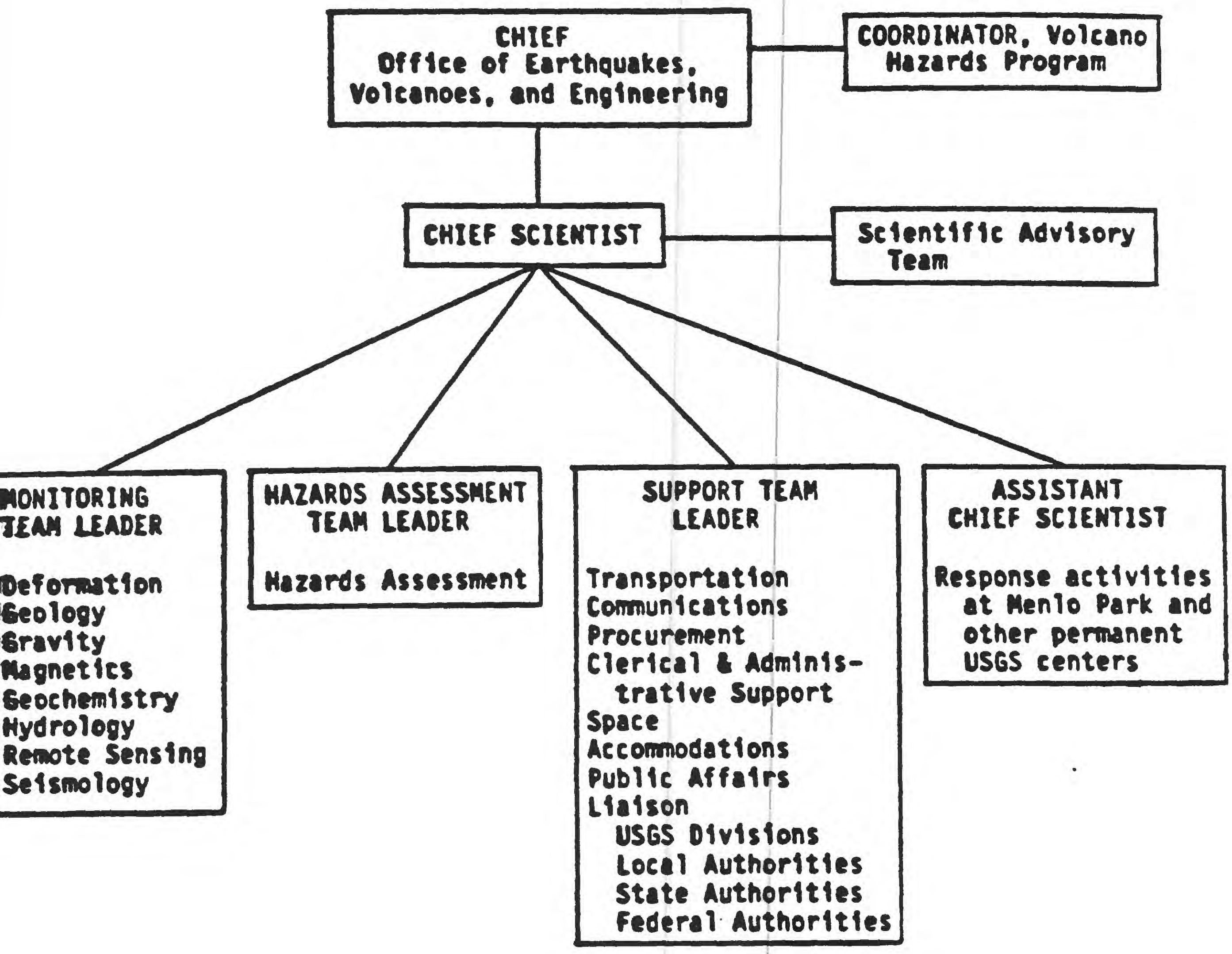

CHIEF
Office of Earthquakes, Volcanoes, and Engineering
COORDINATOR, Volcano Hazards Program
CHIEF SCIENTIST
Scientific Advisory Team
MONITORING TEAM LEADER
Deformation
Geology
Gravity
Magnetics
Geochemistry
Hydrology
Remote Sensing
Seismology
HAZARDS ASSESSMENT TEAM LEADER
Hazards Assessment
SUPPORT TEAM LEADER
Transportation
Communications
Procurement
Clerical & Administrative Support
Space
Accommodations
Public Affairs
Liaison
USGS Divisions
Local Authorities
State Authorities
Federal Authorities
ASSISTANT CHIEF SCIENTIST
Response activities at Menlo Park and other permanent USGS centers

FIGURE 3

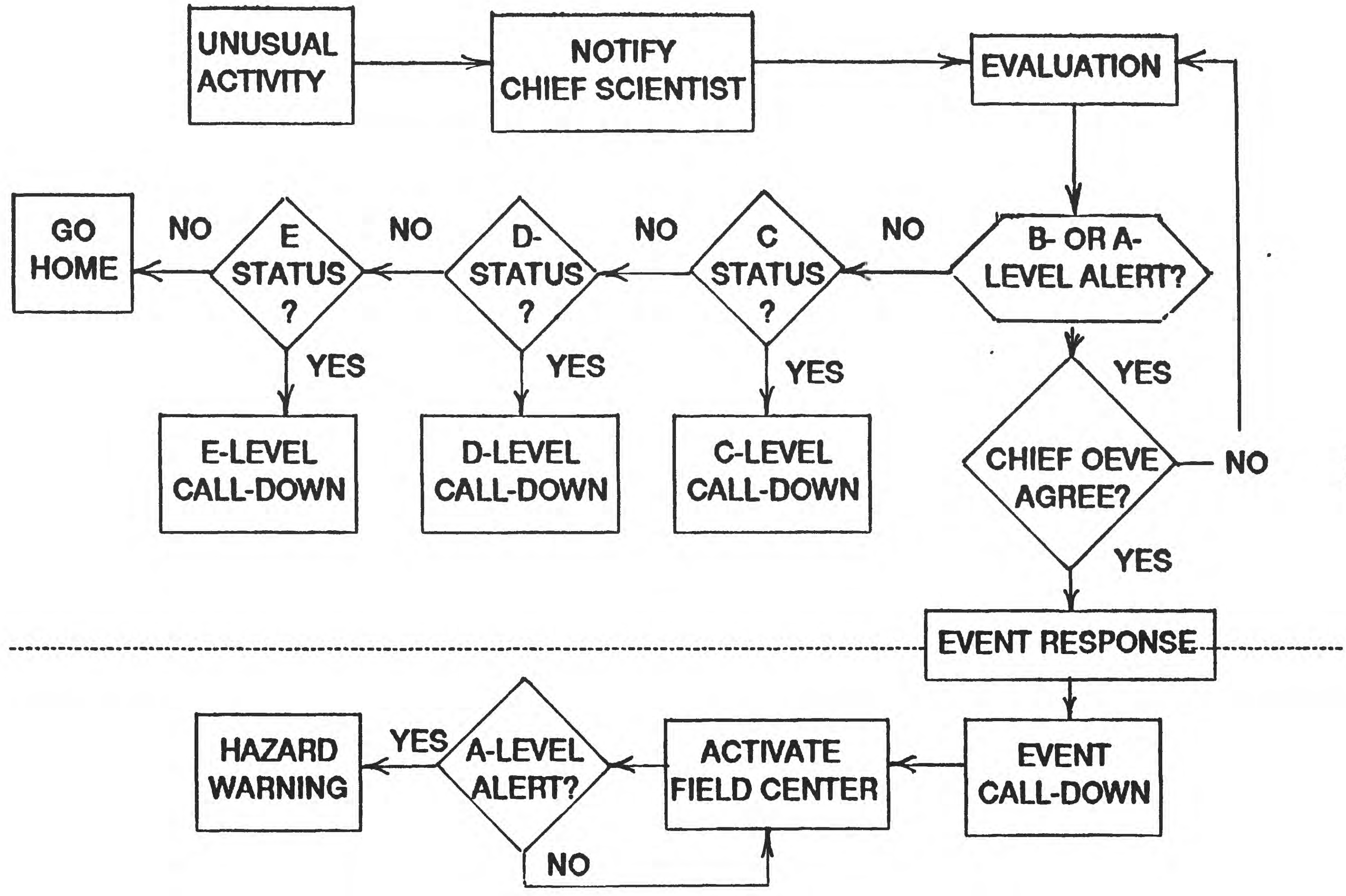
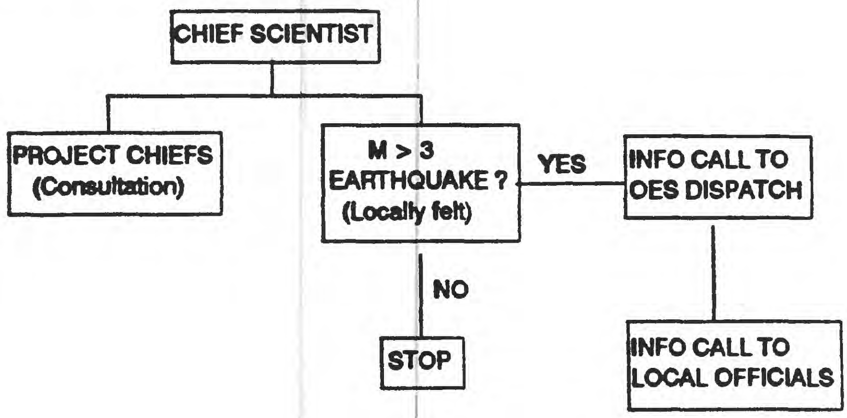
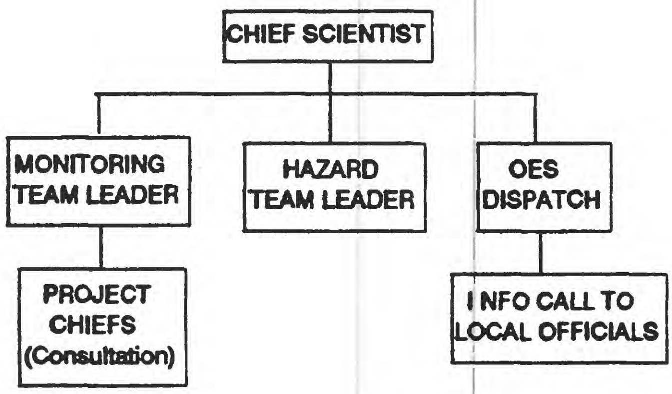

UNUSUAL ACTIVITY
NOTIFY CHIEF SCIENTIST
EVALUATION
B- OR A- LEVEL ALERT?
NO
C STATUS ?
YES
C-LEVEL CALL-DOWN
NO
D- STATUS ?
YES
D-LEVEL CALL-DOWN
NO
E STATUS ?
YES
E-LEVEL CALL-DOWN
NO
GO HOME
YES
CHIEF OEVE AGREE?
NO
YES
EVENT RESPONSE
EVENT CALL-DOWN
ACTIVATE FIELD CENTER
A-LEVEL ALERT?
NO
YES
HAZARD WARNING

FIGURE 4

E-STATUS CALL-DOWN



D-STATUS CALL-DOWN



C-STATUS CALL-DOWN

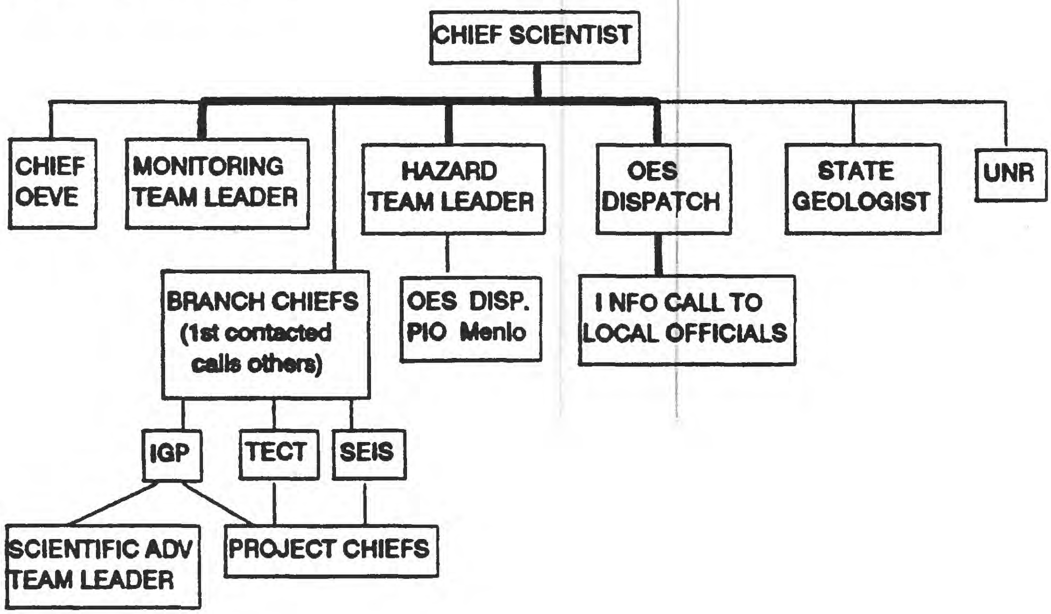


FIGURE 5 (more)

B- AND A-STATUS (EVENT RESPONSE) CALL-DOWN

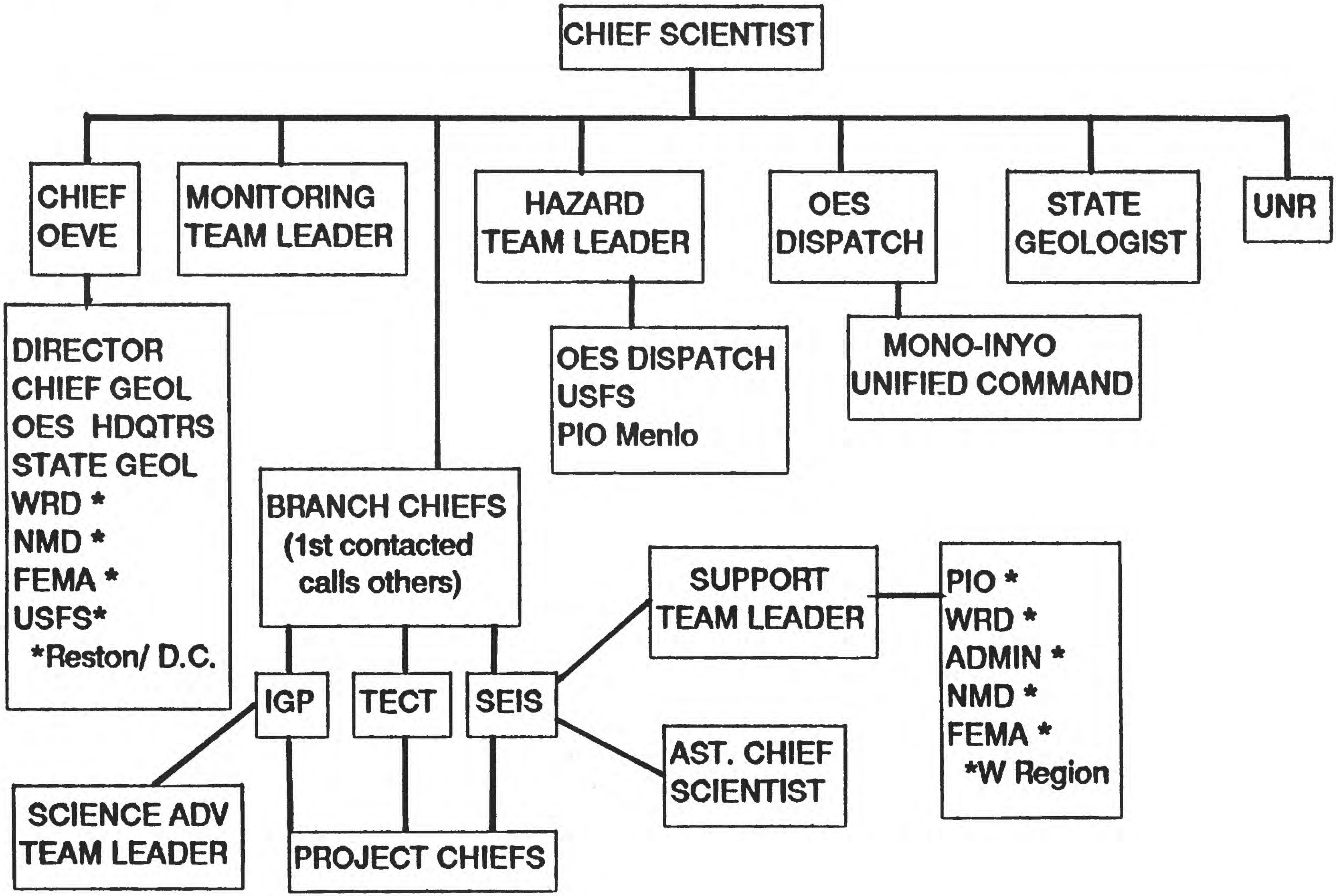


FIGURE 5 (contd)

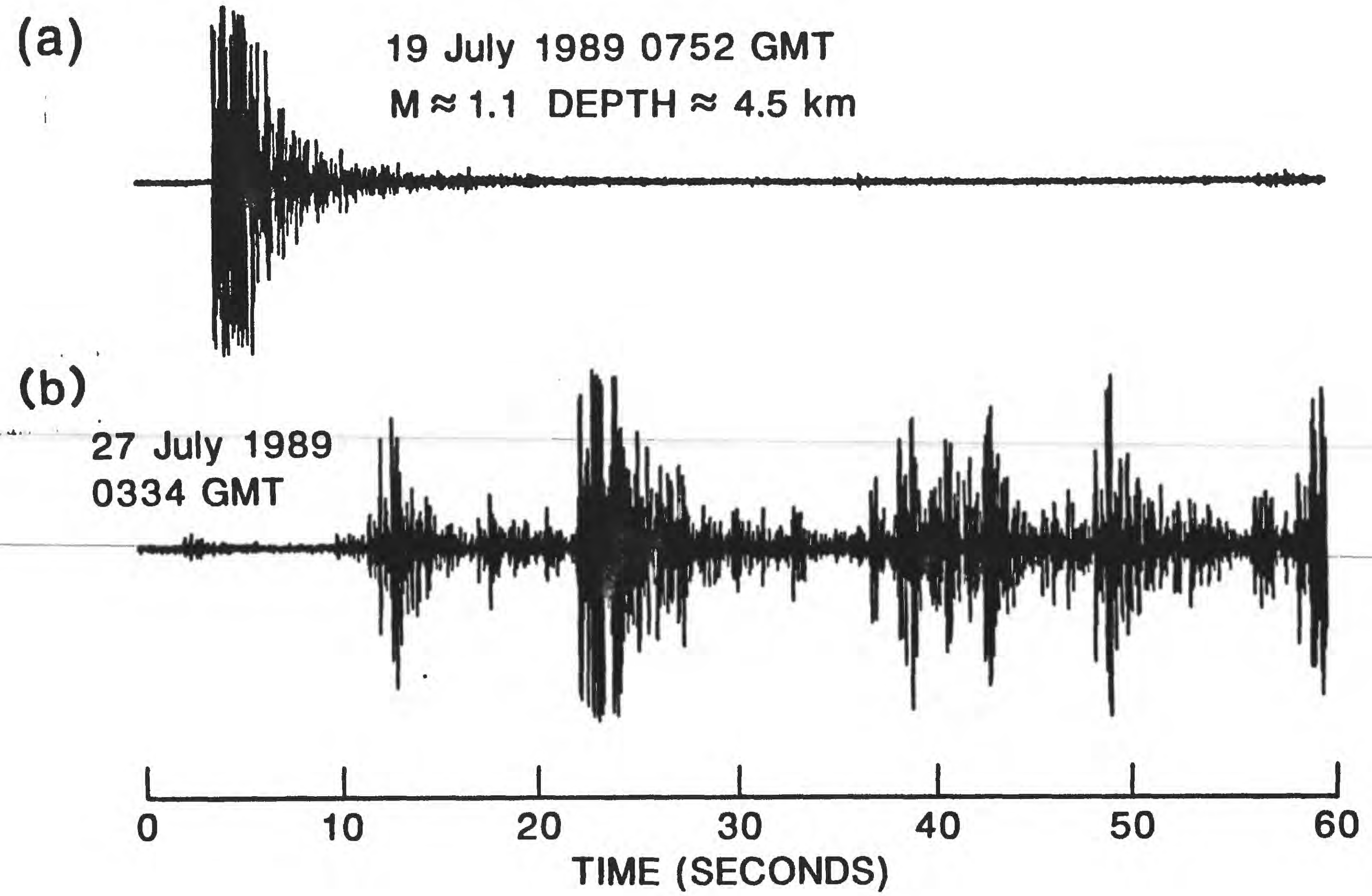

(a)
19 July 1989 0752 GMT
M ≈ 1.1 DEPTH ≈ 4.5 km
(b)
27 July 1989
0334 GMT
0
10
20
30
40
50
60
TIME (SECONDS)

FIGURE B1

NEVADO DEL RUIS Sept. 9, 1985 (From Bruno Martinelli, ETH Zurich)

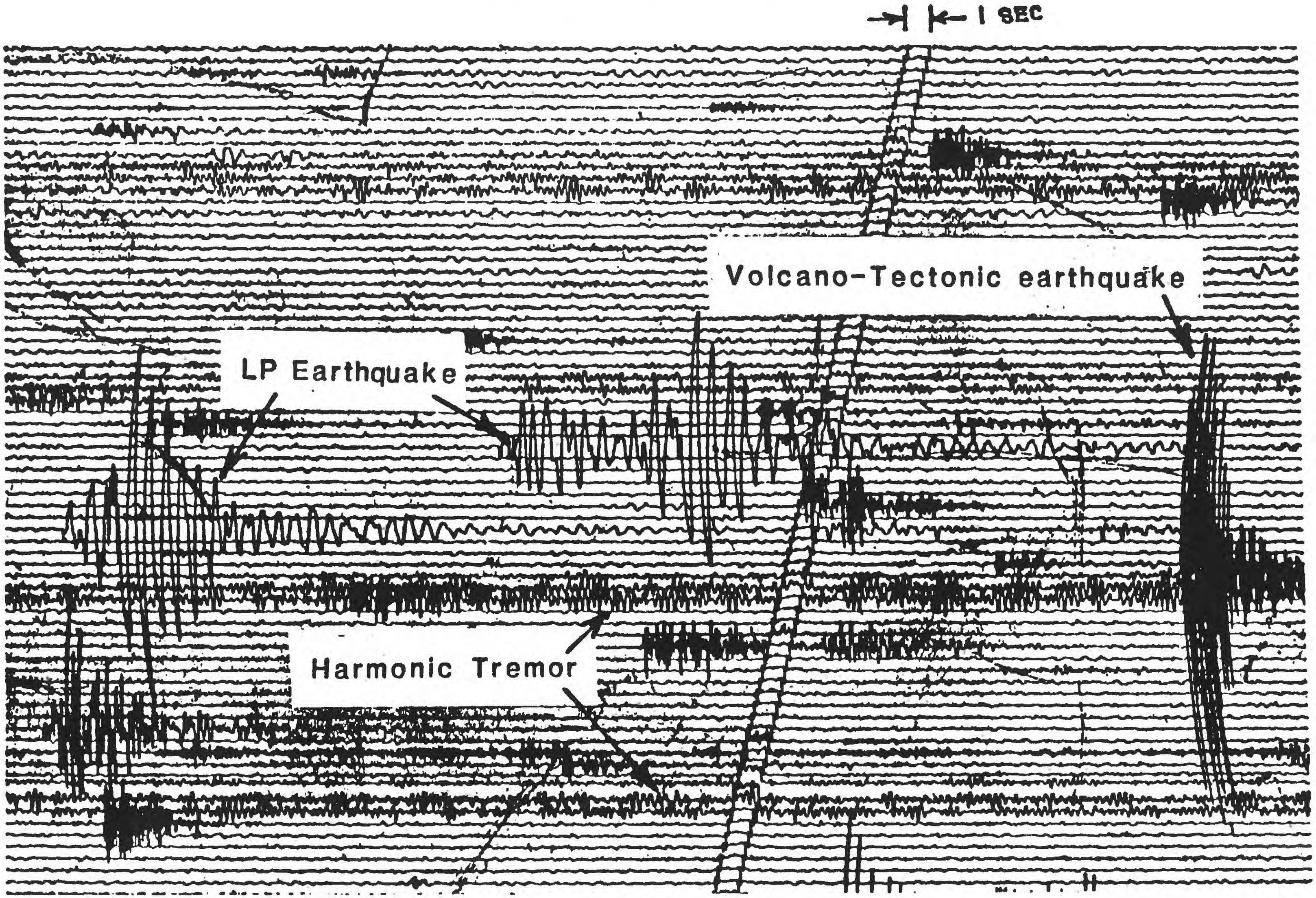


FIGURE B2

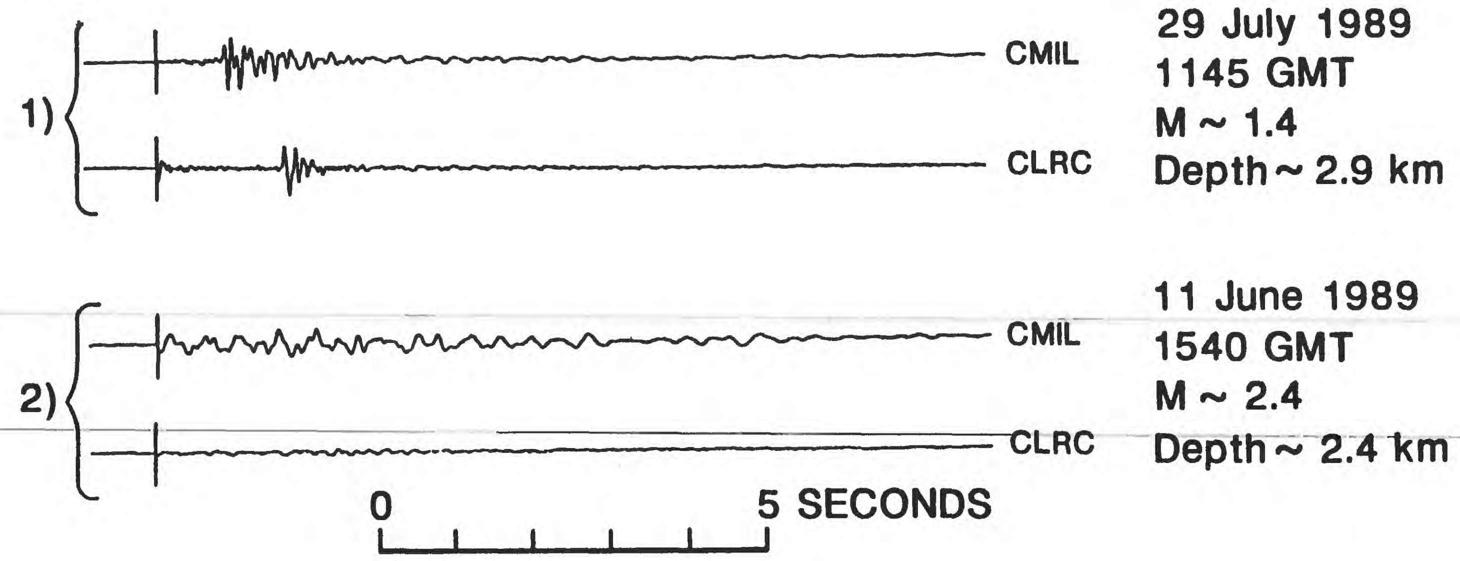

1)
CMIL
CLRC
29 July 1989
1145 GMT
M ~ 1.4
Depth ~ 2.9 km
2)
CMIL
CLRC
11 June 1989
1540 GMT
M ~ 2.4
Depth ~ 2.4 km
0
5 SECONDS

FIGURE B3

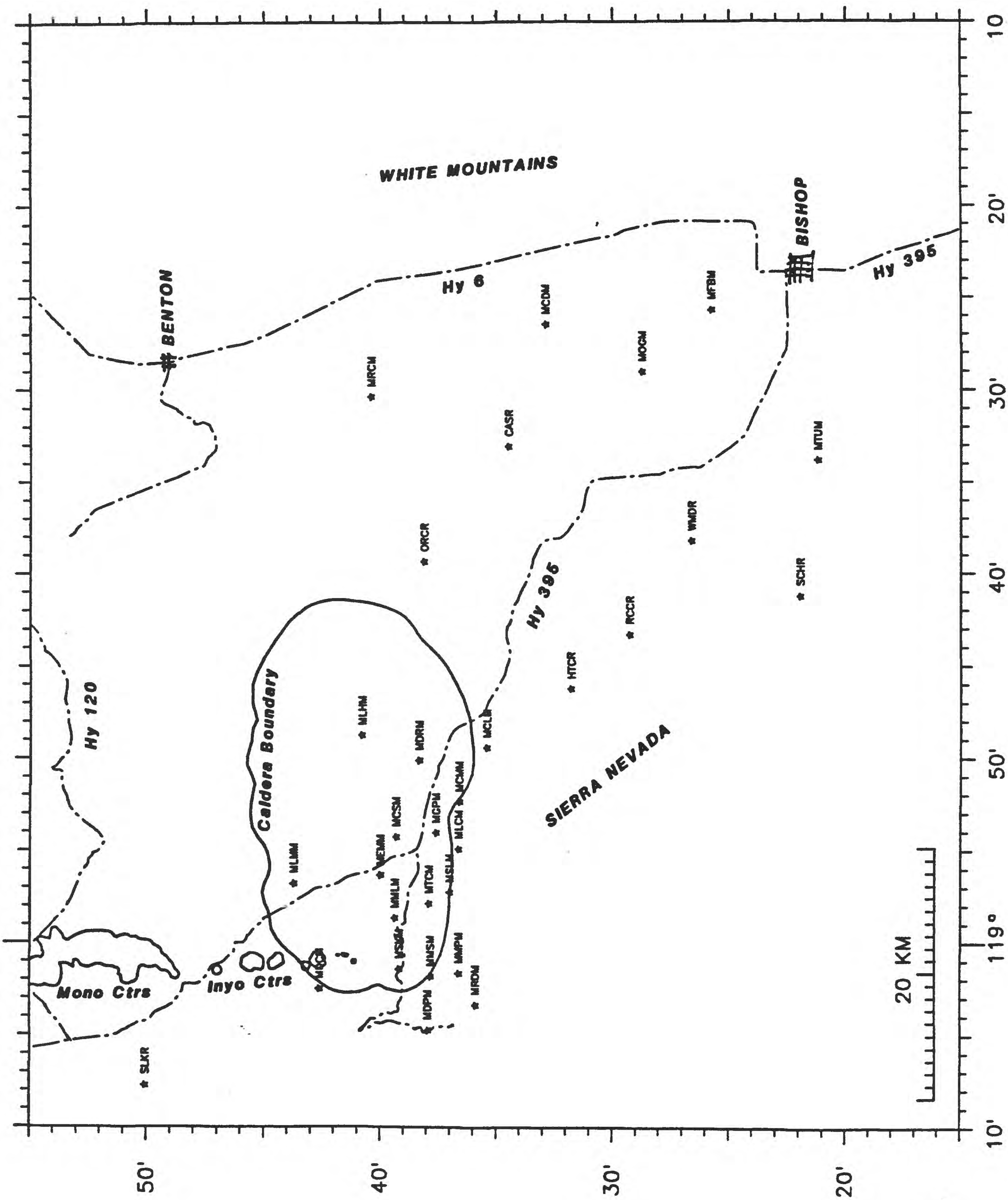
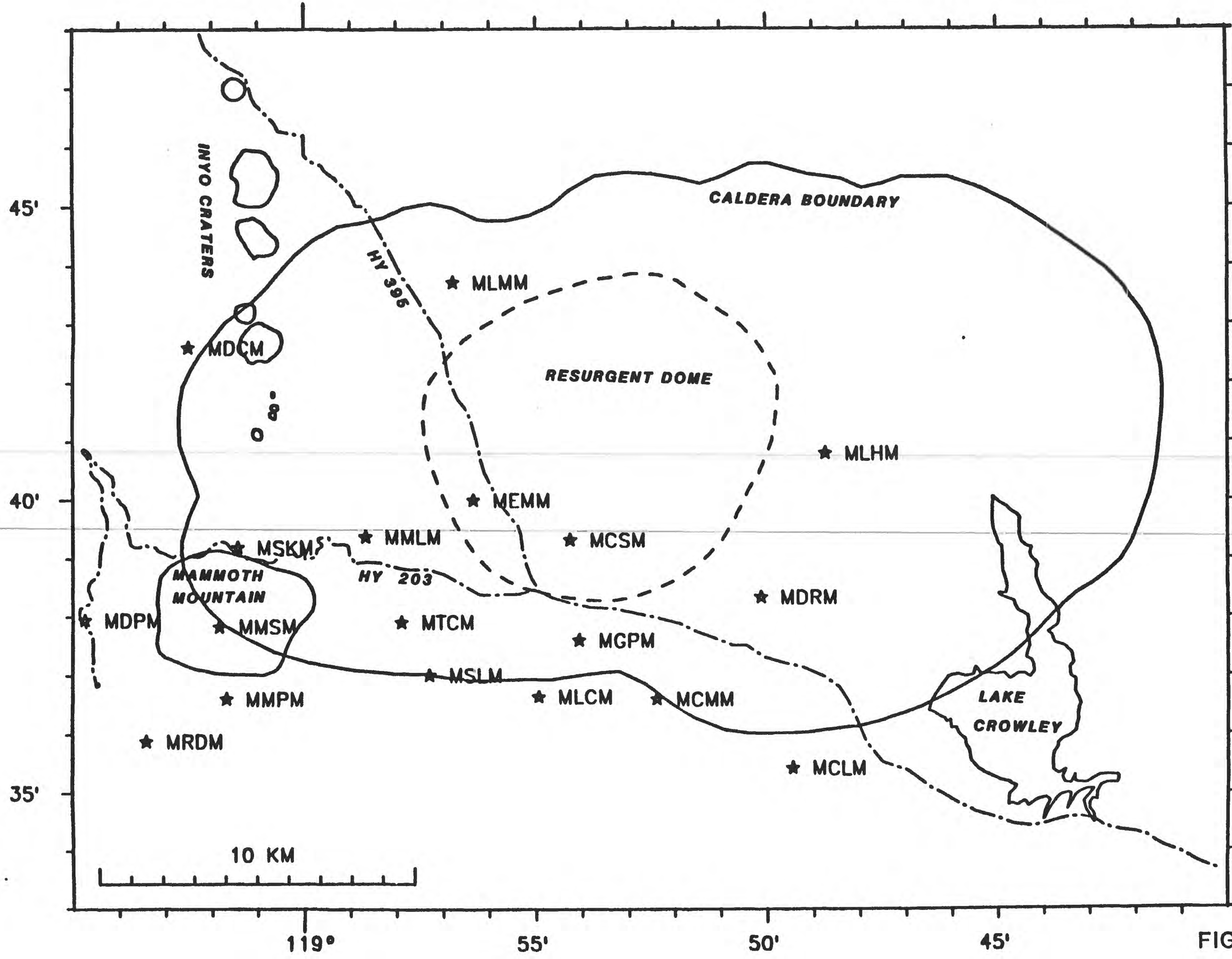

WHITE MOUNTAINS
BENTON
BISHOP
Hy 6
Hy 395
Hy 395
Hy 120
Caldera Boundary
SIERRA NEVADA
Mono Ctrs
Inyo Ctrs
20 KM
MRCM
MCDM
MFBM
MOGM
CASR
MTUM
ORCR
WMDR
SCHR
RCCR
HTCR
MLHM
MDRM
MCSM
MCPM
MCMM
MLMM
MTCM
MLCM
MMPM
MDPM
MROM
SLKR
50'
40'
30'
20'
10
20'
30'
40'
50'
119°
10'

FIGURE C1



45'
40'
35'
119°
55'
50'
45'
INYO CRATERS
CALDERA BOUNDARY
RESURGENT DOME
HY 395
HY 203
MAMMOTH MOUNTAIN
LAKE CROWLEY
MLMM
MDCM
MLHM
MEMM
MMLM
MSKM
MCSM
MDRM
MDPM
MMSM
MTCM
MGPM
MSLM
MLCM
MCMM
MMPM
MRDM
MCLM
10 KM

FIGURE C2

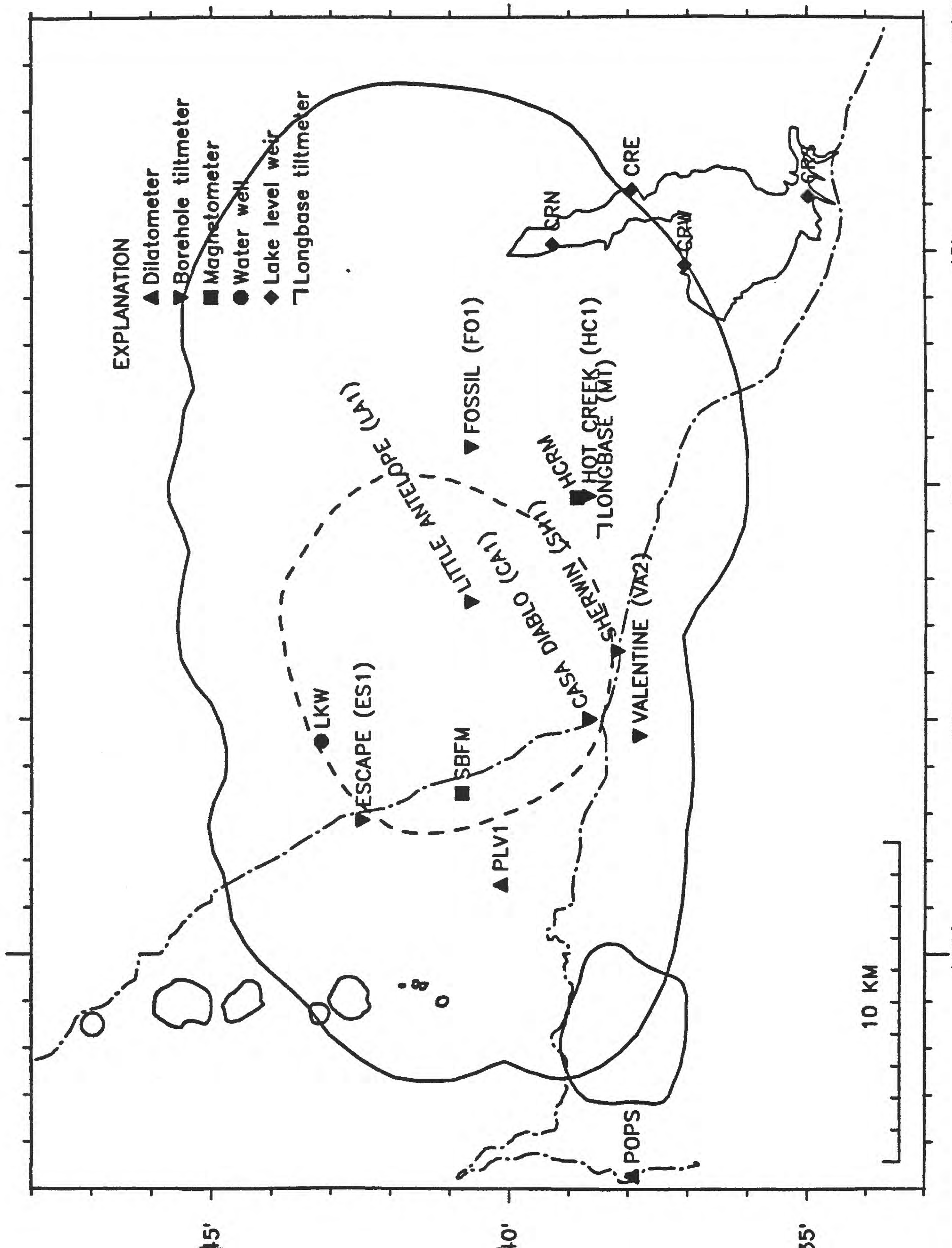

EXPLANATION
Dilatometer
Borehole tiltmeter
Magnetometer
Water well
Lake level weir
Longbase tiltmeter
FOSSIL (FO1)
LITTLE ANTELOPE (LA1)
HOT CREEK (HC1)
LONGBASE (MT)
HCRM
CASA DIABLO (CA1)
SHERWIN (SH1)
VALENTINE (VA2)
LKW
ESCAPE (ES1)
SBFM
PLV1
POPS
CRN
CRE
CRW
10 KM
45'
50'
55'
119°
40'
35'

FIGURE C3

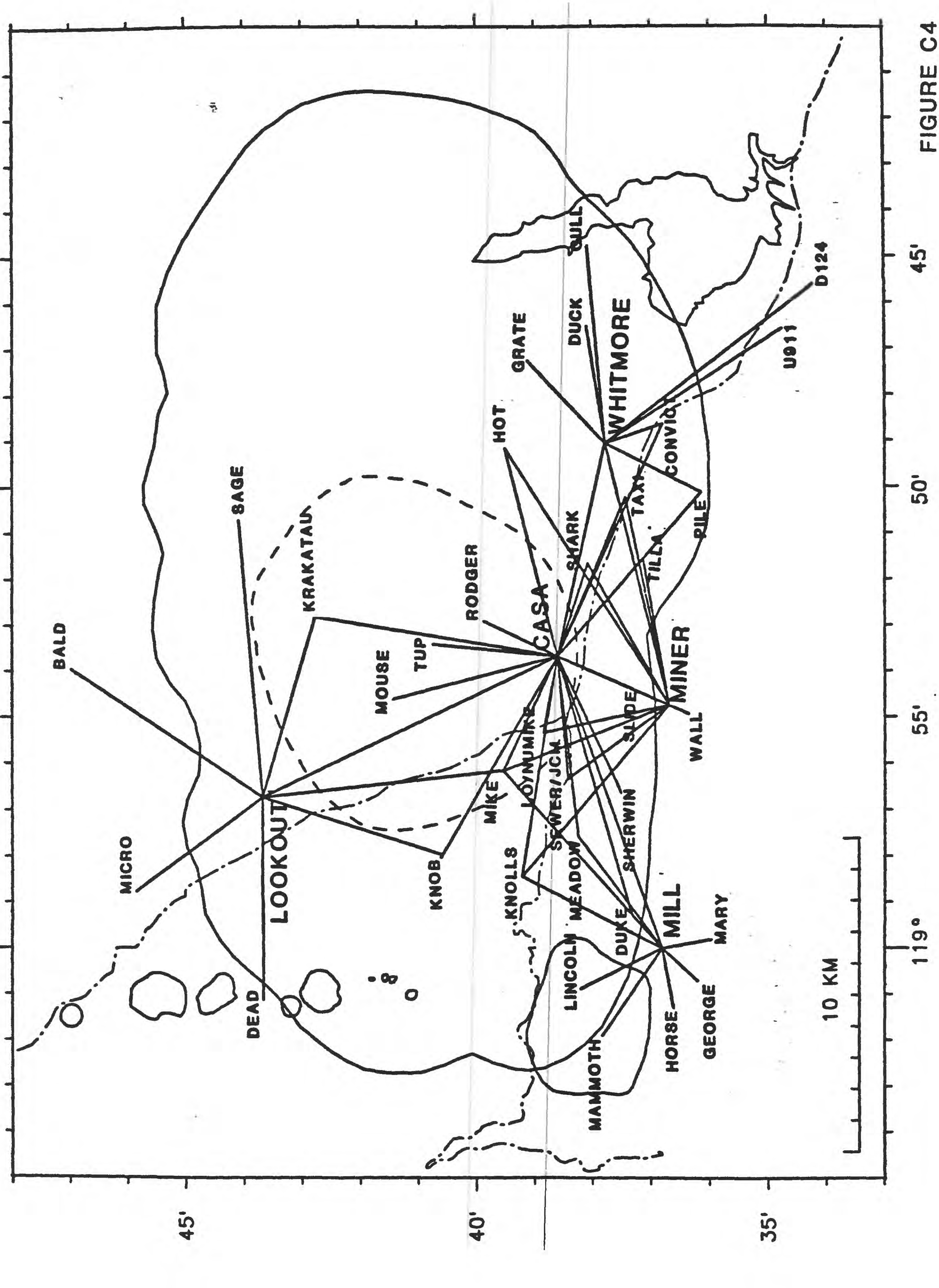

BALD
SAGE
KRAKATAU
RODGER
HOT
GRATE
DUCK
GULL
WHITMORE
CONVICT
TAXI
PILE
SHARK
CASA
TILLA
MINER
WALL
SLIDE
TUP
MOUSE
MIKE
LOOKOUT
MICRO
KNOB
KNOLLS
MEADOW
SHERWIN
DUKE
MILL
MARY
LINCOLN
GEORGE
HORSE
MAMMOTH
DEAD
D124
U911
10 KM
45'
50'
55'
119°
40'
35'

FIGURE C4

GPS STATIONS

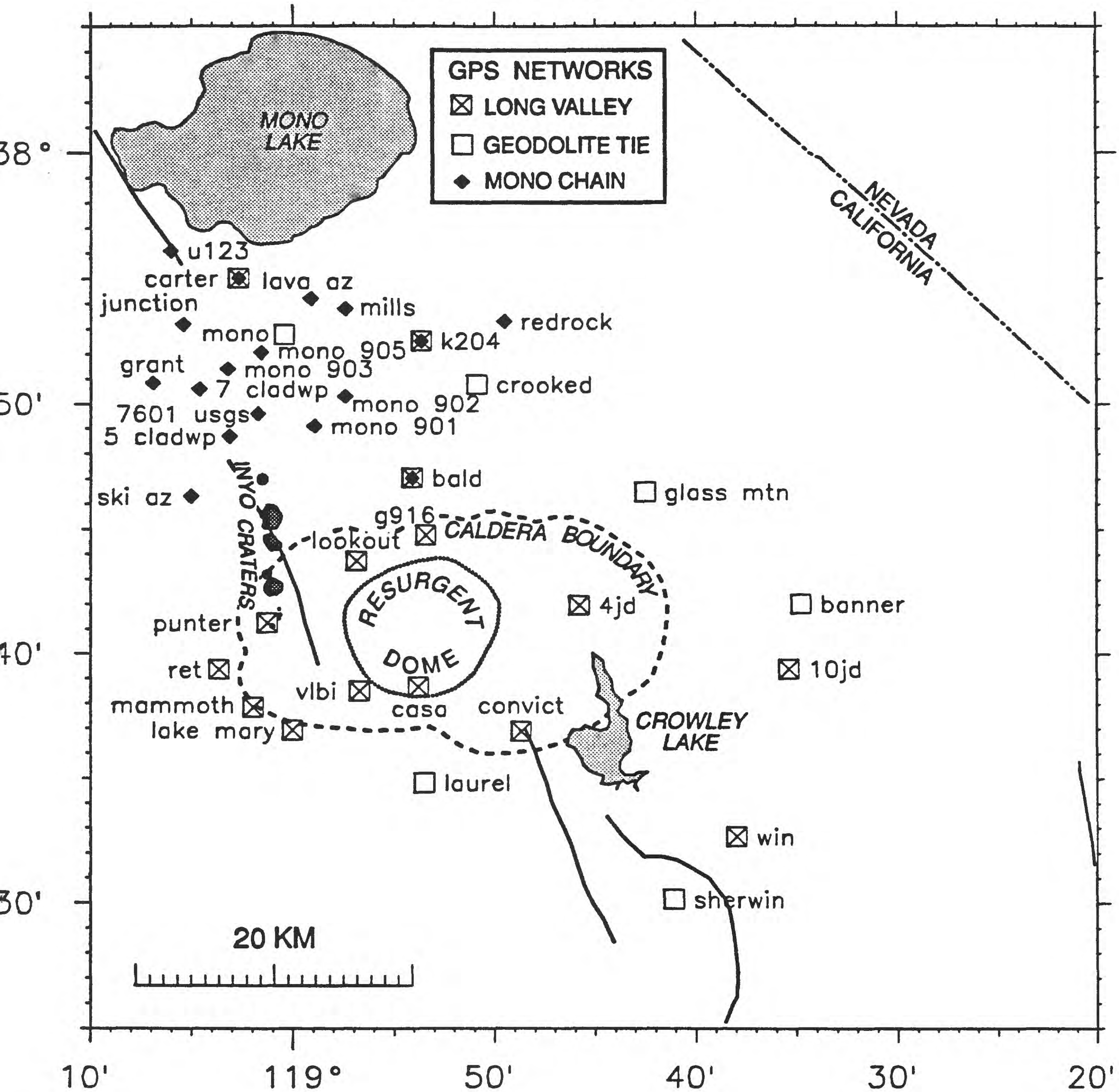


FIGURE C5