U.S. DEPARTMENT OF THE INTERIOR
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DEVELOPMENT OF ALERT CRITERIA FOR FUTURE VOLCANIC UNREST IN LONG VALLEY CALDERA, CALIFORNIA

by

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INTRODUCTION

Long Valley caldera and the Mono-Inyo volcanic chain in eastern California represent one of several youthful volcanic systems in California that pose hazards to adjacent population centers from future volcanic eruptions (Miller, 1989). Recurring earthquake swarms and episodes of ground uplift that have dominated the geologic unrest in Long Valley caldera for the last decade emphasize that the magmatic system beneath this large silicic system is still active and capable of producing further volcanic eruptions (Hill and other, 1985a,b; Rundle and Hill, 1988. To improve communication of scientific information on future episodes of unrest and its significance in terms of potential volcanic hazards posed to local population centers, the U.S. Geological Survey is developing a set of alert criteria for activity in Long Valley caldera and along the Mono-Inyo volcanic chain. These alert criteria and response plans are based on results from geophysical monitoring networks in the area over the last decade as well as on documented premonitory activity for volcanic eruptions elsewhere in the world.

GEOLOGIC SETTING AND RECENT UNREST

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 (see Figure 1). 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.

The region of eastern California that includes Long Valley caldera has been a persistent source of volcanic activity over the last 3 my (Bailey and others, 1976). Long Valley caldera itself was formed approximately 720,000 years ago with the catastrophic eruption of more than 600 km^3 of rhyolitic lavas (the Bishop tuff) and simultaneous collapse of an elliptically-shaped basement block 1 to 2 km into the partially evacuated magma chamber. Numerous smaller eruptions from widely distributed vents in the western section of the caldera continued over the next 600,000 years. Beginning about 40,000 years ago, volcanic activity shifted to the Mono-Inyo Craters volcanic chain (Figure 1). The most recent eruptions in the region occurred at the north end of the Mono Craters about 600 years ago (Bursik and Sieh, 1989) and along the south end of the Inyo Craters within Long Valley caldera (Miller, 1985) about 550 years ago. In both cases, the eruptions resulted from the intrusion of an 8-10 km-long, north-striking silicic 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 Paoha Island (Lajoie, 1968; Stein, 1987).

Historically documented unrest within Long Valley caldera has developed in two episodes separated by five years of relative quiescence. (The earliest settlers of European descent arrived in eastern California in the mid-1800's and the instrumental record for local earthquakes dates from the early 1930's.) The initial and strongest unrest began in 1979 and persisted through mid 1984 with recurring earthquake swarms (including the May 1980 sequence of four $M \approx 6$ earthquakes and the January 1983 swarm that included two $M \approx 5.2$ events) accompanied by a cumulative uplift of the resurgent dome by nearly 50 cm (Hill and others, 1985a,b; Rundle and Hill, 1988). Five years of relative quiescence within the caldera followed (mid-1984 through mid-1989) characterized by relatively slow inflation of the resurgent dome (approximately 1 microstrain per year; Langbein, 1989; Savage, 1989) accompanied by occasional small earthquakes. Strong activity continued in the region, however, with a $M = 5.8$ earthquake 20 km south of the caldera in November 1984 and a $M = 6.4$ earthquake 30 km east of the caldera in July 1986 (see Figure 2).

The second and most recent episode of unrest within the caldera began with a swarm of small earthquakes under Mammoth Mountain on the southwest rim of the caldera in early May 1989 that persisted to the end of the year. This swarm appears to have been associated with a dike-like intrusion at depths between 6 to 10 km beneath Mammoth Mountain (Figure 3; 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 (rapid-fire bursts of small earthquakes with overlapping coda).

Inflation of the resurgent dome increased abruptly in late September 1989 with strain rates increasing from less than a microstrain per year through mid-1989 to over 5 microstrain per year as revealed by frequent measurements of the two-color geodimeter trilateration network (Figure 4). In mid-December, nearly two months after the onset of increased inflation, earthquake swarm activity resumed in the south moat and southern margin of the resurgent dome just as the Mammoth Mountain activity gradually tailed off. This renewed south moat swarm activity showed much the same spatial distribution as the 1981-84 earthquake swarms (see Figure 2). The activity rates peaked during February and early March reaching 100 to 300 $M \geq 0.5$ events per day with the largest events in the M 3.0 – 3.5 range. Both the extensional strain rate and earthquake swarm rate have gradually slowed over the spring and summer months of 1990.

This pattern of episodic unrest characterized by months to years of recurring earthquake swarms and rapid inflation separated by years to decades of relative quiescence (with gradual uplift or partial subsidence) appears to be typical of large calderas. Three other large calderas (Campi Flegrei caldera, Italy; Rabaul caldera, New Guinea; and Yellowstone caldera, Wyoming) have shown similar patterns of unrest over the last two decades, and to date, none of the unrest episodes has culminated in a volcanic eruption (Newhall and Dzurisin, 1988). Developing alert criteria for future activity at these calderas that will reliably indicate whether a developing episode of unrest is likely to culminate in an eruption or another extended period of quiescence represents a difficult challenge. The 1989 "Off-Ito" eruption just east of the Izu Peninsula in Japan provides some important clues to this problem, and we will incorporate results from Japanese studies of this eruption in our alert criteria. Unrest along the Izu Peninsula has much in common with that at Long Valley caldera including 1) distributed volcanic centers, 2) development of a dome-shaped uplift over a decade or more, 3) recurring earthquake swarms, and 4) large (M 6-7) strike-slip earthquakes in the immediate region.

ALERT THRESHOLDS.

The alert criteria being developed for activity in Long Valley caldera follow the five-level, lettered system established for the Parkfield earthquake prediction experiment (Bakun and others, 1987). N is the "normal", or background, level, and an increase in alert level from E through A correspond to an increasing threat that activity will culminate in an eruption. Level A corresponds to the strong possibility that the activity will culminate in an eruption within hours to a week or so (the prediction of a volcanic eruption) and triggers a formal GEOLOGIC HAZARD WARNING.

Because the most recent eruptions in the region occurred 500 to 600 years ago, we have neither historic or instrumental records on the particular patterns of activity that preceded eruptions in Long Valley caldera or along the Mono-Inyo volcanic chain. Accordingly, the activity associated with each alert level is based on a combination of premonitory activity to eruptions on well-monitored volcanoes elsewhere in the world and on the multiple episodes of unrest in Long Valley caldera that followed the four $M = 6$ earthquakes in May, 1980. For the same reason, 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 of the alert levels and will attempt to make them once sufficient data are available. In the meantime, however, we plan to use the alert levels specified in Table 1 to guide our (USGS) response to future episodes of geologic unrest within Long Valley caldera and along the Mono-Inyo volcanic chain.

Prompt recognition of changes in activity and rapid assessment of the activity in terms of alert levels requires an essentially continuous stream of reliable data that is available in real time. The instrumentation currently operating in Long Valley caldera that fulfills this monitoring requirement includes a telemetered seismic network, four telemetered strain-monitoring networks, and a geodetic (trilateration) network that is measured several times a week using a two-color geodimeter. We have developed preliminary alert criteria for each of these monitoring networks and a set of rules for combining the alert levels obtained for each network to decide the final alert level indicated in Table 1. The alert criteria for the seismic network are given in Table 2 as an example. (Note that we use lower case letters to specify alert levels derived from a given monitoring network and upper case letters for the final alert level used in Table 1.)

Two important issues of judgement must be kept in mind with the alert criteria being developed for the monitoring networks as illustrated in Table 2:

1) Because we have yet to witness an eruption in Long Valley caldera, we may not have anticipated all significant variations in activity patterns that might precede an eruption. We must be prepared to incorporate unexpected variations in activity within the system of alert levels as the activity develops.

2) Numbers for activity rates, magnitudes, etc. associated with each alert level are approximate; they are intended as rough quidelines only. It is important to bear in mind, for example, that initial estimates of earthquake magnitudes may be uncertain by a quarter of a magnitude unit, and that adverse conditions (high winds, noisy telemetry, dead stations, etc.) could reduce the activity rate reported by the real-time processor by 10-20% or more.

RESPONSE

Figure 5 illustrates the organizational structure for USGS response to activity in the Long Valley-Mono Craters area. The role of this organization depends on the alert level in effect. Under B- or A-LEVEL ALERTS and an EVENT RESPONSE (see Figure 6), this organization has authority from the Director of the USGS to direct all USGS activities concerning the response. During periods of normal activity or E- through C-LEVEL ALERTS, 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.

The U.S. Geological Survey response to specific ALERT LEVELS listed in Table 1 is as follows:

[1] *ALERT LEVELS 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 C-, D-, or E-LEVEL ALERTS make the appropriate advisory calls (Figure 6).

[2] *ALERT LEVEL B. Declaration of EVENT RESPONSE:* If, upon evaluation of the data and consultation with the available 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 of OEVE (Office of Earthquakes Volcanoes, and Engeneering) declare EVENT RESPONSE conditions. Such a declaration will trigger the establishment of a field center in Mammoth Lakes within the caldera (see below). USGS, local, state, and federal officials will be notified of this decision through the B-level call-down procedure (see Figure 6).

[3] *ALERT LEVEL A. GEOLOGIC HAZARD WARNING:* If, upon evaluation of the data and consultation with available 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 declare an A-LEVEL ALERT and, with concurrence of the Chief of OEVE, recommend that the Director declare a formal 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 center for field operations from Mammoth Lakes to Bridgeport.

In the case of an A- or B-LEVEL ALERT, 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 center 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 (60 km north of the caldera) 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.

CONCLUSIONS

Developing alert criteria for the possible onset of volcanic eruptions from a large caldera that has not erupted in historic time is a difficult problem laced with uncertainties. Without well documented case histories from previous eruptions in the caldera, we must rely on descriptions of activity documented before eruptions elsewhere in the world and on the patterns of unrest shown by other large calderas. Large calderas seem to pose a special problem because, as we have learned from several examples in the last 20 years, they are capable of recurring episodes of intense unrest separated by years or decades of quiescence without producing an eruption. In spite of the difficulties and attendant uncertanties, however, some form of staged alert criteria keyed to various levels of unrest must be established as a framework for developing emergency response plans. Such criteria are especially important as a means of establishing and maintaining clear communication between scientists monitoring the volcanic system and civil authorities responsible for protecting local population centers from the hazards posed by a possible volcanic eruption.

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FIGURE CAPTIONS

FIGURE 1. Location and geologic setting of Long Valley caldera and the Mono-Inyo volcanic chain (from Hill et al., 1985a).

FIGURE 2. Earthquake epicenters in the Long Valley caldera region from 1978 through 1986. Earthquakes in the region through mid-1990 continue to be restricted to essentially the same areas active from 1978-1986.

FIGURE 3. Seismicity map and depth sections for the 1989 Mammoth Mountain earthquake swarm: (a) epicentral map: +, events in May and June; x, events in July; O, events in August; (b) depth section with hypocenters in (a) projected onto the plane A-A'; (c) depth section with hypocenters projected onto the plane B-B'; (d) T-axis orientations of 303 focal mechansims determined for well-recorded swarm earthquakes (from Hill et al, 1990).

FIGURE 4. Extensional deformation across the resurgent dome in Long Valley caldera based on two-color geodimeter measurements from mid-1983 through mid-1990; (a) map showing two-color geodimeter trilateration network with instrument sites at CASA, MINER, WHITMORE, LOOKOUT, and MILL; (b) line-length changes from the instrument site CASA (see Langbein, 1989).

FIGURE 5. Block diagram of structure for the USGS response to potential volcanic hazards in the Long Valley-Mono Craters area, California.

FIGURE 6. Block diagram of decision flow for determining alert levels and response activities for varying levels of unrest in the Long Valley-Mono Craters region.

TABLE 1. ALERT LEVELS

ALERT LEVEL[1]	USGS RESPONSE[2]	ACTIVITY LEVEL	RECURRENCE INTERVALS[3]
A	Issue GEOLOGIC HAZARD WARNING	ERUPTION LIKELY within hours to days	decades to centuries
B	Alert Director, Trigger EVENT RESPONSE	intense unrest	years to decades
C	Alert Office Chief, OES Hdqtrs. State Geologist	strong unrest	months to years
D	Alert Team Leaders, Branch Chiefs, OES comm., USFS, CDMG, & UNR	moderate unrest	weeks to months
E	Alert 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 weighted combination of alert levels for individual monitoring networks including the seismic alert level illustrated in Table 2.

[2] USGS RESPONSE for a given alert level will include the responses specified for all lower alert levels.

[3] estimated RECURRENCE INTERVALS for a given alert level 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.

TABLE 2. SEISMIC ALERT LEVELS[1].

Seismic Alert Level	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	≥ 1 $M \geq 5$ event, ≥ 5 $M \geq 4$ events/day, ≥ 25 $M \geq 3$ 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-level alert 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 $M \geq 4$ event, ≥ 5 $M \geq 3$ events/day, or ≥ 25 $M \geq 2$ events/day. OR >30 RTP events/hr sustained for 4 or more hrs, or >300 RTP events/day. OR >10 $M \geq 1$ 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 alert 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 $M \geq 3$ events/day, or >5 $M \geq 2.5$ 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 $M \geq 3$ events/day (may be locally felt) OR >20 or more RTP events/hour OR >5 $M \geq 2$ 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

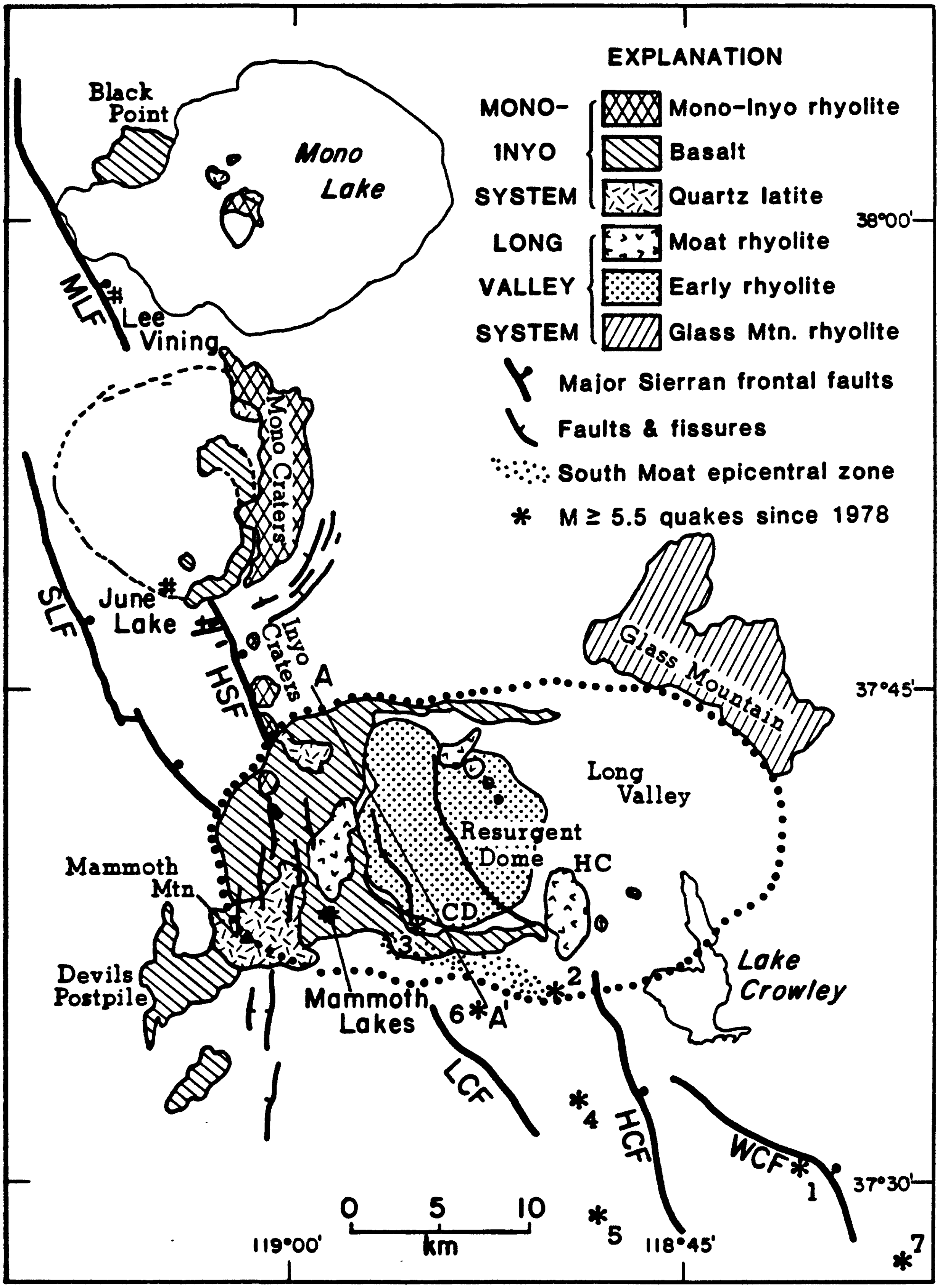

EXPLANATION
MONO-INYO SYSTEM
Mono-Inyo rhyolite
Basalt
Quartz latite
LONG VALLEY SYSTEM
Moat rhyolite
Early rhyolite
Glass Mtn. rhyolite
Major Sierran frontal faults
Faults & fissures
South Moat epicentral zone
M ≥ 5.5 quakes since 1978
Black Point
Mono Lake
MLF
Lee Vining
Mono Craters
SLF
June Lake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

FIGURE 1

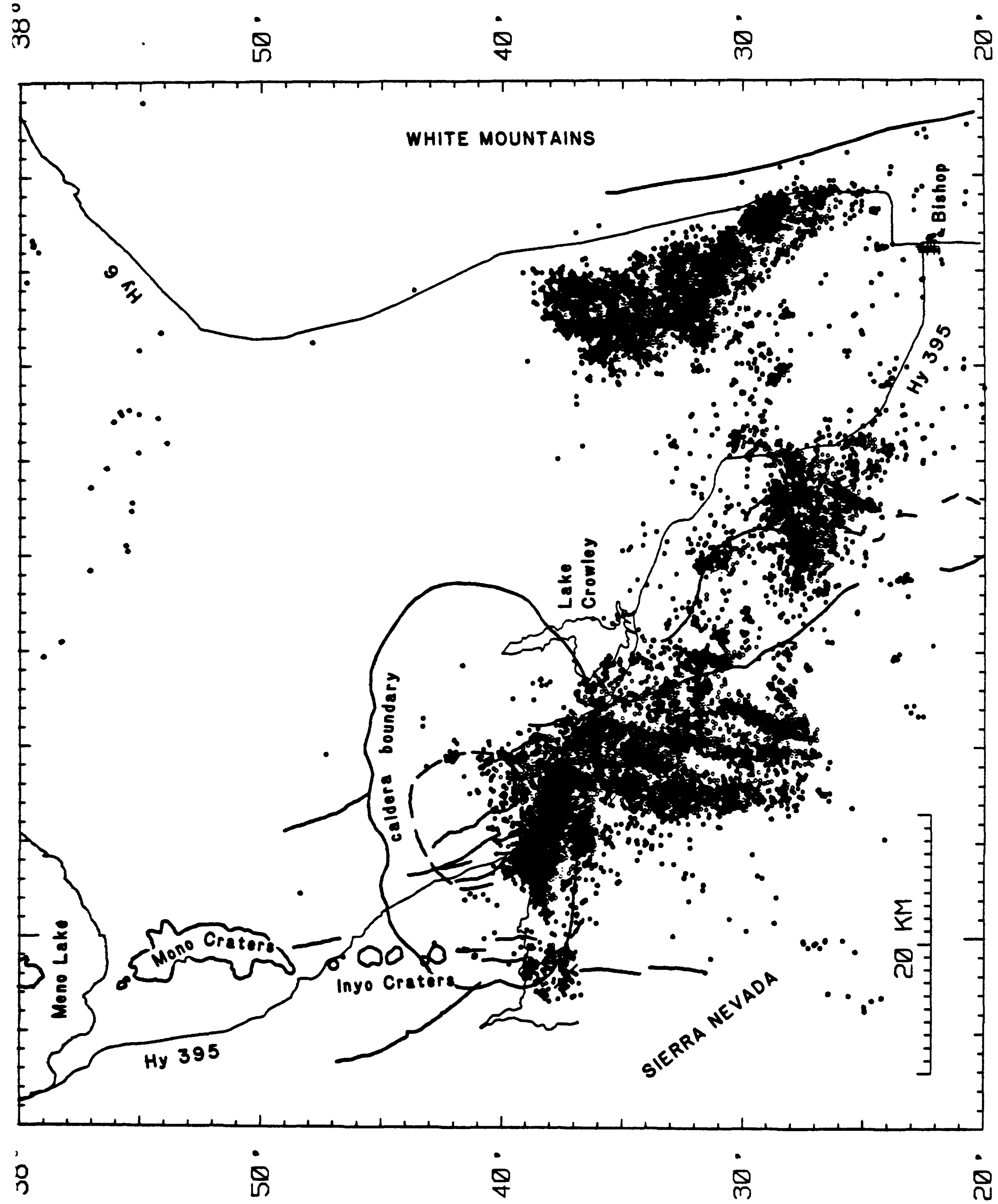
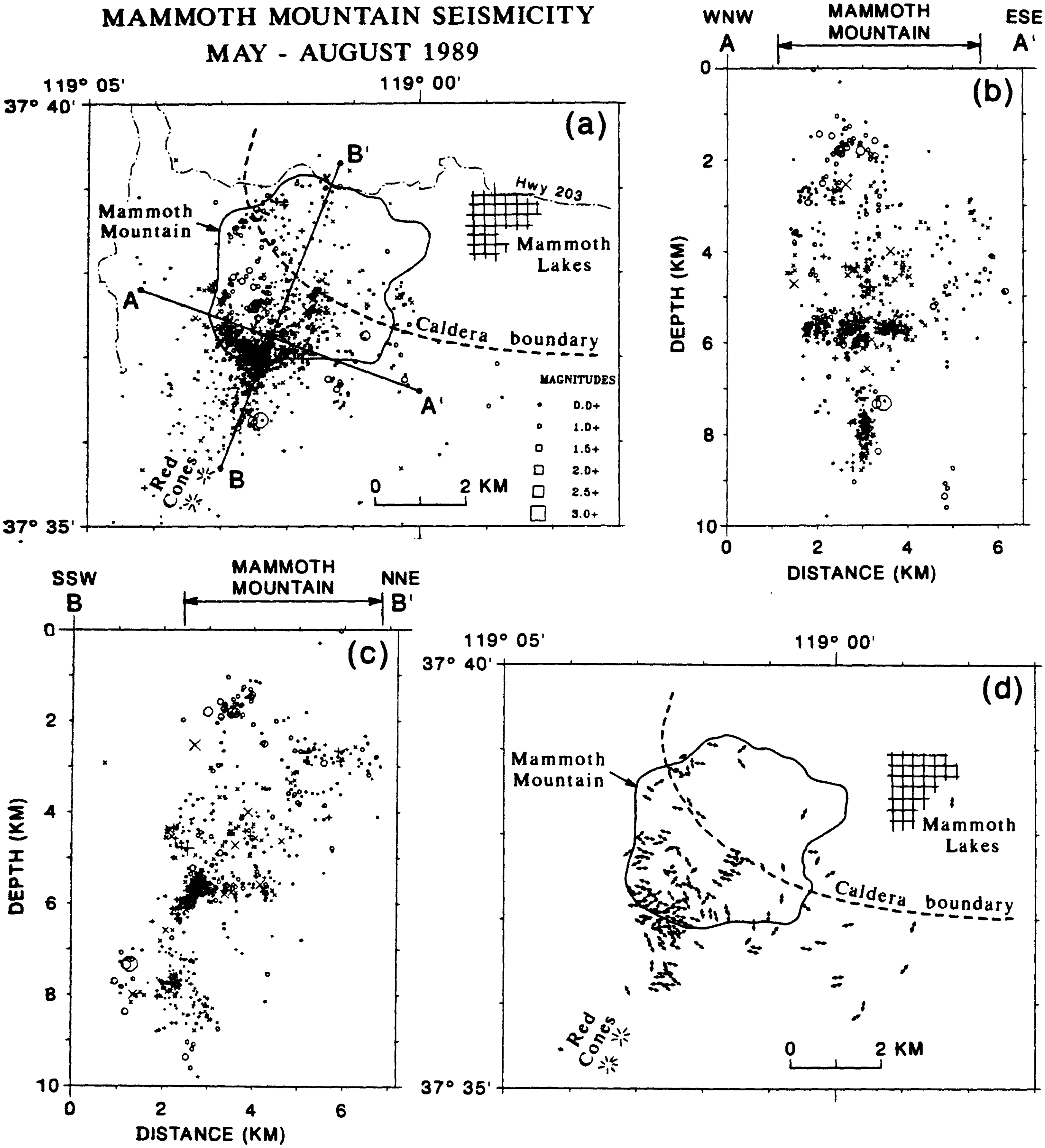
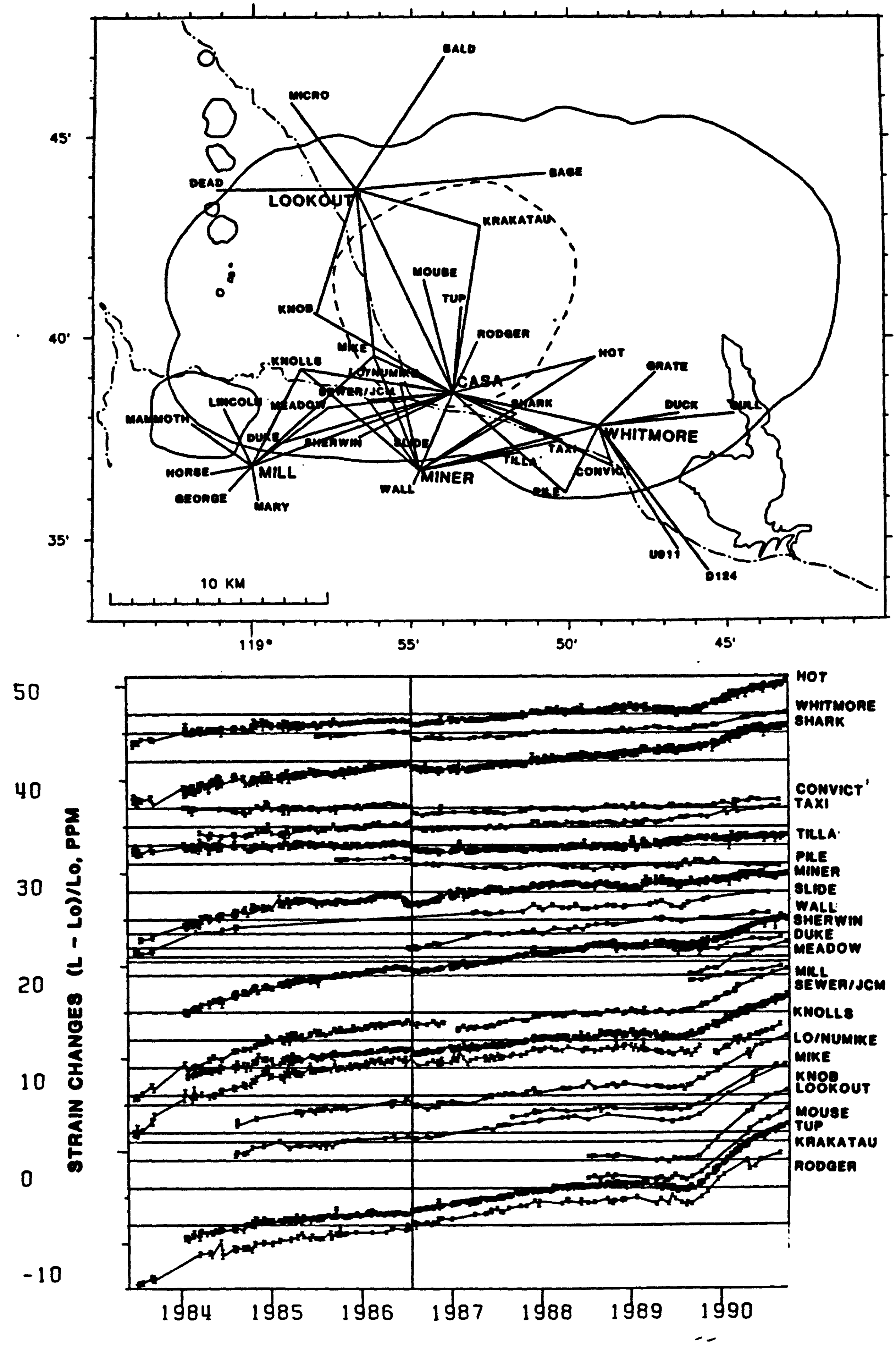

38°
50'
40'
30'
20'
WHITE MOUNTAINS
Hy 6
Bishop
Hy 395
Lake Crowley
caldera boundary
Mono Lake
Mono Craters
Inyo Craters
Hy 395
SIERRA NEVADA
20 KM
20'
30'
40'
50'
119°
10'

FIGURE 2



MAMMOTH MOUNTAIN SEISMICITY
MAY - AUGUST 1989
119° 05'
119° 00'
37° 40'
37° 35'
(a)
Mammoth Mountain
Mammoth Lakes
Hwy 203
Caldera boundary
A
A'
B
B'
Red Cones
MAGNITUDES
0.0+
1.0+
1.5+
2.0+
2.5+
3.0+
0
2 KM
WNW
A
MAMMOTH MOUNTAIN
ESE
A'
(b)
DEPTH (KM)
DISTANCE (KM)
SSW
B
MAMMOTH MOUNTAIN
NNE
B'
(c)
DEPTH (KM)
DISTANCE (KM)
(d)
Mammoth Mountain
Mammoth Lakes
Caldera boundary
Red Cones
0
2 KM

FIGURE 3



BALD
MICRO
45'
DEAD
SAGE
LOOKOUT
KRAKATAU
MOUSE
TUP
KNOB
RODGER
40'
MIKE
HOT
KNOLLS
GRATE
LO/NUMIKE
CASA
SEWER/JCM
LINCOLN
MEADOW
SHARK
DUCK
BULL
MAMMOTH
WHITMORE
DUKE
SHERWIN
SLIDE
TAXI
TILLA
HORSE
MILL
MINER
CONVICT
GEORGE
WALL
PILE
MARY
35'
U911
D124
10 KM
119°
55'
50'
45'
STRAIN CHANGES (L - Lo)/Lo, PPM
50
40
30
20
10
0
-10
1984
1985
1986
1987
1988
1989
1990
HOT
WHITMORE
SHARK
CONVICT
TAXI
TILLA
PILE
MINER
SLIDE
WALL
SHERWIN
DUKE
MEADOW
MILL
SEWER/JCM
KNOLLS
LO/NUMIKE
MIKE
KNOB
LOOKOUT
MOUSE
TUP
KRAKATAU
RODGER

FIGURE 4

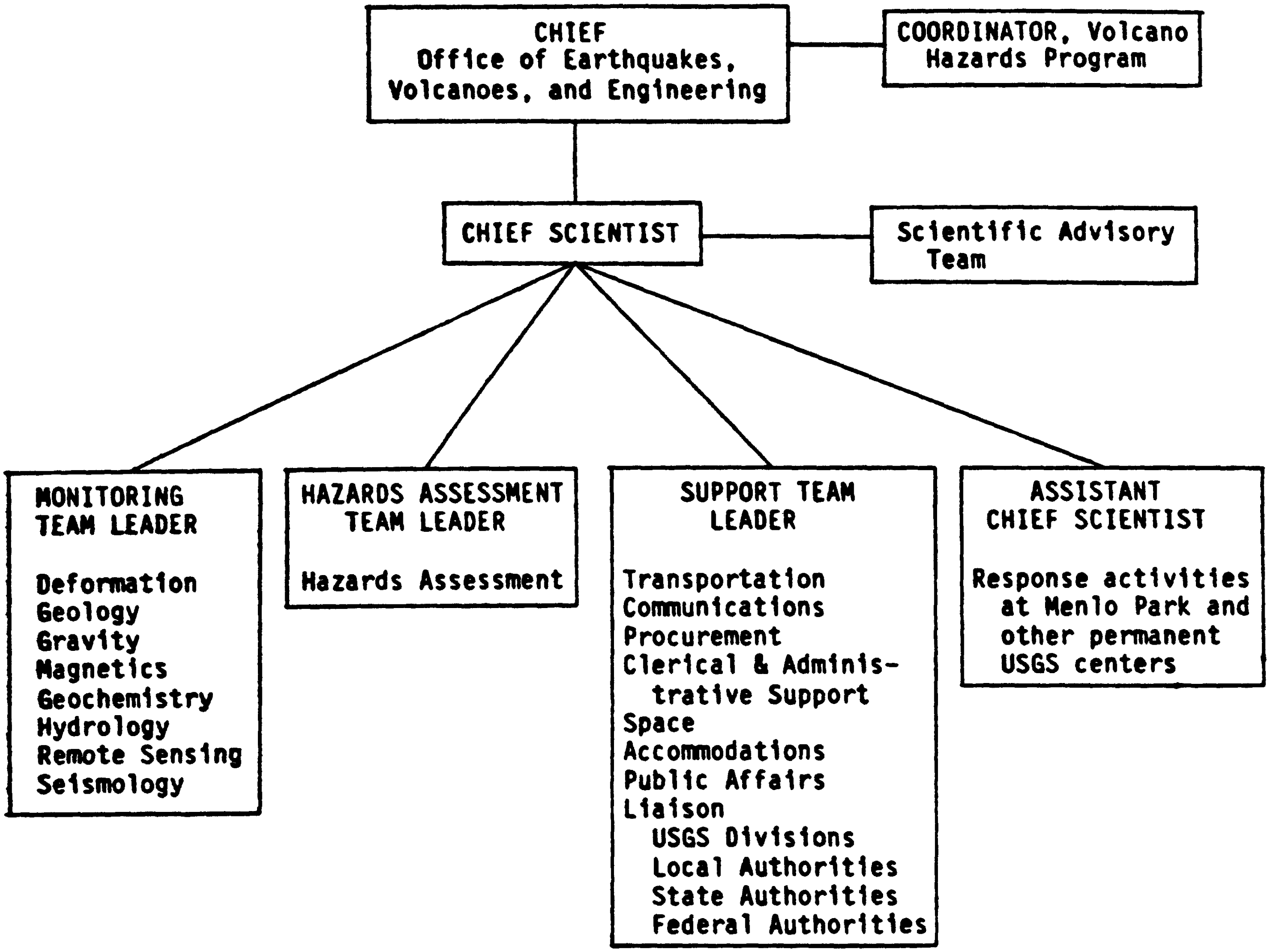

CHIEF
Office of Earthquakes, Volcanoes, and Engineering
COORDINATOR, Volcano Hazards Program
CHIEF SCIENTIST
Scientific Advisory Team
MONITORING TEAM LEADER
Deformation
Geology
Gravity
Magnetics
Geochemistry
Hydrology
Remote Sensing
Seismology
HAZARDS ASSESSMENT TEAM LEADER
Hazards Assessment
SUPPORT 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 5

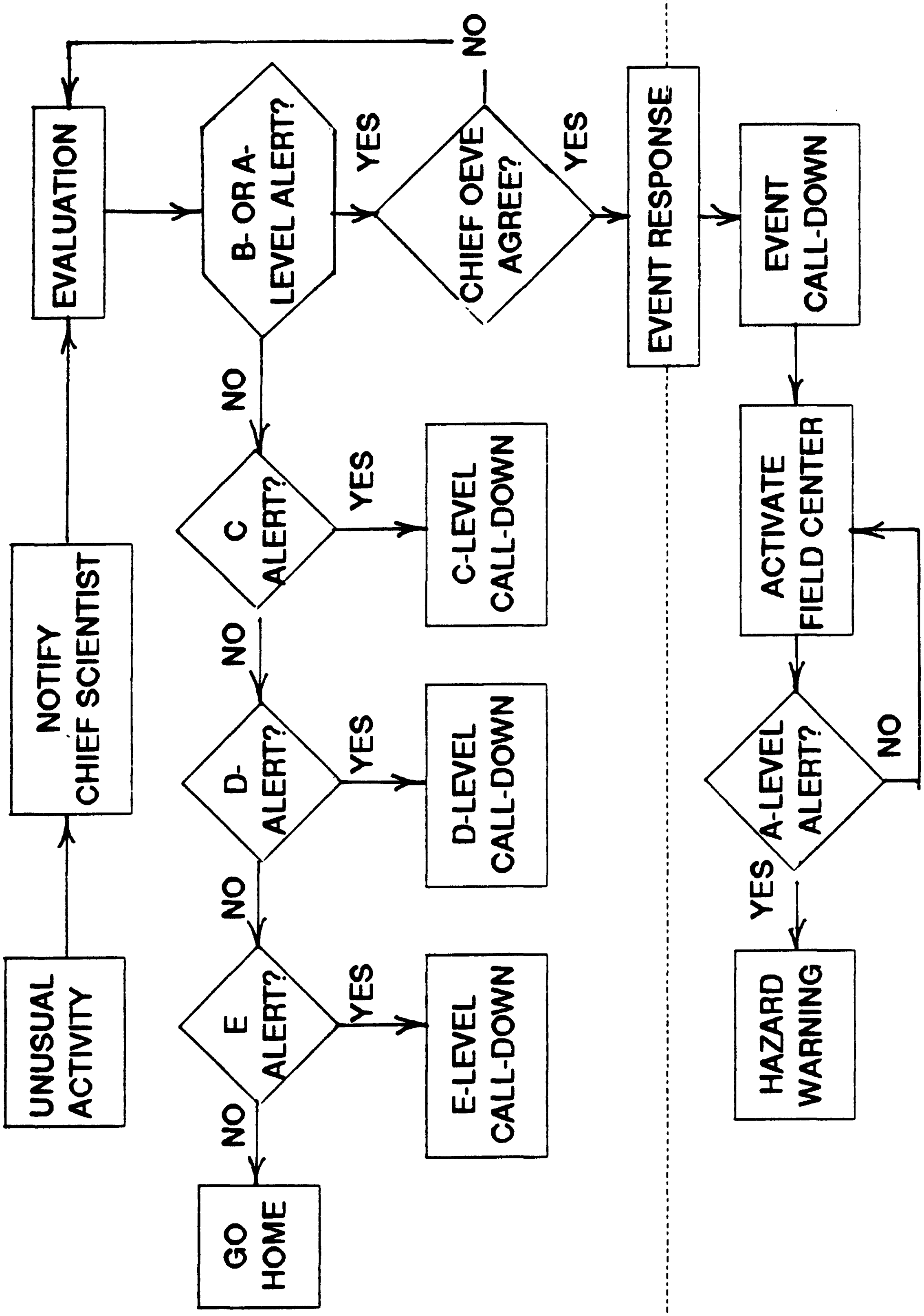

UNUSUAL ACTIVITY
NOTIFY CHIEF SCIENTIST
EVALUATION
B- OR A-LEVEL ALERT?
YES
NO
CHIEF OEVE AGREE?
YES
NO
EVENT RESPONSE
EVENT CALL-DOWN
ACTIVATE FIELD CENTER
A-LEVEL ALERT?
YES
NO
HAZARD WARNING
C ALERT?
YES
C-LEVEL CALL-DOWN
NO
D-ALERT?
YES
D-LEVEL CALL-DOWN
NO
E ALERT?
YES
E-LEVEL CALL-DOWN
NO
GO HOME

FIGURE 6