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Proceedings of the
Workshop on Geophysical Modeling of
The Long Valley Caldera

Lawrence Berkeley Laboratory
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Berkeley, California
February 8–9, 1984

July 1984

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Wannamaker

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WORKSHOP ON GEOPHYSICAL MODELING OF THE LONG VALLEY CALDERA

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N.E. Goldstein, Editor

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INTRODUCTION

A workshop was hosted by the Earth Sciences Division of the Lawrence Berkeley Laboratory on 8-9 February 1984 to review critically and to integrate the results of geophysical investigations made in the Long Valley area since 1980 and to attempt to reach a consensus, including present uncertainties and outstanding issues, on the key elements of a geophysical model for the caldera. The workshop not only concentrated on the analysis and interpretations of geophysical data but also on the significance of results obtained to questions of Sierran Front tectonics, caldera evolution and structure, past and current hydrothermal processes, and recent magma movement.

This workshop differed from other Long Valley caldera workshops, meetings, and symposia of recent years in that participation was limited to the relatively few scientists from national laboratories, the U.S. Geological Survey, and universities who have been directly involved in data acquisition and interpretation. The workshop was structured to provide adequate time for presentations and thorough discussions that would establish accepted elements of the structure while defining critical issues and that would help formulate an approach for acquiring the complementary geophysical data needed for a better understanding of subsurface conditions beneath this geologically complex area.

The Long Valley caldera (Fig. 1) is one of the most intensively studied geological features in the United States (Bailey et al., 1976; Hermance, 1983). Scientific studies of the hot springs and volcanic history of the caldera began about 40 years ago, and the pace of detailed geological, geophysical, hydrological, and geochemical investigations grew abruptly in 1972-1973 in response to the need for an assessment of the geothermal energy

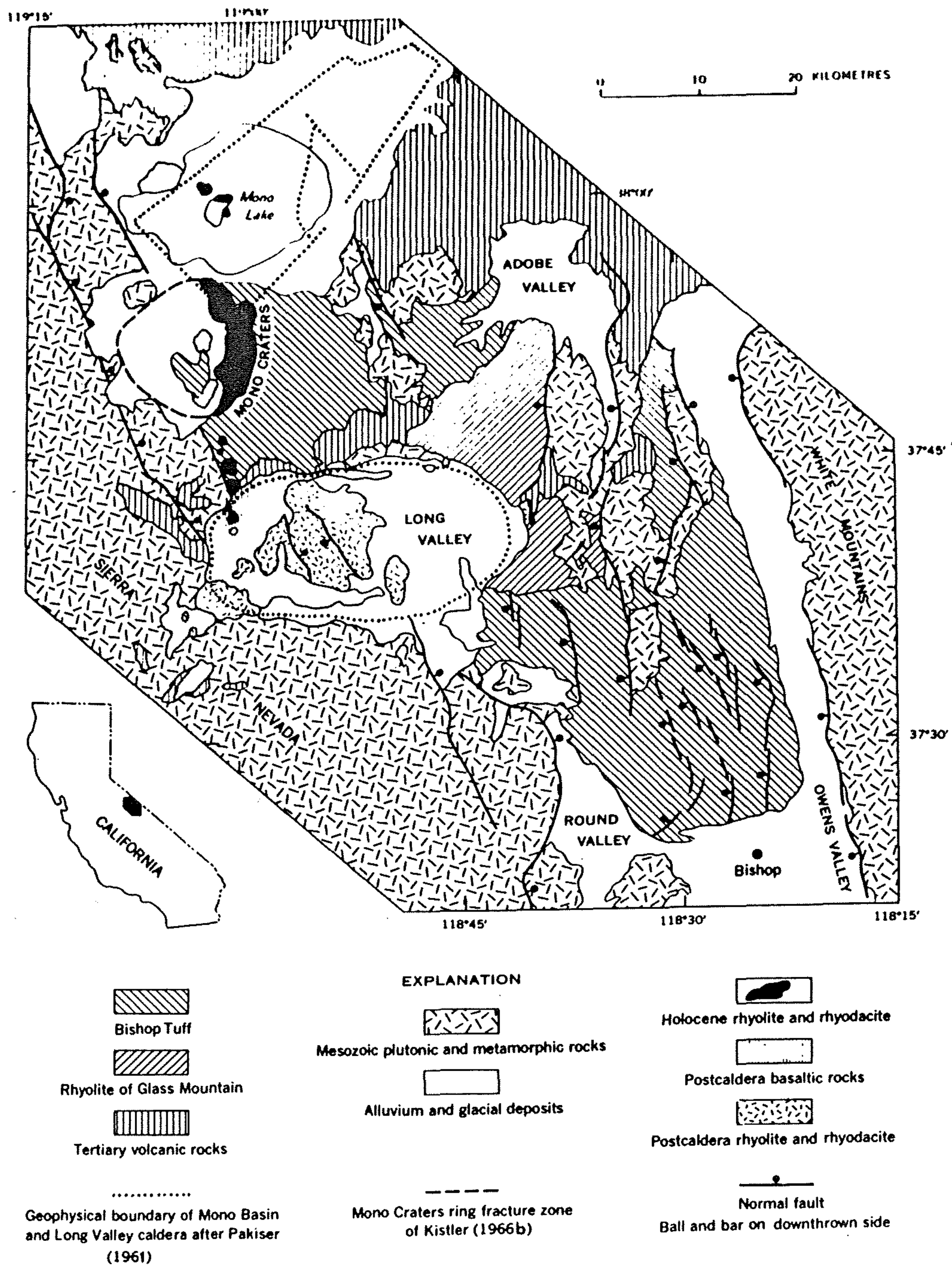


Fig. 1. Location map and generalized geologic map of the Long Valley caldera, Mono craters and Mono Lake basin area, Mono County, California (from Bailey et al., 1976).

potential of the caldera (Muffler and Williams, 1976). Parts of the caldera were declared a Known Geothermal Resource Area (KGRA) and opened to competitive leasing and further exploratory investigations by private developers. This activity has led to the drilling of several deep wells and the planned development of a 75 MW geothermal power plant near Casa Diablo Hot Springs.

In 1979 the Long Valley caldera was one of five sites selected by the Thermal Regimes panel of the Continental Scientific Drilling Committee for review in preparation for proposed drilling into an active hydrothermal-magmatic system for scientific purposes (Kasameyer, 1980; Goff and Waters, 1980; Luth and Hardee, 1980; and White et al., 1980). Similar in some respects to other young silicic calderas in the western U.S., the Long Valley caldera has a history of episodic volcanic activity that began about 1 m.y. ago and has continued to as recently as 500 years ago when a chain of eruptive centers became active along what is called the Inyo fracture zone. Suspicions that there was renewed magma movement from a deeper chamber arose following a series of large magnitude ($M_L \geq 5$) earthquakes and aftershocks in 1980 and the analysis of U.S. Geological Survey (USGS) leveling data. Concern over a possible volcanic eruption caused the USGS to issue in 1982 a "notice of potential volcanic hazard" and to intensify its seismic, deformation, and geochemical monitoring activities within the caldera (Miller et al., 1982). The USGS workers were joined by other scientists from State agencies, universities and DOE laboratories who, supported by the USGS, DOE Geothermal and Hydropower Technologies Division, and DOE Office of Basic Energy Sciences, initiated supplemental surveys and implemented monitoring projects. It was soon recognized that the seismic activity was occurring principally beneath the south moat area, just east of the town of Mammoth Lakes, and beneath the adjacent Sierran block to the south of the caldera.

This area became the main focus of scientific investigations, mainly seismological. Since 1980 a great deal of earthquake-related and refraction seismic data have been collected by many researchers. While this has provided new information and insights into the elastic wave parameters and stress-release processes occurring within the region, the studies have opened scientific debate concerning the fundamental nature of the earthquakes and the degree to which the seismic, gravity, deformation, thermal, and electrical data can detect and delineate the distribution of magma.

Answers to these questions are needed for the volcanic hazards program, for planning future CSDP (Continental Scientific Drilling Program) scientific investigations and for the DOE Magma Energy Extraction Research Program. In a broader sense, scientists are also endeavoring to unravel the volcanic-structural development of the caldera and the relation of Sierran Front and Basin-and-Range tectonics to deformation and possible magma movement.

The Workshop Agenda is given in Appendix 1 and the participants are listed in Appendix 2. The workshop was divided into four sessions:

1) Geological Background and Overview of the Long Valley Hydrothermal-Magmatic System and Processes,
2) Concepts and Models Based on Seismological Data,
3) Concepts and Models Based on Electric and Electromagnetic Data, and
4) Concepts and Models Based on Deformation, Thermal, and Gravity Data.

The workshop's goal was to define points of agreement and disagreement as to the various geophysical data sets and their interpretation, and to point the way to resolution of important outstanding questions.

Rapporteur's summary reports for each session are given in this report.

HYDROGEOLOGICAL BACKGROUND

H.A. Wollenberg, Rapporteur

Caldera Development and the Hydrothermal System

M. Sorey provided an overview of current models for the Long Valley hydrothermal system, stating at the outset that we do not yet have a unique or firm idea of how the system has evolved. The Long Valley caldera (LVC) can be compared to two other young, silicic calderas in the western U.S. with which it shares some common features such as episodes of continued volcanism and active faulting. Table 1 compares the size and current heat discharge of the three volcanic systems. A heat flow of 4 to 5 μcal cm^{-2} s^{-1} could be expected from a magma cooling conductively at a depth of 6 to 8 km.

TABLE 1

Comparison of Three Silicic Volcanic Calderas

Site	Age (m.y.)	Fluid Discharge (kg s^{-1})	Heat Discharge (10^7cal s^{-1})	Heat Flow (μcal cm^{-2} s^{-1})
Yellowstone	0.6	3000	100	50
Valles	~1	35	1.8	12
Long Valley	~0.7	250	7	15

NOTE: The heat flow is the heat discharge (conductive and convective) divided by the effective area.

Present knowledge of the Long Valley hydrothermal system comes mainly from temperature and chemical compositions of hot and cold springs, fumaroles, and shallow wells (Fig. 2). West of the Hilton Creek fault, thermal features occur for the most part along normal faults. East of the Hilton

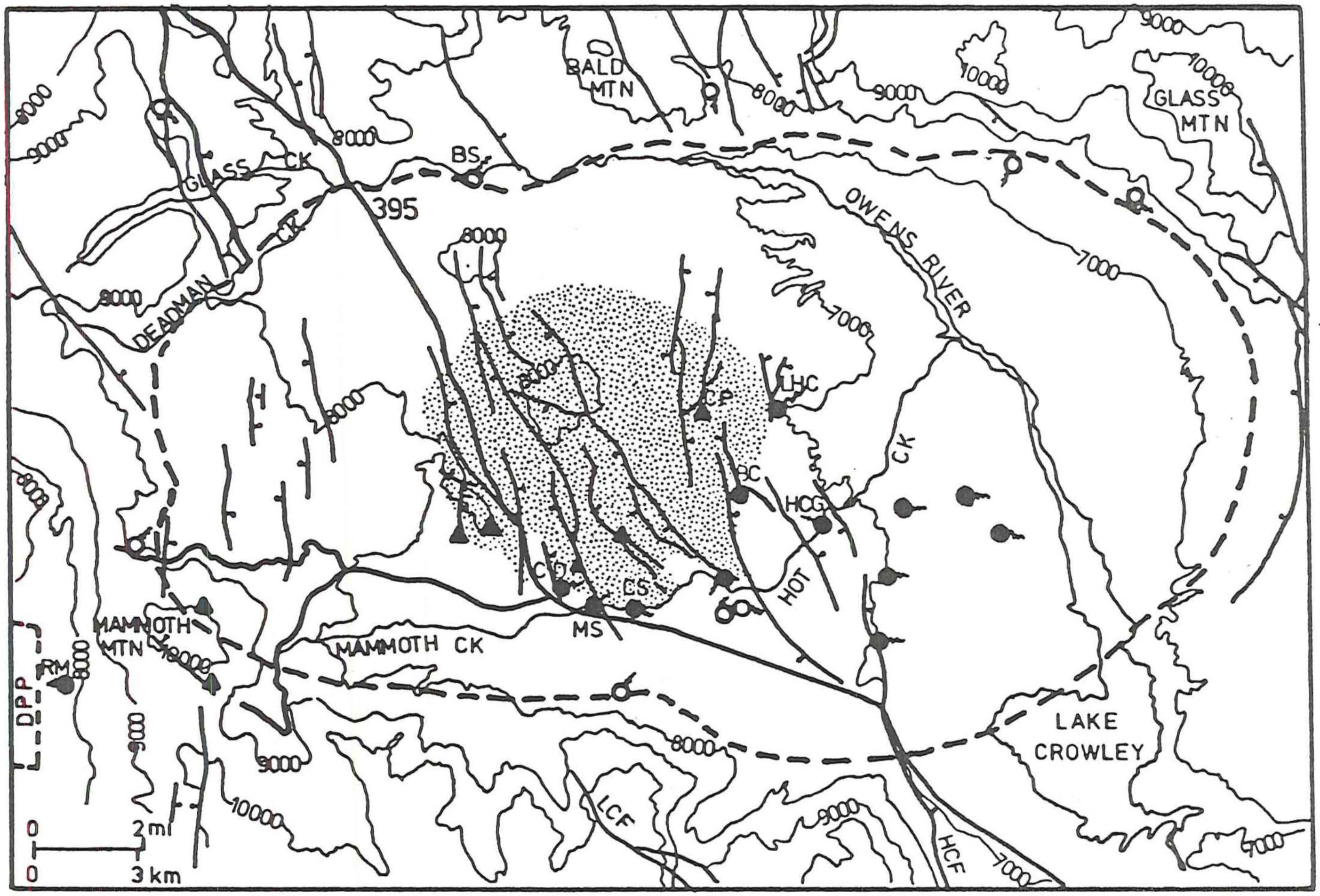


Fig. 2. Map of Long Valley caldera (heavy dashed line outlines caldera floor) showing locations of active thermal springs (filled circles with tails), nonthermal springs (open circles with tails), fumaroles (triangles), and areas of fossil hydrothermal alteration noted in text (CP = Clay Pit, BC = Blue Chert outcrop). Also shown are principal faults with bar and ball on downthrown side (from Bailey and Koeppen, 1977), contours of land-surface altitude (in feet), paved roads (heavy solid lines), and the patterned area encompassing the structural outline of the resurgent dome. HCF denotes the Hilton Creek fault and LCF denotes the Laurel-Convict fault.

Creek fault, the chemistry of thermal springs suggests they are supplied by upward leakage of eastward-moving warm water from caldera-fill sediments. The water at Casa Diablo Hot Springs is highest in Cl, B and As, while springs to the east are successively more dilute. This is in keeping with calculated chemical geothermometer temperatures, which are highest at Casa Diablo, ~240°C, and decrease in springs to the east.

Fumaroles and hot springs at Casa Diablo have temporary variations in discharge that may be associated with earthquake activity in and near Long Valley. A new hot spring (Colton Spring) developed in 1982, 2 km east of Casa Diablo behind the Sheriff's Substation. Presently, this spring has a chloride content similar to the Casa Diablo springs, and while it is not in an area of a known fault, there are signs of previous spring acivity. Areas of past spring activity and hydrothermal alteration occur in the vicinity of the Clay Pit and the blue chert outcrop on the eastern side of the resurgent dome. These areas may have been sites of major discharge ~300,000 years ago.

The youngest heat sources may underlie the western moat area, evidenced by the N-S chain of Inyo craters, containing some vents only a few hundred years old. Small fumarolic zones and warm springs (46°C) on Mammoth Mountain may also be related to a young, shallow heat source.

The evaporite deposits of Searles Lake provide an approximate record of emanation of elements in the Long Valley caldera that can be used to trace the evolution of the hydrothermal system. As described in a paper by Smith (1976) Searles Lake, ~290 km downstream of Long Valley, is considered the sink for the Owens River, and as such is the ultimate depository of elements leached from rocks of the Long Valley caldera. Although the Coso volcanic field is situated nearly along the path between Long Valley and Searles Lake, discharge from the Coso volcanic-hydrothermal system may have contributed only a small amount to the Searles Lake evaporites. Drilling has shown that Owens Lake and China Lake do not contain significant evaporite deposits, even though they are part of the Owens River drainage system. Sodium carbonate and borate concentrations at Searles Lake indicate that there may have been a major outflow of hot-spring minerals from LVC ~300,000 years ago and a rather steady flow during the last 30,000-40,000 years. The volume of B in the recent evaporites (<32,000 years old) requires the leaching of about 100 km^3 of silicic rocks. This is reasonable, given the volume and composition of the Bishop Tuff and western moat rhyolites. The present convective heat flux from the caldera, ~$5x10^7$cal sec^{-1}, could be supplied from the cooling (from 800-300°C) of ~1 km^3/1000 y of silicic intrusions beneath the western moat. Longer-term discharge indicated by the Searles Lake observations requires that the hydrothermal system was more deeply circulating in the past than at present. Given the Searles Lake record and temperature data from a few deep wells, Sorey proposes the following evolution of the Long Valley hydrothermal system.

Evolution of Hydrothermal System
(years before present)

700,000-300,000:	Magma chamber reinflated; plumbing system developed.
300,000-150,000:	Maximum activity; leaching of minerals from reservoir rocks contributes sodium carbonate into Searles Lake; output decreased with time.
150,000-40,000:	Intermittent discharge; magma down to 8-10 km; thermal regime is predominantly conductive.
40,000-5,000:	Discharge reactivated at relatively constant rate; heat supplied by portions of the Inyo-Mono and Long Valley magma chambers beneath the west moat; leaching of boron from ~100 km^3 of Bishop Tuff.

Evolution of Hydrothermal System (cont.)
(years before present)

5,000-0: West moat intrusions initiated shallow west to east flow system within and above Bishop Tuff; reinflation of parts of the Long Valley magma chamber to depths of 5 km beneath the resurgent dome.

A conceptual thermal model of the caldera, developed by Lachenbruch and Sass (1977) to account for high surface heat flow over periods of hundreds of thousands of years was also described. As shown in Figure 3, a convecting hydrothermal system occupies fractured caldera fill and basement material, and overlies relatively unfractured basement rock through which heat is conducted from a shallow magma body. The measured bottom-hole temperatures in deep wells on the resurgent dome would be consistent with this model if the integrated convective-conductive heat flow (~15 μcal cm^{-2} s^{-1}) had been supplied to such a deep circulation system by the main Long Valley magma chamber for periods sufficient to reach thermal steady state (~300,000 years). Alternatively, the temperature versus depth trend from the bottom-hole temperature data could represent conductive equilibrium with magma at deeper levels, with no deep fluid circulation. In this case, the difference between the associated conductive heat flow (~4 μcal cm^{-2} s^{-1}) and the measured convective-conductive heat flow could be supplied to the shallow convection system by magma beneath the west moat.

Observations from springs, shallow wells, and the several deep holes that penetrate deep into the Bishop Tuff (and in one case into sub-caldera basement rock) permit conceptualization of the present-day hydrothermal system of the caldera. This is illustrated in Figure 4 by Sorey (1984) of a cross section along the southern edge of the resurgent dome. On the basis of

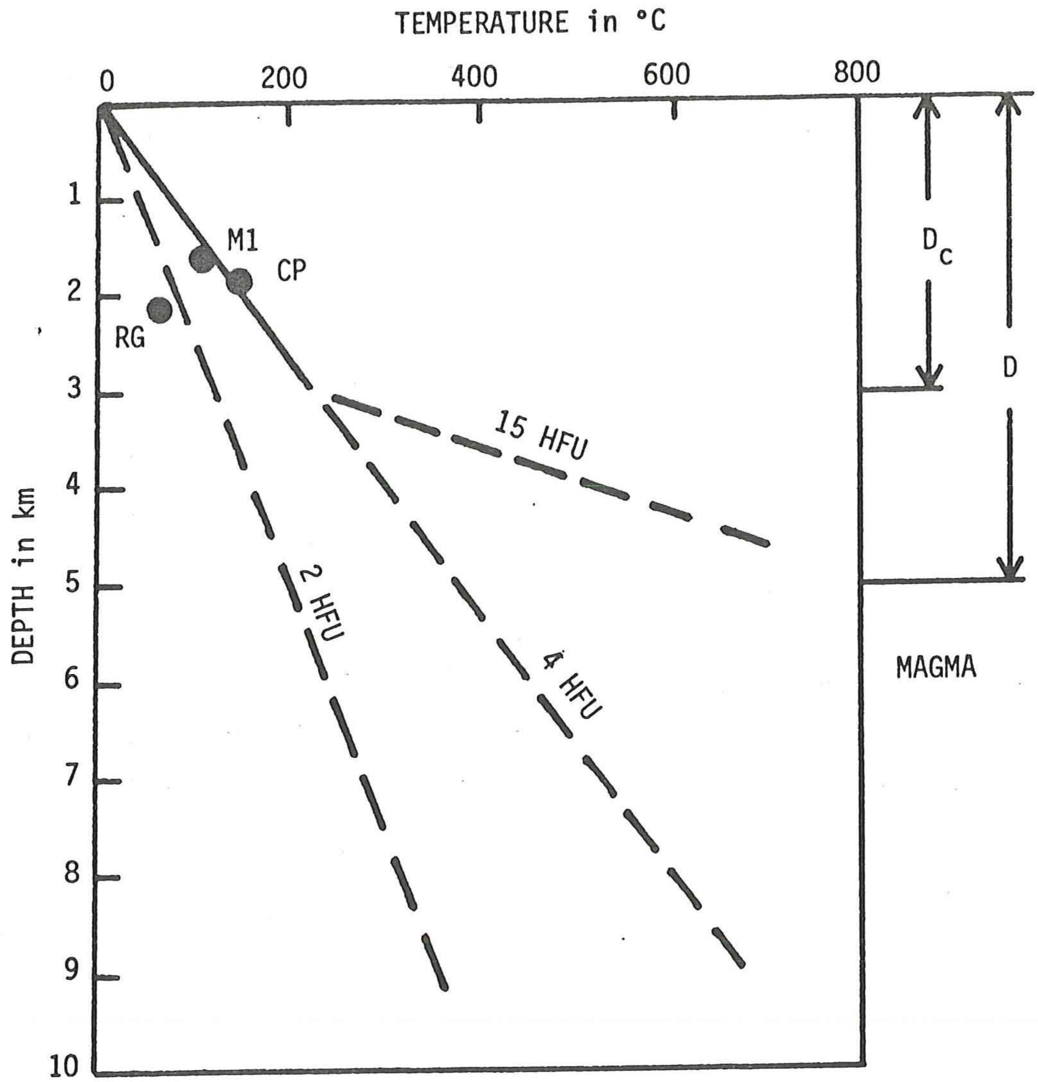


Fig. 3. Plots of temperature versus depth for conductive heat flow at various rates (thermal conductivity = 5 mcal/(s°C cm) and bottom-hole temperatures in deep wells in Long Valley caldera. Solid line represents the inferred background temperature gradient beneath the resurgent dome, based on data for wells M1 and CP. D is the depth to magma at 800°C that would produce a heat flux of 15 HFU under steady-state conditions beneath a zone of fluid convection of thickness D_c.

temperature reversals in wells, there appears to be a continuous zone of hot water flowing laterally from Casa Diablo eastward at altitudes near that of Lake Crowley (2,070 m). Temperatures in this zone decrease from about 170°C under Casa Diablo (well M1) to less than 70°C near Lake Crowley. Hydrologic continuity for such a flow could be provided within lacustrine sediments that underlie this region, with some complexity introduced by the normal faults crossing the section. Although temperature profiles in wells west of Casa Diablo show no evidence of the thermal flow zone near 2,070 m altitude, a deeper hot-water reservoir in the Bishop Tuff beneath the west moat is suggested by a high temperature gradient measured in well P1 below a depth of 550 m. This reservoir may contain water at temperatures near the 240°C temperature estimated from geothermometer calculations and be continuous with the deeper flow zone delineated by the temperature reversal at an altitude of 1,590 m in well M1 at Casa Diablo. A portion of the flow in this deeper reservoir may move upward along fault conduits west of Casa Diablo to charge the shallow flow zone around the south side of the resurgent dome.

Analyses of the shapes of the measured temperature profiles suggest that the age of the present-day circulation system is on the order of a few thousand years (Blackwell, 1984). Therefore, longer periods of convective heat flow and hot-spring discharge indicated by the Searles Lake evaporites must have involved deeper levels of fluid circulation (Fig. 4) beneath the west moat and/or the resurgent dome and heat inputs from significant volumes of magma within the Inyo-Mono and Long Valley chambers.

Caldera Structure

Although geologists and geophysicists have a general idea of caldera structure, subsurface information is weak or lacking in many respects. A

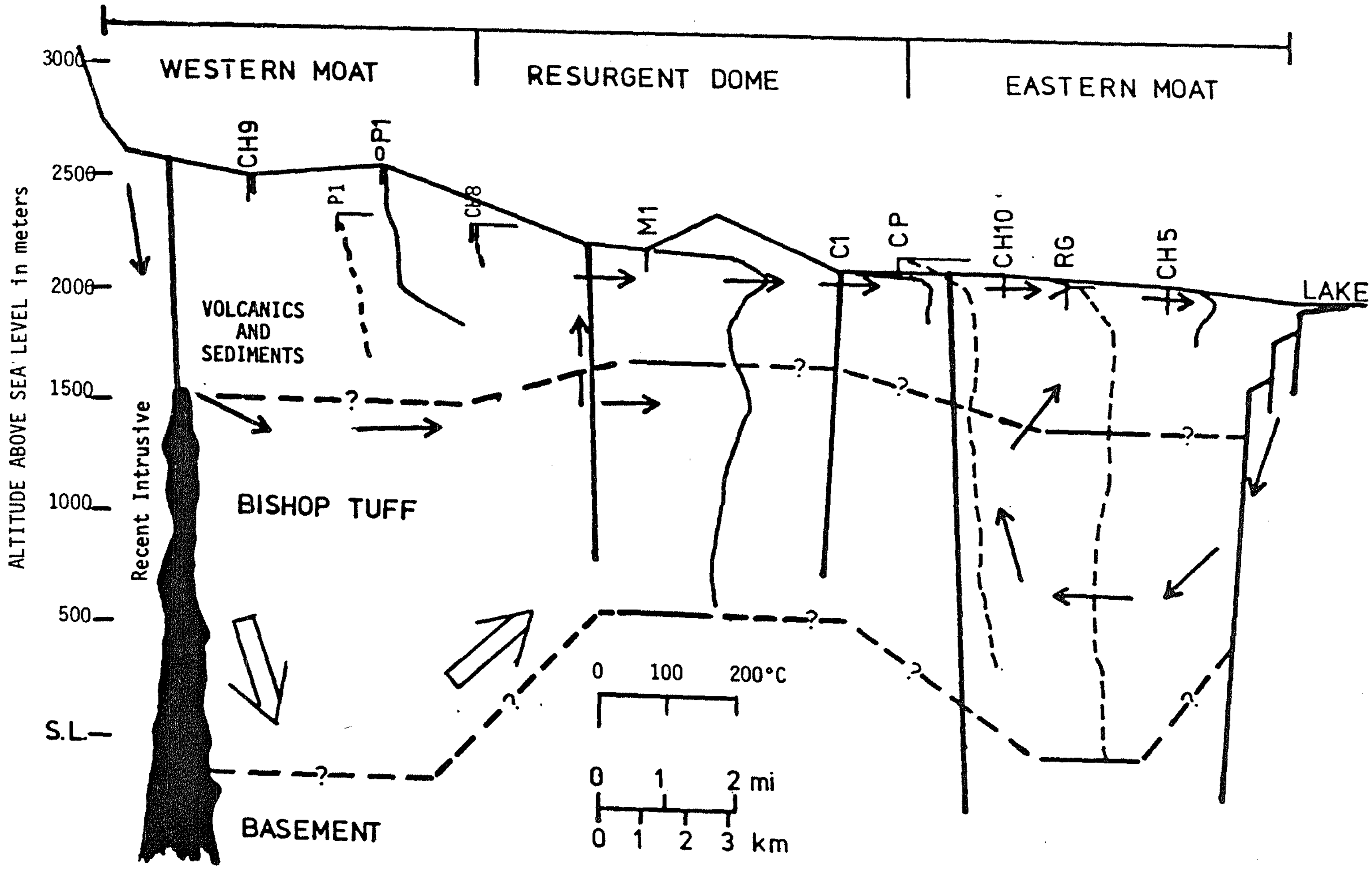


Fig. 4. Temperature profiles in wells located in Long Valley caldera along or projected onto an E-W cross section. Indicated scale for temperature profiles is the same for all wells. Profiles for wells projected onto this section are shown by dashed lines originating at the local land-surface altitude. Principal northwest-trending faults drawn with heavy solid lines and contacts at the top and bottom of the Bishop Tuff are shown as solid lines where control is provided by well data and by dashed lines where control is provided by seismic and gravity data. Inferred directions of fluid flow in the present-day system indicated by narrow arrows; deeper circulation during previous periods of activity indicated by wide arrows.

student at Brown University is attempting to fit gravity data from the LVC to Dave Hill's seismic refraction models to get an improved 2-D model of basin structure (Fig. 5). Gravity interpretations have been constrained using lithology from several drill holes, and a velocity-density relationship that has been established from borehole data. Reasonably good fits between calculated 2-D models and the seismic refraction data have been obtained to delineate the outline of the caldera, but there is no close agreement for structure in the basement beneath the caldera.

John Hermance expressed the need for 3-D gravity models, 3-D magnetotelluric models, active EM studies using a high power source, and seismic reflection profiling, all leading to intermediate-depth drilling. He specified a reflection experiment focused on the shallow to intermediate-depth hydrothermal regime: velocities configured for the upper 5 km, travel times for the 5-15 km depth range. Several lines were proposed including east-west and north-south profiles across the caldera, with one line extended into and across the hypothesized Mono craters ring fracture zone. The survey should also include traverses of the hypothesized dike in the Inyo craters area. Hermance pointed out the need for a "bright spot": a drillable target to get the attention of the continental drilling community and to elevate thermal regimes drilling to high priority.

Gas Monitoring and Magma Movement

T. Gerlach described the ramifications of recent analyses of gases sampled at the Casa Diablo fumarolic zone and the possible relation of gas anomalies, particularly CO_2, to magma movement. Sampling procedures have been improved to eliminate atmospheric contamination, evidenced by the absence of N_2 and atmospheric noble gases in the samples, and to avoid

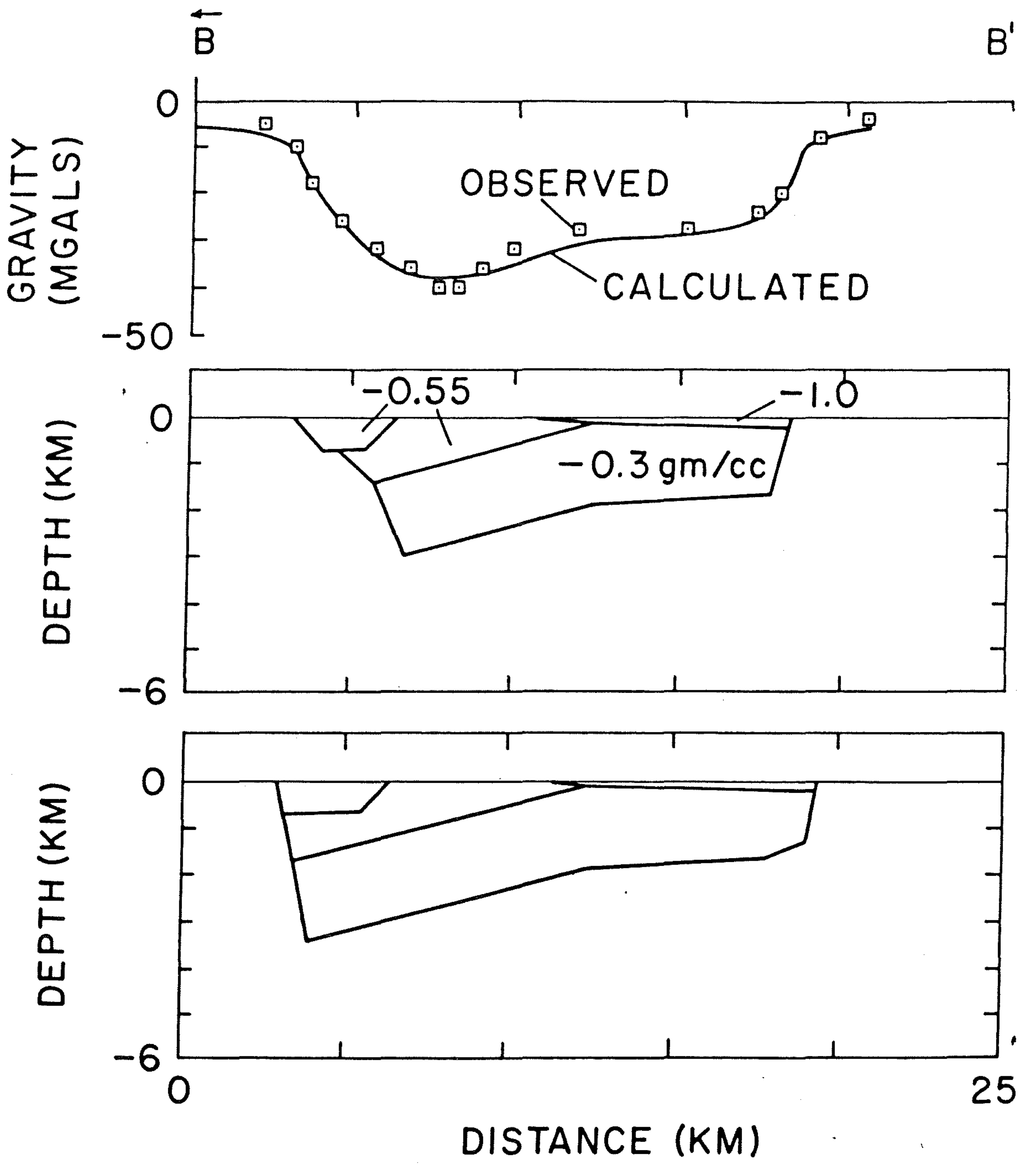


Fig. 5. A model for the structure of Long Valley caldera, which is consistent with gravity, seismic refraction, and drill-hole data (from Abers, 1984). Gravity data are along Hill's (1976) seismic refraction profile B-B' that ran from the northwest to the southeast. Abers' density model is shown in the middle panel and Hill's original structure is shown in the bottom panel.

condensation of H_2O in the 1-m long sampling tube driven into the ground. The water/CO_2 ratios of successive samplings appear to be nearly steady at ~250, but H_2S and SO_2 contents vary somewhat. The $\delta^{13}C$ of CO_2, measured in the range -5.5 to -7.5, may indicate a magmatic (perhaps basaltic) component to the Casa Diablo gases. Although this range is similar to that of atmospheric $\delta^{13}C$, the absence of atmospheric gas components in the samples rules out this source. Other possible sources of CO_2 to give the observed $\delta^{13}C$ values include:

1) CO_2 stripped from fluid inclusions in the Bishop Tuff and/or from Sierran granite that underlies and borders the caldera, and
2) CO_2-rich groundwater.

The possibility of fluid inclusion sources of CO_2 is being checked by laboratory measurements of $\delta^{13}C$ in rock, and a groundwater source will be checked by analyses of a broader set of samples. If the CO_2 is coming directly by advection from a magma, the magma would have to be fairly shallow.

Issues and Questions

Prompted by this background information, the primary question is: What is the heat source for the geothermal system(s) of the caldera? Chemical geothermometry indicates that water at Casa Diablo has attained temperatures to 240°C.

- Is this explained by deep circulation along a permeable fault zone (to ~8 km) in a region of high conductive heat flow, typical of the Sierran Front-western Basin and Range province?
- Or by the presence of a discrete heat source (such as a magma chamber), overlain by a conductive "blanket" of basement rock

through which heat is transmitted to, and drives a circulating hydrothermal system?

- Or by recently (past few hundred years) injected dikes in the western portion of the caldera, which impart heat to eastward-moving groundwater recharged from Sierran runoff?
- Or by a combination of these mechanisms?

The second and third possibilities, whose descriptions are greatly simplified here, are the more likely, and have been proposed as sources by Art Lachenbruch and David Blackwell, respectively. Both are combined in Mike Sorey's model of the hydrothermal system of the caldera, in that the model allows for heat conduction from a deep magma chamber over a substantial area of the caldera, as well as localized heating by relatively recent, shallow dike intrusions near the western border.

Intermediate-depth (1 to 1.5 km) drilling, in the western and southern moat areas, incorporating hydrological testing and hydrogeochemical analyses can best resolve the hydrothermal system. Extension and intensification of geophysical survey coverage into these areas is necessary to site these holes.

Another zone of interest is Hot Creek gorge where hydrothermal circulation is spectacularly evident, with the occurrence of numerous hot springs and a zone of strong boiling in a small rift that lines up well with a branch of the Hilton Creek fault. The questions here are:

- Is this a zone of major emanation of eastward-flowing hot water, caused by fracture permeability associated with the fault?
- Or is this a localized hydrothermal system that results from deep circulation in the fault zone and/or its associated graben, "day-lighting" in Hot Creek gorge?

- If the latter holds, what are the ramifications for the presence of hot dikes and/or relatively shallow magma causing localized heating in this area?

Again, intermediate-depth drilling would help resolve this.

T. Gerlach's comments prompted the questions:

- Is the CO_2 a good indicator of a magmatic source?
- May other isotope ratios (e.g. noble gases) provide concurrence?

Of importance to scoping and interpretation of geophysical surveys is the lithologic complexity of the basement underlying Long Valley caldera fill. Paleozoic metasedimentary rocks of the Mt. Morrison pendant probably form a substantial portion of the basement under the western part of the caldera, while Sierran granitic rock probably predominates under the eastern half of the caldera. As mapped and described by Rinehart and Ross (1964), approximately 20% of the Mt. Morrison pendant is carbonate rock: marble, calcareous sandstone and calc hornfels, while the remainder is predominantly siliceous clastic rock and silicified calc hornfels. Small dioritic intrusions (<1 km in maximum dimension) occur within the metasedimentary assemblage, and if present in the sub-caldera basement, might provide localized contrasts in density and magnetic susceptibility. Similarly, graphitic zones in the sedimentary rocks, as reported in the deep Union Oil hole at Casa Diablo Hot Springs, would provide strong contrasts in electrical resistivity. These lithologic variations must be taken into account when geophysical surveys are planned and possible models of the hydrothermal system, based on geophysical and geochemical data, are considered.

CONCEPTS AND MODELS BASED ON SEISMOLOGICAL DATA

T.V. McEvilly, Rapporteur

SPATIAL DISTRIBUTION OF SEISMICITY

South Sierran Block

Total seismic energy release from earthquakes of the present sequence that have occurred outside the Long Valley caldera, taken over the entire sequence, surpasses that from events within the caldera by a factor of about six. This fact underlies the University of Nevada conclusion that the sequence is primarily of tectonic origin. The currently active seismic zone outside the caldera extends into the Sierran block 5 to 10 km to the SSE from the south rim of the caldera. The rate of activity is substantially less than that in the caldera. Extra-caldera seismicity is spatially quite diffuse, but sharply bounded on the west, giving a clearly defined edge of seismicity on that side. There is virtually no clustering seen, nor any systematic depth variation over the region, which contains the source zone of the large 1980 events. Absolute depths are less well determined in this region than in the south moat intra-caldera cluster, so that details of any possible differences in focal depth cannot be seen.

South Moat Area

Since May 1980 earthquake swarms have been concentrated mainly in the south moat area of the Long Valley caldera (Fig. 6a,b). The dual clusters with the low activity zone separating them represent a large proportion of the current Long Valley seismicity. In general, past hypocenter locations are accurate only to about ± 0.5-1.0 km due to structural bias, although the dense networks deployed in the past and now in place in the recently aug-

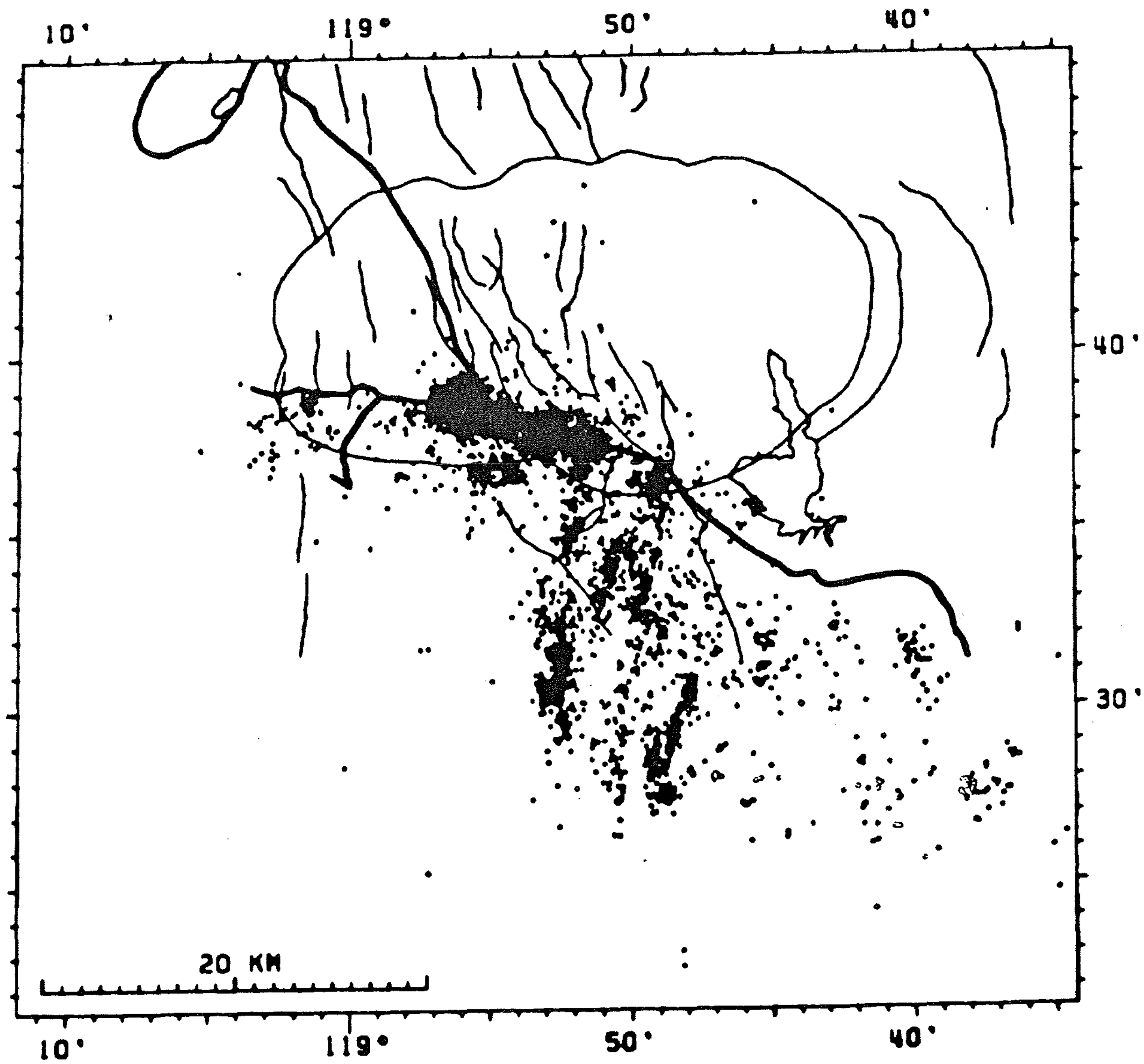


Fig. 6a. Epicenter plot of approximately 7500 earthquakes located by the U.S. Geological Survey in the Long Valley caldera area for 1983.

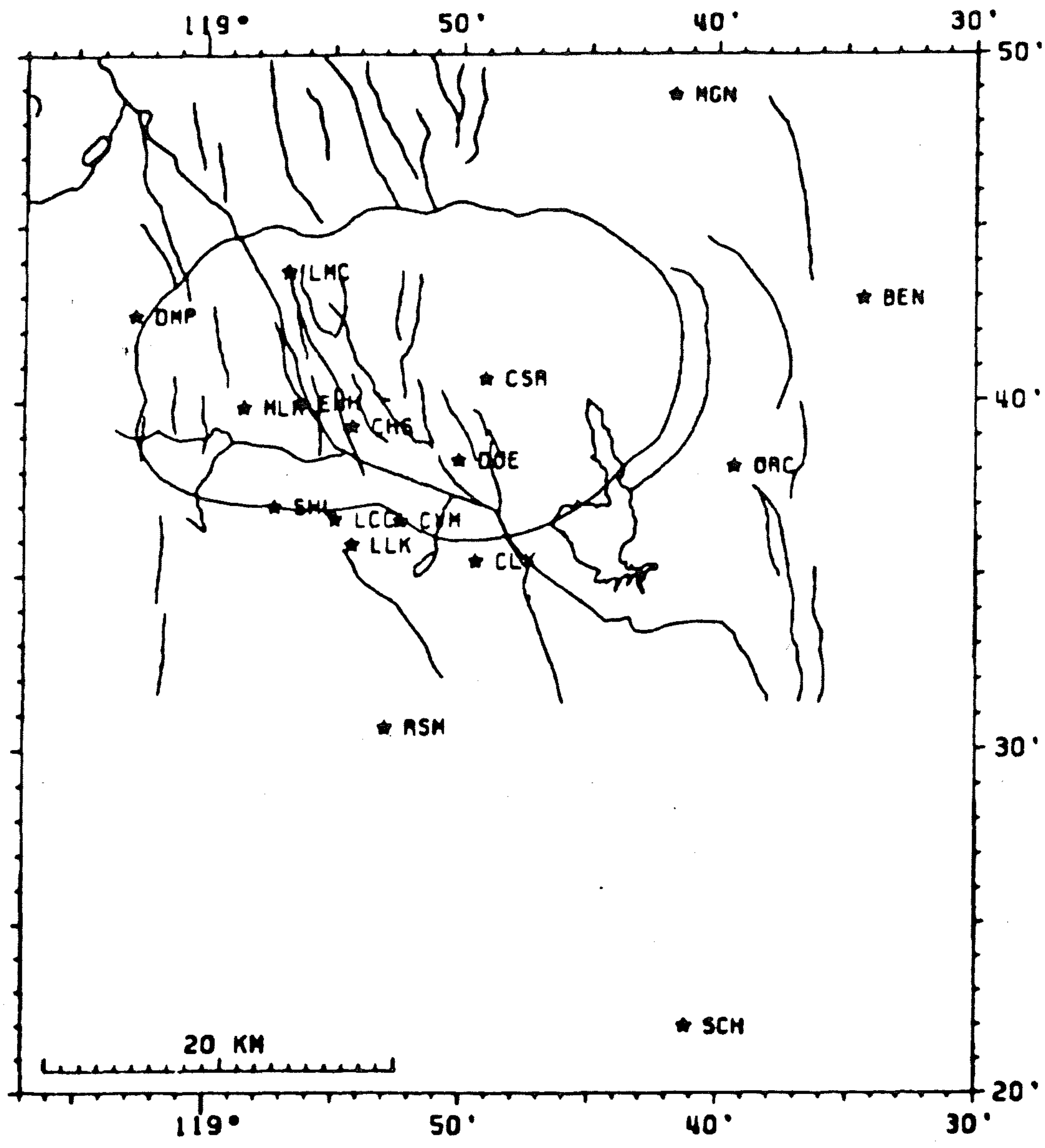


Fig. 6b. Locations of seismic stations used in calculating the epicentral locations plotted in Fig. 6a. All locations were calculated using HYPO71 location program and a P-wave velocity model and station travel-time corrections appropriate for this area.

mented permanent USGS network indicate an improved potential accuracy of probably ±200 m (Fig. 7). Even with the improved accuracy, the south moat clusters in general do not define clear fault planes. An exception is the swarm of several small events over a few hours seen in the LLNL 1982 data (Fig. 8a,b). There are suggestions that other such "mini-swarms" may also define lineations. Focal depths range to 8-10 km.

Other Areas

A few events have occurred on the northeastern edge of the resurgent dome, and in 1984 activity has begun to the southwest under Mammoth Mountain. The Inyo-Mono craters trend on the western edge of the caldera seems aseismic at a detection threshold of $M_L \simeq 1.5$. There seems to be little or no correlation of epicenters with surface hydrothermal activity.

TEMPORAL DISTRIBUTION OF SEISMICITY

Overall Sequence

Taken as a single post-1980 sequence, the seismic activity is following a normal decrease in seismicity, roughly as t^{-1}, with major exceptions in late Sept.-Oct. 1981 and Jan. 1983 (Fig. 9). Of course, there are imbedded swarms and large aftershocks in the sequence (Fig. 10). The swarms are of particular interest; for example, those in the south moat region recur in essentially the same source volume.

Spasmodic Tremor

Following the strong shocks in 1980, earthquakes in the south moat area just east of the town of Mammoth Lakes began to occur as intensive swarms, with a typical swarm lasting 1-2 hours, producing hundreds of microearthquakes and having the appearance of spasmodic tremor observed in volcanic

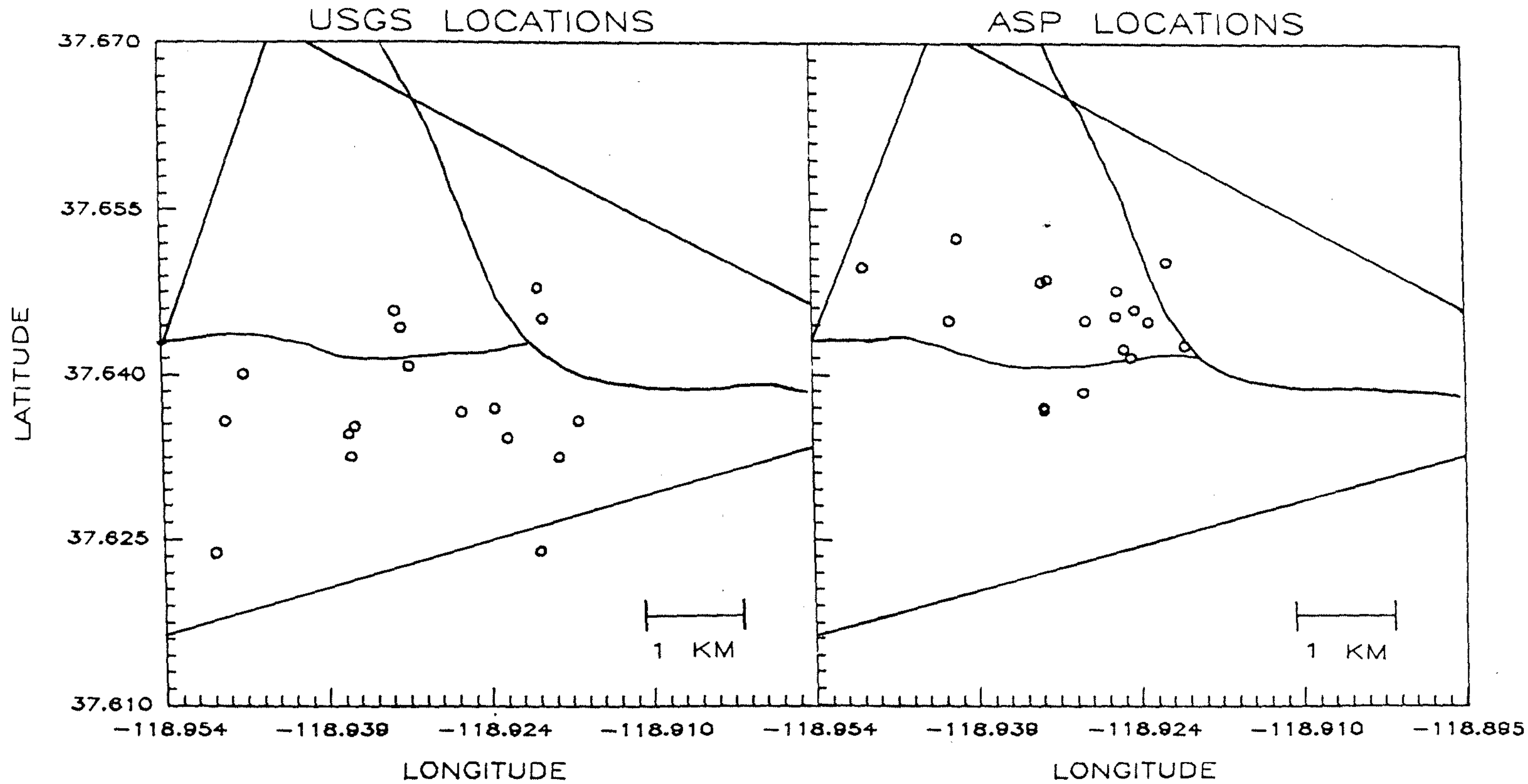


Fig. 7. A comparison of events (M_L approximately 0.8-2.5) recorded simultaneously by USGS and LBL networks between July 23 and August 4, 1983. The triangle outlines the extent of the dense LBL 15-element array which was processed on-line by the Automated Seismic Processor (ASP). The curved lines are U.S. Route 395 and State Route 203 (running east-west). The tighter cluster of the ASP locations demonstrates uncertainties of about 1 km in routine hypocenter locations in mid-1983.

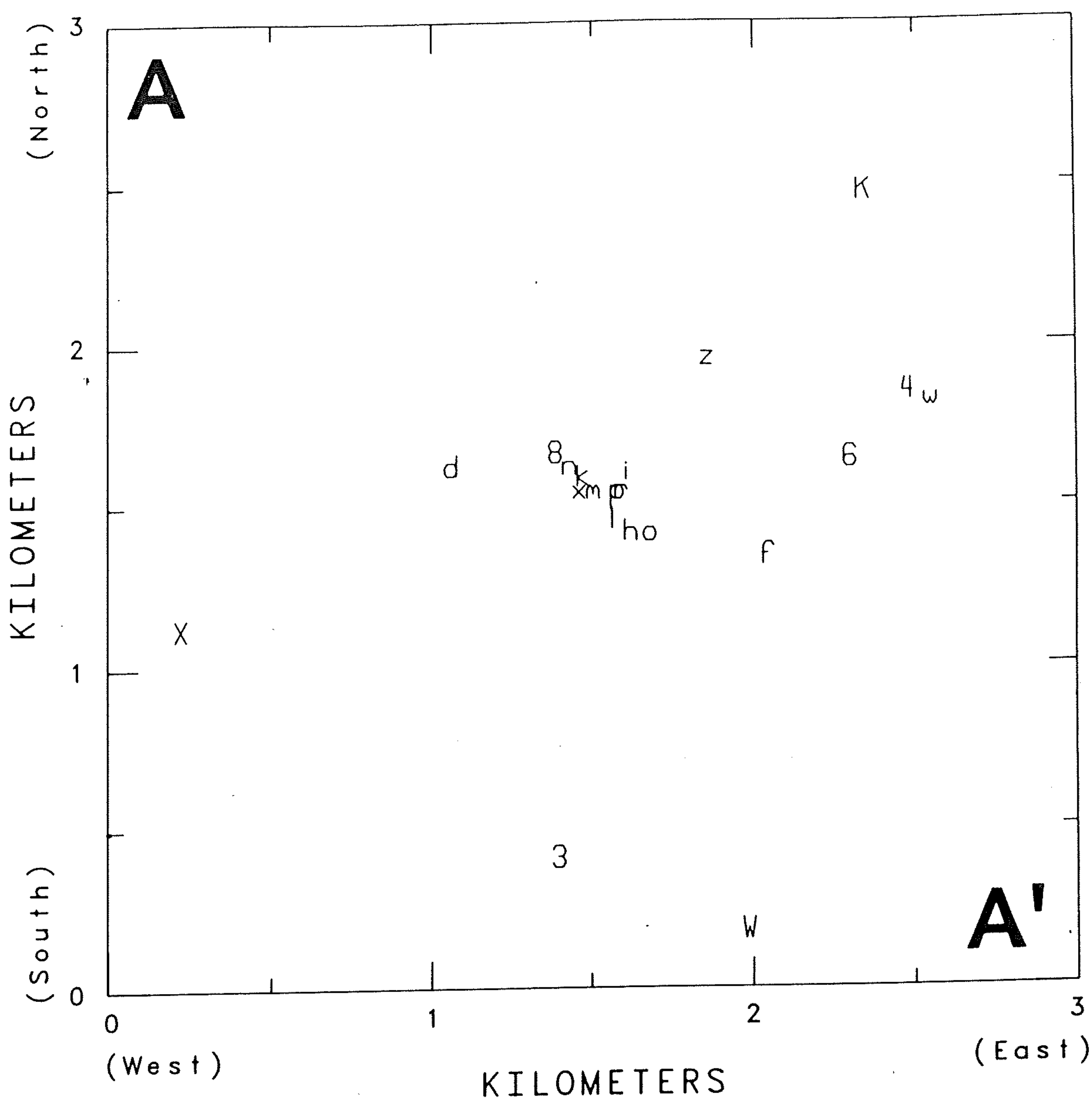


Fig. 8a. Expanded view of the swarm region on August 9, 1982. The map covers a 3 km square in the south moat swarm region. The epicenters are indicated by letters representing their order of occurrence: A through Z, a through z, and 0 to 9. Events h through r occurred during a three-hour period starting at 0500. These events define a segment of a vertical plane oriented from A to A'. The maximum coda magnitude for these events was 1.5.

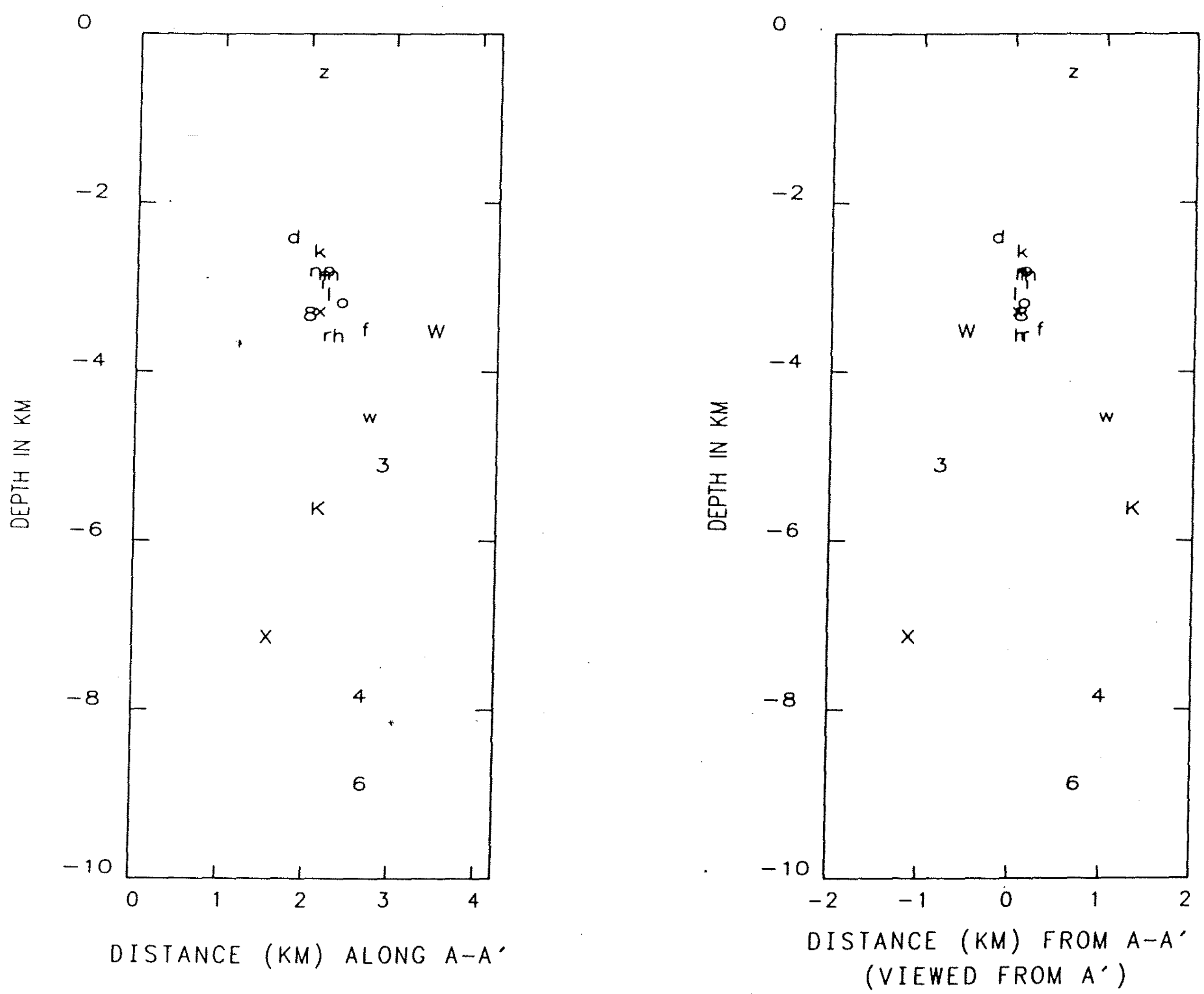


Fig. 8b. Depth sections from A to A' and perpendicular to A-A' in Figure 8a. The hypocenters use the same symbols as Figure 8a and no exaggeration is used in the plots. The plot on the left shows a depth section along the trend of seismicity, A to A'. The swarm now appears between depths of 2.5 to 3.5 km, while deeper events may delineate a vertical sheet intrusion. Looking from A' to the NW along the trend of the swarm, the plot on the right indicates that the deeper events do not lie directly below the swarm, but outline the possible intrusion.

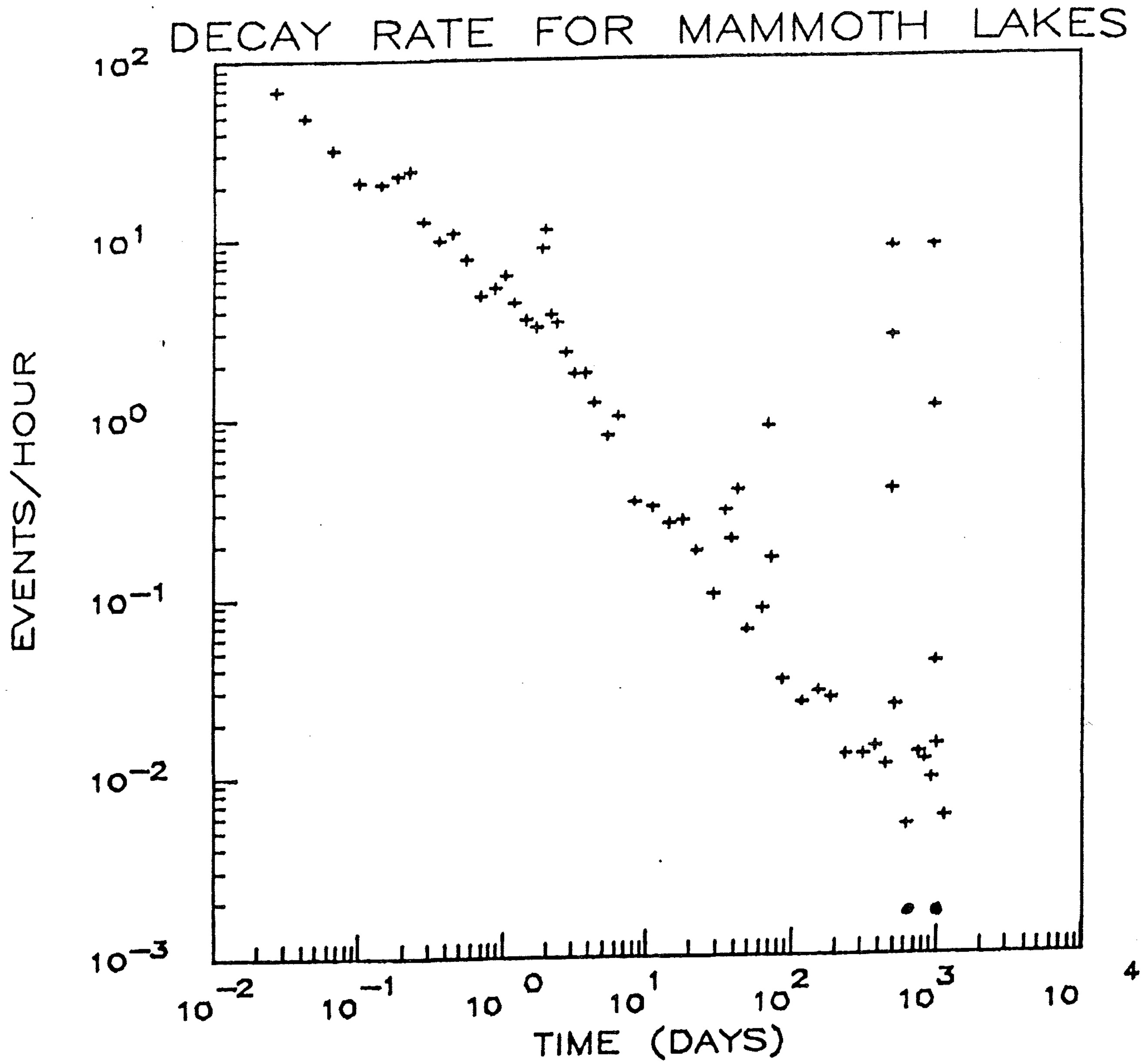


Fig. 9. Plot of the number of earthquakes ($M_L \geq 2.9$) per hour, taken in successive bins of 20 events and plotted at the median time of their occurrence relative to the 25 May 1980 onset of activity. The two major swarms of September 30-October 1, 1981 and January 7-9, 1983, indicated by the dots (•) along the abscissa, are the only significant deviations from a t^{-1} decay in activity.

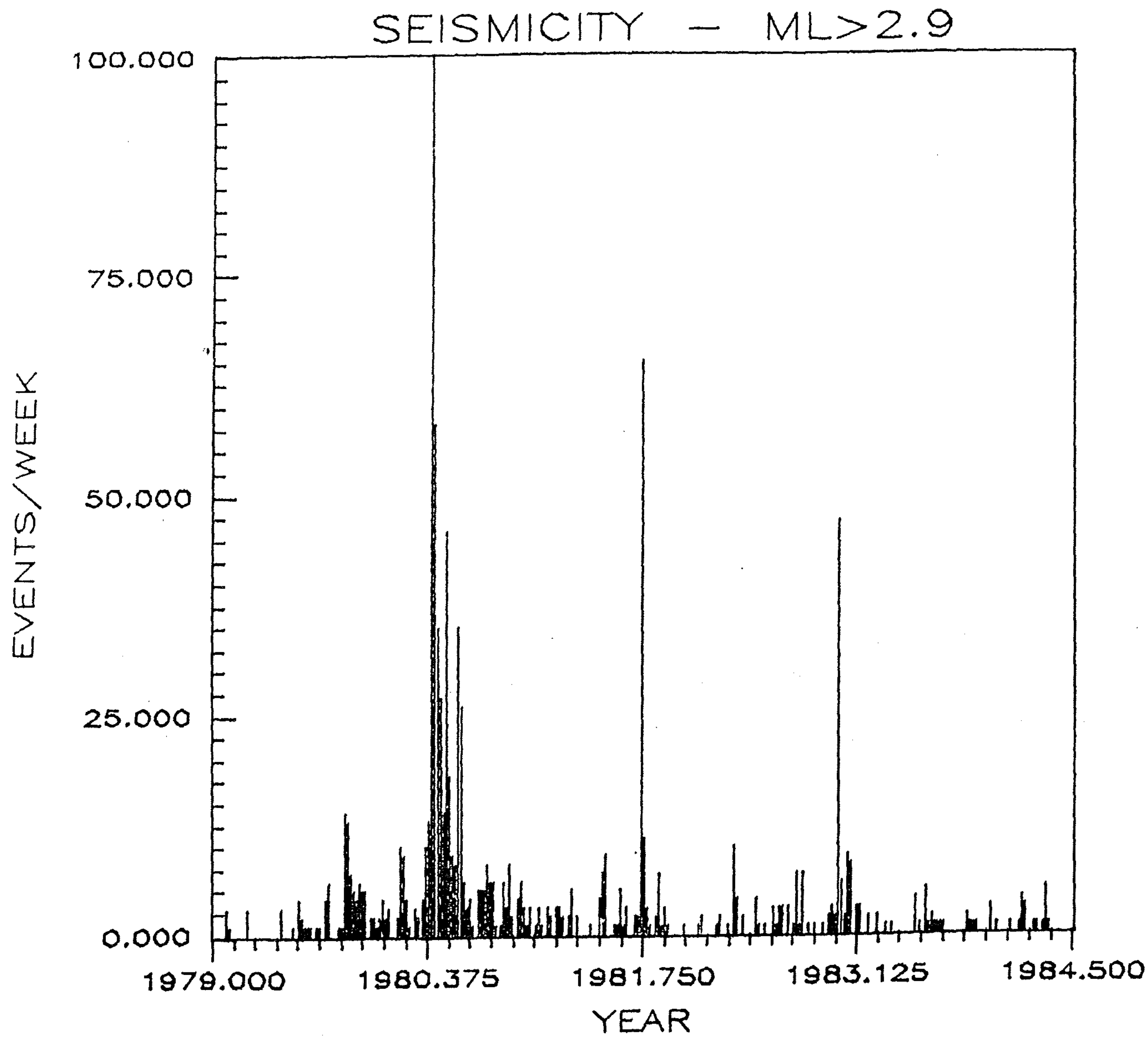


Fig. 10. Weekly totals for earthquakes for $M_L > 2.9$ since 1979 at Mammoth Lakes, showing a suggestion of periodicity in activity. The ordinate for the first peak, which is off scale, is 515 events.

regions. Such swarms--with the largest events having $M_L \approx 4$ or less--have not been observed at other locations within the active area, and did not occur before 3 July 1980.

South Moat Swarms

After the large magnitude events of May 1980, swarm activity occurred in the south moat area. Following two events of $M_L > 5$, major swarm activity resumed in January 1983 with substantially increased activity throughout the dual cluster. No anomalous hydrothermal manifestations at the nearby springs and fumaroles can be linked to the January 1983 activity.

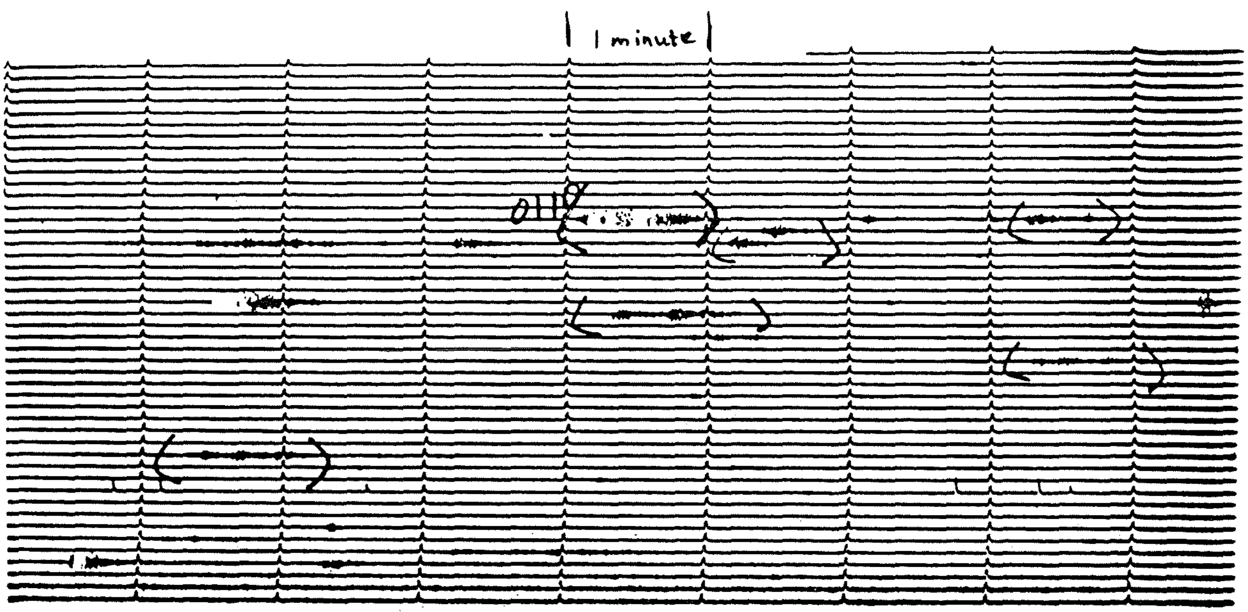
Mammoth Mountain Swarm

Beginning with a M3+ event in February 1984, a series of small events are occurring at depths of 2.5-3 km in the Mammoth Mountain area, just SW of the caldera boundary. This swarm of earthquakes is accompanied by a series of strange energy bursts, coming from the same general source area roughly at amplitude levels equivalent to $M \sim 0.5$, but lacking the characteristic impulsive P- or S-waves seen in typical microearthquake waveforms (Fig. 11).

EARTHQUAKE MECHANISMS

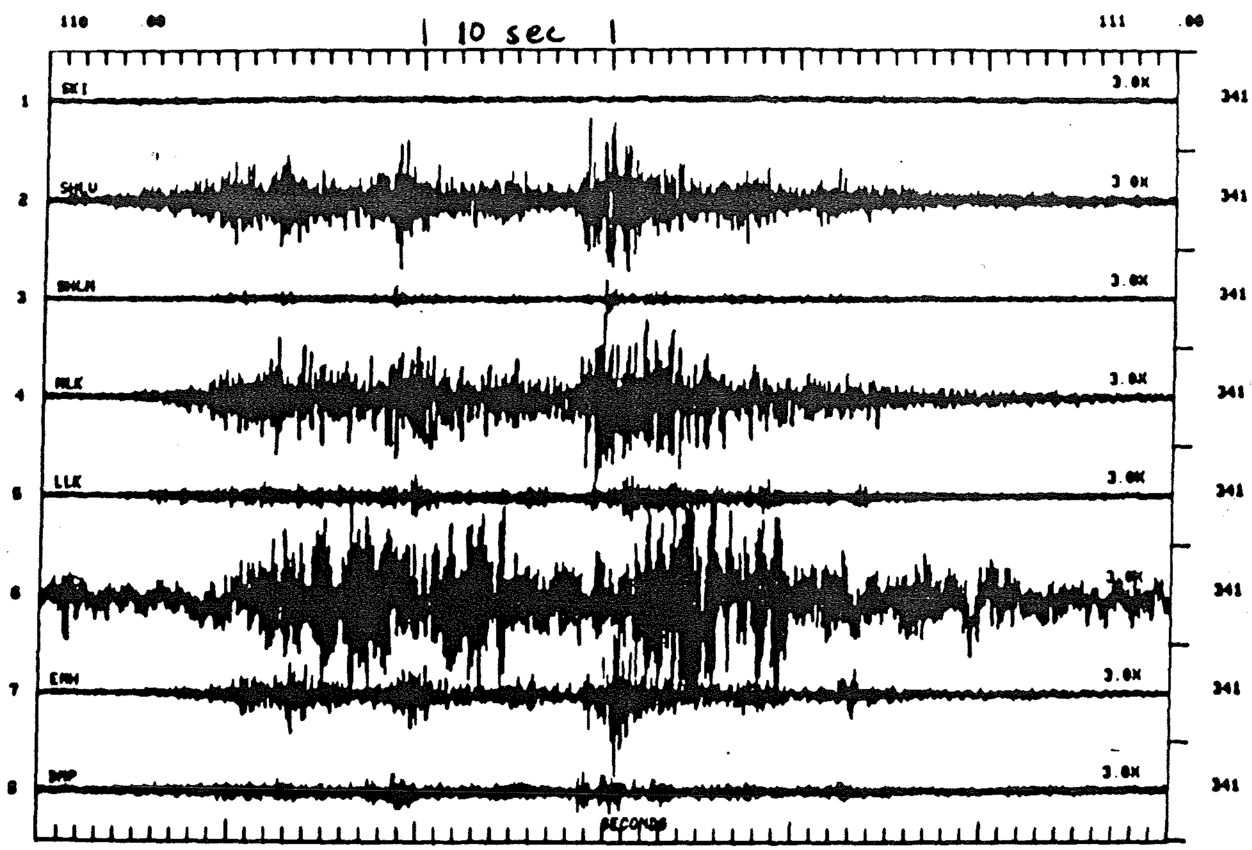
Sierran Block

Within the Sierran block, Vetter and Ryall (1983) found a change in mechanisms, from strike-slip for earthquakes shallower than 9 km to oblique- or normal-slip for events deeper than 9 km (Fig. 12a,b). The change was explained by a model in which overburden pressure increased more rapidly with depth than the maximum horizontal stress. Station coverage is poorer than that within the caldera, however, for determining mechanisms for the ongoing smaller microearthquakes in this area. Limited results, including those for the 1980 events, point to regional ENE-WSW extension in the area.



(a)

Fig. 11. An example of an unusual "burst" of seismic energy originating from the Mammoth Mountain area. No clear P-wave arrival is observed, but the change in frequency (a) and amplitude (b) suggests S-wave arrivals, therefore implying that these are comprised of many small earthquakes. Each "burst" lasts for about 1 minute and this particular sequence on Jan. 2, 1984 lasted for approximately 14 hours.



(b)

Fig. 11 (Continued).

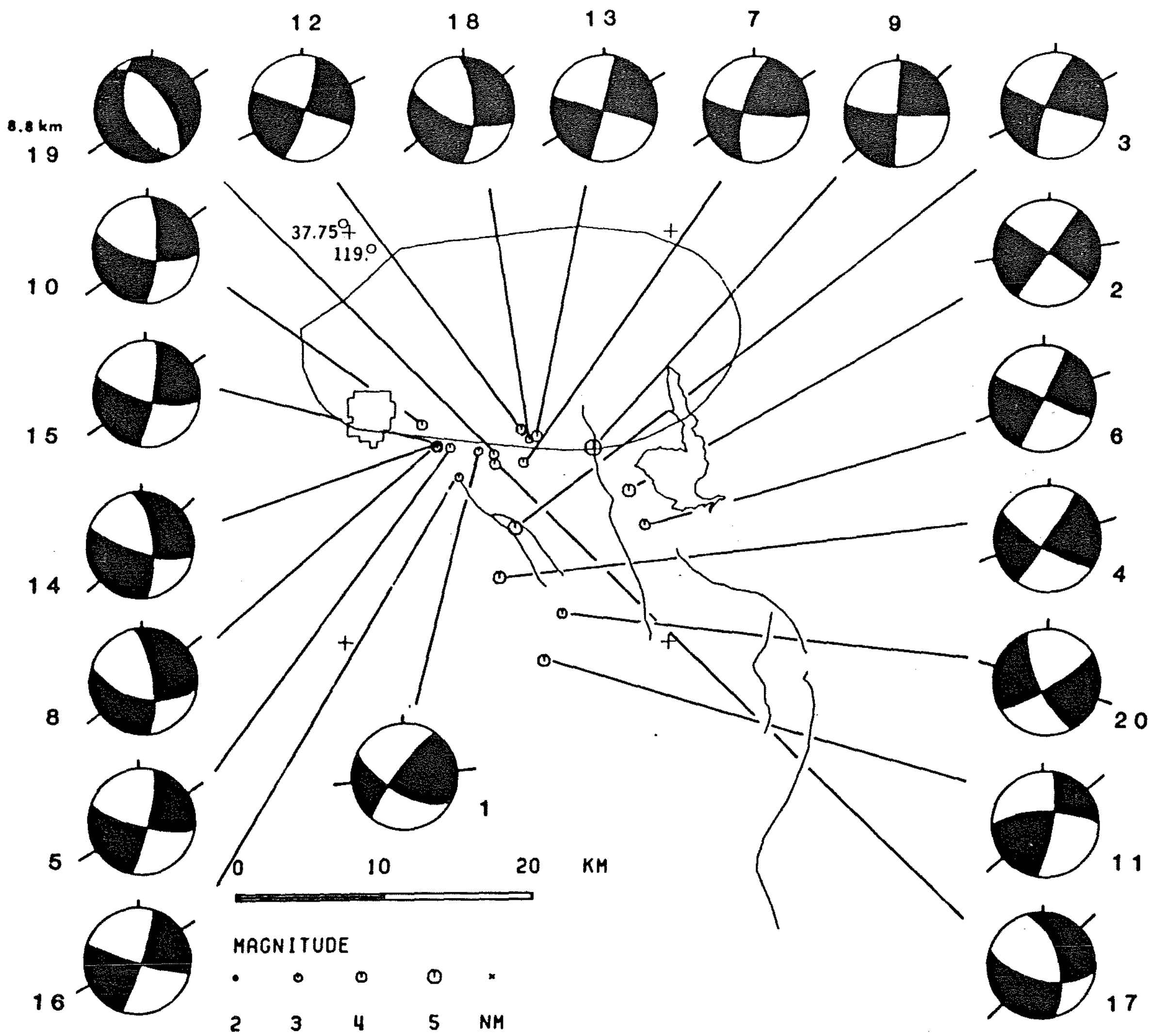


Fig. 12a. Fault plane solutions for earthquakes with depth less than 9 km in the Mammoth Lakes area, eastern California. (Lower-hemisphere, equal-angle projection; shaded areas are compressions).

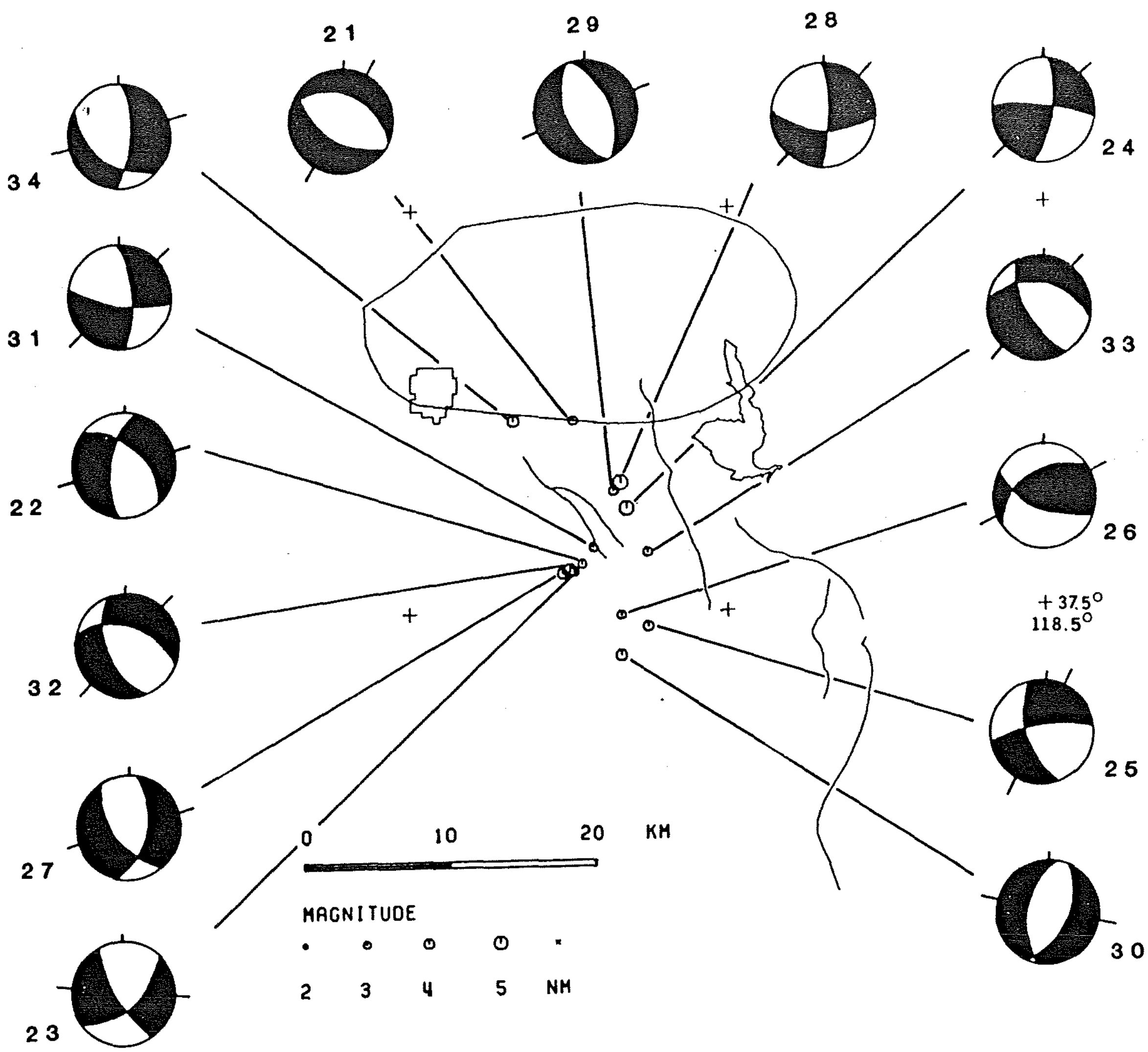


Fig. 12b. Fault plane solutions for earthquakes with depth greater than 9 km in the Mammoth Lakes area, eastern California.

South Moat Area

Several results are reported for mechanisms in the south moat area. Ryall reported that work by Vetter on the January 1983 swarm in this region did not show the dramatic depth-dependence of mechanism reported for the Sierran block (Vetter and Ryall, 1983). Most depths were less than 8 km, and, within the sample, the strike-slip events were shallower than others. Mechanisms are consistent with NE-SW tension. USGS data analyzed by R. Cockerham (Fig. 13a-c) do not show such a separation, but rather a mix of all types of events at all depths. A. Smith showed a mini-swarm of several events in the summer of 1982 in a tight vertical pattern with mechanisms consistent with conjugate strike-slip faults associated with NE-SW extension, hypothesized as possibly indicative of local intrusion (Fig. 14). E. Majer showed data from a summer 1983 dense network deployment with intermediate-stress axes oriented systematically in the cluster, but no systematic orientation for the maximum or minimum stress axes (Fig. 15). Moment-tensor inversion for these microearthquakes generally required no CLVD (compensated linear vector dipole) components.

1980 Events

The need for a CLVD component in the source mechanisms of the large 1980 events is disputed by Ryall. He argues, using the relative amplitudes of the first swings of the P-waves compared to magnitudes, that these large events are multiple sources, confounding the point-source inversion methods (Fig. 16). In addition, a study of aftershocks of the 1980 events (Lide and Ryall, 1984) shows a number of NNE lineups (Fig. 17)--appropriate for the NNE-striking left-lateral strike-slip solutions reported by the Nevada group, but not for the formation of NW-striking dikes corresponding to Julian's (1983) CLVD

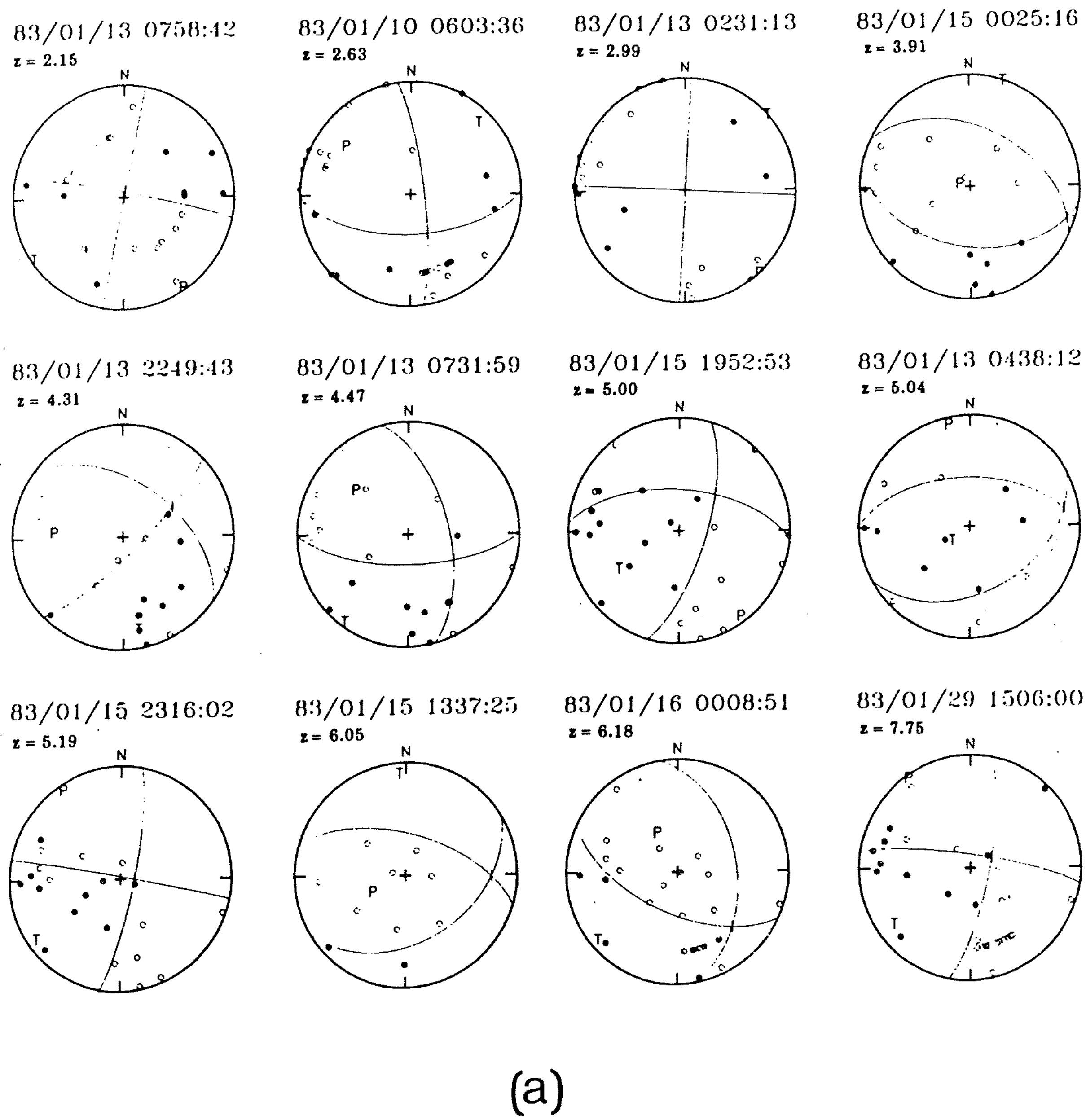
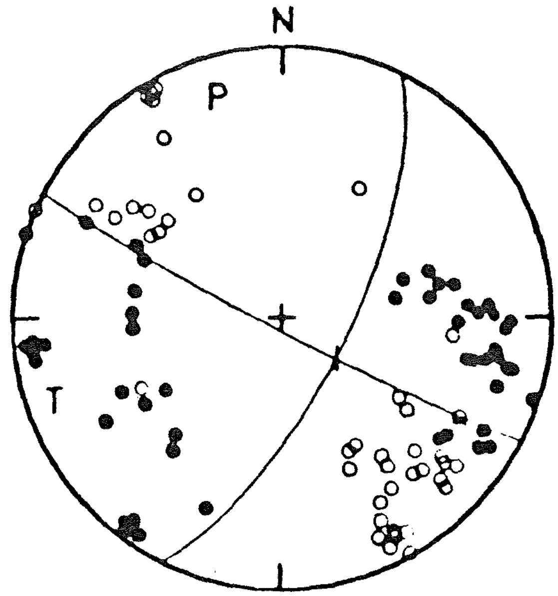
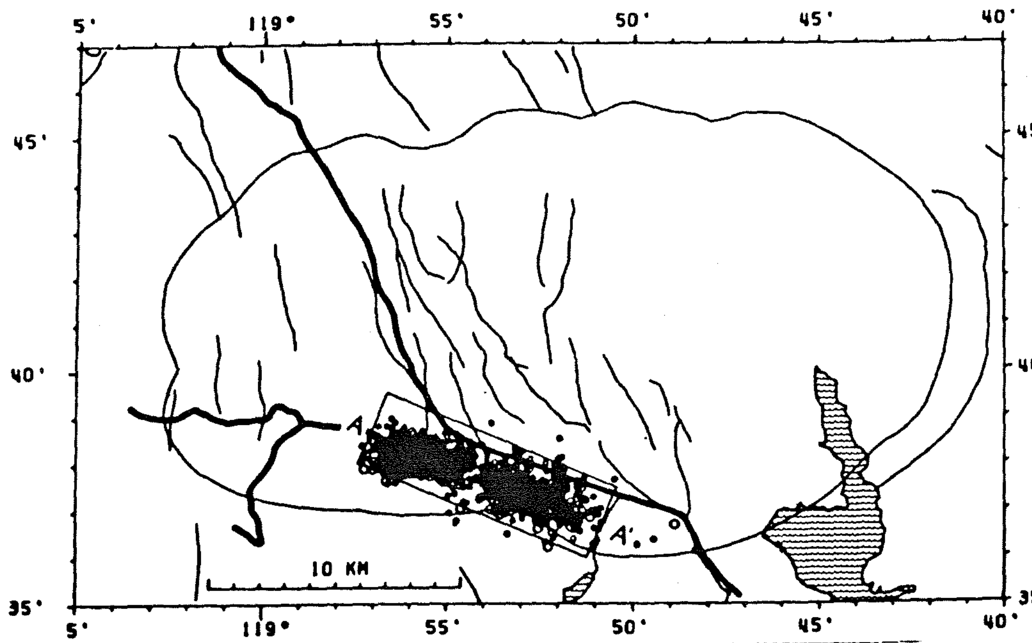


Fig. 13. (a) P-wave first motion focal plane solutions (lower hemisphere, equal-area projections) for selected events in the western half of the box in (c). Solid circles are compressions first motions, open circles are dilational, P and T represent calculated compression and extension axes. The events are labeled by date, origin time, and depth.



(b)



(c)

Fig. 13. (b) Composite solution of events selected from the eastern half of the box in (c). Symbols and projections are the same as in (a). (c) Epicenter of events for the interval January 7, 1983 to January 31, 1983. Outline of Long Valley caldera and prominent faults are shown by light solid lines and the principal highways by heavy lines. From these data presented here no obvious correlation between depth and focal mechanism type is observed (from Savage and Cockerham, 1984).

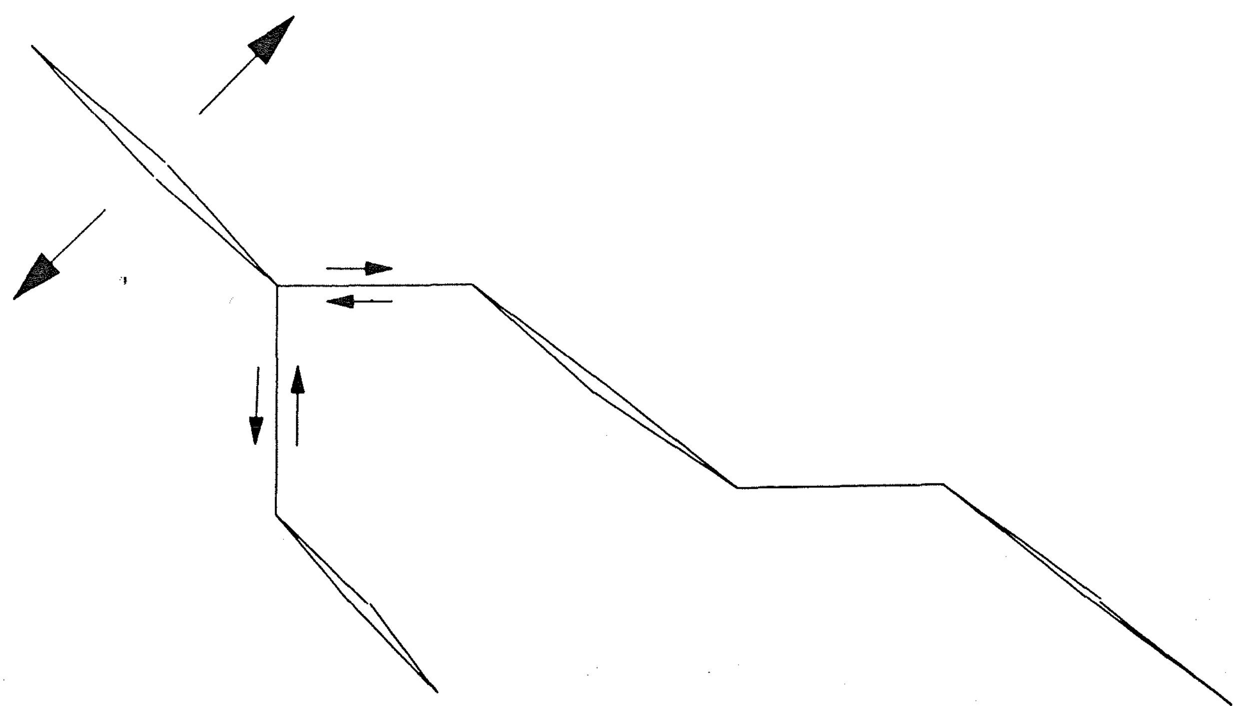


Fig. 14. A stress diagram after Pollard (1973) and Hill (1977) showing a map view of an en-echelon structure which Smith (1984) has proposed to explain the swarm activity near Mammoth Lakes. A series of left stepping extensional zones with dike intrusions would allow a more northerly orientation of individual dikes relative to the east-west trend in seismicity observed by the USGS (Cockerham and Hill, personal communication, 1983). The August 9 swarm represents activity on just one dike structure, while activity on the other dikes and strike-slip offsets may account for the more east-west trend of seismicity. The permanent UNR/USGS network is unable to resolve the activity on individual dikes, but instead outlines a diffuse N80W trend.

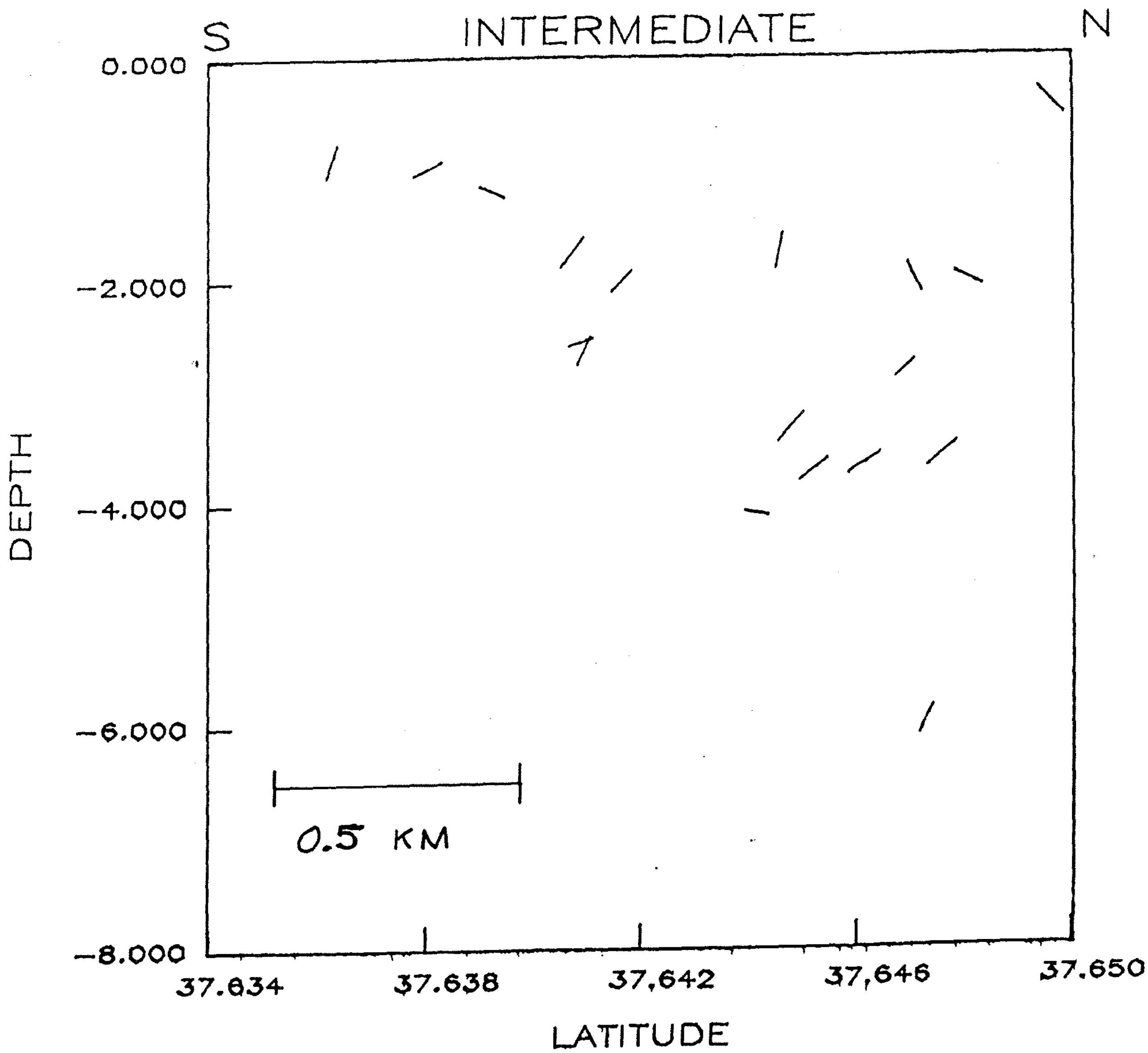


Fig. 15. The intermediate stress axes of the ASP-determined moment tensors for events near the intersection of Highways 395 and 203 (see Fig. 7), projected onto vertical N-S cross section through the south moat swarm area. The intermediate stress axes lie in the fault planes of the sources, suggesting generally radial faulting with respect to the volume below the region of intense activity in the south moat area. The maximum and minimum stress axes do not show such systematic patterns of orientation.

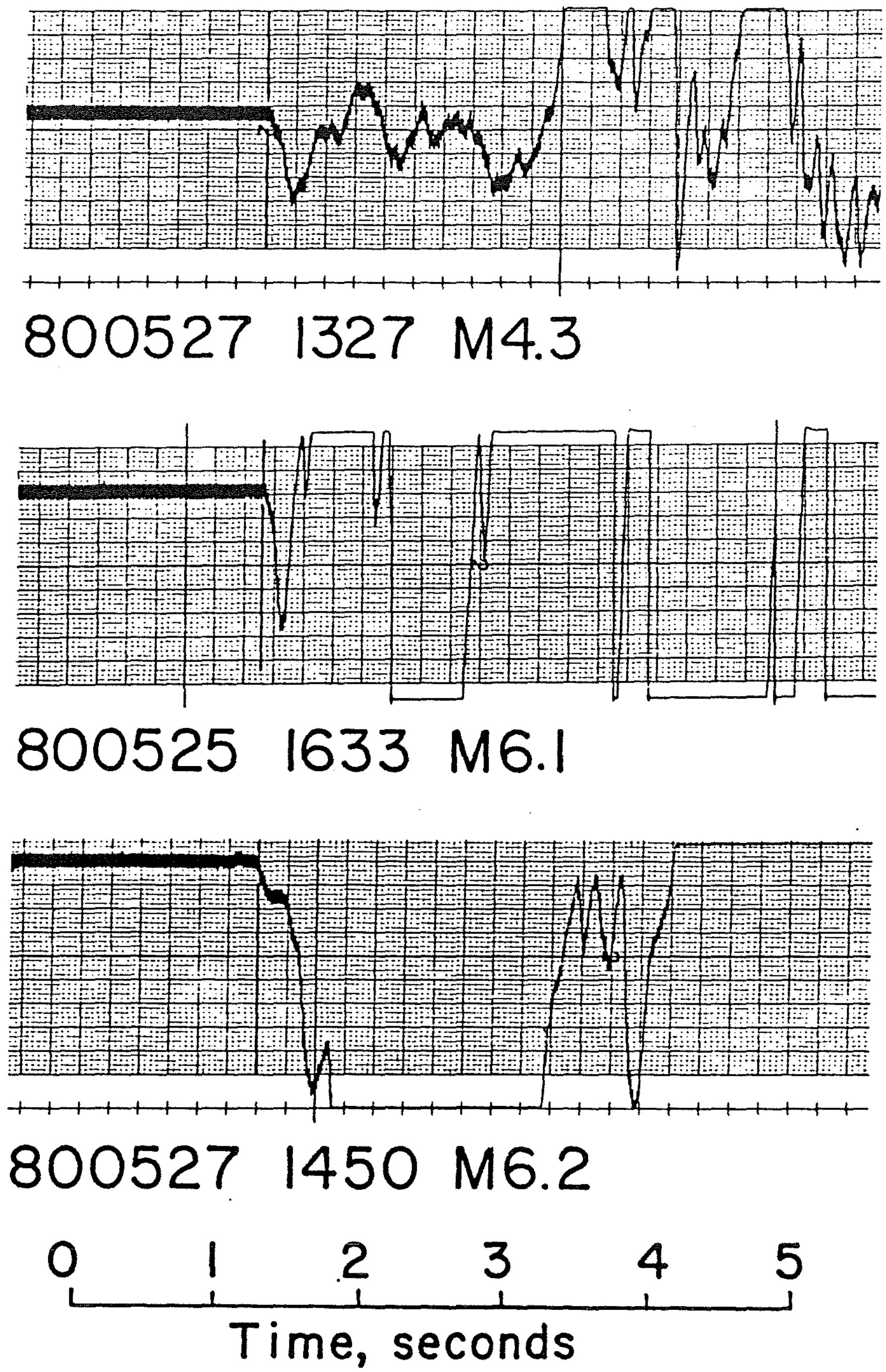


Fig. 16. Vertical-component digital recordings made at Mammoth Ranger Station for two largest shocks on 25 and 27 May 1980, plus an event with M_L = 4.3, to show complex rupture process for larger events. Gain is the same for all records.

Fig. 17. Map of Long Valley caldera showing faults, caldera boundary, town of Mammoth Lakes (SW part of caldera), Lake Crowley (SE part of caldera), M6+ earthquakes in May 1980 (solid circles), aftershocks (crosses), and stations used in the analysis (solid triangles). Note NNE lineups of aftershocks in the Sierran block and WNW lineup along the southern caldera boundary (from Lide and Ryall, 1984).

mechanisms. It is generally agreed, however that these large earthquakes represent ENE-WSW extension.

GEOLOGICAL STRUCTURE WITHIN THE CALDERA

Velocity Units

Seismic refraction surveys give a general model in which the caldera appears to be filled to some 3 km depth with a shallow layer up to about 1 km thick of sediments and post-caldera volcanics overlying 2 to 3 km of Bishop Tuff, which rests probably on a crystalline or metamorphic basement (Fig. 18). Velocities associated with these three units are about 2-2.5, 4-4.5, and 6 km/sec, respectively. Refracted arrivals are seen from the two interfaces, but the extended geometry of conventional refraction spreads does not allow for definition of the two surfaces, in the presence of severe lateral variations. A tomographic reconstruction of velocity perturbations on 5 km blocks, based on joint analysis of some 7000 relocated earthquakes reported by R. Cockerham, yields a zone of about 10% velocity decrease at 3-7 km depth, roughly beneath the resurgent dome (Fig. 19). Teleseismic P-delays are seen by Steeples and Iyer (1976) roughly in the same area. The south moat area does not seem to exhibit a low velocity anomaly.

Attenuation Anomalies

Several types of attenuation anomalies have been reported for P- and S-seismic waves propagating within and under the caldera (Fig. 20a,b).

1) Resurgent dome area. P- and S-waves from an event 8.5 km deep on the NNE edge of the resurgent dome show severe loss of high frequency content at stations across the dome, but normal frequency content at sites to the north. S-waves from local events recorded at regional distances are seen in a back-projection type of

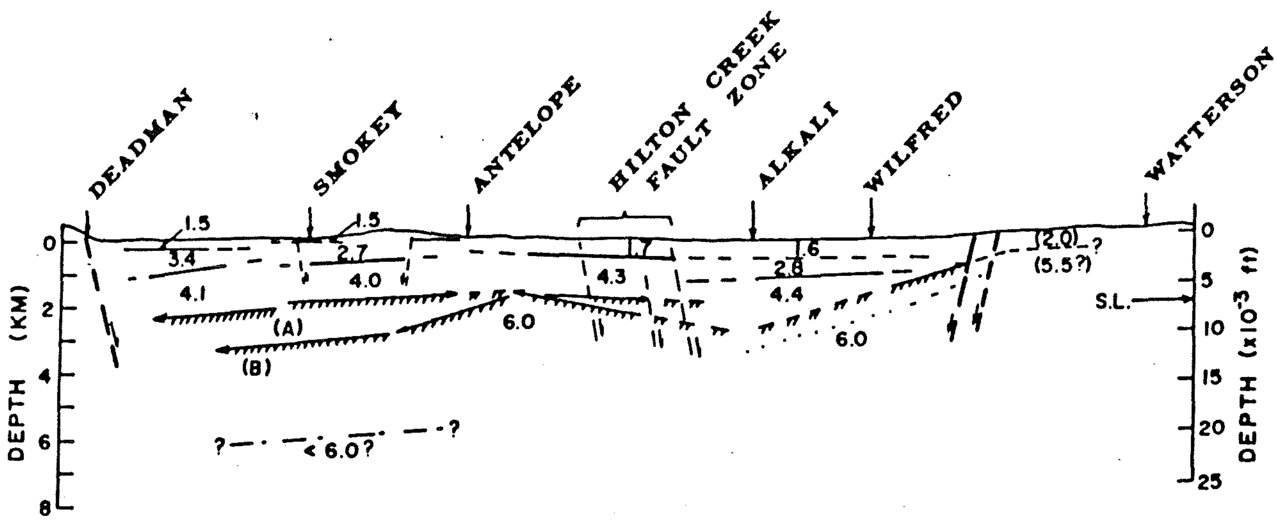


Fig. 18. Interpretive cross section along profile between Deadman and Alkali shotpoints shown in Figure 24a (Hill, 1976). Numbers give P-wave velocity in km/sec.

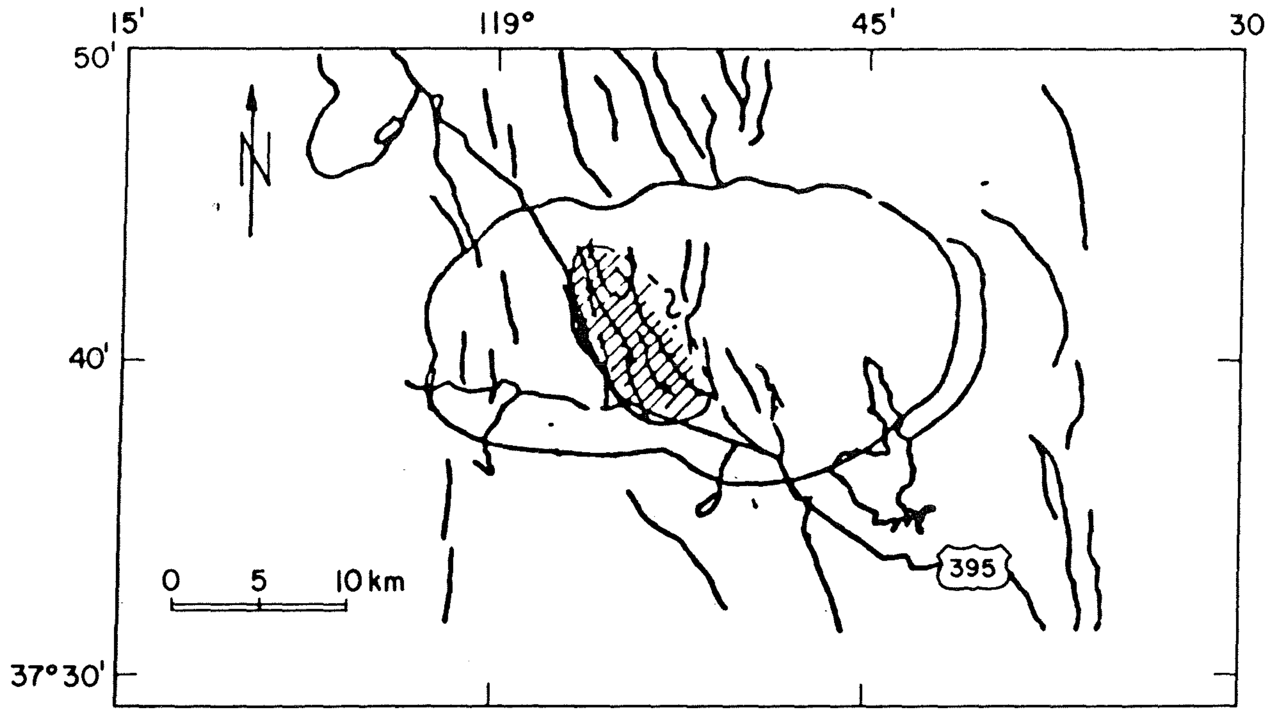


Fig. 19. Map of Long Valley caldera area showing location of a zone of low velocity at depths of from 3 to 7 km below the surface determined from a three-dimensional inversion method using about 7000 earthquakes and 50,000 P-wave arrivals (Savage and Cockerham, 1984).

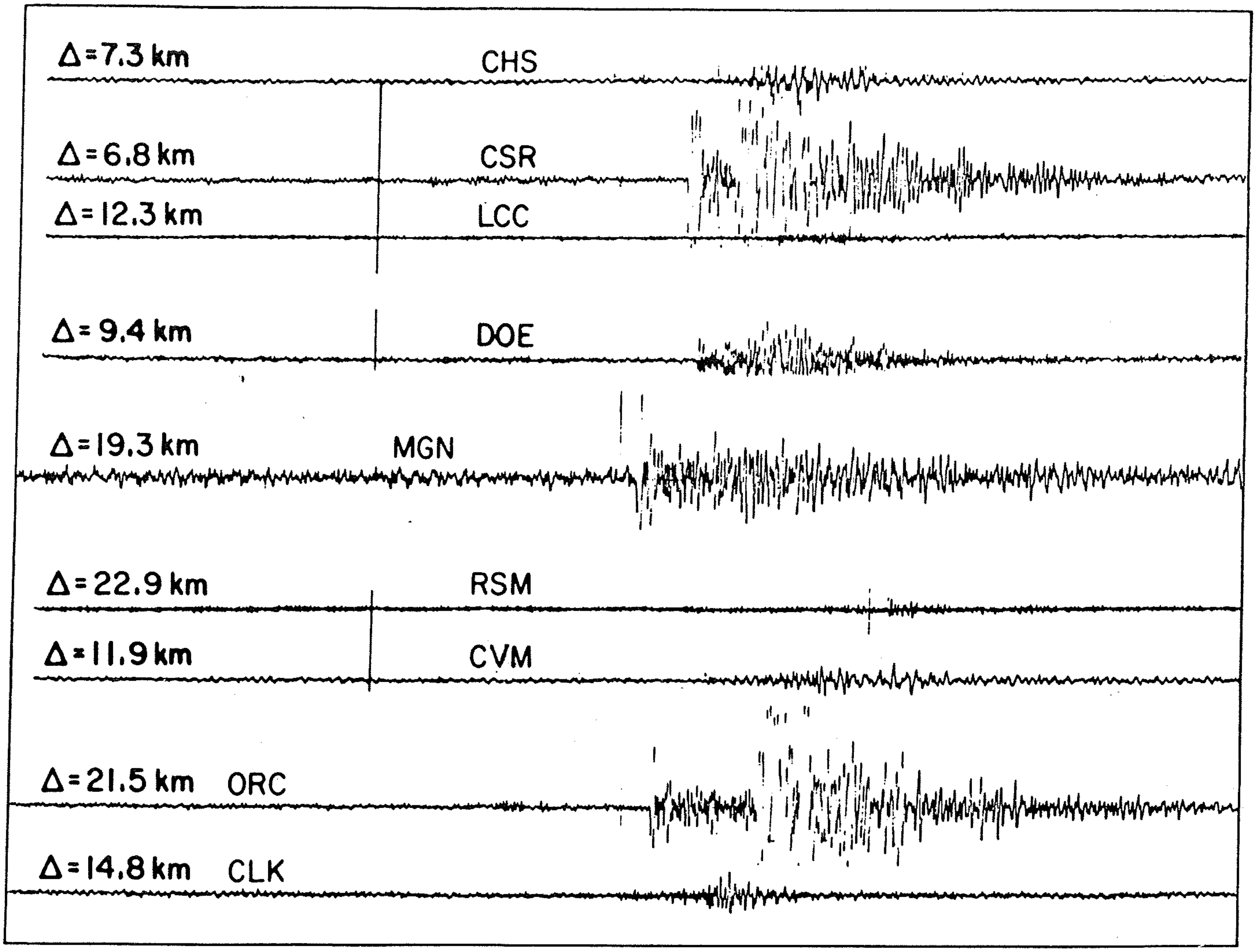


Fig. 20a. Seismograms from an earthquake which occurred on Dec. 15, 1983 at :0054:56.46 UTC, 37°43.78'N, 118°52.72'W, 8.44 km. These records clearly show the effects of an attenuating zone beneath the resurgent dome inside Long Valley caldera (Fig. 20b). The reader should compare CSR with CHS, EMH, MLK, and CVM noticing the change in frequency as well as in amplitude for both P- and S-wave codas. The low velocity zone has a rather sharp east-side boundary as seen by comparing CVM and DOE records. Also one should compare the clear and "clean" record at MAT, 89 km at an azimuth of 280°, with other nearby stations. The station locations and event location are shown in Fig. 20b. All caldera stations and CLK, RSM, and LLK have the same gain setting; MAT has a gain of 6 dB lower. Stations MGN, BEN, and ORC are Univ. of Nevada at Reno seismic stations and have different gain settings.

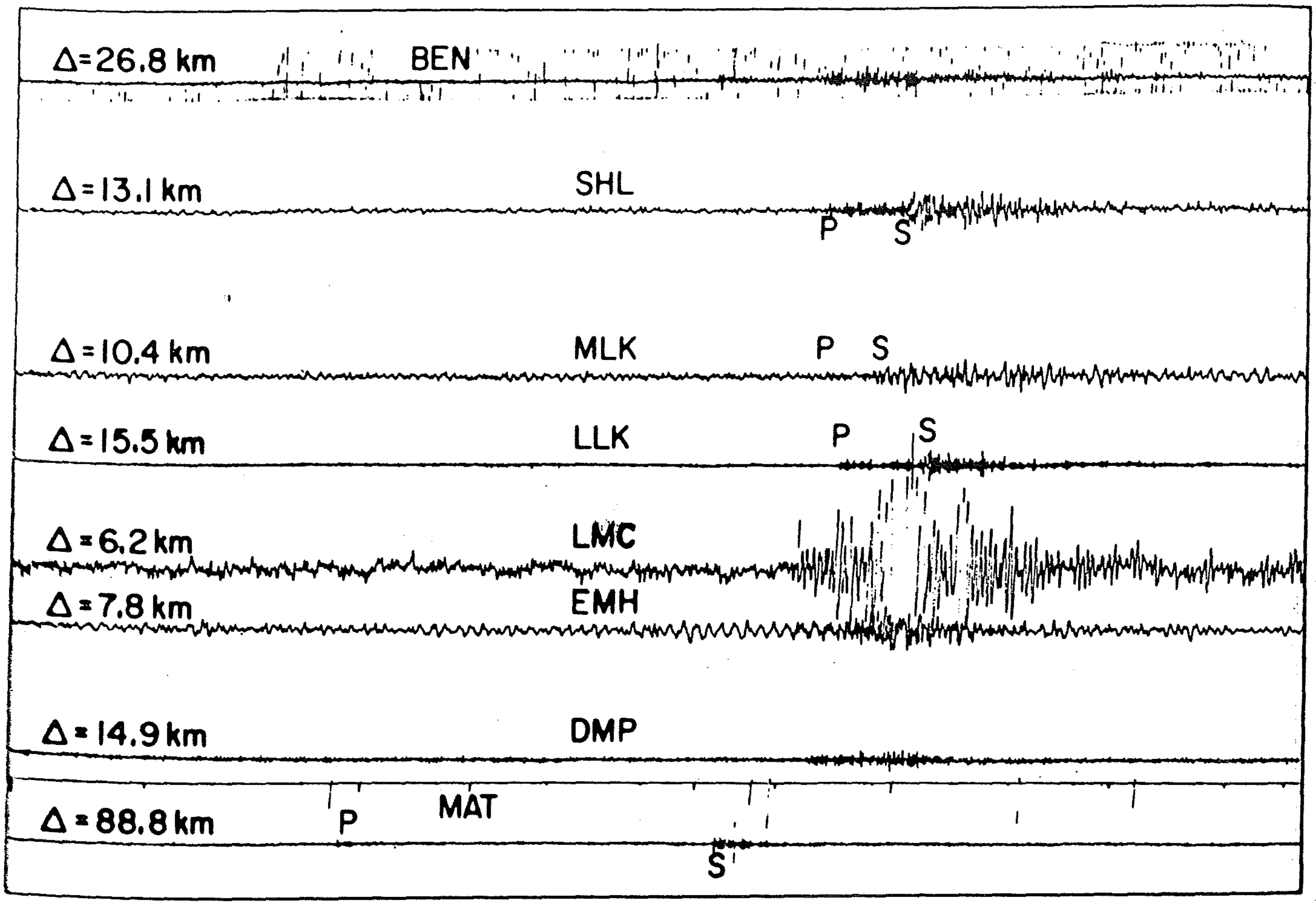


Fig. 20a (Continued).

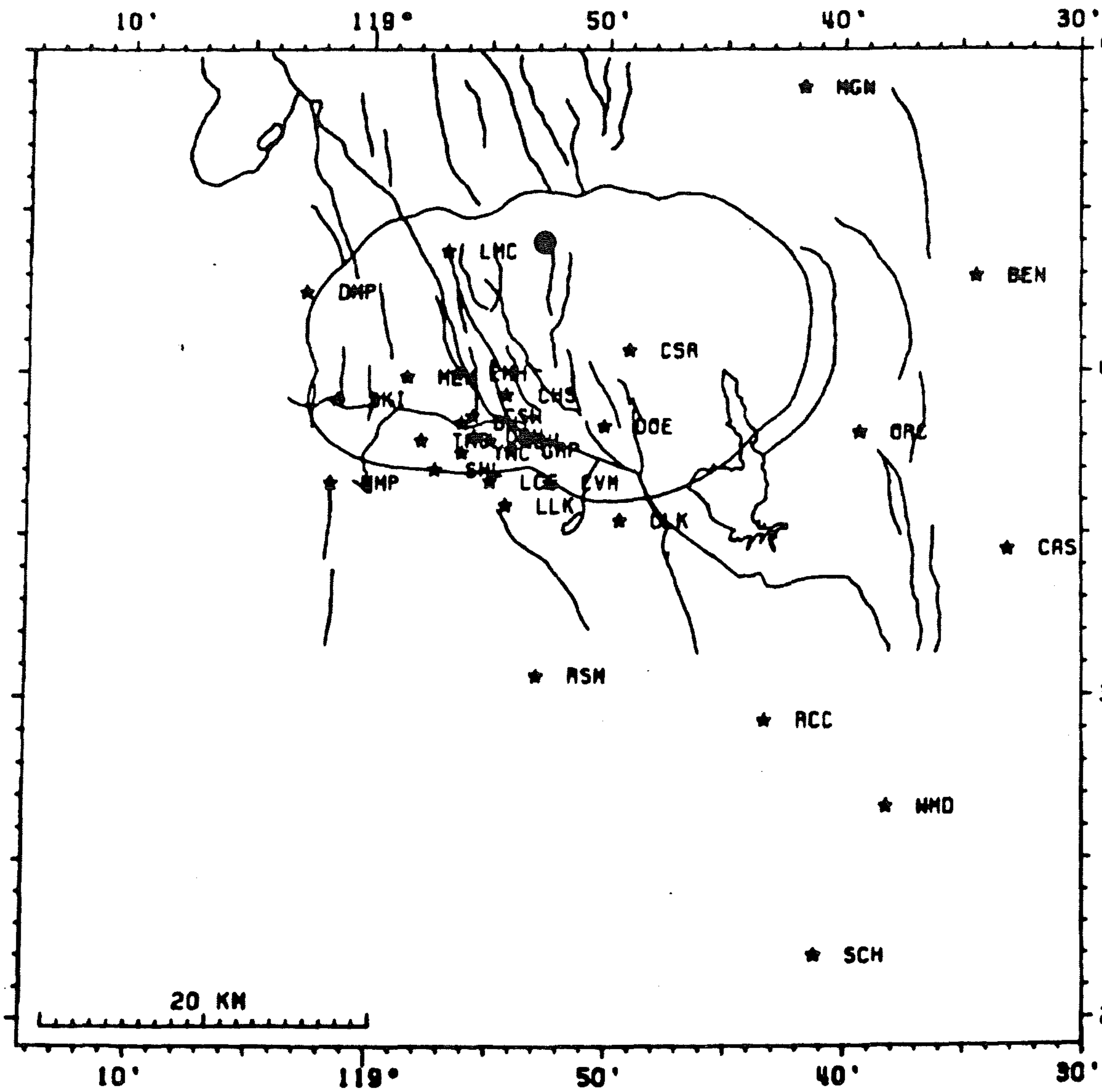


Fig. 20b. Locations of stations and event in Long Valley.

analysis by C. Sanders to be severely attenuated when propagating at depths below 5 km under the eastern part of the resurgent dome (Figs. 21,22).

2) Southwest Moat and Mammoth Mountain. Earthquakes separated by only a few km at these two sites within and outside the caldera show strikingly opposite relative attenuation at regional stations on NW and SW azimuths (Fig. 23).

Possibly Reflected Waves

Intriguing evidence exists in refraction survey lines for the presence of localized reflections from interfaces within the caldera. Two intersecting lines show similar strong secondary arrivals which can be interpreted as a reverse-polarity reflection from 6-7 km depth in the NW-Central part of the caldera, near one of the attenuation anomalies seen by C. Sanders (Fig. 24a,b). On another SW-NE line a strong second arrival is seen, at distances 31-40 km, which can be interpreted as a reflection from a NE-dipping interface at 16 km depth (Figs. 24a,25). Taken together, these two observations can be used as evidence for the upper and lower surfaces of a fluid magma chamber between 6 and 16 km depth in the western part of the caldera.

GEOLOGICAL STRUCTURE OUTSIDE THE CALDERA

Velocities in the Sierran block south of the caldera (where most of the non-caldera seismicity is) start near 3.5 km/sec at the surface and reach values similar to those of the caldera basement by 2-3 km. Below that depth, velocity models within and outside the caldera are very similar.

Several areas outside the caldera show localized attenuation zones at depths generally below 5 km for S-waves from local events seen at regional

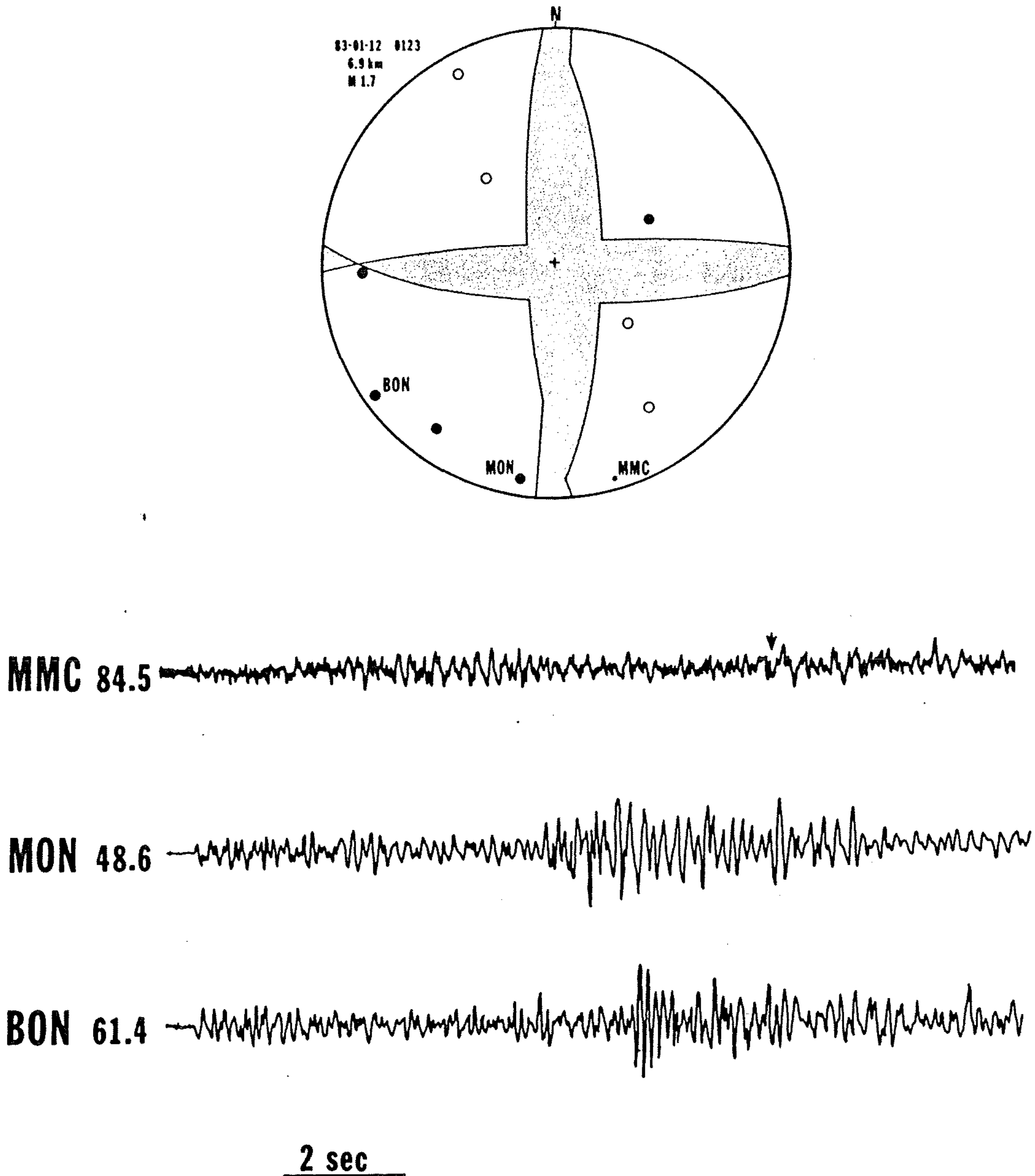


Fig. 21. Seismograms and source mechanism for a 6.9 km deep Long Valley event studied by Sanders (1984). Note the very low amplitude shear wave arrival at station MMC and the normal shear wave signals at MON and BON. The ray to station MMC (northwest of the caldera) passes through the central attenuating body while the rays to stations MON (northeast) and BON (east) do not. As the source mechanism indicates, the anomalous signal at MMC cannot be explained by source effects (since MON and MMC are located similarly on the radiation pattern) and is probably due to transmission through magma beneath Long Valley.

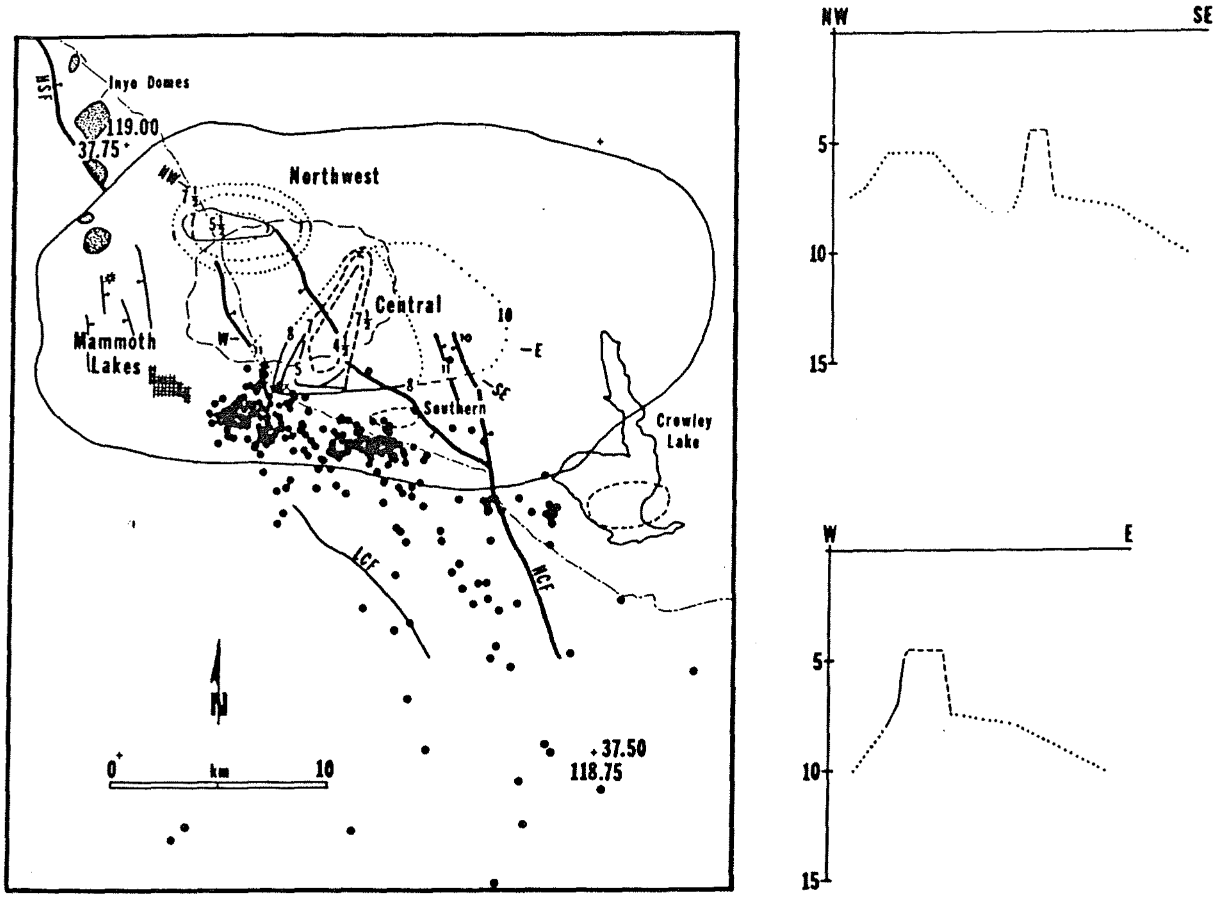


Fig. 22. Map of Long Valley caldera showing the epicenters of earthquakes used in the study of shear wave attenuation beneath the valley by Sanders (1984), the locations of massive shear wave attenuating bodies beneath the central and northwest caldera and small anomalous areas in the southern caldera and beneath Crowley Lake, and related geological features. The earthquake epicenters are indicated by solid dots. The northwest and central caldera bodies are outlined at various depth intervals (in kilometers). The smaller numbers near the central body indicate the shallowest depth that attenuating effects are actually seen in those areas. The solid lines mark well-located boundaries. The dashed contours are more interpretative; the dotted contours are the most interpretative. The "x" in the SW corner of the central body marks the location of Casa Diablo Hot Springs. The surface projections of the areas of anomalous crust in the southern caldera and beneath Lake Crowley are shown with dashed outlines. Major faults in and near the caldera are drawn with heavy lines, and the area of the resurgent dome is outlined by long, thin dashes. HCF--Hilton Creek fault, LCF--Laurel-Convict fault, HSF--Hartley Springs fault. The late-Holocene Inyo Domes and craters (last active about 700 years ago) are shown in the northwest caldera. The thin, solid line in the northwest caldera encloses the approximate area of the deep "magma roof" reflection seen by Hill (1976) (Fig. 24a). The location of U.S. Highway 395 is marked by the line of long and short dashes running diagonally across the map.

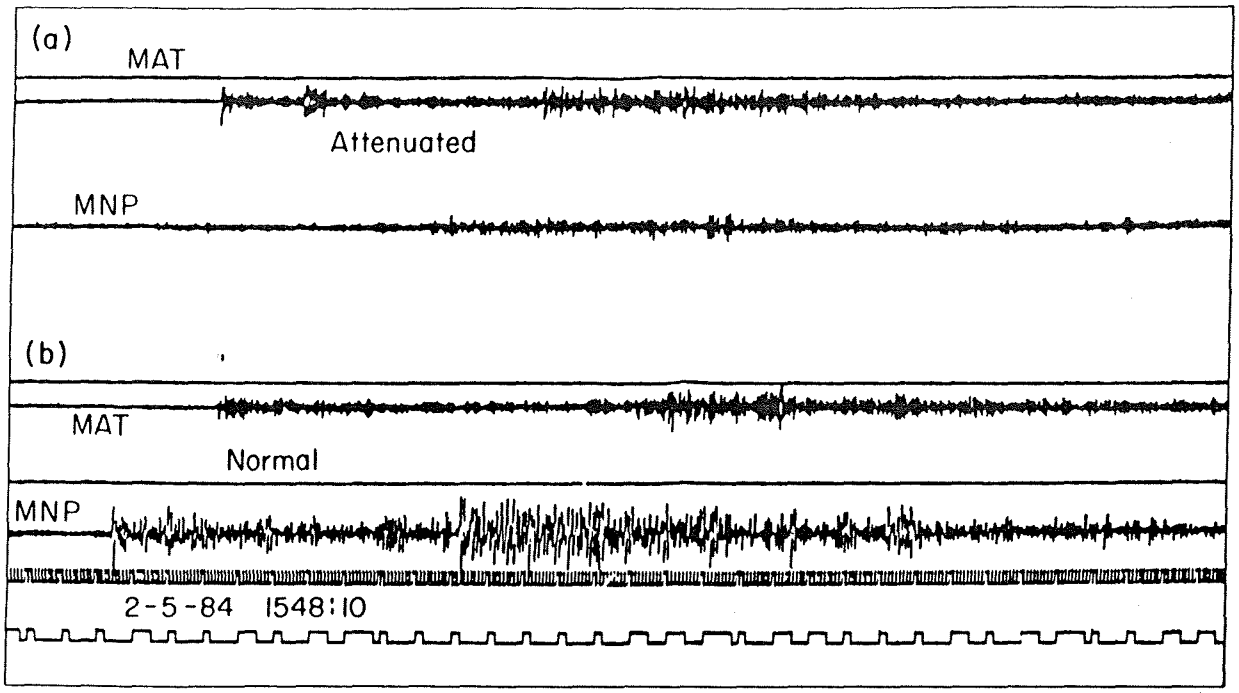


Fig. 23. Seismogram of two earthquakes located approximately 2-3 km (a) and 8-9 km (b) east of Mammoth Mountain. These seismograms are from U.S. Geological Survey seismic stations MNP (Nipinnawasse, Calif.) and MAT (Mather, Calif.) which are located approximately 70-80 km and 80-90 km at azimuths of 250° and 280°, respectively. (a) shows an "attenuated" record at MNP compared with MAT for an event only 2-3 km east of Mammoth Mountain. (b) shows a "normal" record where MNP has a much larger amplitude signal than MAT for events 8-9 km east of Mammoth Mountain.

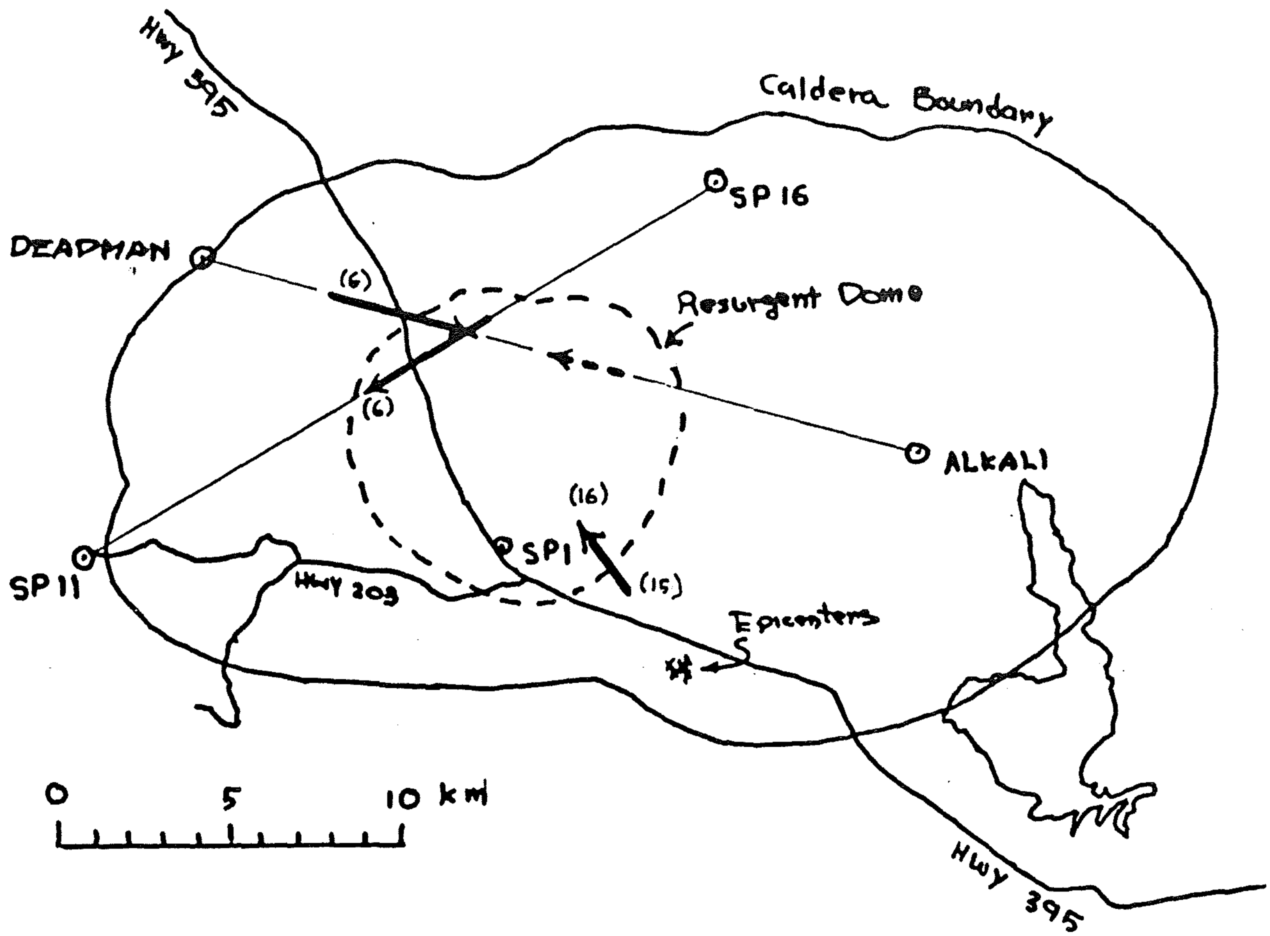


Fig. 24a. Location of refraction profiles and loci of subsurface reflection points (heavy lines) for secondary arrivals. Arrows indicate shot-to-receiver direction. Parenthetic numbers indicate approximate depth in km to reflecting boundary. Cluster of crosses near southern boundary of caldera are epicenters of earthquakes used in profiling.

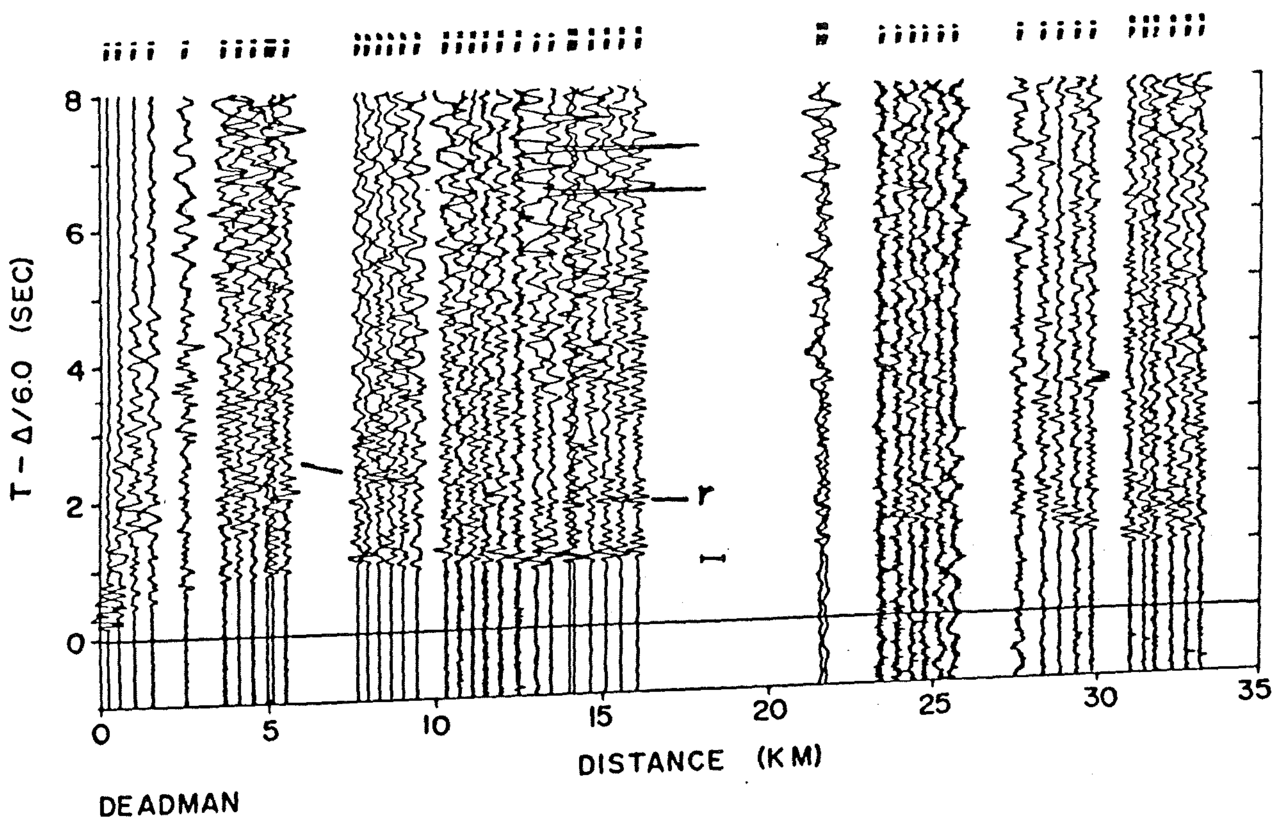


Fig. 24b. Reduced traveltime record section, Deadman east (Hill, 1976), showing reflected arrival, r.

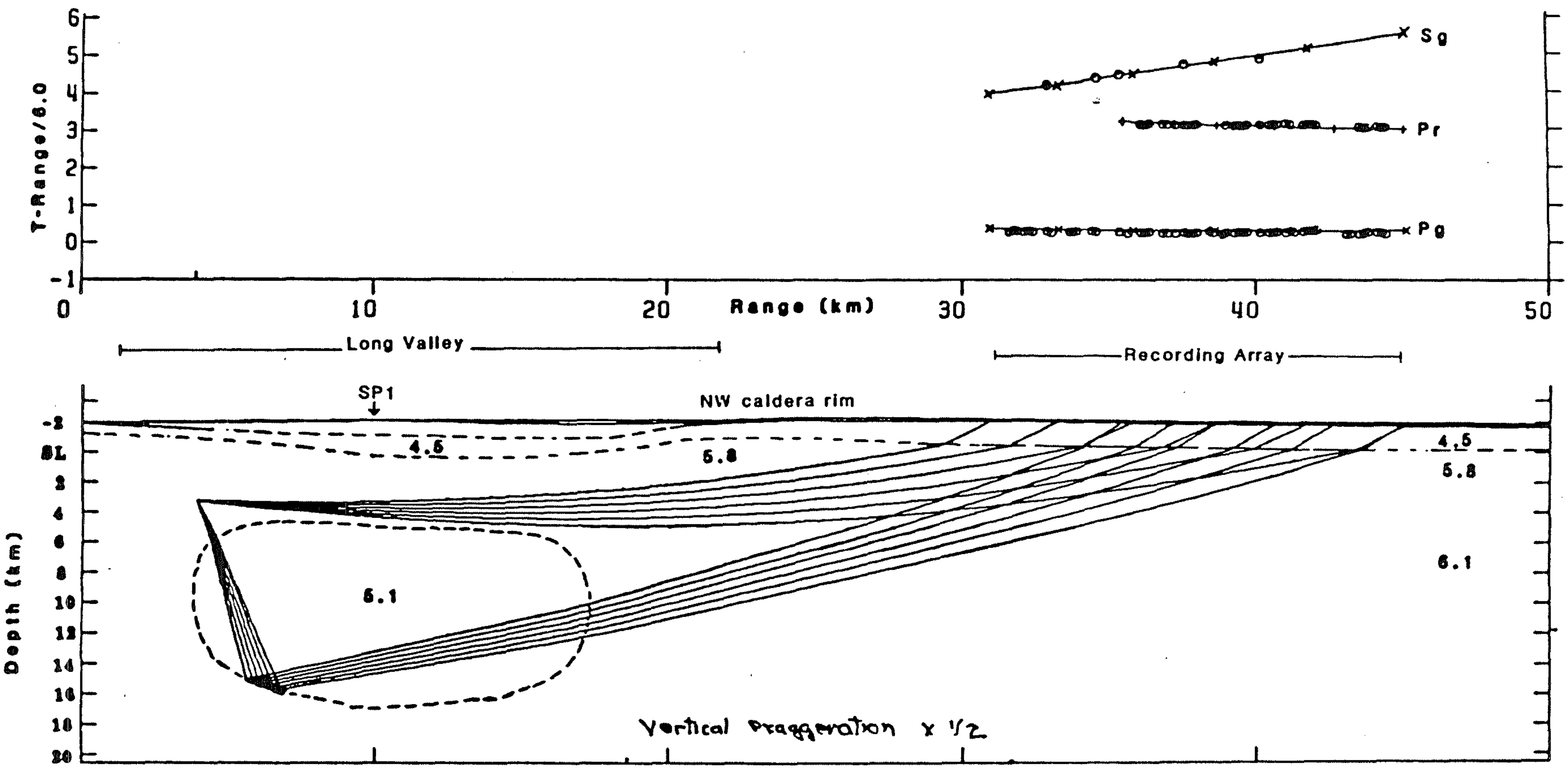


Fig. 25. Reduced traveltime curve of major phases in earthquake record section and cross section showing ray traces for Pg and for the Pr phase, assumed reflected from the base of a magma chamber. Numbers indicate P-wave velocity in km/sec. Dashed line indicates approximate basement geometry based on the 1982 refraction profile (Luetgert and Mooney, 1984).

stations (Fig. 22). The zones are found, as in the case of that beneath the resurgent dome by a back projection method on raypaths at varying azimuths.

OUTSTANDING ISSUES

Seismicity

- At what scale, if any, do hypocenters define fault planes? Do the lineations with dimensions about 1 km, our spatial resolution, reveal structure?
- Does the present permanent network yield maximum detection capability and location accuracy, and, if not, is there compelling need to add more stations?
- Are mechanisms consistent with magma intrusion along the diffuse cluster area in the south moat (Savage model), with slip on planar zones of weakness in response to the stress field due to magma injection at depth NE of cluster area (Rundle model), with both, or with some other process? What additional evidence will provide the means for discriminating among models?
- What is driving the anomalous swarm activity seen at Mammoth Mountain and in the south moat seismicity in 1980?
- Are there possibly any unique source properties in those events showing apparently anomalous S-wave attenuation?
- Why are earthquakes occurring in the sharply bounded distribution of activity in the Sierran block to the south?
- Is (and if so, why) the recently active Inyo-Mono trend of volcanic vents truly aseismic?

Structure

- Will a more precise definition of the top and bottom of the Bishop Tuff resolve some of the questions of hydrogeology and heat transfer?
- To what degree of confidence and resolution is it possible with seismological methods to detect and define a magma chamber or a smaller thin planar zone or finger of intruding magma, and to estimate its melt fraction?
- Can we better define and thus understand more fully the nature of the localized zones of S-wave attenuation within the caldera and in the Sierran block?
- How can we better delineate the two apparently strongly reflecting surfaces (6-7 and 16 km) seen in the refraction profiles?
- Does seismic reflection profiling offer a substantial increase in resolution for defining the main structural features such as the high-angle caldera-rim and intracaldera faults, the top of the Bishop Tuff, the basement surface, and possible magma bodies within the caldera complex?

ELECTRICAL AND ELECTROMAGNETIC MODELS

H.F. Morrison, Rapporteur

Studies of the distribution of electrical resistivity within and beneath the Long Valley caldera have had three main objectives:

1) detection and mapping the present hydrothermal-geothermal system,
2) mapping caldera structure concealed by younger sediments and volcanics, and
3) detection of magma.

Early studies by the USGS were mainly useful for mapping the resistivity distribution in the upper 1-2 km of the caldera. The magnetotelluric (MT) and controlled source electromagnetic (CSEM) methods that have been applied in the past four years have attempted to extend the depth of study to 10 km or so.

Regional Conductivity Model

Because of the very large scale of the natural low frequency inducing fields and resulting currents, the MT method is strongly influenced by major regional structural features. By means of regional measurements and models J. Hermance (Hermance et al., 1984) has identified several major electrical blocks that strongly influence current flow in the upper crust (Fig. 26):

1) The Owens Valley conductor,
2) The Long Valley caldera conductor,
3) The Mono Basin conductor,
4) The Sierra Nevada and White Mountain resistors, and
5) The broad region north of Mono Lake between the Sierra and White mountains of moderate resistivity.

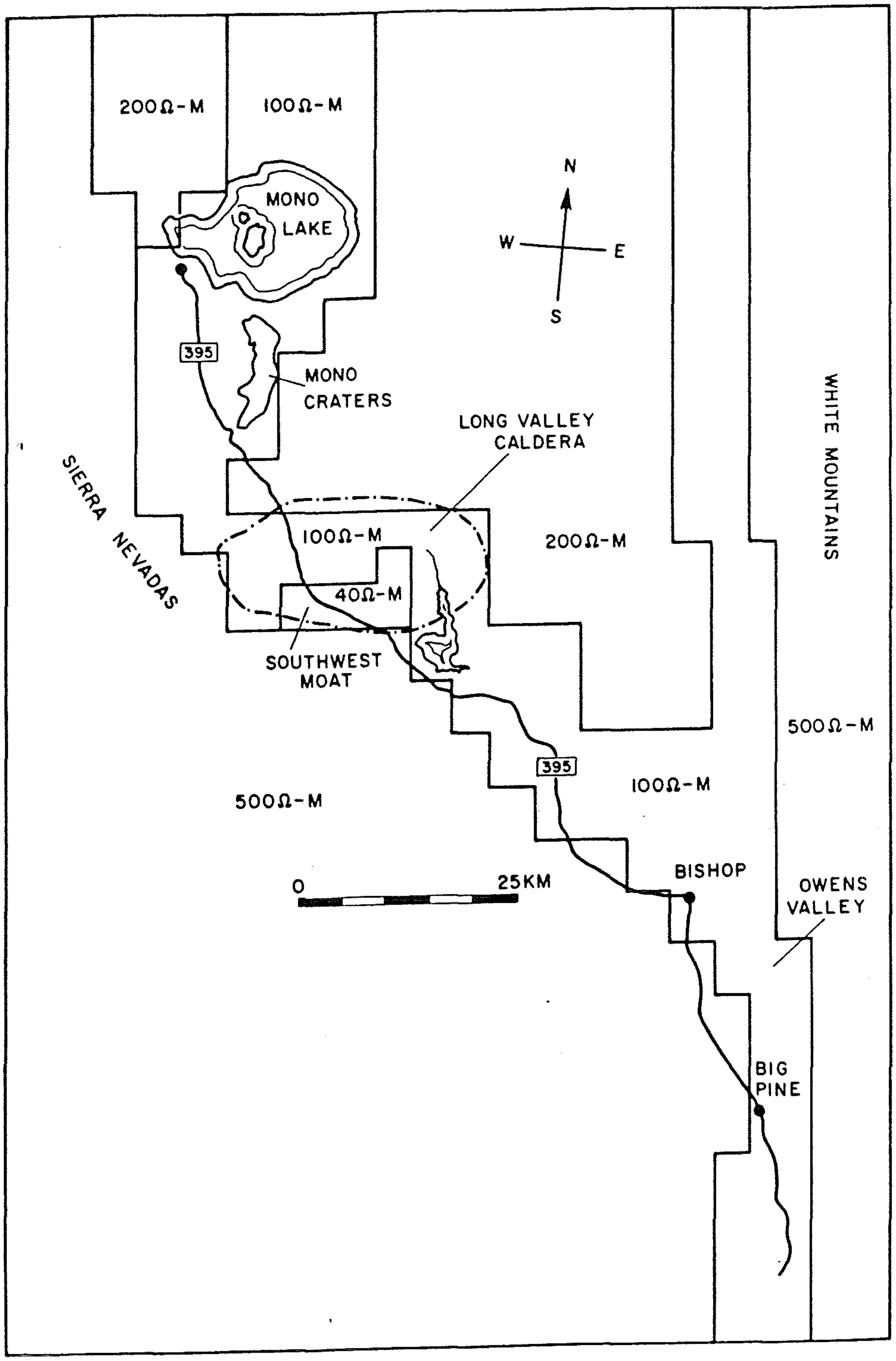


Fig. 26. Plan view showing the principal electrical elements in the Owens Valley and the Long Valley/Mono craters volcanic complex.

This regional distribution was modeled by means of a dc approach, and the resulting electric field (E) ellipses (assuming a circularly polarized "incident" E field) and magnetic induction arrows are in excellent agreement with the regional field data.

Long Valley Caldera Model

On a more detailed scale, the orientations and dimensions of the telluric ellipses have been used, semiquantitatively, to map the distribution of high conductivity material within the caldera. Hermance has found a broad concave-north arcuate conductor south of the resurgent dome with this method (Fig. 27). On a still more detailed scale, an analysis of the frequency dependence of MT parameters suggests the presence of a good conductor at a depth of 7.0 km beneath the south moat (Hermance et al., 1984). It has not been determined whether this is a confined conductor or a broad feature underlying the whole region. The very strong imprint of the regional electric structure makes detailed interpretation of conventional MT apparent resistivity soundings very difficult. To assess the sensitivity of the MT method to the presence of a magma body, Hermance has conducted a series of model studies to determine how changes in the conductivity distribution at depth affect measured values at the surface. This analysis is essential for determining the resolution of the technique as well as determining whether the method could be used to monitor changes with time as an intrusion occurred.

Because the dipolar inducing fields used in the controlled-source EM method fall off rapidly with distance from the source, this method is less affected than MT by the regional conductivity structure. For measurements within the LVC, this feature makes CSEM data somewhat easier to interpret

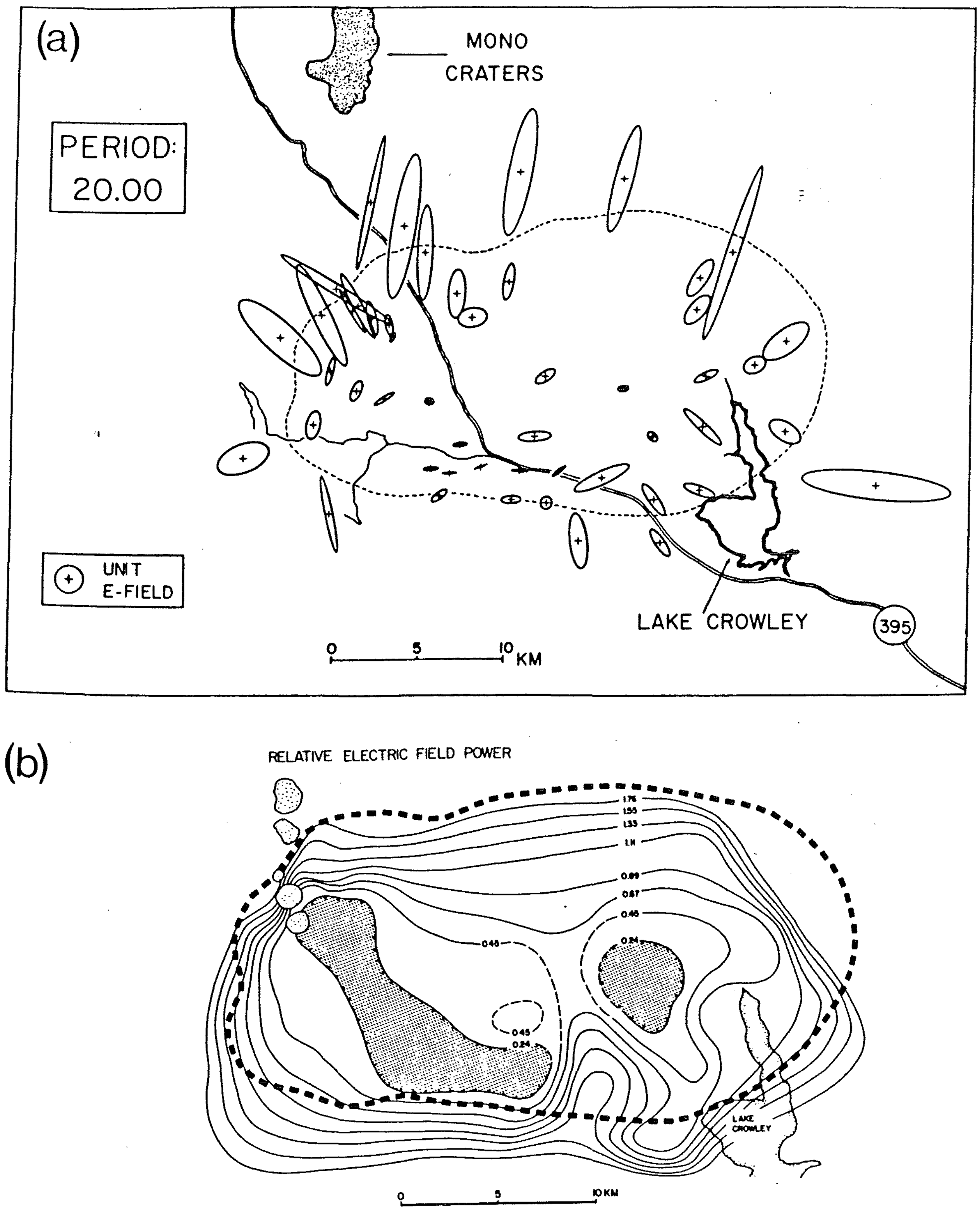


Fig. 27. (a) Normalized telluric ellipses in Long Valley caldera.
(b) Relative electric field power contoured on the basis of the area of the telluric ellipses in (a). Zones of low electric field power (shown as shaded) are likely caused by zones of high conductivity in the crust.

than MT data. However, if there are strong lateral variations that invalidate simple layered interpretations, then the two- or three-dimensional models that must be used to interpret CSEM data tax the capacity of the largest computers.

LBL has obtained data from 46 transmitter-receiver pairs (from 5 transmitters, Fig. 28) concentrated in the south moat and parts of the resurgent dome areas. Much of the data from the south moat area were strongly influenced by the large resistivity contrast present across the south rim of the caldera. Away from this feature the data from small transmitter-receiver separations yielded good layered interpretations which show near-surface resistivity features that correspond well to the earlier results of AMT, bipole-dipole, transient EM and Schlumberger soundings reported by workers from the U.S. Geological Survey (Stanley et al., 1976). These shallow conductors in the upper 300 to 500 m (Fig. 29) are probably due to lake sediments and late-stage zeolitized volcanic tuffs saturated with water ranging in temperature from about 170°C near Casa Diablo to <100°C to the east (Stanley et al., 1976).

Some of the larger transmitter-receiver separations gave evidence for two conductors, apparently separated, at ~3 km apart; one beneath the south moat, the other at the northeast edge of the resurgent dome (Fig. 30). Together, the deep and shallow conductors conform very well with the general arcuate conductor found by Hermance (Fig. 27).

Basement Conductors

The cause of the deeper conductors is not conclusively known, and there is considerable interest and speculation on their possible relationship to present hydrothermal conditions. The south moat conductor (C1) correlates

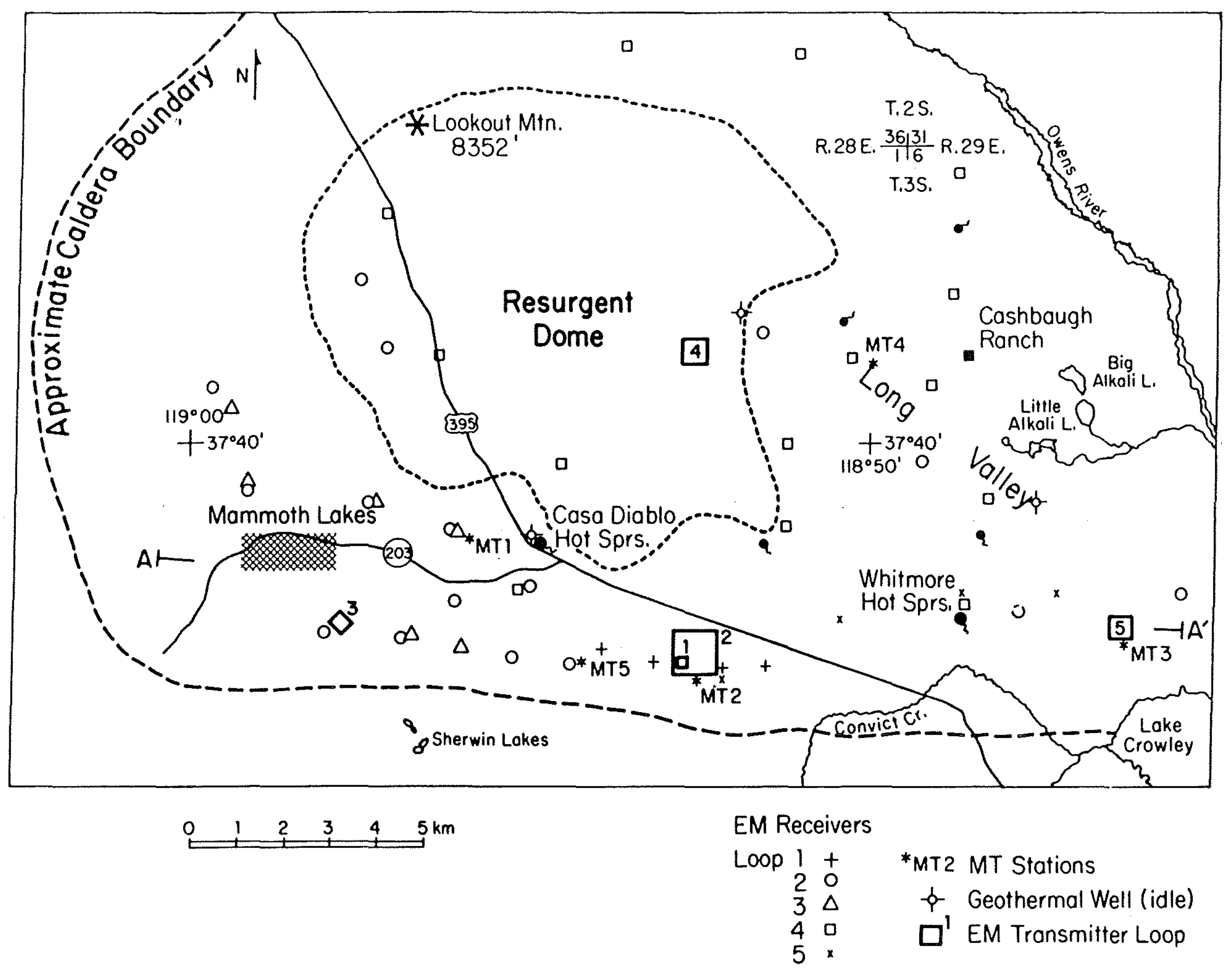


Fig. 28. Location of horizontal loop, electromagnetic dipole transmitters, and magnetometer-receiver sites occupied in the Long Valley caldera.

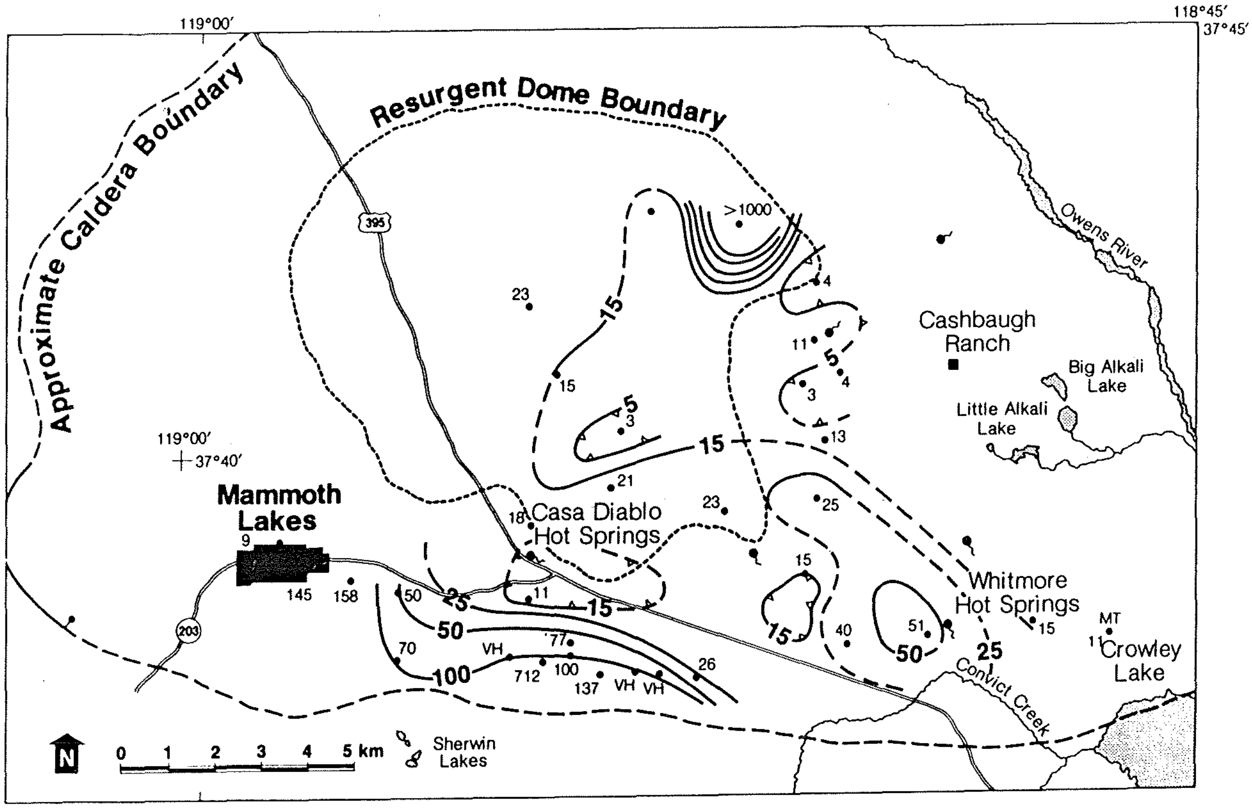


Fig. 29. Near-surface resistivities (ohm-m) determined from electromagnetic soundings. Values represent conditions in the upper 300-500 m, and are plotted, by convention, midway between transmitter loop and detector. VH denotes poorly constrained but very high values of resistivity.

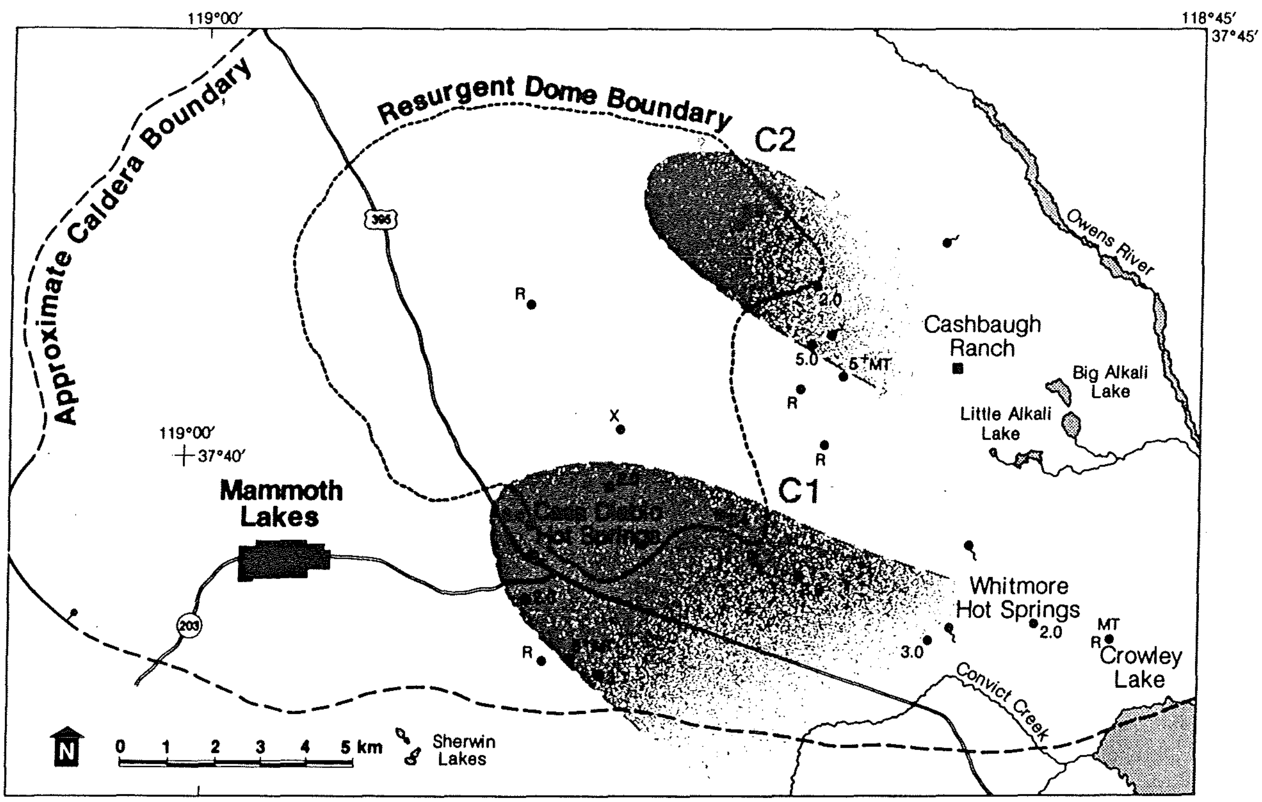


Fig. 30. Approximate locations of two conductors, C1 and C2, interpreted to lie within basement complex. Both have a resistivity of approximately 2 ohm-m; depths to conductor top, in km, are indicated. MT is a magnetotelluric sounding, R denotes a resistive basement.

reasonably well with the epicenters of recent earthquake swarm activity, and it is likely that the conductor indicates the presence of fractured basement rocks whose conductivity is enhanced by the circulation of high temperature (~200-240°C) waters. The intersection of Paleozoic metasediments at 1.4 km in Union Well Mammoth #1 near Casa Diablo Hot Springs and a general aeromagnetic low does not allow us to exclude the possibility that graphitic shales and schists are contributing to the south moat anomaly.

The deep conductor (C2) beneath the northeast rim of the resurgent dome is an aseismic and cooler area. The presence of nearby widespread argillic hydrothermal alteration at the surface and a magnetic anomaly closely concordant with the conductor in plan (but apparently shallower in depth) suggests that there may be a causal relationship between the present conductor and intrusive-hydrothermal activity related to the line of east moat rhyolite domes dated at 0.3 m.y. However, because these rhyolites do not appear magnetic and because there is no evidence for a recent heat source beneath the area, other explanations have been sought. One speculation based on mapped faults, limited deep drilling, seismic refraction (Hill, 1976), and shallow resistivity soundings is that the anomalies are related to a concealed graben trending NW-SE within the caldera. This suspected graben, whose western margin appears to be the extension of the Hilton Creek fault, could have been created by basin-and-range extension which, in this model, has resulted in the intrusion of a sheeted mafic dike complex to fairly shallow depth (Fig. 31). According to J. Savage, present east-west extension across this area is of the order of 30 mm per year over a 30 km baseline. However, one cannot rule out the possibility that Paleozoic metasediments and older dioritic bodies, as found in the roof pendant in the Mt. Morrison quadrangle to the south, are the cause of the electrical and magnetic anomalies.

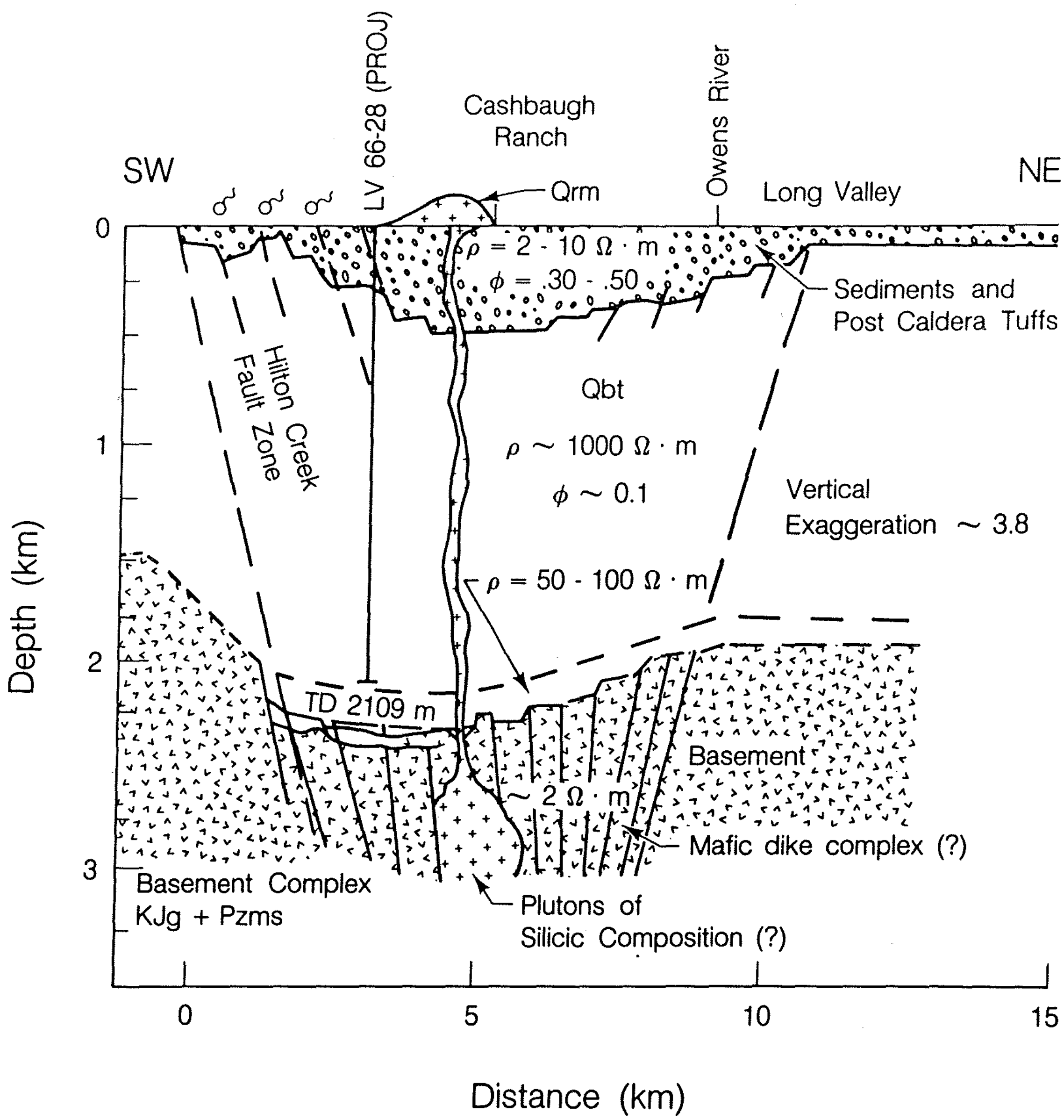


Fig. 31. Schematic of one possible geophysical model for central part of the caldera along a SW-NE profile line. Model is based on results from limited deep drilling (Republic well LV 66-28), seismic refraction (Hill, 1976), electromagnetic soundings, and aeromagnetics (Kane et al., 1976). Qrm is a moat rhyolite, Qbt is Bishop Tuff, and KJg + Pzms is the basement complex composed of Sierran granite and Paleozoic meta-sediments and minor dioritic intrusives.

The hydrogeology studies, deformation measurements, and recent seismic activity increasingly point to the south moat and perhaps part of the west moat as areas where shallow intrusion of magma has been occurring. It is in these areas that additional electrical studies, including self-potential, should be concentrated. More MT and CSEM stations in this area are necessary to sort out the structure. A greater effort must be put in the detailed interpretation of both techniques to answer some key questions about the thermal regions in the area.

Outstanding Issues

The recent telluric MT and CSEM surveys reveal a very complex resistivity structure within the Long Valley caldera. The survey results have opened new questions regarding caldera structure and evolution, and rekindled older questions regarding our ability to interpret MT and CSEM data to extract the information that may be present. The major issues are as follows:

- Are the two deep conductors detected thus far part of a more extensive conductor region at depth, or are they discrete, confined inhomogeneities?
- Do the two conductors have a strong non-thermal component (presently), e.g., graphitic schists in a roof pendant or hydrothermally altered rocks, or are the conductors mainly a result of active hydrothermal-magmatic conditions?
- Assuming the conductors are due to active hydrothermal conditions, what does this signify in terms of the evolution of the caldera and the location of present heat sources?
- If there exists a partial melt zone at depths $\geq$ 6 km as many geophysicists believe, can it be resolved by means of MT and CSEM

methods? If so, how? Field techniques and instrumentation could be improved, but the biggest deficiency still seems to be in the area of interpretation.

- Is there a geological connection between the basement electrical anomalies and the seismic anomalies such as shear wave attenuation zones beneath the resurgent dome and the reflecting interfaces beneath the northwest corner of the resurgent dome?

DEFORMATION AND GRAVITY

E.L. Majer, Rapporteur

Proposed Models

Several simple models were put forth to explain the gravity, leveling, and horizontal extension data collected in the Long Valley caldera. The main emphasis was on interpreting the data collected between August 1982 and August 1983. The leveling data (Fig. 32) indicate an uplift with a sharp gradient beginning between the Sheriff's Substation and Casa Diablo Hot Springs on Highway 395. The gravity data also indicate a sharp uplift in this area and a separate sharp uplift north of the resurgent dome not seen in the leveling data (Fig. 33).

All proposed models require a volume increase of 0.02 to 0.03 km^3. The earthquake activity in the south moat area as well as along the Laurel Canyon and Hilton Creek faults is an element of additional complexity. The observed deformation cannot be accounted for by either faulting or inflation of a magma chamber alone, but by some combination of the two.

J. Rundle (Rundle and Whitcomb, 1984) proposed a model with two point-source "magma" chambers: a deep chamber at 8 km below the center of the resurgent dome and a shallower chamber at a depth of 5 km centered a few hundred meters east of Casa Diablo Hot Springs (Fig. 34). Uplift and trilateration results for different time intervals were fitted to models for differing volumes of injected "magma" and for varying dislocations on the south moat fault (strike-slip only) and on the Hilton Creek fault (dip-slip only). Figure 35 shows one calculated fit to the surface deformation believed associated with the earthquakes of May 1980. It is hypothesized

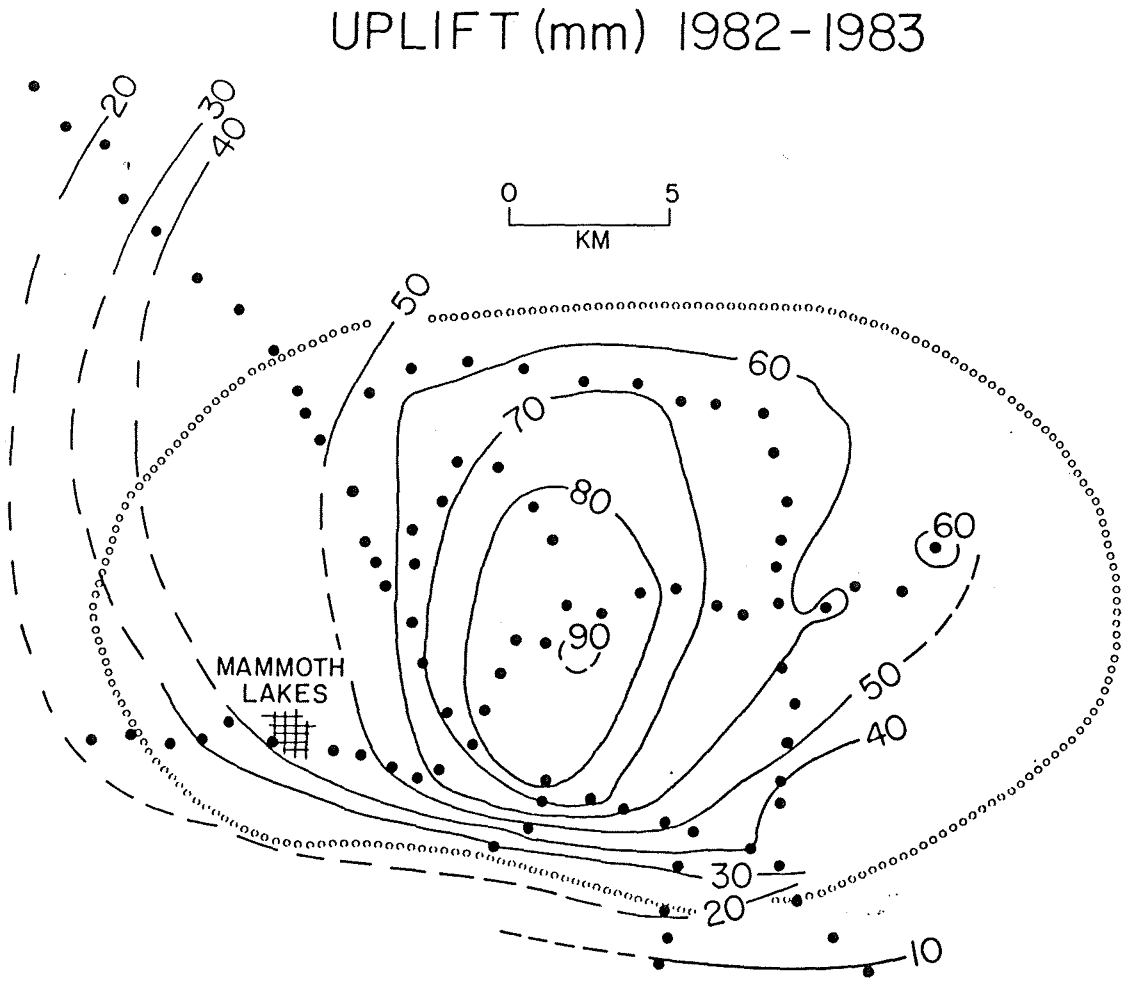


Fig. 32. Contour map of the 1982-1983 uplift in millimeters after Castle et al. (1984). The dotted oval locates the boundary of the Long Valley caldera, and the black dots locate bench marks at which elevation changes were available.

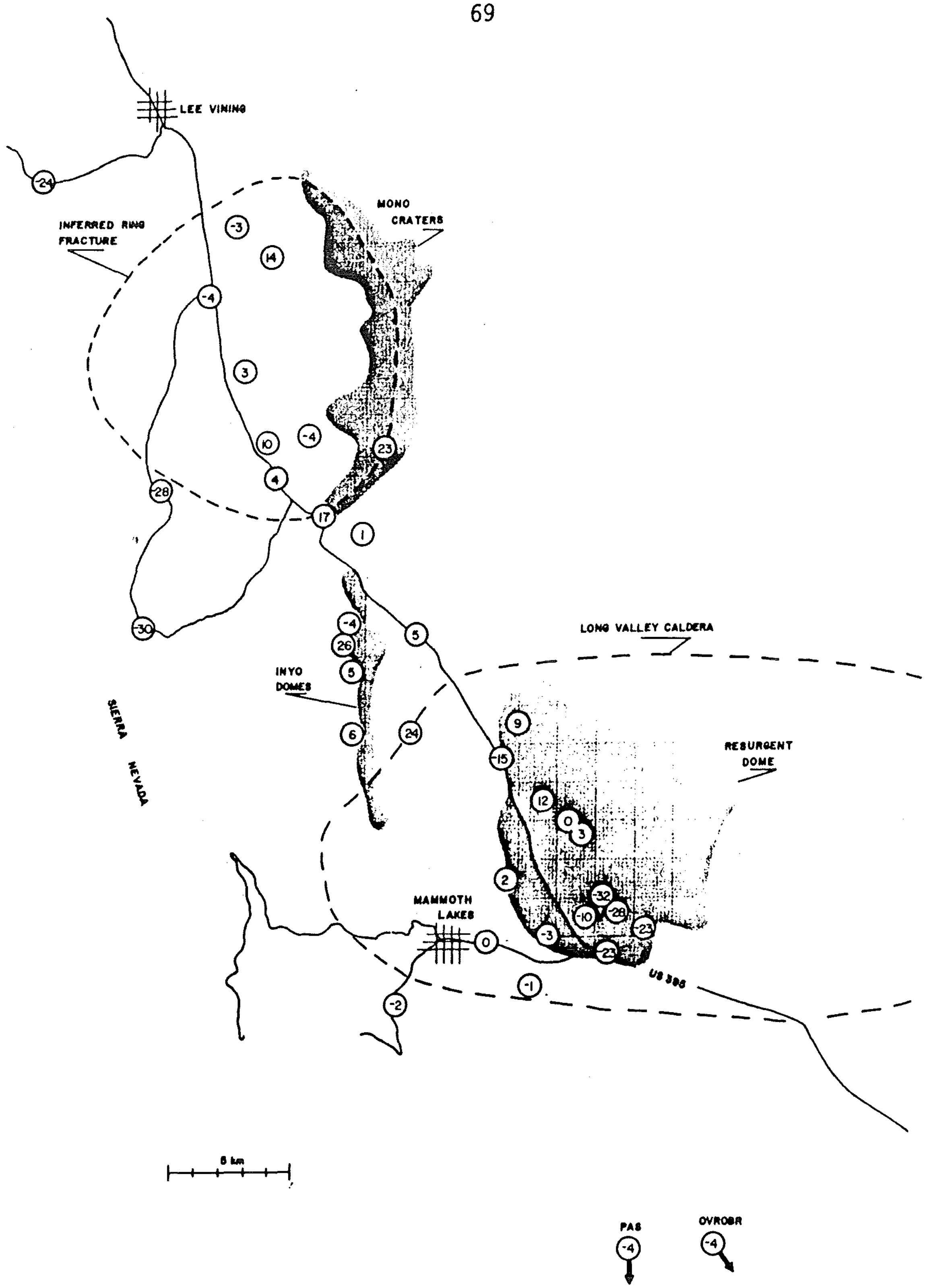


Fig. 33. Gravity changes (microgals) observed 1982-1983. Peak uplift (gravity decrease) occurred at the Sheriff's Substation, southern part of the resurgent dome.

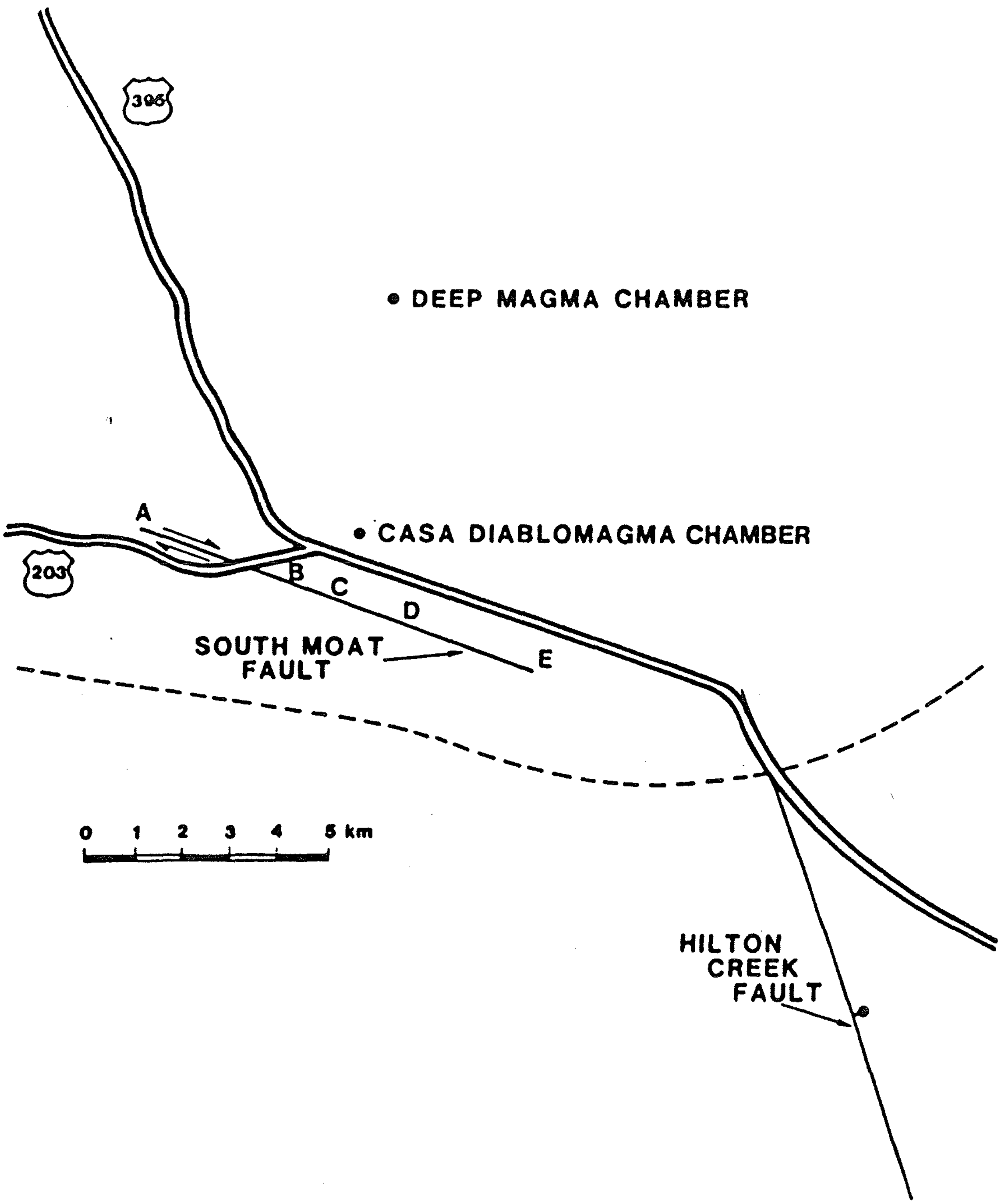


Fig. 34. Map of the southwest part of Long Valley with the surface projections of the two point-source magma chambers assumed by Rundle and Whitcomb (1984). Model fits to leveling and trilateration data also assume strike-slip motion on the south moat fault and dip-slip motion on the Hilton Creek fault.

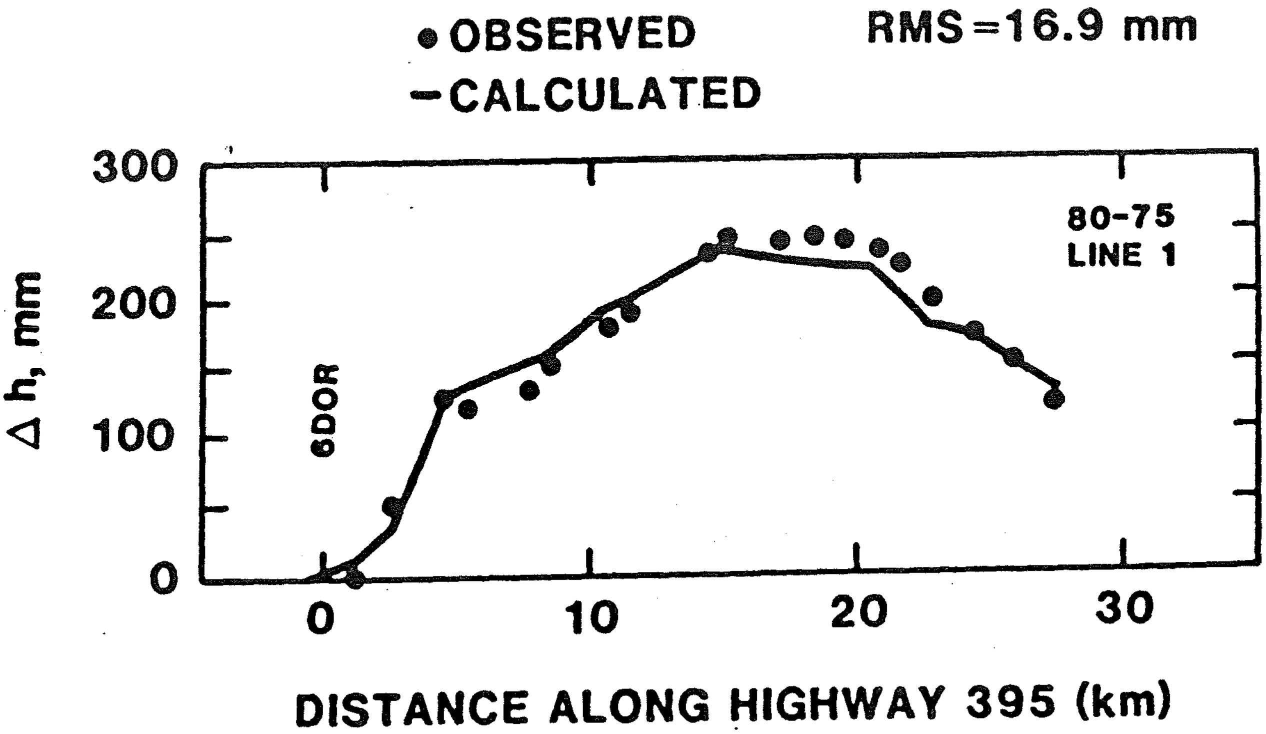


Fig. 35. Fit of the leveling data between 1975 and 1980 to the two magma chamber model. Most of the uplift is presumed associated with the earthquake activity in May 1980. Solid circles are the benchmarks used; solid line is the calculated model for the following conditions: (a) 0.05 km^3 magma injected into deep chamber, (b) 0.0045 km^3 magma injected into Casa Diablo chamber, (c) south moat fault slip occurred between A and D (see Fig. 34) with 0.25 m of slip in the depth range 0.5 to 0.7 km and 1 m of slip in the depth range of 7 to 12 km, and (d) normal slip (west side up) on the Hilton Creek fault was 0.125 m from the surface to 2 km depth and 0.29 m from 2 to 5 km depth.

that magma injection causes stresses which produce displacements along the south moat fault and the observed seismicity. However, simple point-source inflation cannot alone produce stresses consistent with the observed strike-slip displacement along the south moat fault. Leveling data between the summers of 1982 and 1983 indicate that inflation of the two chambers may have accompanied or triggered the intense swarm activity in January 1983.

J. Savage proposed a model with a 30° dipping slab from 8 to 10 km depth and a vertical dike intrusion from the slab to within 3 km of the surface (Fig. 36). This model seemed to fit all the data except J. Whitcomb's gravity data. Simple right lateral slip motion is occurring along the vertical portion of the Savage model. However, hypocenters seem to be distributed over a zone more than 1 km in width, too wide perhaps to satisfy the narrow vertical dike in the Savage model. However, Savage's model is also consistent with a distribution of small dikes in an equivalent volume. Also, the distribution of earthquake activity may be in a much wider zone than the actual dikes themselves.

Because the uplift data are relatively expensive and time consuming to obtain, the rate and exact nature of the uplift and deformation are difficult to determine. Also, it should be pointed out that the models are very non-unique, and to fit the data reliably one must use other data as well.

One should keep in mind the purpose of obtaining deformation data. If hazard prediction is the only purpose, rather than generic studies on magma intrusion, then measurements must be made rapidly enough to detect any significant change. Sudden increases in tilt or uplift may signify a hazardous condition. If an understanding of the mechanism (important for determining the hazard) and the rate and location of the magma is desired,

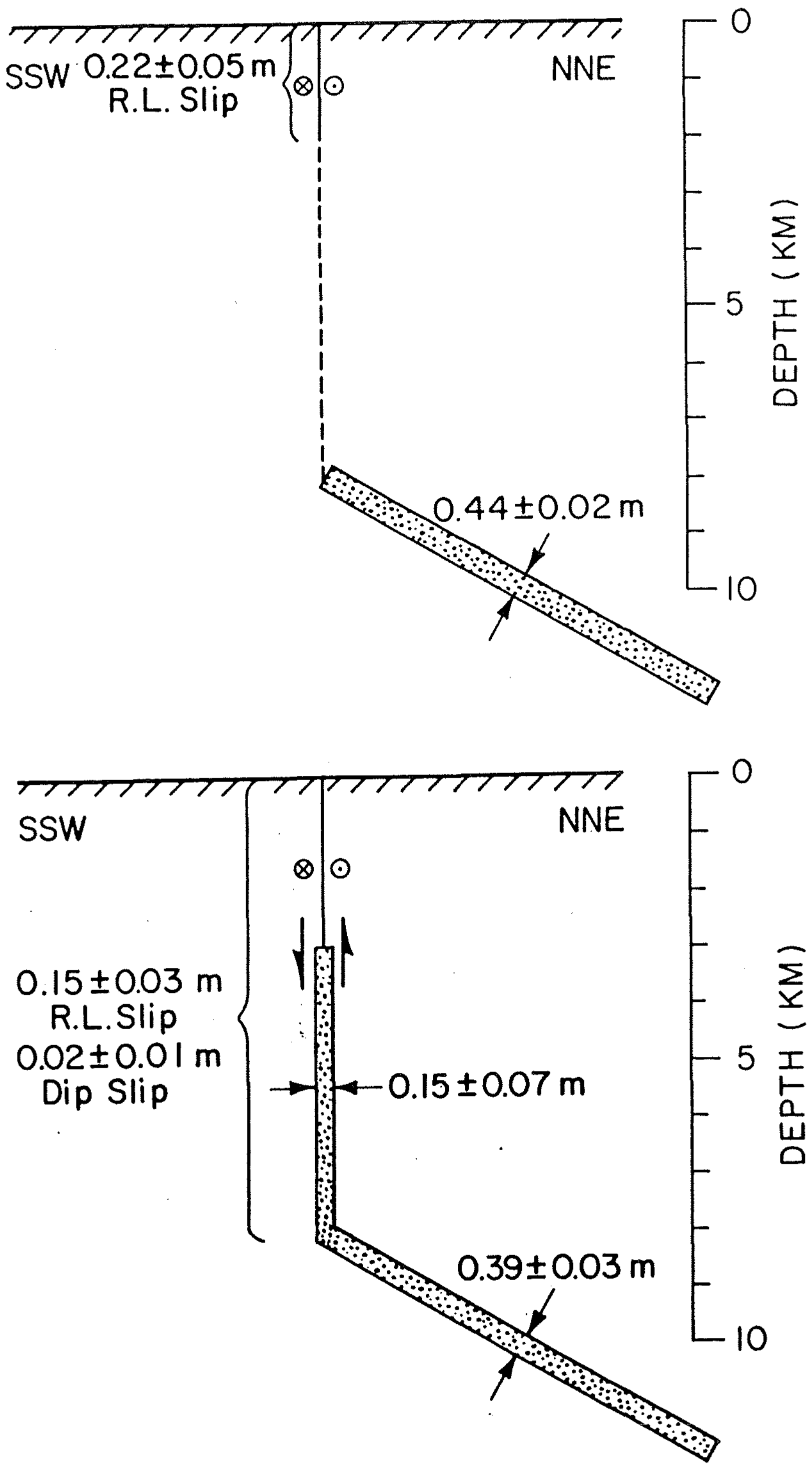


Fig. 36. South-southwest to north-northeast cross sections through two source models that reproduce the observed surface deformation relatively well. The vertical surface represents the rupture surface defined by the January swarm, whereas the surface dipping down to the right represents a tabular magma reservoir. The speckled areas represent regions where magma has been intruded, and numbers indicating the thickness of the speckled areas represent the increment in the width of the tabular magma reservoirs. The amounts of strike slip and dip slip on the rupture surface are also indicated for each model.

then more detailed studies involving stress release, deformation due to earthquake activity, and the hydrologic model are then required in addition to uplift or surface deformation data.

Outstanding Issues

Presently, the unanswered questions seem to be:

- What is the rate and spatial distribution of the surface deformation off the present lines?
- Although most models cannot account for the deformation without some fluid injection, what effect does the hydrology (both deep and intermediate) have on the measurements?
- What is the failure mechanism of the earthquakes? Reliable focal mechanisms must be obtained for the small as well as large events. The stress field causing the small shallow events may be different from the stress field causing the larger events, and/or deeper events.
- Are there mechanisms other than magma injection that could be causing the surface deformation, i.e., dilatancy etc.?
- Should we be measuring deformation at high frequencies (10 to 100 sec) to determine fluid injection or other mechanisms? The borehole dilatometer installed just west of the caldera may help resolve this.
- Because we have been studying this area for a relatively short time, is the uplift periodic (over 10's of years), and what does the observed deformation mean in terms of volcanic systems, i.e., is this "normal" for this type of environment?
- Are point measurements at the surface adequate for determining the spatial deformation of such a large body?

- What is the temporal relation between the various observed phenomenon and the surface deformation?
- What combination of telemetered, point, and "long baseline" measurements in conjunction with surveying techniques will yield an adequate and affordable picture of the surface deformation?
- Which models can be excluded on the basis of known magma behavior in this type of environment or on the basis of magma properties?

SUMMARY

To date it has not been possible to reconcile all the pieces of information from geophysical, geological, geochemical, and hydrological investigations and produce a consistent and comprehensive history of the evolution of the caldera. To do this one must take into account recent magma movement, Sierran Front tectonics, and Basin and Range deformation. However, it appears that some advances have been made in this direction during the last two years.

Research studies have been conducted with three general objectives:

1) geothermal energy assessment,
2) volcanic history and evolution of the caldera and its magmatic-hydrothermal system, and
3) current seismicity and deformation and their relations to regional tectonics and zones of melt and magma intrusion within the caldera.

Because the time reference scales, detail and certainty of information, and nature of the geologic processes involved in these three research areas are so different, scientists have labored hard to reconcile results, sometimes contradictory, and explain past and present processes and thermal conditions within the framework of available information and theory.

One of the major issues has been the degree to which geophysical and other geoscience data can be used to map the distribution of shallow magma beneath the caldera. There is also the related question of how accurately can we resolve such regions. Independent lines of research now show intriguing anomalies which, when viewed together, provide compelling evidence for one, perhaps multiple, partial melt zones at depth of $\geq$ 6 km beneath the western part of the caldera. The principal points are as follows:

1) Surface heat flow data are consistent with a magma cooling conductively at 5 to 8 km.
2) Igneous activity deduced from intrusive/extrusive rocks in the west moat and the leaching of rocks necessary to produce the Searles Lake borate deposits point to a rejuvenated magmatic system 30,000 years ago and intrusions in the west moat area during the last 5000 years.
3) A tomographic reconstruction of velocity variations, based on joint analysis of some 7000 relocated earthquakes, shows a zone of about 10% velocity decrease at 5 to 10 km, roughly beneath the resurgent dome. This is consistent with the earlier findings from a P-wave delay study of teleseisms.
4) Attenuation anomalies are reported for P- and S-seismic waves propagating within and under parts of the caldera at depths of 5 to 10 km.
5) Seismic refraction survey and earthquake data show localized reflectors from interfaces that can be taken as evidence for the upper and lower surfaces of a magma chamber between 6 and 16 km depth in the western part of the caldera.
6) Telluric field data fit a model with a conductor at about 7 km beneath the western part of the caldera.
7) Recent deformation could result from movement of magma from a mid-crustal chamber to shallower chambers at depths in the 3 to 8 km depth range below the resurgent dome and the south moat.

While the results are by no means conclusive, they do show a certain consistency and agreement with one geological concept that thermal energy supplied by basaltic magma rising from the asthenosphere in response to regional east-west extension is being emplaced as dikes or other plutons whose heat sustains a silicic magma chamber. It is estimated that the current rate of magma reaching the surface is of the order of 1 km^3 per 500 years; the total rate of magma movement from a high level chamber could be several times larger (as much as 10 times larger) on the basis of volume estimates for dikes freezing before reaching the surface (Crisp, 1984). Direct and indirect evidence for recent dike emplacement has been found at several places such as (1) along the north-south Inyo fracture zone, (2) beneath Mammoth Mountain, and (3) in the south moat. A combination of recent dike heat sources at the western end of the caldera and a deeper (5^+ km) magma also seems to be consistent with known and inferred subsurface temperatures and hydrology.

A current issue among geophysicists is whether geophysical data and present methods of interpretation will yield reliable solutions for the location and geometry of the magma or partial melt zones. There is less than total geophysical agreement on the configuration and location of specific zones of magma or partial melt residing within the caldera complex. At this stage of development, electric and electromagnetic techniques provide the lowest resolution regarding the existence and location of possible magma chambers. The intrinsic resolution of these techniques is poor when conductor width is small compared to conductor depth, such as for dikes. Better lateral and depth resolution of conductors will depend to some extent on ability to carry out 3-D MT modeling for complex structures and to develop more effective field techniques such as transient EM with ultra-large source moments and short off-set distances between transmitter and receiver.

On the other hand, seismic wave attenuation and velocity variation studies based on large numbers of well-located earthquakes, and anomalous deep reflectors observed in seismic refraction profiles provide more definite information on where melt zones probably occur.

The earthquake studies and geodetic results following the large magnitude earthquakes and aftershocks in 1980 and 1983 have not provided unequivocal information on the mechanisms of magma movement. While the 1983 geodetic data support a volume increase, the data do not provide a unique model for the distribution, shape, and orientation of individual dislocation sources. Shallow dike injection to within 3 km of the surface and inflation of a chamber at a depth of 5 km have been proposed by two independent research teams to explain deformation that accompanied the January 1983 earthquake activity. It is not yet known what caused the earthquake activity and whether the earthquake mechanisms are consistent with either model or, perhaps, indicate an entirely different model for magma movement. Moreover, it is not clear that the spatial distribution of earthquakes points to any one model.

A single narrow dike of magma coming to within 3 km of the surface, as postulated in one model, could be emplaced and freeze in a short period of time, modifying only slightly the average ambient thermal and resistivity conditions in an enclosing volume of rock. While there is no basis to presume that this type of magma injection process could be identified by means of resistivity measurements made at the surface, there is some computational and field evidence for the possible presence of a larger conductor at >5 km in depth. This could be a partial melt zone. However, the problems of resolving the conductor electromagnetically in the presence of near-surface, basement and regional conductors would be a formidable undertaking requiring many more soundings than available and the capabilities for carrying out 3-D numerical modeling on a Class VI computer.

Measurements of magmatic gases exsolving from an advecting magma and reaching the surface via some transport mechanism are useful indicators of recent magma movement, but may not be specific to the location and composition of the magma. Anomalous CO_2, a good indicator of magma because of its low solubility in magma, could originate, in part, from hydrothermal circulation through carbonate rock in a Paleozoic roof pendant believed to underlie the Bishop Tuff in the western part of the caldera.

A major issue for seismologists seems to center on the related questions of whether the spatial and temporal distributions of seismicity, microearthquake waveform information, and focal mechanisms for small, as well as the larger, events can be obtained with sufficient reliability to provide diagnostic information on the stress field and on the mechanism of volume change and possible magma movement. In this regard, what type of seismic network is necessary to study this problem with the location accuracy and detection sensitivity needed? Furthermore, to what degree will it be necessary to integrate more comprehensive and longer-term rock mechanics and deformation studies into the investigation to interpret the seismic results better?

A second set of seismic issues involves geological inferences that may be drawn on the basis of the apparently strong reflecting surfaces (6-7 and 16 km) seen in the refraction profiles and the zones of S-wave attenuation. Are these features a manifestation of a melt zone or are they related to other structural or hydrothermal conditions? Seismic reflection profiling is being considered across the caldera. This technique may help resolve some of the main structural features, but it is not known to what extent it can help resolve the presence of possible magma bodies within the caldera complex. As a minimum, seismic reflection profiling and modern imaging techniques might delineate major basement features such as faults, zones of fractured hydrothermal altered rock, and the Paleozoic roof pendant.

ACKNOWLEDGMENTS

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REFERENCES

Abers, G., 1984, The subsurface structure of Long Valley caldera, Mono County, California: A preliminary synthesis of gravity, seismic and drilling information: J. Geophys. Res., in press.

Bailey, R.A. and Koeppen, R.P., 1977, Preliminary geologic map Long Valley caldera, Mono County, California: U.S. Geological Survey, Open-file Map 77-468.

Bailey, R.A., Dalrymple, G.B., and Lanphere, M.A., 1976, Volcanism, structure, and geochronology of Long Valley caldera, Mono County, California: J. Geophys. Res., v. 81, no. 5, p. 725-744.

Blackwell, D.D., 1984, A model of the geothermal system of the Long Valley caldera, California: U.S. Geological Survey Open-file Report "Active Tectonic and Magmatic Processes in the Long Valley Caldera," in press.

Castle, R.O., Estrem, J.E., and Savage, J.C., 1984, Uplift across Long Valley caldera, California: Submitted to J. Geophys. Res.

Crisp, T.A., 1984, Rates of magma emplacement and volcanic output: J. Geophys. Geoth. Res., v. 20, p. 177-211.

Goff, F. and Waters, A.C., eds., 1980, Continental scientific drilling program thermal regimes: Comparative site assessment geology of five magma-hydrothermal systems: Los Alamos National Laboratory Report LA-8550-OBES, 100 p.

Hermance, J.F., 1983, The Long Valley/Mono Basin volcanic complex in eastern California: Status of present knowledge and future research needs: Rev. Geophys. Space Phys., v. 21, no. 7, p. 1545-1565.

Hermance, J.F., Slocum, W.M., and Neumann, G.A., 1984, The Long Valley/Mono Basin volcanic complex; A preliminary magnetotelluric and magnetic variation interpretation: J. Geophys. Res., in press.

Hill, D.P., 1976, Structure of Long Valley caldera, California, from a seismic refraction experiment: J. Geophys. Res., v. 81, no. 5, p. 745-753.

Hill, D.P., 1977, A model for earthquake swarms: J. Geophys. Res., v. 82, p. 1347-1352.

Julian, B.R., 1983, Evidence for dyke intrusion earthquake mechanisms near Long Valley caldera, California: Nature, v. 303, p. 323-325.

Kane, M.F., Mabey, D.R., and Brace, R., 1976, A gravity and magnetic investigation of the Long Valley caldera, Mono County, California: J. Geophys. Res., v. 81, no. 5, p. 754-762.

Kasameyer, P., 1980, Comparative assessment of five potential sites for magma-hydrothermal systems: Geophysics: Lawrence Livermore National Laboratory Report UCRL-52980, 52 p.

Lachenbruch, A.H., and Sass, J.H., 1977, Heat flow in the United States and the thermal regime of the crust: American Geophysical Union Monograph 20, p. 626-675.

Lide, C.S. and Ryall, A.S., 1984, Relationship between aftershock locations and mechanisms of the May 1980 Mammoth Lakes earthquake in Active Tectonic and Magmatic Processes in Long Valley Caldera: U.S. Geological Survey Open-File Report, in press.

Luetgert, J. and Mooney, W.D., 1984, Crustal refraction profile of the Long Valley caldera, California, from the January 1984 Mammoth Lakes earthquake swarm: Bull. Seism. Soc. Am., in press.

Luth, W.C. and Hardee, H.C., 1980, Comparative assessment of five potential sites for hydrothermal-magmatic systems: Summary: U.S. Department of Energy, Office of Energy Research, DOE/TIC-11303, 51 p.

Miller, C.D., Cradell, D.R., Mullineaux, D.R., Hoblitt, R.P., and Bailey, R.A., 1982, Preliminary assessment of potential volcanic hazards in the Long Valley-Mono Lake area, east-central California and southwest Nevada: U.S. Geological Survey Open-File Report 82-583.

Muffler, L.J.P. and Williams, D.L., 1976, Geothermal investigations of the U.S. Geological Survey in Long Valley, California, 1972-1973: J. Geophys. Res., v. 81, no. 5, p. 721-724.

Pollard, D.D., 1973, Derivation and evaluation of a mechanical model for sheet intrusions: Tectonophysics, v. 19, 233-269.

Rinehart, C. D. and Ross, D. C., 1964, Geology and mineral deposits of the Mount Morrison Quadrangle, Sierra Nevada, California, U.S. Geological Survey Professional Paper 385.

Rundle, J.B., and Whitcomb, J.H., 1984, A model for deformation in Long Valley, California, 1980-1983: Sandia National Laboratory, draft report.

Sanders, C.O., 1984, Location and configuration of magma bodies beneath Long Valley, California determined from anomalous earthquake signals: J. Geophys. Res., in press.

Savage, J. and Cockerham, R.S., 1984, Earthquake swarm in Long Valley caldera, California, January 1983: Evidence for dike inflation: J. Geophys. Res., in press.

Smith, A.T., 1984, High-resolution microseismicity study of possible magmatic intrusion in the Long Valley caldera: Lawrence Livermore National Laboratory Report UCRL-90278, 14 p.

Smith, G. I., 1976, Origin of lithium and other components in the Searles Lake evaporites, Calfornia, in Lithium Resources and Requirements by the Year 2000, J.D. Vine, ed., U.S. Geological Survey Professional Paper 1005, p. 92-103.

Sorey, M.L., 1984, Evolution and present state of the hydrothermal system in Long Valley caldera: U.S. Geological Survey Open-file Report "Proceedings of the Red Book Conference on Active Tectonic and Magmatic Processes in Long Valley Caldera," in press.

Stanley, W.D., Jackson, D.B., and Zohdy, A.A.R., 1976, Deep electrical investigations in the Long Valley geothermal area, California: J. Geophys. Res., v. 81, no. 5, p. 810-820.

Steeples, D.W. and Pitt, A.M., 1976, Microearthquakes in and near Long Valley, California: J. Geophys. Res., v. 81, no. 5, p. 841-847.

Vetter, U.R. and Ryall, A.S., 1983, Systematic change of focal mechanism with depth in the western Great Basin: J. Geophys. Res., v. 88, p. 8237-8250.

White, A., Boldridge, W.S., Gerlach, T.M., and Knauss, K., 1980, Comparative assessment of five potential sites for hydrothermal magma systems: Geochemistry: Lawrence Berkeley Laboratory LBL-11410.

APPENDIX 1

AGENDA

WORKSHOP ON GEOPHYSICAL MODELING OF THE LONG VALLEY CALDERA

8-9 February 1984
Building 90, First Floor Conference Room
Lawrence Berkeley Laboratory

Wednesday, 8 February

8:45 - 9:00	Assemble in Conference Room
9:05 - 9:30	Introductions and Discussion of the Workshop Plan (T.V. McEvilly)
9:30 - 10:30	Geological Background and Overview of the Long Valley Hydrothermal-Magmatic System and Processes: Current Concepts, Data and Conflicts Discussion Leader: M. Sorey Contributors: J. Hermance, T. Gerlach Rapporteur: H. Wollenberg
10:30 - 10:45	Break
10:45 - Noon	Continuation of Discussions
Noon - 1:30	Working Lunch, catered
1:30 - 3:00	Concepts and Models Based on Seismological Data Discussion Leader: D. Hill Presentations: R. Cockerham, C. Cramer, E. Majer, J. Mills, A. Ryall, C. Sanders, A. Smith Rapporteur: T. McEvilly
3:00 - 3:15	Break
3:15 - 6:00	Continuation of Discussions

Thursday, 9 February

9:00 - 10:30	Concepts and Models Based on Electric and Electromagnetic Data Discussion Leader: J. Hermance Presentations: N. Goldstein J. Hermance Rapporteur: F. Morrison
10:30 - 10:40	Break
10:40 - 11:00	Continuation of Discussions
11:00 - 12:30	Concepts and Models Based on Deformation, Thermal and Gravity Data Discussion Leader: J. Rundle Presentations: J. Rundle J. Savage J. Whitcomb Rapporteur: E. Majer
12:30 - 1:30	Working Lunch, catered
1:30 - 3:30	Summary Session Reports from the Rapporteurs: E. Majer T. McEvilly F. Morrison H. Wollenberg
3:30 - 4:00	Wrap-Up (N. Goldstein) Review of Agreements/Disagreements, Key Questions, Critical Experiments or Calculations Needed to Resolve Open Issues and Conflicts

APPENDIX 2

WORKSHOP ON GEOPHYSICAL MODELING OF THE LONG VALLEY CALDERA

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