SEISMIC MONITORING AT THE GEYSERS

GEOTHERMAL FIELD, CALIFORNIA

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CONTENTS

Tables

Figures

Plate

Abstract

Two distinct clusters of microearthquakes have been identified at The Geysers, possibly relating to two independent pressure sinks resulting from steam production described by Lipman, and others (1977). Unlike earthquakes in the Maacama-Rodgers Creek fault zone to the south and west, earthquakes at The Geysers are confined to depths of less than 5 km. The present level of seismicity at The Geysers appears to be higher than the preproduction level and is higher and more continuous than the seismicity in the surrounding region. Earthquakes in the steam production zone at The Geysers resemble earthquakes in the surrounding region with regard to focal plane solutions, source characteristics and magnitude distribution (b slope). Subtle differences in earthquake characteristics may be resolved by analysis of more extensive data now being gathered in the region.

Introduction

The Geysers is the only geothermal area in the United States where electric power is being generated from underground steam. It lies adjacent to the Clear Lake volcanic system in which eruptions date from 2.04 million years ago to almost the present (.03 million years ago) (Donnelly, and others, 1977). The recent volcanic activity (Hearn, and others, 1976), the presence of a large negative gravity anomaly (Isherwood, 1976), the delay of P-wave traveltimes from distant earthquakes (Iyer, and others, 1978), and the extreme shallowness of the seismogenic zone (Bufe and Lester, 1975; Bufe, and others, 1978) suggest the presence of an intensive heat source in the form of a molten or near-molten magmatic body beneath the area. The Franciscan assemblage and Great Valley sequence in which The Geysers development lies have been mapped by McLaughlin (1977).

Commercial power generation began at The Geysers in September 1960 with an 11 megawatt plant, but extensive development did not occur until 1967-68, when power production rose to 78 megawatts. Current production is 502 megawatts, with projections to exceed 900 megawatts in the near future. The region around the production area is under active investigation by several geothermal companies for future development. Currently, at full production, steam is being removed at a rate of 3.97×10^6 kg per hour, (Reed and Campbell, 1976) with 20 to 40 percent being reinjected.

This report describes preliminary results of an ongoing investigation of earthquake activity at The Geysers. The objectives of this study are:

1. To determine attenuation characteristics of the undersaturated (dry steam) region and source characteristics (from spectra and fault-plane solutions) of earthquakes occurring at The Geysers and to compare them with the characteristics of earthquakes outside the region.
2. To identify the degree of differentiation that is possible between microearthquakes natural to the geothermal area and those induced by production activities and to examine the relation of seismicity to rates of steam withdrawal, water injection, and subsidence.
3. To define in three dimensions the seismogenic zone at The Geysers, estimate deformation rate, and predict cumulative deformation in 5 to 10 years if microearthquake activity continues at the present level.

Seismicity

The Geysers geothermal development (see inset, Figure 1) is located 50 km northeast of the San Andreas fault within the broad zone of transform faulting between the Pacific and North American plates, and it thus lies in a tectonically active region. The segment of the San Andreas system opposite The Geysers last ruptured in the great earthquake of 1906. In October 1969 the largest earthquakes (M = 5.6 and M = 5.7) since 1906 in the Coast Ranges between San Francisco Bay and Cape Mendocino occurred on the Rodgers Creek fault at Santa Rosa, 40 km south of The Geysers.

Current (1975-1977) microseismicity in the vicinity of The Geysers is shown in Figure 1. Events in or near The Geysers cluster are also shown in map view and cross section on an expanded scale of 1:24,000 in Plate 1.

Seismographic Coverage

From 1911-1972 the only continuous network coverage of The Geysers was the regional network of seismographs of the University of California at Berkeley (UCB). The nearest station in continuous operation was Berkeley, 100 km southeast of The Geysers. During this period only two earthquakes (M = 3.1, 1963; M = 2.9, 1970) are listed in the UCB earthquake catalog (Bolt and Miller, 1975) as occurring within the boundaries of the area of Plate 1. In contrast, during 1973-74 Berkeley located two M $\geq$ 3 events in this zone.

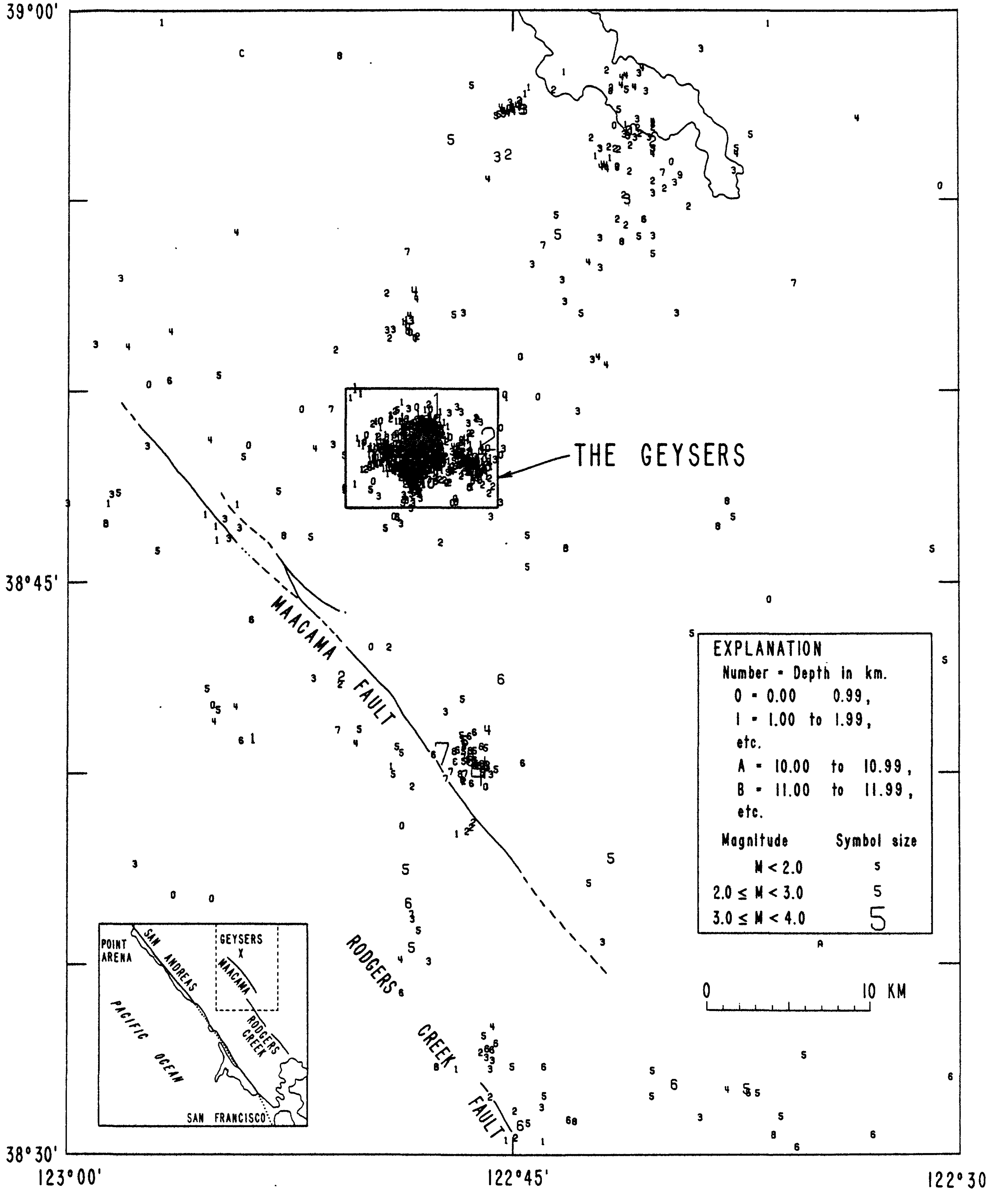

Fig. 1. Recent earthquakes (June 1975-Sept 1977) at The Geysers and along the Maacama and Rodgers Creek faults.

In the early 1960's, before extensive steam production had begun, UCB operated a seismographic station at Calistoga (CLS), 30 km southeast of The Geysers. CLS was a high-gain, short-period station that recorded many local earthquakes too small to be located by the Berkeley network. Thus it is not possible to ascertain whether these events originated at The Geysers. During March and April 1971, Hamilton and Muffler (1972) operated an 8-station seismic array for three weeks in The Geysers production area to monitor seismic activity. They located 53 small earthquakes within 10 km of the heavily exploited geothermal area.

In response to the interest generated by this work and reports of frequently felt earthquakes in the production area, the U.S. Geological Survey began upgrading its northern California network by adding more seismic stations to encompass The Geysers area (Fig. 2). In September 1973, the USGS network was extended into the vicinity of The Geysers, with stations installed at Alexander Valley and Pine Mountain. Although The Geysers was outside the network, earthquakes of $M \geq 2$ were routinely located there. At the beginning of 1975, the network was extended to surround The Geysers (Fig. 2). The distribution of stations presently operating in and around the steam production area at The Geysers is shown in Figure 3.

Temporal Variation in Seismicity

Since July 1975, seismographic coverage has been relatively complete, with location threshold approximately $M = 1.2$. Most of the microearthquakes located by Hamilton and Muffler (1972) were much smaller.

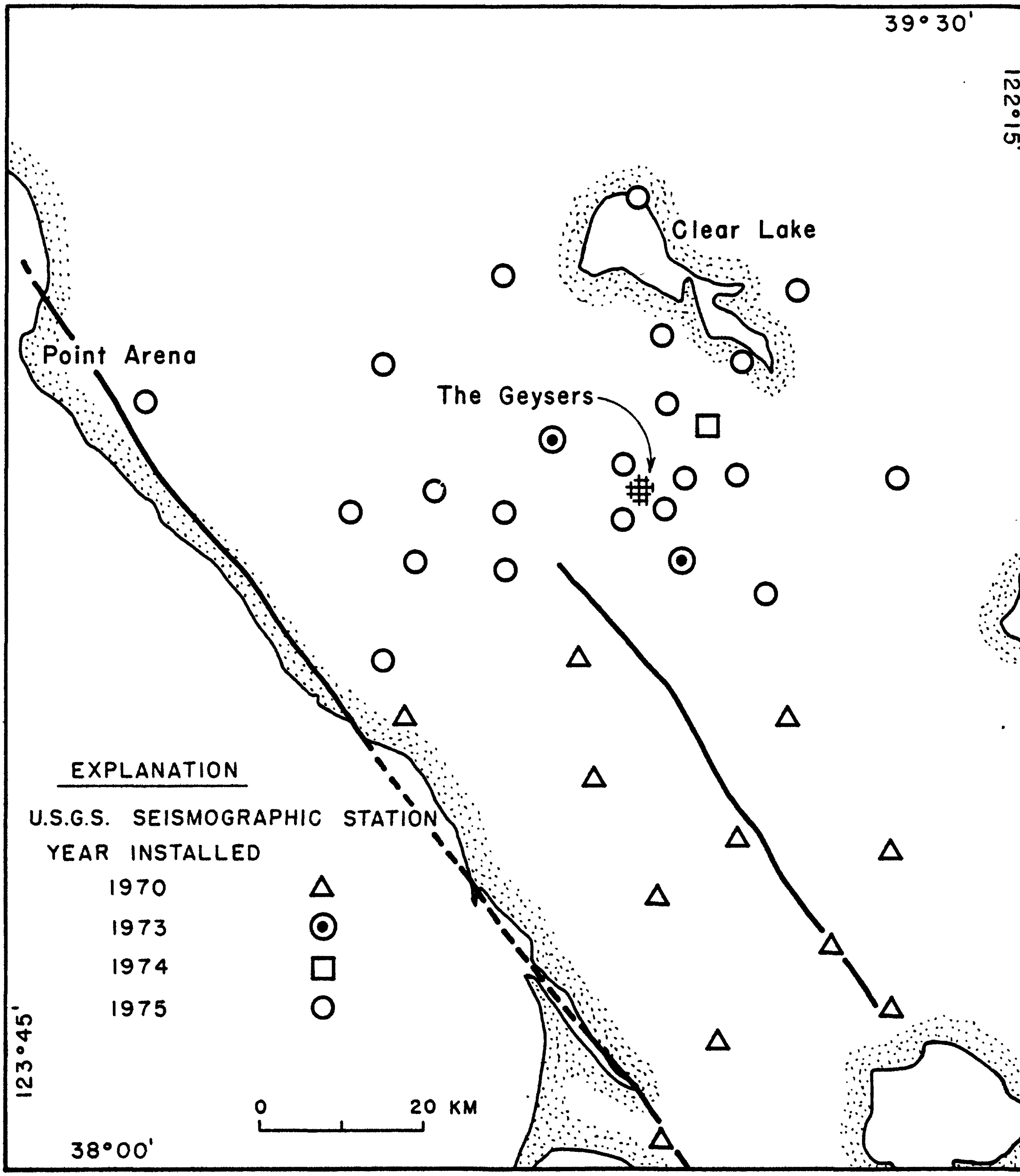

Fig. 2. U.S. Geological Survey seismographic stations, 1977. The stations immediately around The Geysers are shown in more detail in Figure 3.

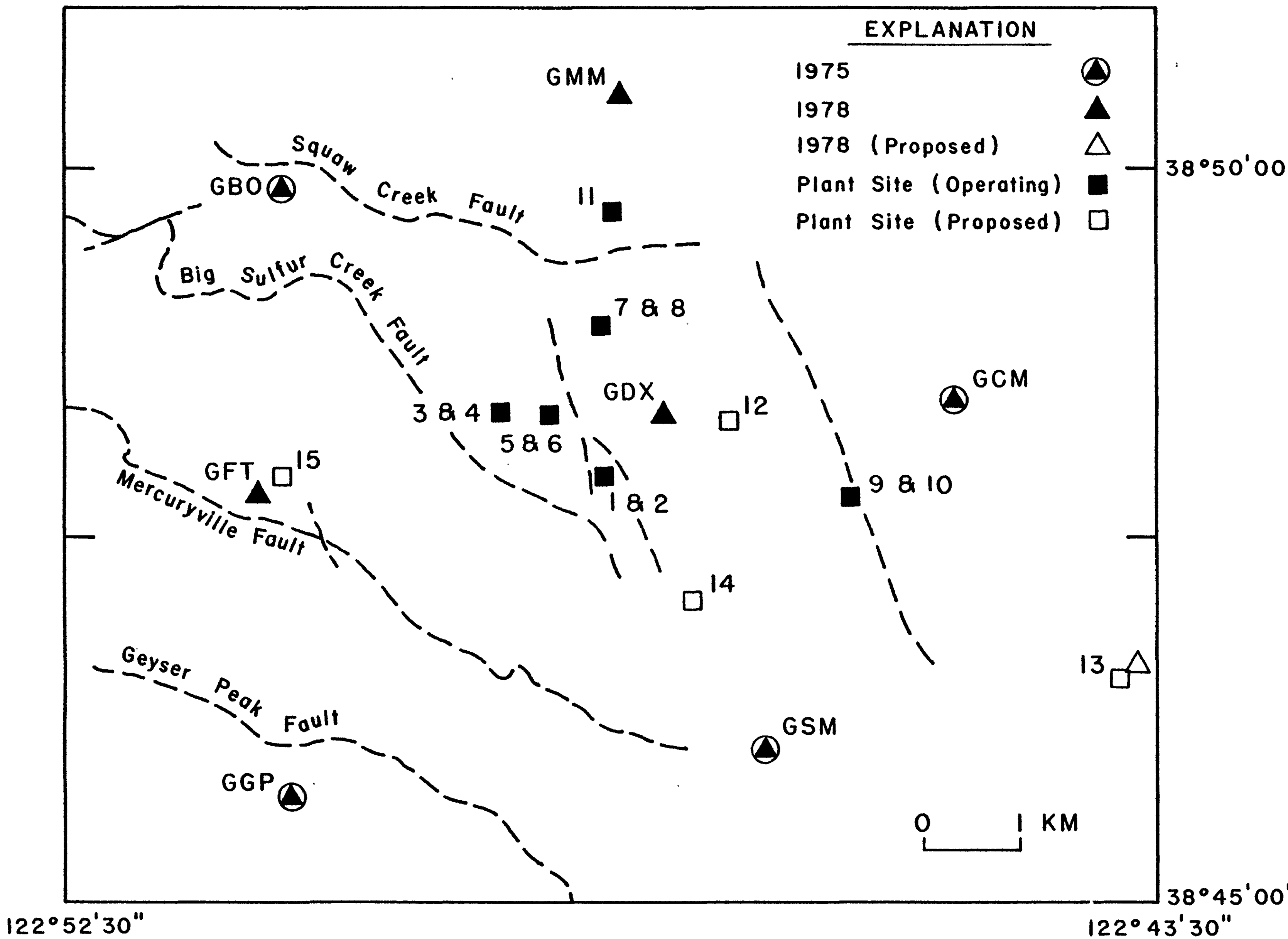

Fig. 3. History of the seismographic coverage of The Geysers area. Approximate traces of a few of the local faults are indicated by dashed lines. New telemetered stations went on line in late 1977 and early 1978.

Their largest event in three weeks of recording was of estimated magnitude 1.5. Since 1975 events of this magnitude occurred, on the average, every 2 or 3 days.

In an attempt to determine whether the level of activity in the region including The Geysers has changed significantly since the early 1960's, we have analyzed data from the UCB station at Calistoga (CLS). Magnitudes of events within a 60-km radius of CLS have been estimated from signal durations (coda lengths) assuming a linear relation between log duration and magnitude. The region examined can be approximated by the circular area with radius = 60 km (Fig. 4) corresponding to an S-P time of about 7 seconds. The Geysers lies well within this region. A log-log plot of cumulative number of events as a function of duration (D) was prepared (Fig. 5), and a linear relation ($\log N = -2.78 \log D + 5.46$) determined. This relation breaks down for coda lengths less than about 25 seconds; thus some events of shorter coda length are not being detected within the circle.

In order to convert the Calistoga coda information to magnitude estimates, it was necessary to tie duration to Richter magnitude. This was done at M = 3, for which Richter magnitudes are available from the UCB earthquake catalog (Bolt and Miller, 1975). Average coda length at M = 3.0 ± 0.1 was 68 seconds, (see dashed circle in Fig. 6). The range of Richter magnitudes was not adequate, however, to determine the slope of the M vs. log D line. This was done by assuming the b slope for the region to be constant through time. A regional b value of 1.2, determined from USGS network 1975-77 data for the rectangular zone shown in

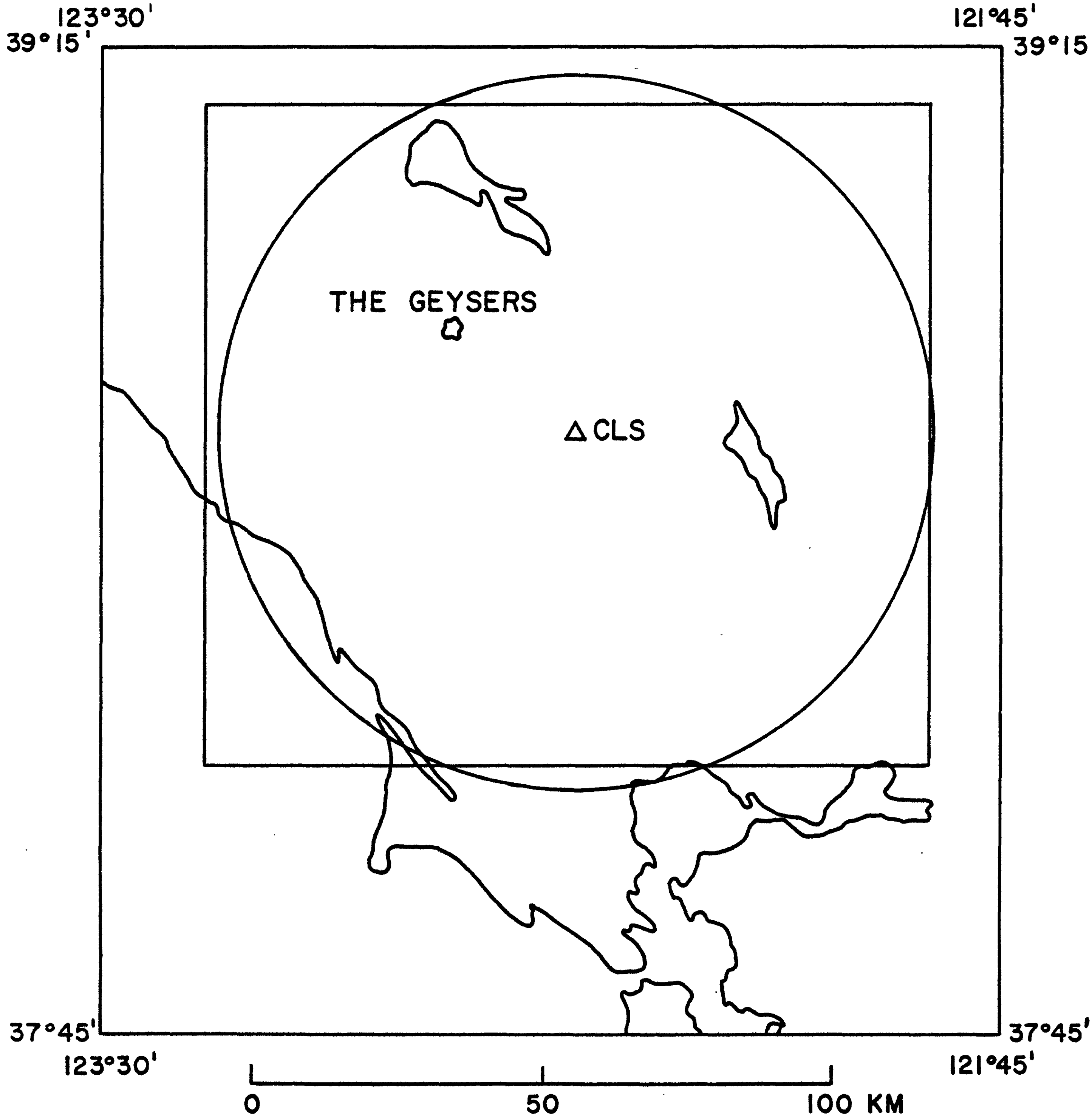

Fig. 4. Zones searched in comparison of present (1975-1977, outlined by square) and preproduction (1962-1963, outlined by circle) seismicity levels. Circle represents a 60 km radius from CLS.

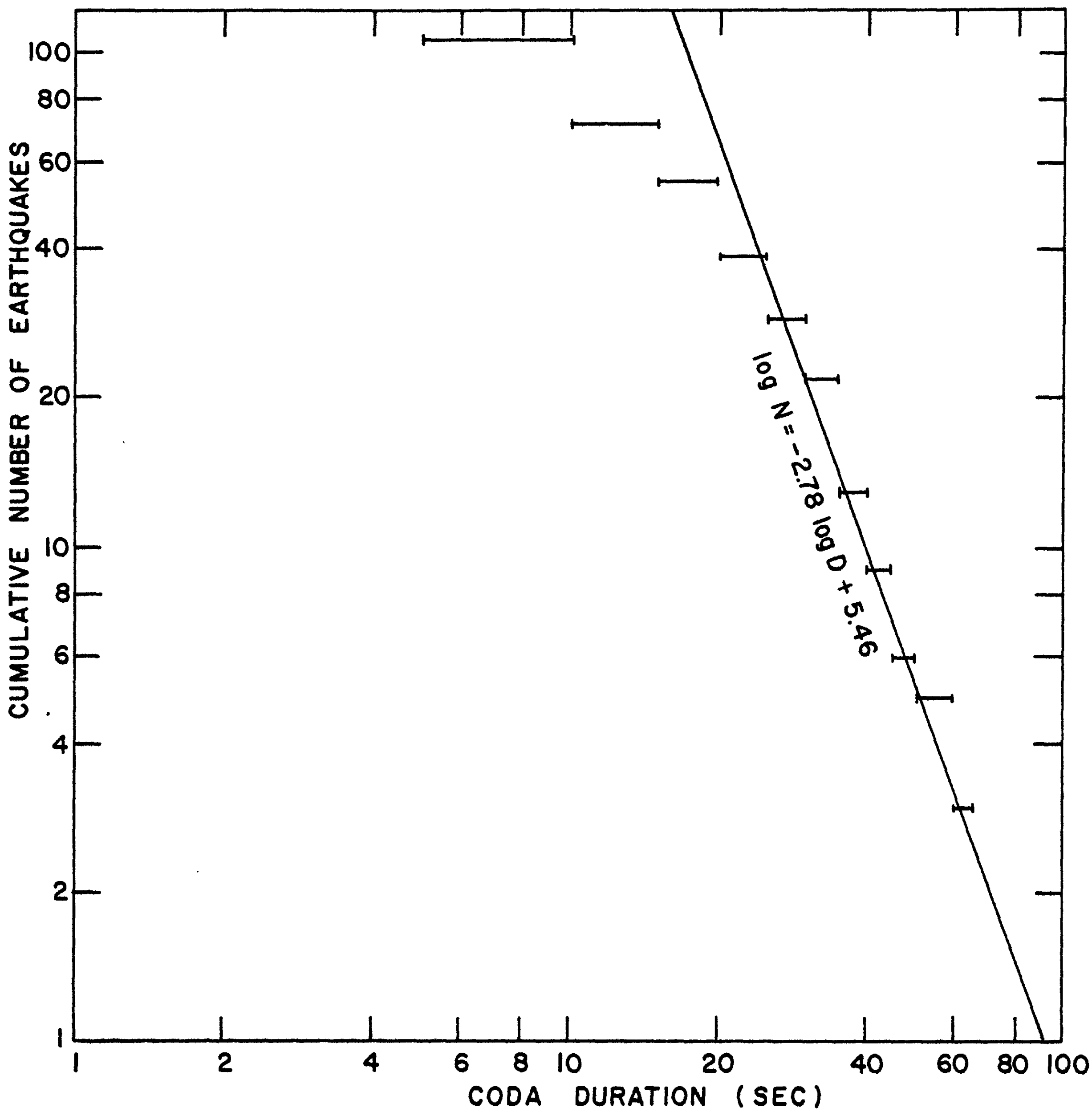

Fig. 5. Cumulative distribution of number of earthquakes as a function of coda duration at the Calistoga station, January 1962 through June 1963.

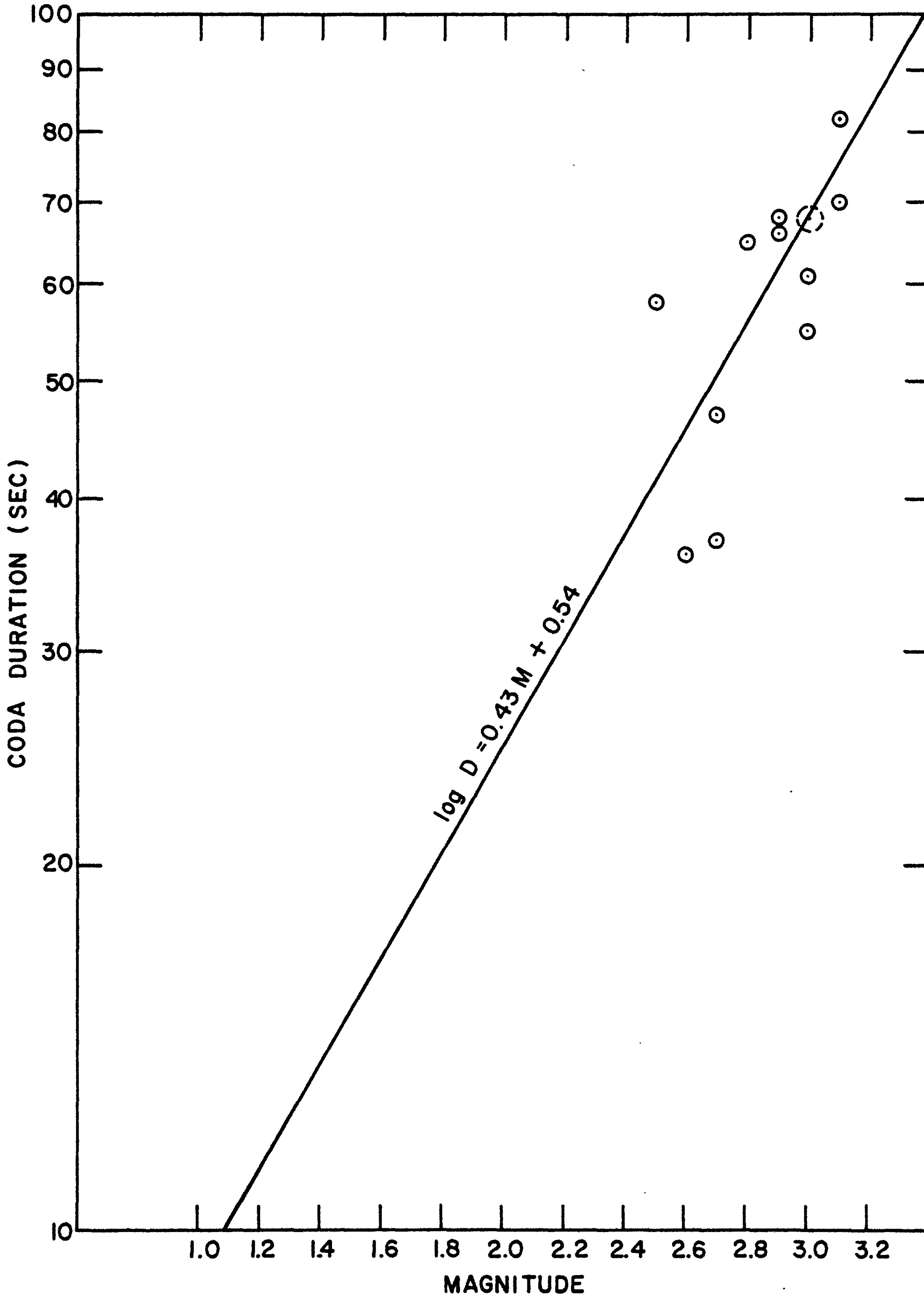

Fig. 6. Relation between coda duration and magnitude at the Calistoga station, based on events ($M \geq 2.5$) for which Richter magnitudes were determined (for circled area shown in Figure 3, and a b slope of 1.2). Average coda (dashed circle) length at $M = 3.0 \pm 0.1$ was 68 seconds.

Figure 4, was adopted. This b value is the same as that determined for The Geysers 1975-1977 earthquakes. Thus, since

$$\log N = a - 1.2\,M \text{ and}$$
$$\log N = -2.78 \log D + 5.46,$$

the slope of the log D vs. M line is .43, and the duration-magnitude relation, constrained by the 68 second coda for magnitude 3, is

$$\log D = .43\,M + .54$$

The data set is complete down to 25 seconds duration, which is M = 2.0 (Fig. 5). Thus, 37 earthquakes of $M \geq 2$ occurred in the circular region during the 18 month period January 1962-June 1963. Table 1 compares the preproduction (1962-63) rate of occurrence of $M \geq 2$ events with the present (April 1975-August 1977) rate of activity in the rectangular region of Figure 4. Magnitudes of 1975-1977 earthquakes were determined from durations at USGS stations after Lee, and others (1972).

Table 1: Comparison of pre-production and current seismicity at The Geysers and surrounding region, normalized for a 12-month period.

Period	No. of events/yr (M $\geq$ 2) in region	No. of events/yr (M $\geq$ 2) Geysers only
1962-63 (pre-production)	25	unknown
1975-77 (current)	47	24

From Table 1, we might conclude that the regional seismicity has increased and infer that the increase is attributable to increased seismicity within The Geysers 7.5' quadrangle.

Spatial distribution of hypocenters

Earthquakes located since 1975 (Plate 1) using the standard USGS central California crustal model (see, for example, Lester, and others, 1976) appear to define two distinct clusters of microearthquakes at The Geysers. The zone of greatest concentration of microearthquakes surrounds plants number 1 & 2, 3 & 4, 5 & 6, and 7 & 8. Plant 11 lies on the north edge of this zone. A secondary cluster of activity occurs in the vicinity of plants 9 & 10. Plants 12 and 14, which are not yet in production, lie along a seismic gap between the clusters. The location error for a blast fired south of plant #12 is only 200 meters horizontally, and less than 1 km vertically; thus the earthquake locations are reasonably accurate and no large bias is present.

The shapes of the earthquake clusters overlap fairly well two pressure sinks in the steam field described by Lipman, and others (1977) and outlined on Plate 1. One sink developed as a result of steam withdrawals for Plants 1-8 and 11 and is reflected in high rates of subsidence described by Lofgren (1978). The other is a result of production for Plants 9 & 10. The sinks are apparently distinct from each other with no detectable pressure communication. The westward-dipping seismic gap between the earthquake clusters in Plate 1 may be the expression of a relatively unfractured, impermeable zone forming a barrier between reservoirs.

An east-west cross section through The Geysers on which hypocenters and injection wells have been projected is shown at the bottom of Plate 1. Earthquakes at The Geysers with reliable locations occur only at shallow depths ($h \leq 5$ km). However, shallow seismicity appears to be the rule for the entire region overlying the presumed magma body extending at depth from The Geysers to Clear Lake. In contrast, most earthquakes along the Rodgers Creek and Maacama faults south and west of The Geysers occur at depths greater than 5 km (Bufe, and others, 1978).

Seismicity of subregions

In order to identify differences in seismic characteristics of geothermal (steam or hot water) and regional tectonic regimes, subregions

(Fig. 7) were determined on the basis of the distribution of steam-producing wells and analysis of geothermal waters (Goff, and others, 1977, Julie Donnelly, oral communication, 1977). The "steam" subregion is complex, as The Geysers (Plants 1-8 and 11) and Geysers East (Plants 9 & 10) subregions have been removed from it.

Magnitude-frequency relations

Magnitude distribution [log N (m) = a - bM] of earthquakes in The Geysers region shows a relatively high "b" value, which indicates an unusually rapid decrease in number of earthquakes with increasing magnitude. Such a high value may result from the structural heterogeneity of a geothermal region, but could also be characteristic of induced seismicity (Gupta and Rastogi, 1976). Table 2 summarizes b values and occurrence rates. Comparison of the b slope of earthquakes in the production zone with that of earthquakes elsewhere in the geothermal area suggests that the high b value is natural and not related to production. The "tectonic" subregion to the southwest has a somewhat lower b slope, but the difference is not statistically significant.

Seismic Deformation

Seismic moment (M_o) rates by subregion were estimated from earthquake magnitudes (M) by the empirical relation log Mo = 1.5 M + 16 (Bakun and Bufe, 1975). The moment is the product of slip along the fault, area of the fault surface, and rigidity of the rocks and is thus a measure of strain release. Moment rate per unit map area (Table 2) is highest in

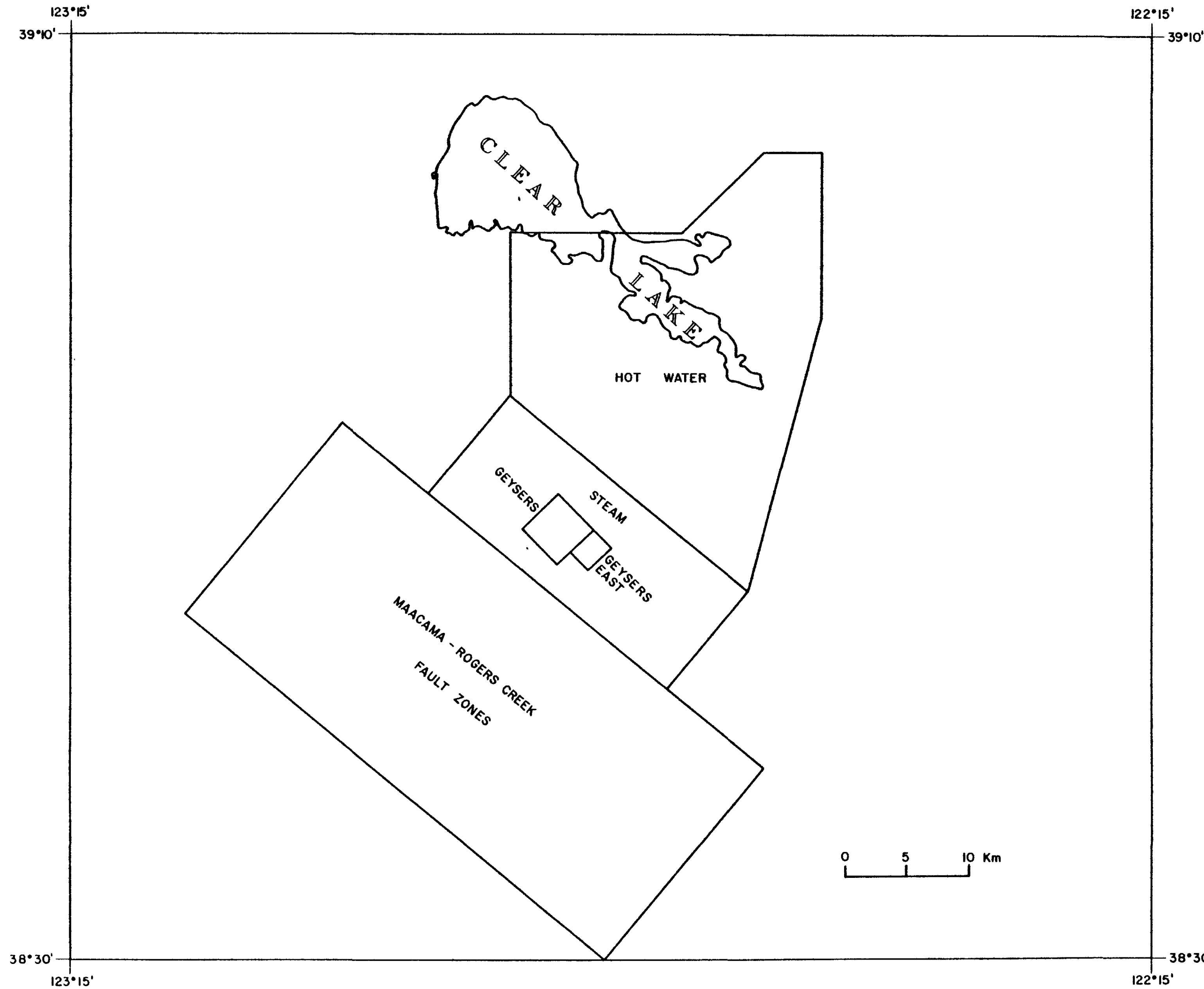

Fig. 7. Index map of subregions for which moment-time histories and b slopes have been determined.

Table 2. April 1975-August 1977. Earthquake frequency and cumulative moment data

	b	N (M ≥ 1.2)	N/yr M ≥ 1.2)	N/yr/km^2	Moment Rate dyne-cm x 10^{17}/ km^2/yr
Geysers.........	1.2	498	206	12.41	928.
Geysers East....	1.3	57	24	4.53	396.
Undeveloped Steam...........	1.5	55	23	.10	6.74
Hot Water.......	1.2	95	39	.07	4.94
Maacama-Rodgers Creek...	1.1	64	26	.03*	1.74*

*Swarm activity along the Maacama fault since August 1977 indicates that these numbers do not accurately reflect the Maacama-Rodgers Creek seismicity which is episodic, in contrast to the more constant seismicity level presently observed at The Geysers.

the production zones. This result is consistent with surface deformation rates published by Lofgren (1978) showing horizontal (2 cm/yr convergence) and vertical (3 cm/yr subsidence) changes which suggest that the deep geothermal reservoir is being compressed both vertically and horizontally as fluid pressures within it are drawn down by production.

Focal plane solutions and stress orientation

Selected focal mechanisms of earthquakes are superimposed on a preliminary fault map of The Geysers and surrounding area in Figure 8. The lower hemisphere stereographic projections of P-wave first motions at the earthquake focus are interpreted in terms of double-couple earthquake mechanisms. Darkened quadrants are compressional, white quadrants dilatational. Tectonic stress orientation, deduced from P-wave first motions for events between June 1975 and September 1977, indicates maximum compression at N 30° E and minimum compression at N 60°W over most of the region north of 38° 35' (Bufe and others, 1978). This stress orientation is rotated 30° clockwise from that producing maximum right-lateral shear on faults subparallel to the San Andreas and Rodgers Creek systems, including the Maacama fault, and is consistent with northwesterly crustal extension. Stress orientation at The Geysers appears to be much the same as in the surrounding region. The dominant earthquake mechanism at The Geysers during this period was strike slip; fewer events indicated normal faulting.

Synthesis

Microearthquakes at The Geysers are strongly clustered around the regions of steam production and fluid injection. The present level of seismicity at The Geysers appears to be higher than the pre-production level and is higher and more constant than the seismicity in the surrounding region. Geodetic measurements described by Lofgren (1978) suggest that the deep geothermal reservoir is being compressed both

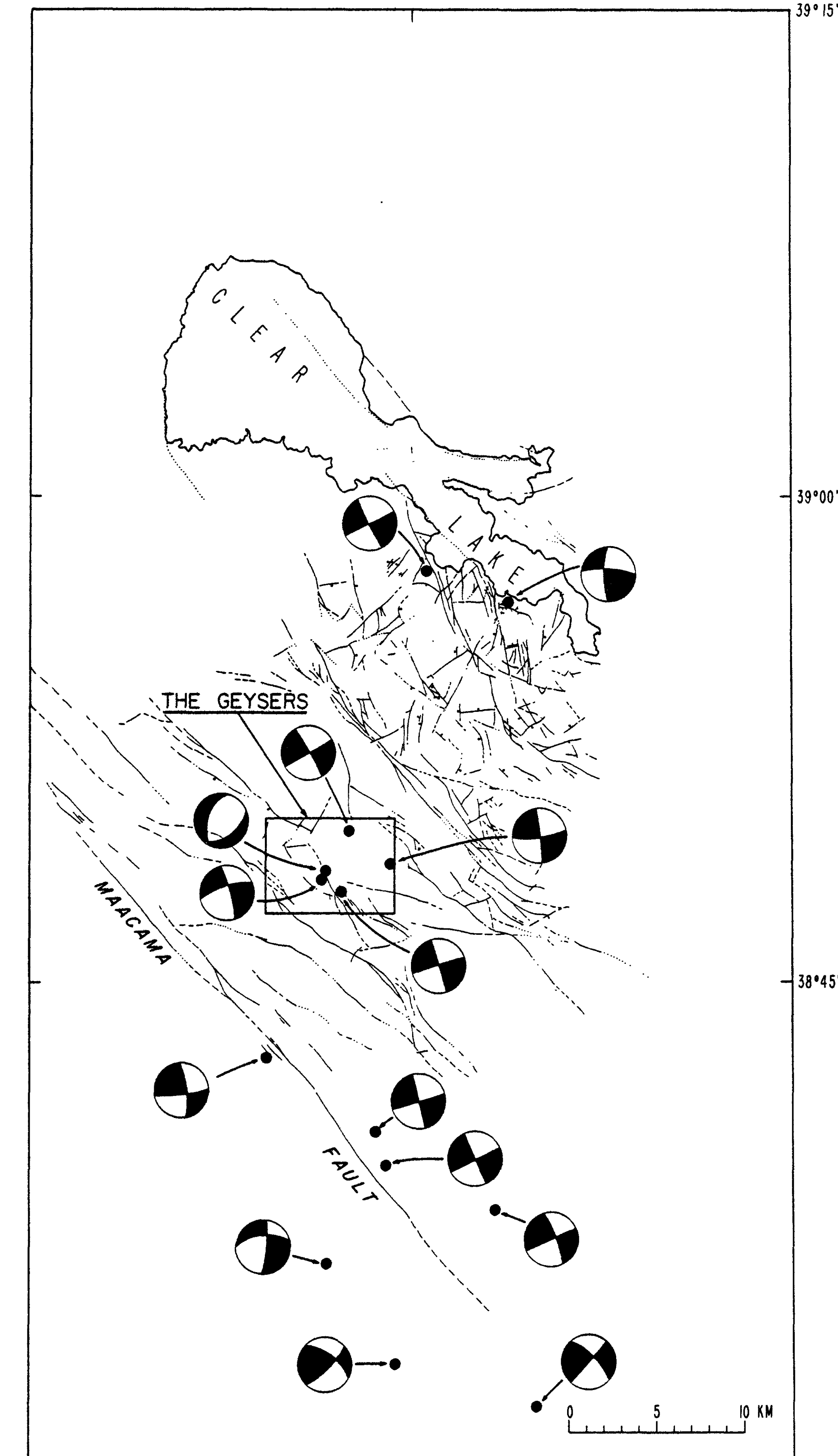

Fig. 8. Representative focal plane solutions for earthquakes at The Geysers and in the surrounding region. Preliminary faults are from McLaughlin and Hearn (unpublished data, 1978).

vertically and horizontally at rates of several centimeters per year as fluid pressures within it are lowered by production. It appears likely that much of the present seismicity at The Geysers is induced by steam withdrawal and/or injection of condensate. The mechanism by which this occurs warrants further study.

Further Studies

Majer and McEvilly (1978) and Peppin and Bufe (1978) have examined spectral characteristics of earthquakes at The Geysers. These earthquakes do not appear to be obviously anomalous in their characteristics, but analysis of data presently being gathered will determine whether there are subtle differences between source characteristics of earthquakes at The Geysers and those in the undeveloped geothermal regions nearby.

The current 502 MW capacity at The Geysers will be increased to 908 MW as soon as the four plants being constructed come on line in 1978 and 1979. Thus it is important to continue monitoring microearthquakes in The Geysers-Clear Lake geothermal field. The study of seismicity during development can be expected to give more definitive information on the effect of production on earthquake activity. The Geysers is the only producing geothermal area in the world where precise seismic monitoring is being done and for which data from a large dense regional network is available to complement the study. The data collected here may provide clues to answer the critical question as to how the seismicity of a geothermal area is altered by intensive exploitation.

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