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Microearthquakes at The Geysers Geothermal Area, California

R. M. Hamilton and L. J. P. Muffler

National Center for Earthquake Research, U.S. Geological Survey
Menlo Park, California 94025

Microearthquakes in The Geysers area of northern California were recorded for 3 weeks with a radio-telemetry array of eight seismograph stations in order to examine their distribution with respect to the area developed for geothermal power. Locations were determined for 53 earthquakes within about 10 km of The Geysers. Most epicenters lie in a zone about 4 km long and 1 km wide passing through the geothermal field along a principal fault zone. Focal depths in this trend range from near surface to about 4 km. A composite fault-plane solution indicates dextral strike-slip faulting on a NNW-striking plane subparallel with the regional fault pattern. The results of this study suggest that accurate mapping of microearthquakes can be useful in the exploration for geothermal resources, if the earthquakes studied here are not somehow caused by development of the field.

A radio-telemetry array of eight seismograph stations was operated in The Geysers area of northern California for a 3-week period from March 16 to April 7, 1971. The purpose of the monitoring was to determine whether earthquake activity was related to the zone being developed for geothermal power. As of June 1970, electrical power capacity at The Geysers was 82 Mw, making The Geysers the third largest producer of geothermal power in the world behind Larderello, Italy, and Wairaki, New Zealand [*Koenig*, 1971]. The Geysers is currently the only commercial geothermal power operation in the United States.

Previous seismic monitoring of The Geysers area was carried out for 120 hours by *Lange and Westphal* [1969], who used a small tripartite seismic array. Epicenters were determined for 19 shocks; no focal depths were reported. The accuracy of determining location with a small tripartite array is limited; therefore, the locations that were reported cannot be viewed with great confidence. Their study showed, however, the existence of earthquakes in The Geysers area and prompted the present study.

INSTRUMENTATION

The seismic array consisted of seven remote stations and a base station. Each remote station was equipped with a vertical-component 1-sec natural period seismometer, an amplifier and voltage-controlled oscillator package, a VHF FM 100-mw transmitter, a Yagi antenna, and a 12-volt lead-acid battery. At the base station the signals from the remote stations were received by seven antennas, radio receivers, and discriminators. A Geotech Develocorder mounted in a truck recorded on 16-mm film these seven signals and the signals from a vertical-component and two horizontal-component 1-sec natural period seismometers connected to the truck by wire. The time-code broadcast by station WWVB and the output from a time-code generator mounted in the truck were also recorded. Power at the base station was provided by the truck engine, which was run continuously. Station locations are shown in Figure 1.

EARTHQUAKE DISTRIBUTION

Locations were determined for 53 earthquakes, all the shocks that were sufficiently well recorded in the vicinity of the seismic network with *S-P* time less than 2 sec. Hypocenters were computed through the use of the program Hypolayr [*Eaton*, 1969]. For each earthquake three types of solutions were attempted: (1) *P* readings with the origin time fixed, when an *S* reading was obtained on a horizontal-component seismometer; (2) *P* readings with the focal depth restricted to 3 km; and (3) *P* readings with the focal depth free. The crustal model adopted was developed by W. H. K. Lee (written

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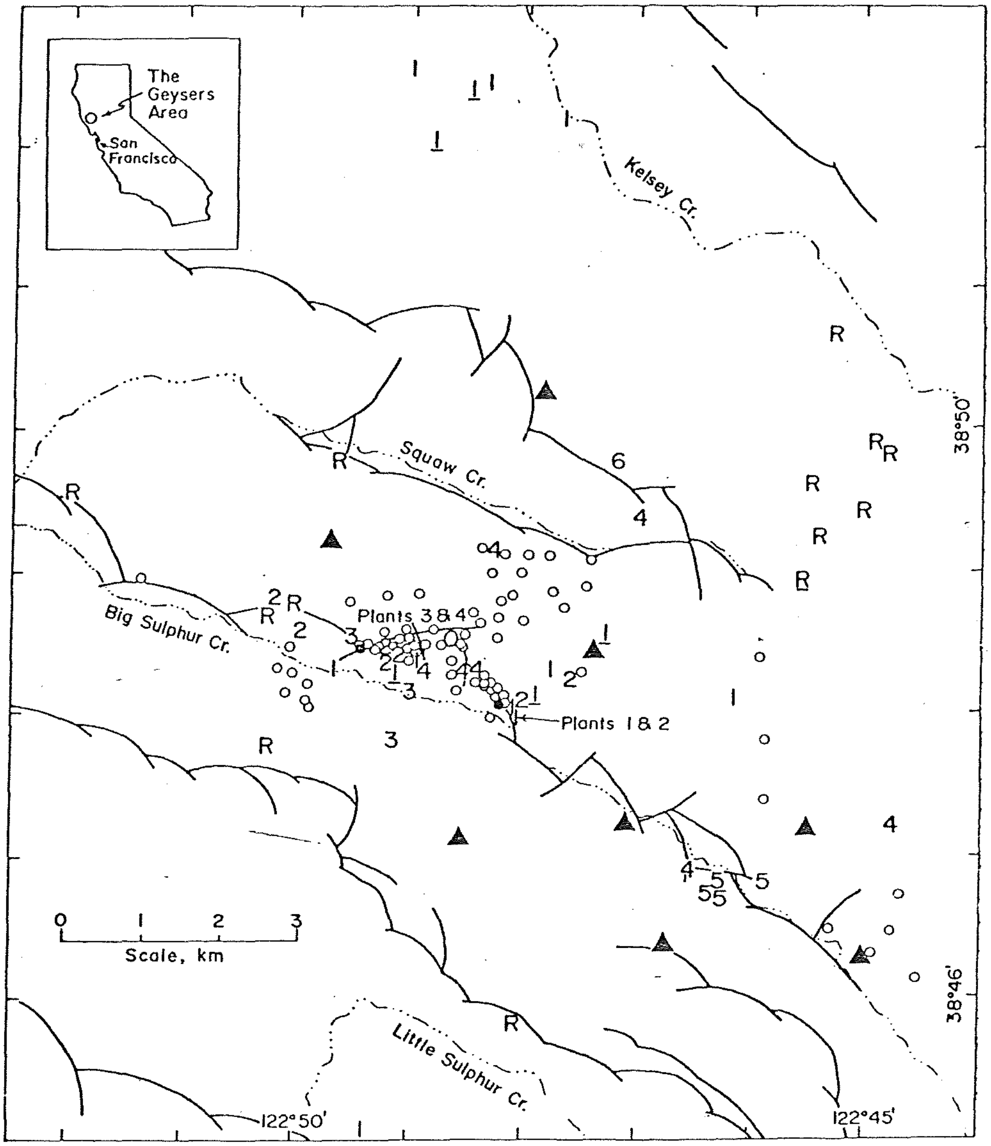


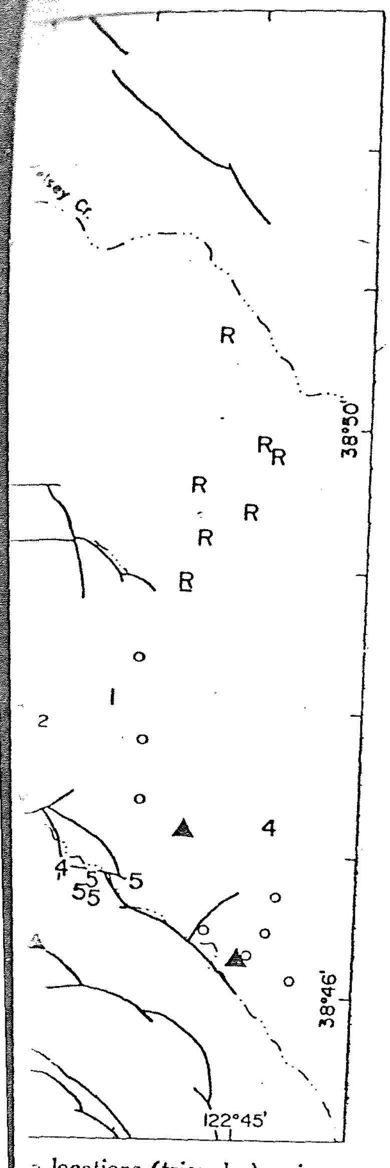
Fig. 1. Map of The Geysers area showing seismograph station locations (triangles), epicenters (represented by numbers indicating focal depth to the nearest kilometer, except where the depth was fixed in computation, in which case an R is plotted), steam wells (circles), injection wells (dots), and faults (heavy solid lines, taken from *McNitt* [1968]). Possible explosions are indicated by line drawn under focal depth of epicenters.

communication, 1970) for a study of earthquakes near Santa Rosa, 40 km to the south:

Depth to top of layer, km	0.0	1.0	4.0	15.0	25.0
Velocity in layer, km/sec	3.3	5.0	5.7	6.7	8.0

It was assumed that the ratio of *P*-wave to *S*-wave velocity is 1.73, corresponding to an assumed Poisson's ratio of 0.25. For earthquakes within the seismic network the depth-restricted solution (type 2) was disregarded. For earthquakes outside the network the depth-free, origin-time-free solution (type 3) was disregarded. Earthquake magnitudes were not computed, but they were very small, probably below 0, except for one event estimated at 1½ magnitude.

Origin-time-restricted (type 1) and origin-



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time-free solutions (type 3) were obtained for 11 events within the network. The epicenters generally agree closely, differences in location being less than 0.5 km, except for one of 1.5 km. Focal depths agree within 1 km for eight of the earthquakes and differ by 1.1, 1.9, and 2.1 km for the other three earthquakes.

The earthquakes within the seismic network are thought to be located with an accuracy generally better than ½ km for the epicenter and 1 km for the focal depth. Outside the network accuracy of location drops rapidly, and errors could amount to several kilometers. Over the area of Figure 1 the network provided fairly uniform detectability.

Epicenters are represented in Figure 1 by a number indicating focal depth to the nearest kilometer. Two earthquakes were a few kilometers outside the area of Figure 1 and are not plotted. Within the network the free solution was generally adopted. Outside the network the depth-restricted solution was used, except north of the network, where solutions based on fixed origin time were adopted. All solutions with fixed origin time for shocks outside the network had shallow focal depth, perhaps because of an incorrect assumption about the *S*-wave velocities.

Twenty-two of the earthquakes lie in a 1-km-wide zone north of Big Sulphur Creek, running about 4 km WNW from nearby power plants 1 and 2. Focal depths in this zone range from near surface to about 4 km. Five foci at depths of about 5 km were located in a cluster 3½ km SE of plants 1 and 2 along the creek. The activity 7–8 km north of the main zone of activity, well outside the network, is not accurately located. A similar poorly located cluster is plotted about 5 km NE of plants 1 and 2.

The earthquake zone delineated by *Lange and Westphal* [1969] also lay along the north side of Big Sulphur Creek. Most of the epicenters were in a cluster between plants 1 and 2 and about 1 km east. Several epicenters were found west of plants 1 and 2 in the main zone delineated in this study.

Some of the events reported here as earthquakes may have been explosions. The Geysers area has a few active mines, and local road construction is underway. Presumably, events occurring between 5 P.M. and 8 A.M. PST (2400 and 1600 GCT) are earthquakes, as are events recorded with at least one clear dilatational first motion. Nine events that do not meet these criteria may be explosions. If, in addition, shocks with well-determined focal depths below 2 km are eliminated, the number of possible explosions is reduced to six. These shocks are indicated in Figure 1; two are in the cluster 7–8 km north of The Geysers, and one is in the cluster about 5 km NE of The Geysers. Thus only three of the seismic events in or near the network could be explosions, but they are not near mines.

FAULT-PLANE SOLUTIONS

First-motion patterns were examined for individual well-recorded earthquakes and for clusters of earthquakes. The first motions for all earthquakes except one in the main epicentral zone were consistent with a single fault-plane solution (Figure 2*a*). One nodal plane dips 60° westerly with a strike of N 13°W; the other dips 74° northerly with a strike of N 85°E. Therefore the motion indicated is predominantly strike slip, right lateral on the northerly striking plane or left lateral on the easterly striking one.

The five earthquakes clustered 3½ km SE of plants 1 and 2 exhibited a different first-motion pattern (Figure 2*b*). Only one nodal plane is well determined; it dips 77° SW and strikes N 41°W. The other can range from a dip of 18° east, striking N 10°E, to a dip of 55° north, striking N 47°E. The movement on the well-defined plane has a dip-slip component.

The essential difference between the two fault-plane solutions is seen by comparing the axes of greatest and least principal stress, or the pressure and tension axes. These axes are approximately the bisectors of the dilatational and compressional quadrants, respectively, of the first-motion pattern. The pressure axes in both solutions lie in the NE quadrant. The tension axes, however, are in different quadrants.

GEOLOGIC STRUCTURE

The geologic structure of The Geysers area has been described by *McNitt* [1963; 1968] and *Bailey* [1946, pp. 209–210]. The area is in the Mayacmas Mountains, a large, complex horst bounded by faults on both the NE and SW. Most of the rocks in these mountains belong to the Franciscan formation. Although fractured and broken on all scales, they generally dip 30°–45° NE. The horst is broken by NW-striking normal faults into a series of elongate

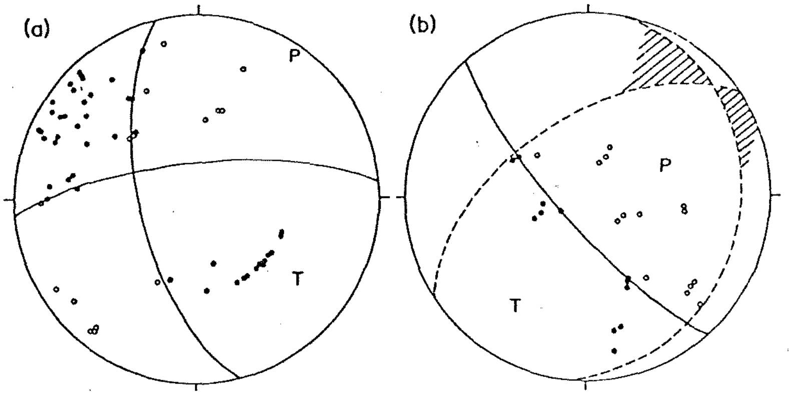


Fig. 2. Lower hemisphere equal-area projections of the first-motion radiation pattern for earthquakes (*a*) in the main epicenter trend running westward from The Geysers and (*b*) in the cluster 3½ km SE of power plants 1 and 2. Compressional and dilatational first motions are represented by dots and circles, respectively. Bisectors of the compressional and dilatational quadrants are plotted at T (tension axis) and P (pressure axis), respectively.

blocks each several kilometers wide. These faults dip steeply to the SW, and along most the SW side is downdropped relative to the NE side, with throws of up to 5 km. The amount of strike-slip displacement, if any, is not indicated by the available data. A major fault zone strikes NW along Big Sulphur Creek and is responsible for the localization of the fumarolic areas. In Figure 1 both the main epicentral zone and the epicentral cluster SE of power plants 1 and 2 lie along this fault.

The fault-plane solutions determined for the main epicentral zone are not readily correlated with the local geologic structure. Strike-slip movement is indicated by the seismic data, in contrast to the predominant dip-slip movement suggested by geologic relations. The dextral strike-slip movement, however, is consistent with regional deformation associated with the San Andreas fault system. For example, a first-motion study of the Santa Rosa aftershocks (J. D. Unger and J. P. Eaton, unpublished data, 1970) indicates dextral strike-slip movement on a plane striking N 31°W, 18° more westerly than the corresponding plane for the main earthquake zone at The Geysers. For an earthquake north of Santa Rosa *Bolt et al.* [1968] found a nodal plane indicating dextral strike-slip movement trending N 22°W, only 9° more westerly than the movement at The Geysers, and dipping 74° NE.

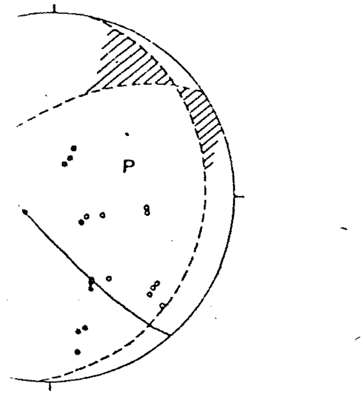
The fault zone passing through the main epicenter trend strikes N 60°W. The nodal plane of Figure 2*a* indicating sinistral strike-slip movement is the closer one to this trend but still differs in strike by about 35°.

Hence it appears that fault movement in the main epicenter trend is responsive to present-day regional deformation. The close correlation of the epicentral trend and the fault along Big Sulphur Creek and the fumarolic area suggests that this area may be a zone of weakness. *Ward and Björnsson* [1971] discussed a mechanism that could cause such a zone.

On the other hand, the cluster of five earthquakes 3½ km SE of plants 1 and 2 yielded a fault-plane solution consistent with the local dip-slip fault pattern. The strike of N 41°W indicated for the well-determined nodal plane is about 10° more northerly than the trend of the fault along Big Sulphur Creek.

EARTHQUAKES AND THE GEOTHERMAL FIELD

The area explored by drilling at The Geysers is indicated by the distribution of wells on Figure 1. The limits of the field are not known; they may extend well to the north and east of the drilled area. During our microearthquake survey steam was produced only from wells within about ¾ km of the four power plants (Figure 1). Wells to the north, east, and SW were not yet used for power generation, although some wells near Squaw Creek were flowing for testing purposes. Wells in the field reach depths of about 2.5 km. The deep reservoir is at a depth of 1.5–1.8 km. As mentioned



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before, focal depths in the main epicentral zone range from near surface to about 4 km.

The main zone of microearthquakes appears to correlate with the part of the field currently under production but extends both to the east and to the NW of the producing areas. Many focal depths are considerably deeper than the deep steam reservoir. The two clusters of earthquakes to the north and NE fall well outside the producing area. In a large part of the geothermal field between Big Sulphur Creek and Squaw Creek ample steam has been found by drilling, and power plants are being constructed to utilize the steam. Only one microearthquake, however, was located in this area.

Our data do not reveal whether the concentration of microearthquakes in the currently producing part of The Geysers steam field is natural or is somehow caused by extraction of steam. In Iceland *Ward and Björnsson* [1971] found that varying the flow of a large geothermal well did not appear to affect the occurrence of microearthquakes. Their observation and the common occurrence of microearthquakes in undeveloped geothermal areas [*Ward*, 1972] suggest that the microearthquakes at The Geysers are not caused by steam extraction. Clear evidence would be obtained by continuing to monitor microearthquakes as new areas at The Geysers are put on line for power production.

Injection of fluids into deep wells has been recognized as the cause of earthquakes in Colorado, near Denver [*Healy et al.*, 1968] and Rangely [*Raleigh et al.*, 1970]. In the past year water has been injected into two wells at The Geysers (Figure 1) at a rate of about 20,000 barrels per day (Union Oil Company, oral communication, 1971). The Geysers field is a dry-steam, or vapor-dominated, geothermal system. Thus pressures at depth in the field are considerably lower than hydrostatic pressure [*White et al.*, 1971], and injection water flows into the wells under hydrostatic head. Only 15% by mass of the produced fluid is injected; the other 85% is evaporated in cooling towers. Accordingly, even with injection the net effect of field operation is to decrease the quantity of H_2O in the geothermal reservoir.

The earthquakes recorded are not tightly clustered near the injection wells, although the wells do lie in the main epicenter zone. It is uncertain whether or not the earthquakes are caused by the water injection; however, the under-pressured nature of the geothermal system and the ratio between fluid extracted and fluid injected lead us to believe that they are not caused by water injection.

USE OF MICROEARTHQUAKES FOR EXPLORATION OF GEOTHERMAL POWER

The use of microearthquakes as a prospecting tool in the development of geothermal resources has been reviewed by *Ward* [1972]. He points out that accurate locations of microearthquakes can be used to map at depth active faults that may channel hot water to the surface. Focal depths in geothermal areas are unusually shallow: 2 to 6 km in Iceland, near surface to 6 km in El Salvador, and near surface to 5 km in Japan. To this list can be added near surface to 5 km for The Geysers. Mapping of faults over such depth ranges may provide valuable information for selecting drilling sites.

Microearthquakes may also give an indication of temperature at depth. Laboratory studies of frictional sliding on fracture surfaces in rocks by *Brace and Byerlee* [1966] suggest that the stick-slip process may be important in the generation of earthquakes. This mechanism has been shown to be dependent on temperature. Elevation of temperature may prevent stick slip and induce stable sliding [*Brace and Byerlee*, 1970]. Brace and Byerlee suggest that the absence of earthquakes below a depth of 15 km along the San Andreas fault in California may be due to such an effect and point out that, if their laboratory experiment accurately models the situation along the San Andreas fault, the presence or absence of earthquake activity could reflect the existence of relatively cold or hot spots, respectively.

If these ideas are correct, the maximum depth of earthquake occurrence in a region could be used to indicate depth to a particular temperature. It is unusual to find a seismically active area in California where no earthquakes are observed below a depth of 5 km. The closest detailed seismicity study was in the Santa Rosa area, where aftershocks of the earthquakes of 1968 were monitored (J. D. Unger and J. P. Eaton, unpublished data, 1970). Focal depths there ranged from near surface to about 10 km. The absence of deep-earthquake activity at

The Geysers could also be due to other factors, such as high pore pressure [*Byerlee and Brace*, 1970], or they may simply be the result of too short a recording period.

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