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SEISMICITY OF THE GEYSERS-CLEAR LAKE REGION, CALIFORNIA

by

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Abstract

Microearthquake activity in the Geysers-Clear Lake region has been monitored continuously since 1975. The seismogenic zone across the geothermal area and gravity low is relatively shallow; earthquake focal depths are generally less than 5 km. The absence of deeper earthquakes is consistent with the hypothesis of elevated temperatures associated with a magma body at depth. The present average tectonic stress orientation, deduced from P-wave first motions, indicates maximum compression at N. 20° E. and minimum compression at N. 70 degrees W. over most of the region. This stress orientation is rotated approximately 20 degrees clockwise from that producing maximum right-lateral shear on faults subparallel to the San Andreas fault, possibly accounting for the diffuse pattern of epicenters in the region. Most fault-plane solutions suggest right-lateral strike-slip motion on short, possibly echelon faults trending more northerly than the geologically well defined Maacama and Collayomi fault systems. Most of the earthquakes in the geothermal region occur in two clusters at The Geysers. Earthquakes in the steam production area and in the surrounding region are characterized by an unusually large number of small earthquakes (high b values). The present seismicity at The Geysers is essentially continuous, in contrast to the episodic nature of earthquake activity in the surrounding region. The spatial distribution of earthquakes with regard to the producing steam field and the continuous nature of earthquake activity strongly suggest that much of The Geysers' seismicity is induced. In late September 1977, the deep (deeper than 2 km) pattern of faulting at The Geysers changed from predominantly strike-slip to predominantly normal faulting, indicating a decrease in northeasterly tectonic compression.

INTRODUCTION

The Geysers-Clear Lake region lies 50-80 km northeast of the San Andreas fault in the broad zone of transform faulting along the west boundary of the North American plate (fig. 1). A pronounced gravity low extends from The Geysers to the vicinity of Clear Lake (Isherwood, in press). Large local delays in teleseismic P-waves (Iyer and others, in press) and, as we shall demonstrate, the shallowness of the seismogenic zone lend credence to the hypothesis that a zone of elevated temperatures and partial melting underlies the region of the gravity low at shallow (5-7 km) depths. Regional structures are bounded or cut by a series of northwest-trending faults, some with major Quaternary right-lateral strike-slip displacement (Herd, 1978, McLaughlin, in press, Hearn and others, in press). The seismically active Maacama fault system passes along the southwest edge of the gravity low and is outside the area of recent volcanic and geothermal activity.

Regional Seismicity

The segment of the San Andreas fault southwest of the Geysers-Clear Lake region last ruptured in the great earthquake of 1906. Since then the region has experienced only minor earthquakes as elastic strain slowly accumulates. Between 1911 and 1969, only one earthquake larger than magnitude 5 (June 1962,

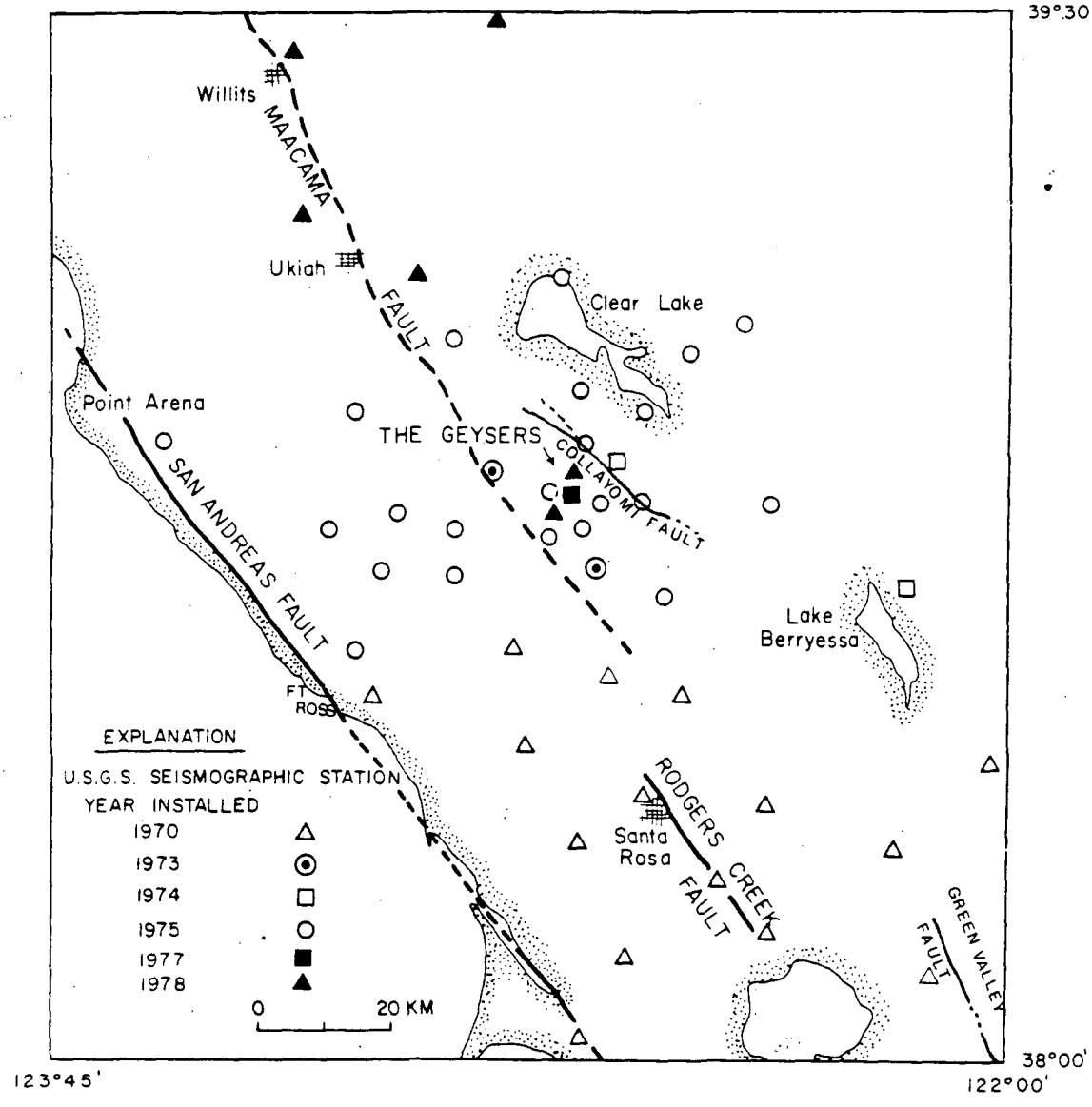


Figure 1.-- Evolution of the U.S. Geological Survey seismographic network north of San Francisco Bay, Calif.

magnitude 5.2) occurred in the region of figure 1, near the town of Ukiah; it was located by the sparse seismographic network of the University of California at Berkeley (Bolt and Miller, 1975).

In October 1969, two earthquakes (magnitudes 5.6 and 5.7) occurred along the Rodgers Creek fault at Santa Rosa, 40 km south of The Geysers. After these earthquakes, the U.S. Geological Survey's dense central California network of seismographs was extended northward into the Santa Rosa area. The evolution of that network north of San Francisco Bay is shown in figure 1. Data analysis procedures are described by Lester, Kirkman, and Meagher (1976). Preliminary epicenters of earthquakes located by the network are shown in figure 2; most of the earthquakes shown were located in 1975-78 after the network had expanded north to Clear Lake. The Geysers, which is marked by the largest cluster of earthquakes, lies along a 100-km-long lineament (dashed line in fig. 2) which is well developed on ERTS imagery and extends from the north end of Lake Berryessa toward Point Arena. Surface faulting and seismicity patterns appear to be disrupted at the lineament. A gap in the rather diffuse pattern of earthquakes southeast of The Geysers corresponds to the northern part of the Sonoma Volcanics, whose basement apparently behaves as a stable tectonic unit. Also evident at the bottom of figure 2 is a seismicity gap southeast of Santa Rosa along the Rodgers Creek fault.

With the exception of The Geysers, the largest concentrations of earthquakes in the area of figure 2 occur along the Green Valley, Rodgers Creek, and Maacama faults. The Maacama system was very active in 1977-78. The Ukiah earthquake sequence of March 1978 (main shock magnitude 4.4) was preceeded on the southeast (10 km south of The Geysers) by the Alexander Valley

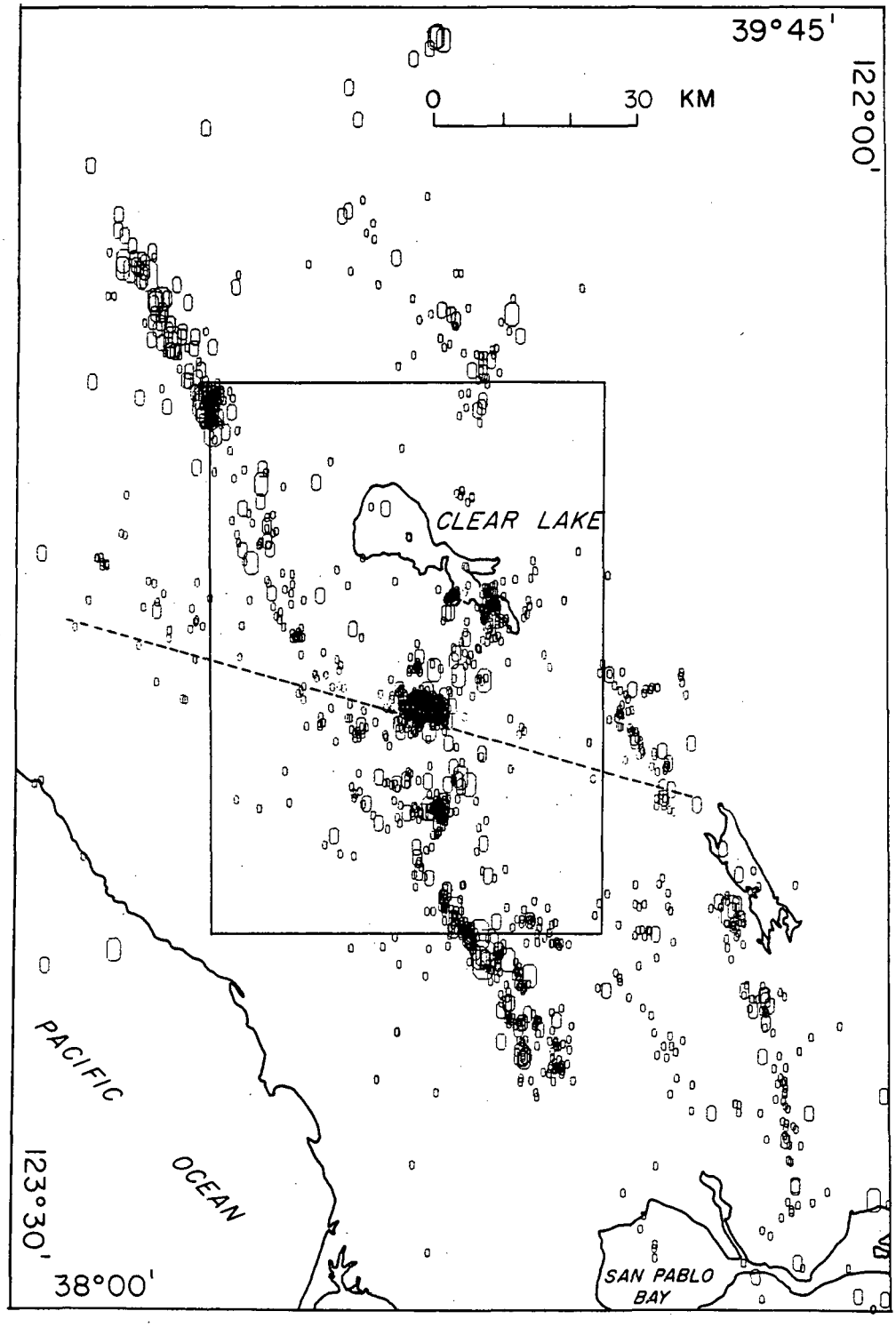


Figure 2.- Preliminary epicenters of earthquakes north of San Francisco Bay, 1969-78. Dashed line indicates 100-km-long lineament from ERTS imagery.

swarm of September 1977 and on the northwest by the Willits sequence (main shock magnitude 4.9) of November 1977. These earthquake clusters span a distance of 100 km along the Maacama fault zone. This zone provides a backdrop of tectonic earthquake activity against which the seismicity of The Geysers-Clear Lake geothermal region can be evaluated.

Seismicity of the Geothermal Area

An epicentral map (July 1, 1975-September 30, 1977) and hypocentral cross section spanning the geothermal area, as outlined by the gravity low, are shown in figure 3. Only those events with adequate depth control (standard error $\pm$ 2 km) are plotted in the section. Most events shown are contained in a catalog and map by Marks and Bufe (1978).

Based on the location error for an explosion fired at The Geysers, earthquake location accuracy is estimated to be a few hundred meters in epicenter and about 1 km in depth. Standard errors of most solutions indicate a location precision of 500 m or better. Section A-A' (fig. 3B) extends from south to north across the Maacama fault at Alexander Valley, through The Geysers and under Mount Konocti. Note that the seismogenic zone at The Geysers and northward across the gravity low is unusually shallow. This dearth of earthquake activity below 5 km is highly unusual in central California. The range of focal depths of earthquakes along the San Andreas system is normally 2-12 km, and deeper (12-20 km) earthquakes occur in a few regions. Yet the lithospheric plates in relative motion across the

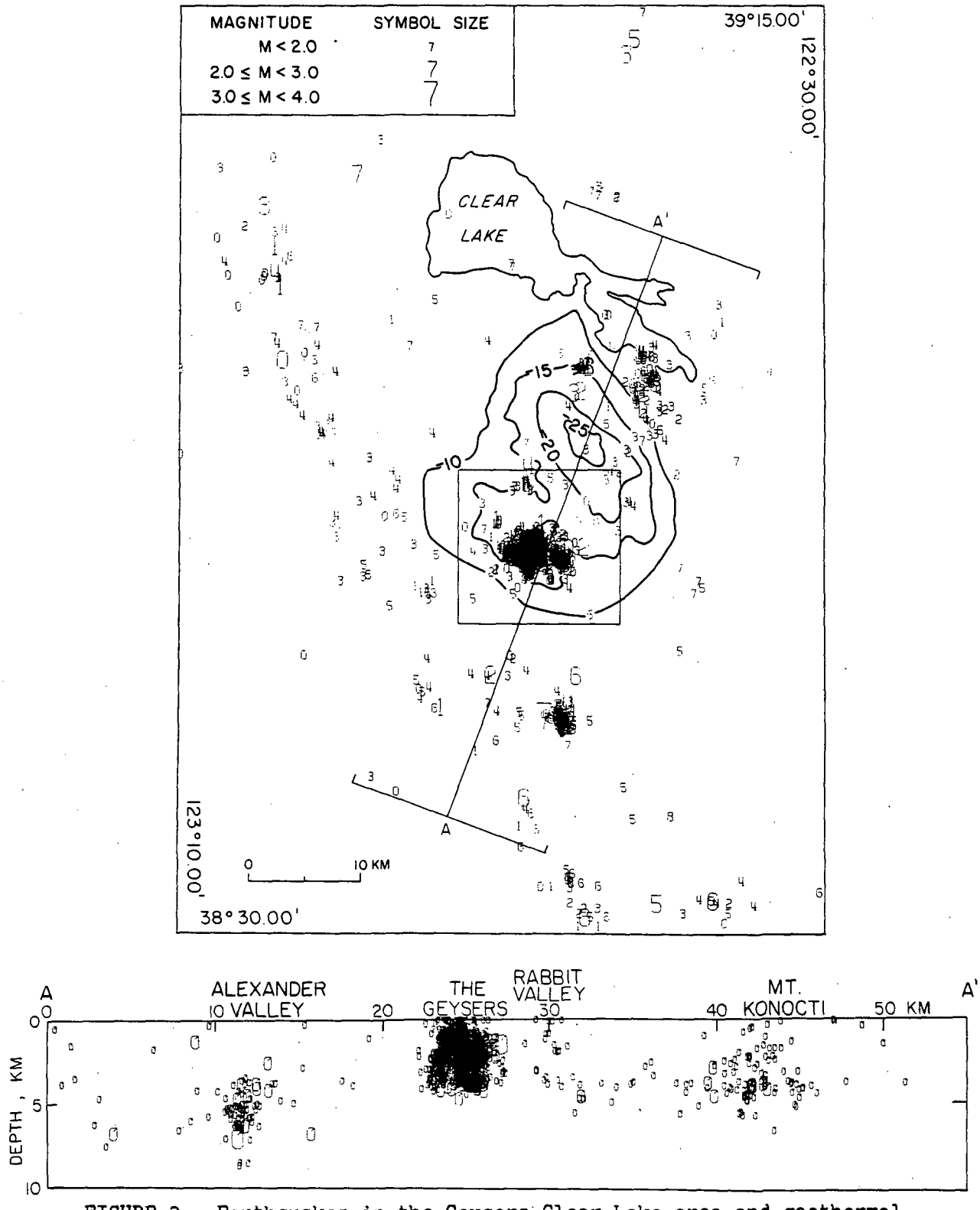


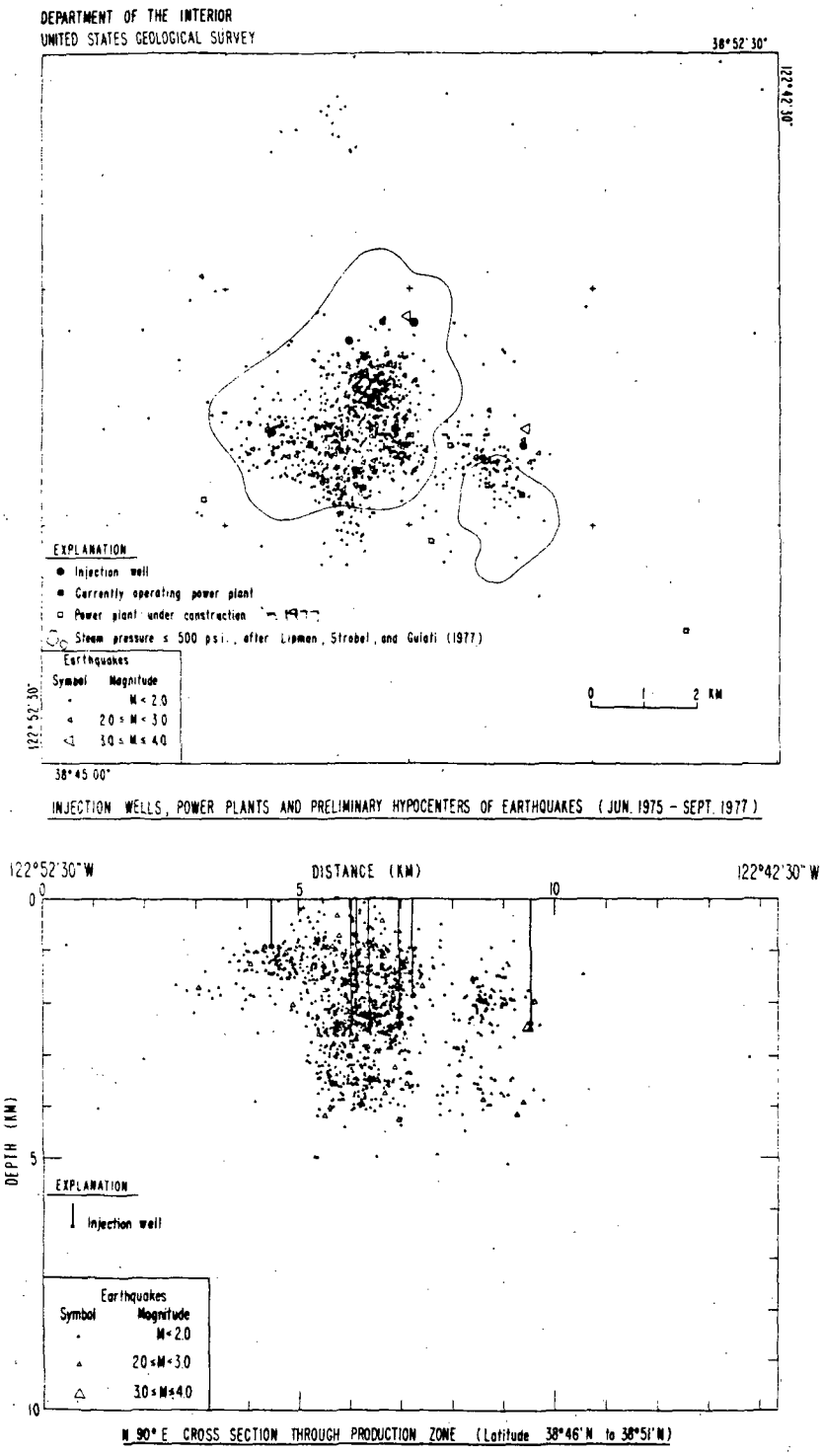
FIGURE 3.- Earthquakes in the Geysers-Clear Lake area and geothermal region. See figure 2 for location. A, Location of earthquake epicenters, June 1975 - September, 1977. Gravity contours, in milligals, are from Isherwood (1976). Numbers indicate focal depths, truncated to integer. B, Section A-A' is a projection of hypocenters within 9 km of a line A-A' onto a vertical plane passing through A-A'.

San Andreas system are believed to be much thicker. Brace and Byerlee (1970) have suggested that the decrease in earthquake activity below 10 km may be due to elevated temperatures which prevent the rock from responding as an elastic solid to long-term increases in shear stress. This explanation may apply to the Geysers-Clear Lake region, with elevated temperatures occurring at much shallower depths.

Elevated temperature at very shallow (5 km) depth is consistent with the presence of a molten or partially molten magmatic body beneath the area. Similar conclusions have been reached from consideration of the gravity data (Isherwood, in press) and P-wave delays (Iyer and others, in press). Aside from the concentrated earthquake activity at The Geysers, most of the seismicity in the geothermal region has occurred southeast of Mount Konocti along the north flank of the gravity low near the areas of most recent volcanism.

The Geysers

The Geysers steam field lies adjacent to the Clear Lake Volcanics in fractured graywacke of the Franciscan assemblage, which is overthrust by ophiolite, sandstone, and shale of the Great Valley sequence. The Franciscan and Great Valley terrane of the steam field was recently mapped by McLaughlin (1978). Two main clusters of microearthquakes can be recognized at The Geysers in figure 4. These clusters, shown on the map and east-west cross



STEAM PRODUCTION ZONE AND CROSS SECTION.

FIGURE 4.- Two main clusters of microearthquakes recognized at The Geysers. See figure 3A for location. A, Preliminary hypocenters of earthquakes, June 1975-September 1977. B, Events between lat 38° 46' N. and lat 38° 51' N. are projected onto an east-west vertical plane in section. Modified from Plate 1 (1:24,000) of Marks, Ludwin, Louie, and Bufe (1978), with improved coordinates for injection wells.

section in figure 4, are spatially correlated with two independent pressure sinks resulting from steam production described by Lipman, Strobel, and Gulati (1978). From earthquake records of the U.C. Berkeley station at Calistoga in the early 1960's and three weeks of data from an eight-station portable network operated at The Geysers by the U.S. Geological Survey (Hamilton and Muffler, 1972), Marks, Ludwin, Louie, and Bufe (1978) concluded that the present level of seismicity at The Geysers is higher than the pre-production level. Thus it appears that the withdrawal of steam and injection of condensate are inducing many of the earthquakes which occur on a daily basis at The Geysers. It is also likely that some of the earthquakes at The Geysers are triggered by natural tectonic processes. These probably occur as infrequent swarms of short duration like the 13 small earthquakes which occurred at Rabbit Valley, 5 km north of The Geysers, on August 22-31, 1975, or the 19 events on the south flank of Mount Konocti (fig. 3, section A-A'), which occurred between September 29 and October 1, 1975.

Although distributed much more uniformly in time than earthquakes elsewhere, the earthquakes at The Geysers show similar source characteristics (Peppin and Bufe, 1980), and the same magnitude distribution (b = 1.2) as those in the surrounding region.

Fault-plane solutions

Representative focal mechanisms of earthquakes in the Geysers-Clear Lake region are shown in figure 5, superimposed on a preliminary, unpublished fault map by B. C. Hearn and R. J. McLaughlin. It is evident from the fault map

that the region is characterized by numerous short faults with many different orientations. The dominant mode of faulting at the present time, as indicated by the focal-plane solutions, is strike slip. This is true of earthquakes in the geothermal region as well as those along the Maacama fault system to the south and west. The earthquakes for which focal-plane solutions are shown in figure 5 are described in table 1. The orientation of regional tectonic stress consistent with these focal-plane solutions is maximum compression at N. 20° E. and minimum compression at N. 70° W. Open fractures thus are most likely to be oriented north-northeasterly. This stress orientation is rotated clockwise approximately 20° from that producing maximum right-lateral shear on faults subparallel to the San Andreas; an apparent clockwise stress rotation east of the San Andreas fault can be traced southward as far as Hollister, opposite the south end of the 1906 rupture. This pattern appears also to be representative of earthquakes as far north as the south shore of Clear Lake. Included in figure 5 are fault-plane solutions for the largest events in the August 1975 swarm, which occurred along the Konocti Bay fault zone south of Mount Konocti, and for events in 1976 near Thurston Lake. Both areas are of interest from the standpoint of geothermal exploration.

Fault-plane solutions at The Geysers are somewhat more complicated and show significant temporal variation. Because of instabilities resulting from fluid withdrawal and injection or perhaps inherent in a steam reservoir, The

TABLE 1. - Descriptions of earthquakes shown on figure 5

Date Yr/Mo/Da	Time UTC	Latitude Deg.	Min.	Longitude Deg.	Min.	Depth (km)	Magnitude	Principal Stresses Maximum (Azi.	Dip)	Minimum (Azi.	Dip)
750527	1711	38	47.71 N	122	47.82 W	3.30	1.92	28°	00°	298°	00°
750603	1447	38	37.78	122	41.70	5.99	2.54	202	16	296	16
750929	1708	38	57.45	122	44.71	3.98	2.00	24	00	114	00
760225	0125	38	42.54	122	50.75	2.14	2.24	217	20	307	16
760331	0706	38	32.93	122	45.57	6.21	1.24	174	10	270	30
760816	2248	38	56.91	122	40.95	2.37	2.53	184	10	275	02
761222	0042	38	49.64	122	47.45	1.01	3.07	194	02	285	06
761223	0123	38	48.02	122	48.53	2.39	2.90	209	20	116	08
770224	2240	38	31.79	122	40.04	5.99	2.09	176	12	268	12
770908	0028	38	39.97	122	46.15	4.99	3.12	22	00	292	00
770911	2346	38	40.28	122	46.09	4.86	3.24	32	06	302	06
770922	2048	38	48.45	122	46.02	3.21	3.27	37	08	307	06
771007	0201	38	48.29	122	48.45	2.73	2.05	47	67	305	03

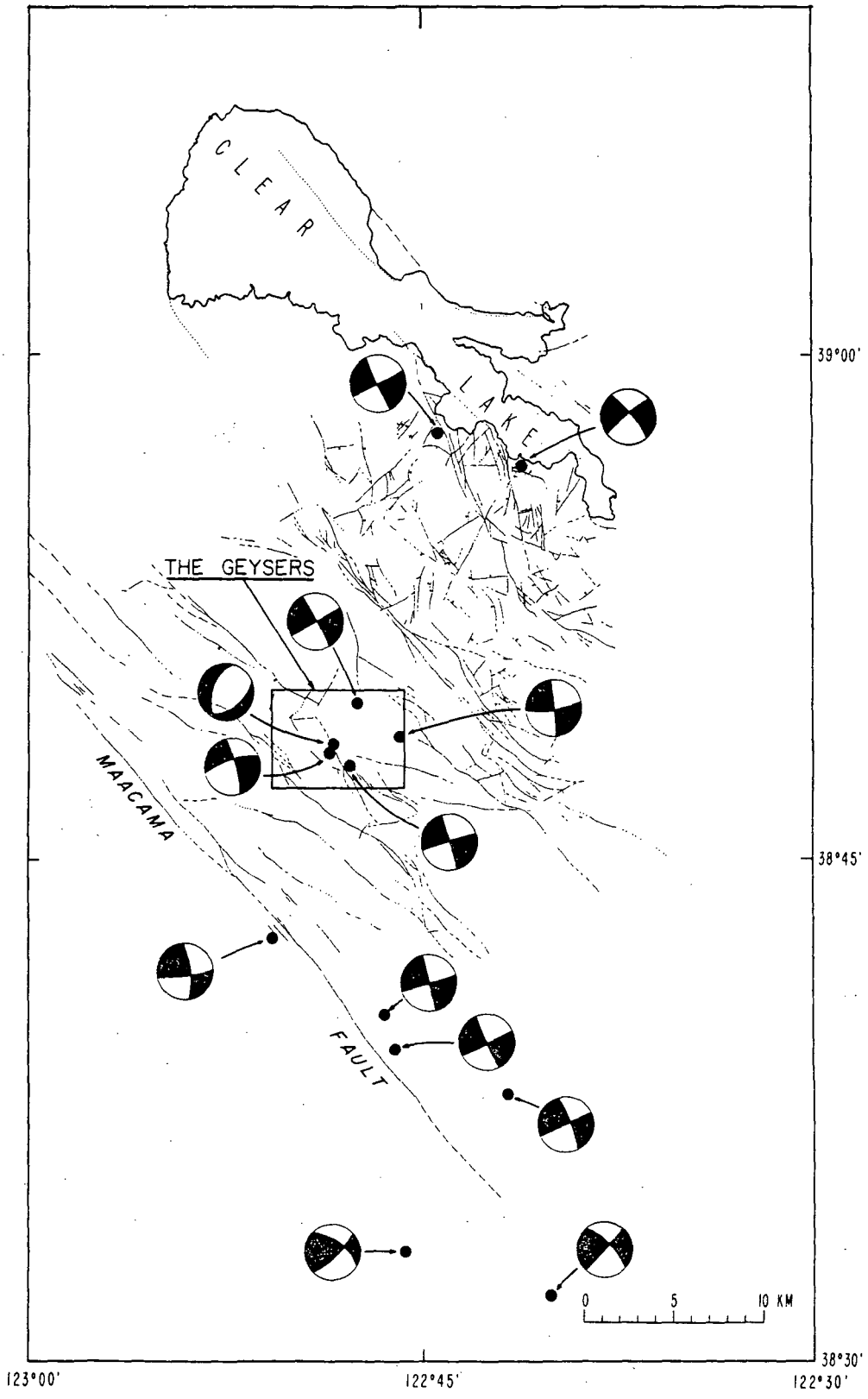


FIGURE 5.- Representative focal plane solutions (lower hemisphere) for earthquakes in the Geysers-Clear Lake region. Preliminary faults from R. J. McLaughlin and B. C. Hearn (unpub. data, 1978). Each earthquake and solution described in table 1.

Geysers may be more sensitive to tectonic stress changes than the surrounding region. Before late September 1977, the dominant mode of faulting was strike slip (Marks and others, 1978; Majer and McEvilly, 1979). From late September 1977 to May 1978 the dominant mechanism was normal faulting. The change in stress orientation (fig. 6) followed a magnitude 3.7 strike-slip event on September 22, the largest earthquake to be located at The Geysers to date. The change can be explained as a reduction in northeasterly compression such that the vertical (lithostatic) compression, which was the intermediate stress, became the principal compression. This interpretation is supported by the observation that most of the very shallow (depth less than 2 km) earthquakes at The Geysers continued to be caused by strike-slip or thrust movement. The majority of deeper (2-4 km) earthquakes had focal mechanisms indicating normal faulting. The reduction (at least 500 bars, or 50 percent) in northeasterly compression may be a local response to the September 22 earthquake, since strike-slip faulting continues to predominate (fig. 6B) along the Maacama fault to the south. However, these strike-slip mechanisms at Alexander Valley show a subtle counterclockwise stress reorientation at about the time of the change in earthquake mechanisms at The Geysers. Regional stress changes may also be inferred from the greatly increased earthquake activity in the surrounding region that began 10 km south of The Geysers with the swarm at Alexander Valley in September 1977. In addition to the

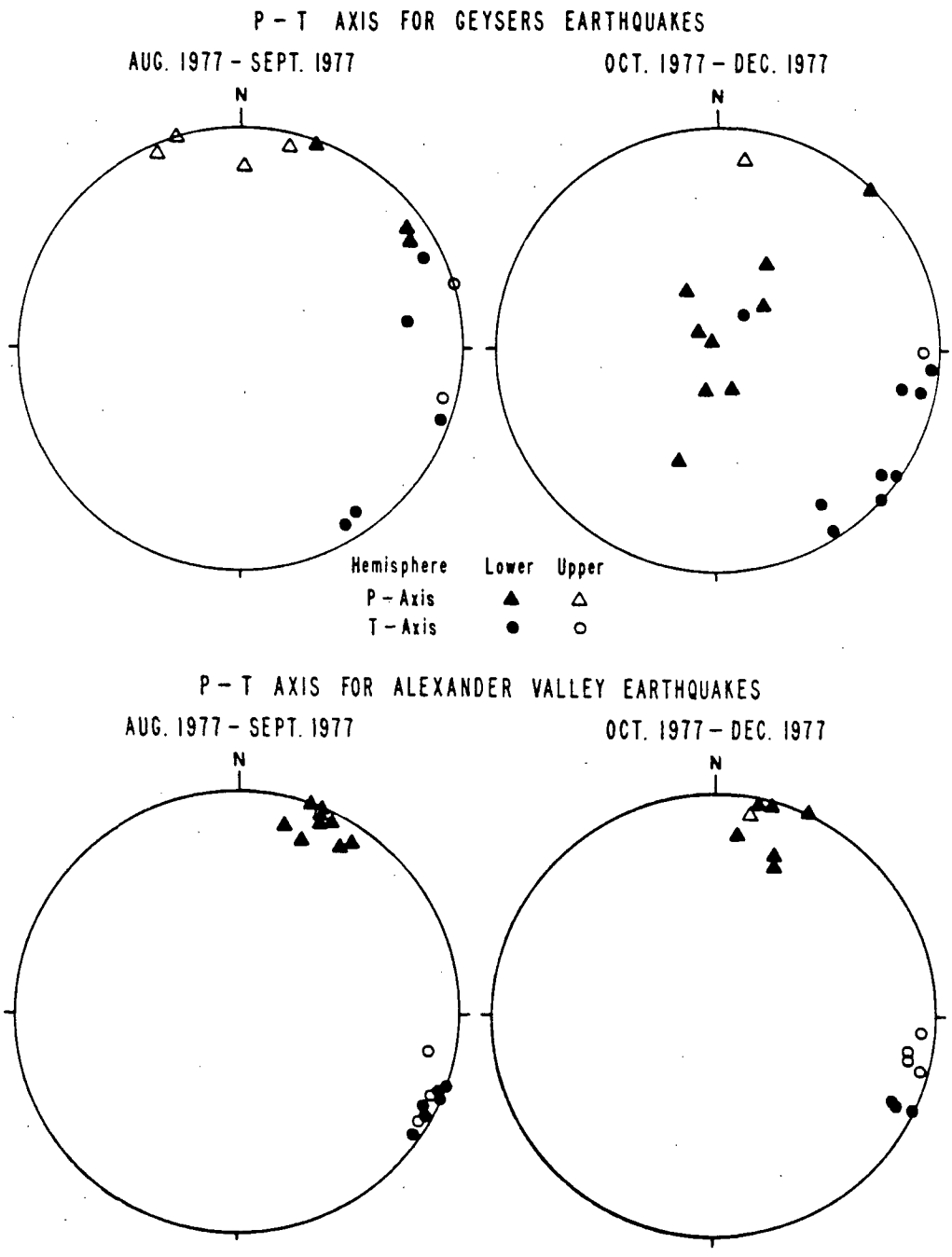


FIGURE 6.- Temporal changes in stress orientation from focal-plane solutions in the Geysers region. A, Inferred maximum (P) and minimum (T) principal stress orientations from earthquakes in or near steam production zone at The Geysers preceding and following the September 22, 1978 earthquake (M=3.7). September 22 earthquake was strike slip. B, Inferred stress orientations from earthquake along Maacama fault at Alexander Valley, 10 km south of The Geysers, during same time periods as 6A.

earthquakes along the Maacama system at Ukiah and Willits, a sequence of earthquakes occurred near the San Andreas fault at Fort Ross, an area normally quiet (Stickney, 1979).

Conclusions

The reduced thickness of the seismogenic zone above the heat source for the Geysers-Clear Lake geothermal region implies that this is a zone of relative weakness within the North American plate. Faulting within this zone is complex and the pattern of earthquakes is diffuse in space and episodic in time. Earthquake activity at the Geysers geothermal development is, on the other hand, highly concentrated and nearly continuous, reflecting local instability and stress concentrations at shallow depths. This result is consistent with surface deformation (Lofgren, in press) of 2 cm/yr of horizontal convergence and 3 cm/yr of subsidence over the geothermal reservoir, and Isherwood's (in press) temporal changes in gravity in the same area.

Withdrawal of large quantities of steam for power production from the already underpressured reservoir and massive injection of relatively cool condensate combine to progressively weaken the reservoir rock. Because of this continuing instability, The Geysers may be a tectonic barometer sensitive to small changes in regional stress.

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