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Microearthquake Studies at the Coso Geothermal Area, China Lake, California

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ABSTRACT

During the summer of 1974, two different arrays of portable high-gain seismographs were installed in the Coso geothermal area. The first array consisted of six vertical-component, smoked-paper drum recorders, while the second consisted of nine three-component magnetic tape recorders. Over the period of recording, the microearthquake activity changed considerably, including days which had only a few events while others had as many as 100 or more distinct local events. During 33 days of recording, more than 2000 events with S-P times of less than 3 sec were detected. Strain release in the Coso geothermal area occurs primarily in swarm-type sequences whereas earthquakes outside the area occur as mainshock-aftershock sequences.

Detailed subsurface velocity data, obtained from nine calibration blasts, indicate an essentially constant P-wave velocity of 4.75 km/sec for the upper 5 km overlying a half space of 6.0 km/sec, which is in excellent agreement with previous refraction studies in the region. Hypocenters are predominantly between 1 and 6 km with an increase in focal depth from the Coso Hot Springs toward the west and northwest. Areas of high seismic noise outlined in an earlier survey tend to coincide with areas of high microearthquake activity with an additional inverse correlation between the focal depth and amplitude of the noise.

Using a reduced Wadati diagram and a least squares linear regression analysis, we obtained a value of 1.57 for the ratio of V_P to V_S compared to values of 1.73 to 1.87 usually obtained in laboratory and field investigations. We calculated an S-wave velocity of 3.03 km/sec. These P- and S-wave velocities infer a Poisson's ratio of 0.16 compared with the values of 0.25 to 0.30 which are normally observed. The low value for Poisson's ratio observed for the Coso geothermal area indicates that the shallow subsurface is either deficient in liquid water saturation or, more likely, that the void spaces (cracks) are filled with steam. These data indicate that the Coso geothermal system is a vapor-dominated system rather than a hot-water system.

INTRODUCTION

Investigations of microearthquake activity associated with geothermal resources in some tectonically active areas as well as volcanic areas have shown that occurrences of these resources are often characterized by a relatively high level of such activity (Westphal and Lange, 1962; Brune and Allen, 1967; Lange and Westphal, 1969; Ward, Pálmason, Drake, 1969; Ward and Björnsson, 1971; Ward and Jacob, 1971; Hamilton and Muffler, 1972; Ward, 1972; Combs and Hadley, 1976).

The Coso geothermal area, located primarily on the China Lake Naval Weapons Center in Inyo County, California (Fig. 1), is situated in a tectonically active area (Hileman, Allen, and Nordquist, 1973) of young basaltic and rhyolitic volcanism (Evernden et al., 1964; Lanphere, Dalrymple, and Smith, 1975; Duffield, 1975). Hot springs and fumaroles associated with the young volcanism have been known for years; consequently, the area has been classified as a Known Geothermal Resource Area, KGRA (Godwin et al., 1971). The Coso geothermal area is of considerable interest for the exploration and development of geothermal resources and has been investigated by a variety of geological, geochemical, and geophysical techniques.

The objectives of this reconnaissance study were to determine the background level of seismic activity associated with the Coso geothermal area prior to the onset of potential effects caused by future drilling, production, and reinjection of fluids into the presumed geothermal reservoir. In addition, from the study of microearthquakes and their precise hypocentral locations, it will be possible to determine any active fault zones in the area which may be functioning as subsurface conduits for the presumed geothermal reservoir. Finally, the present microearthquake survey will be used to speculate on the subsurface physical characteristics of the Coso geothermal system.

GEOLOGICAL AND GEOPHYSICAL BACKGROUND

The geologic setting of the Coso geothermal area consists of Mesozoic granitic and metamorphic rocks overlain by upper Cenozoic volcanic rocks and shallow Quaternary alluvial deposits in the scattered, small basins (Koenig, Gawarecki, and Austin, 1972; Duffield, 1975). Rhyolite domes and rhyolitic and basaltic lava flows which range in age from 0.04 to 0.96 m.y. with most of the units ranging in age from 0.05 to 0.15 m.y. occur on a north-trending

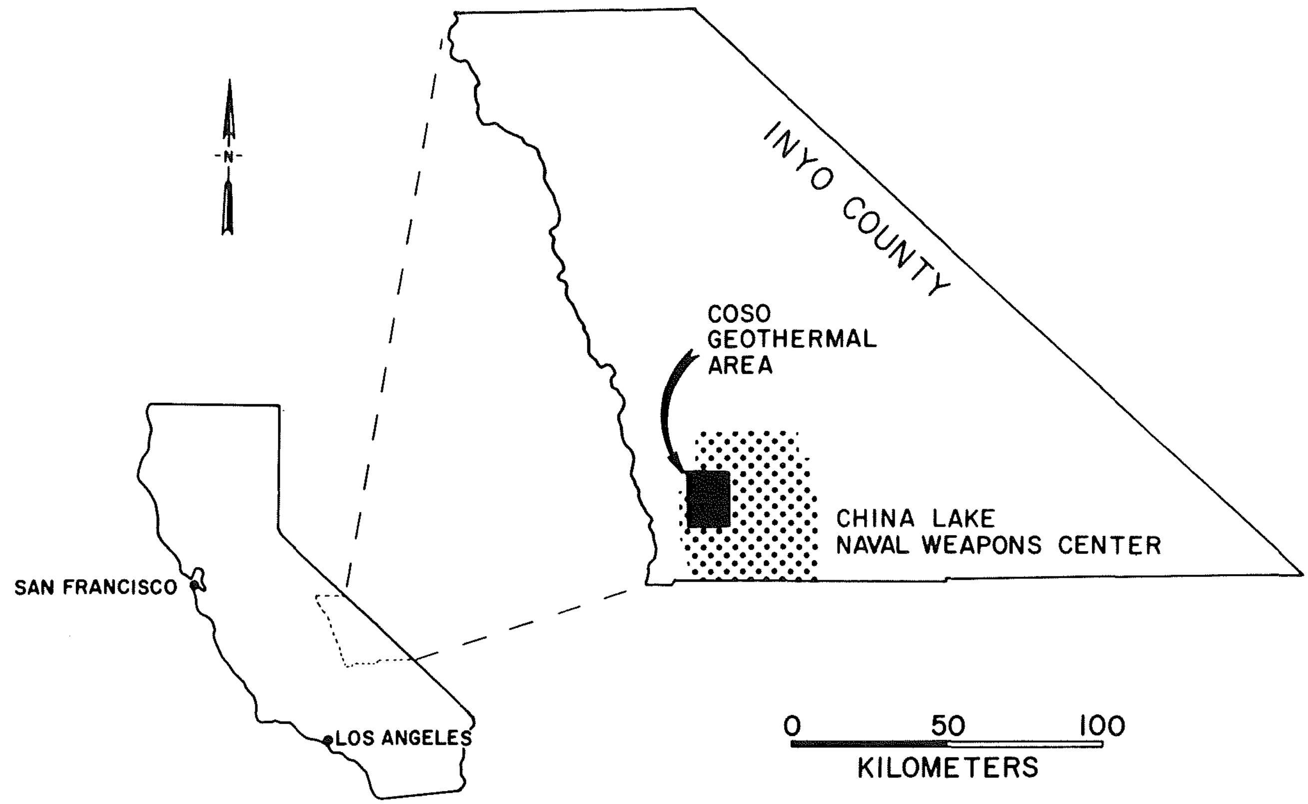

Figure 1. Location map of the Coso geothermal area, California. Shaded rectangle depicts area of the microearthquake investigation.

structural and topographic high (Evernden et al., 1964; Lanphere, Dalrymple, and Smith, 1975).

The area has been extensively faulted with the Coso Mountains broken into a pattern of roughly north- to northeast- and northwest-trending, steeply dipping faults. The geothermal area is characterized by arcuate fractures with radially trending fractures to these arcuate zones (Austin, Austin, and Leonard, 1971; Koenig, Gawarecki, and Austin, 1972). From a detailed study of the volcanism and structural relations of the region, Duffield (1975) has suggested that all of the volcanic rocks are encompassed by an oval-shaped zone of late Cenozoic ring faulting that has dimensions of about 45 km east-west and 35 km north-south defining a structural basin (Fig. 2). The ring structure and associated young volcanic rocks imply a caldera-like feature caused by uplift and fracture accompanied by extrusions and surficial subsidence—in other words, a large underlying magma chamber that appears to have periodically erupted lava to the surface during the past few million years and to have resulted in the present geothermal phenomena.

Fumaroles and hot springs are situated at scattered locations throughout the Coso geothermal area. Although the geothermal activity in the form of fumarolic and hot springs activity has been known for many years (Frazer, Wilson, and Hendry, 1943), the geothermal manifestations were not studied in detail until the late 1960's (Austin and Pringle, 1970). A combination of field geological reconnaissance, photogeology, theoretical petrology, gravity and magnetometer measurements, and mineralogical investigations culminated in 1967 with the drilling of the Coso No. 1 drill hole into the thermally active Coso fault zone adjacent to the Coso Hot Springs (Austin and Pringle, 1970). The hole was drilled to 114 m and has a maximum temperature of 142°C.

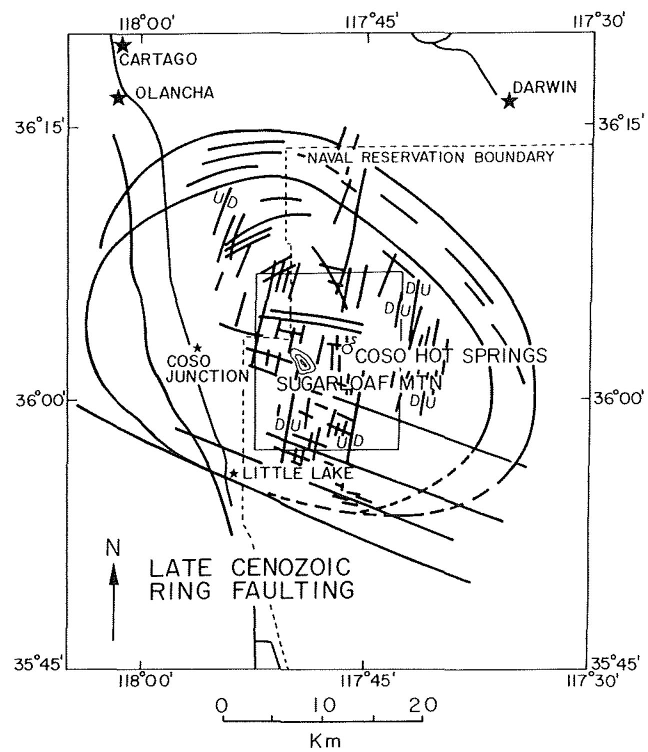

Figure 2. Sketch map of the faults in the Coso geothermal area (modified from Duffield, 1975). Inner rectangle denotes extent of present study area.

Several surface and airborne geophysical techniques have been used in order to detect and to initially determine the potential and extent of any geothermal systems in the Coso

Hot Springs area. Koenig, Gawarecki, and Austin (1972) noted that color photography and snowmelt patterns (White, 1969) were of greatest utility in locating areas of presently active thermal fluid leakage. Infrared imagery appeared to be of value in delineating the arcuate structural patterns associated with the geothermal deposits (Koenig, Gawarecki, and Austin, 1972).

A detailed geothermal seismic noise survey was completed by Teledyne Geotech (1972). The results of the noise survey of the Coso geothermal area clearly show the presence of high noise levels with three separate high-frequency anomalies (Fig. 3). The largest of these anomalies with the highest amplitude is associated with the Coso Hot Springs. Of the two other anomalies, one is close to the fumarolic area known as Devil's Kitchen, while the third is not connected with known surface activity. These data imply a correlation between geothermal phenomena and high seismic noise level.

The geothermal noise survey was followed by a total field dc resistivity investigation (Furgerson, 1973). The granitic host rock has an apparent resistivity of 200 ohm·m or more, whereas the surface thermal manifestations appear to have resistivities below 50 ohm·m (Fig. 4). Thus, from the results of the roving dipole technique there seems to be a contrast in apparent resistivities by a factor of about 10 between the normal and the geothermally effected regions. The dipole maps may be used in locating or extending some of the faults or fractures which appear to control at least the surface geothermal activity and probably the deeper plumbing of the presumed geothermal reservoir.

The Coso geothermal area is tectonically active, manifested in frequent earthquakes, as indicated by the pattern of regional seismicity shown in Figure 5. Epicenters from the California Institute of Technology seismograph network for the period 1953 to 1972 are plotted in Figure 5 (Hileman, Allen, and Nordquist, 1973). These earthquakes are of magnitude 3 or greater. Events appear to occur outside

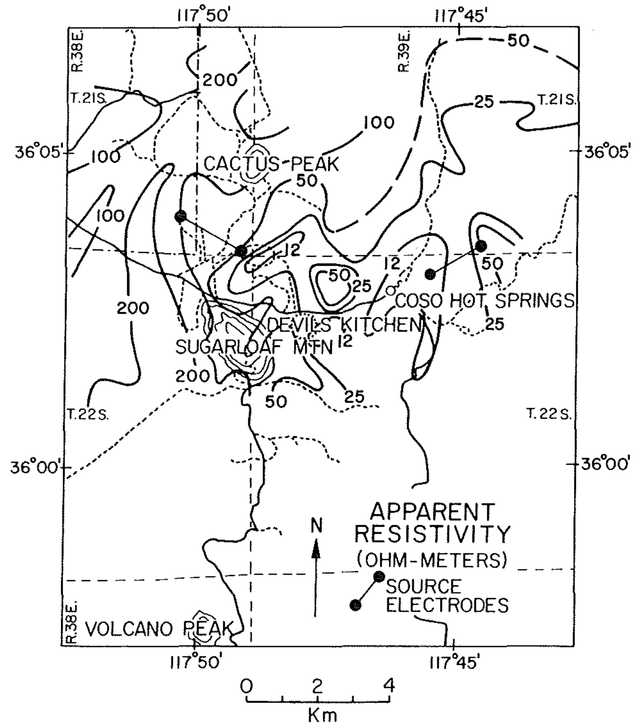

Figure 4. Total field apparent resistivity map of the Coso geothermal area. The minimum apparent resistivity in ohm·m for the two source dipoles is contoured (modified from Fig. 21, Furgerson, 1973).

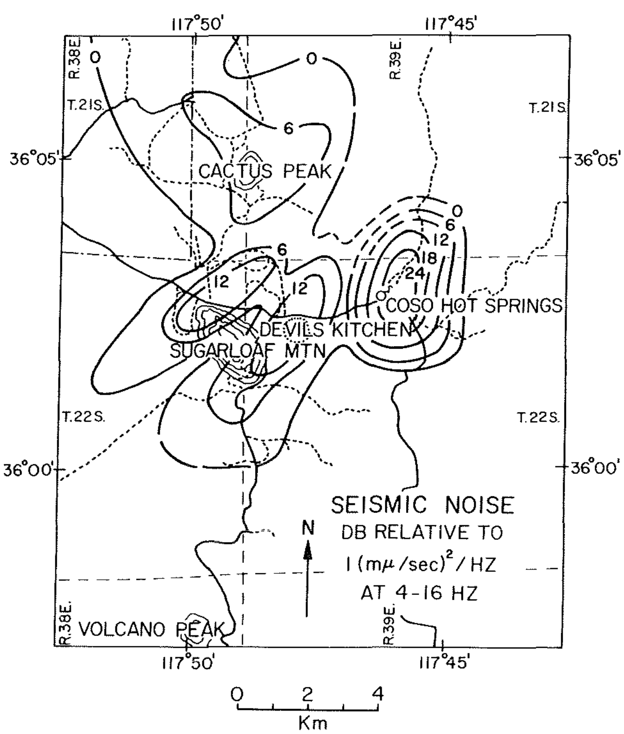

Figure 3. Seismic ground noise map of the Coso geothermal area. Contours are given in decibels relative to 1 $(m\mu/sec)^2/Hz$ in the passband of 4 to 16 Hz (modified from Teledyne Geotech, 1972).

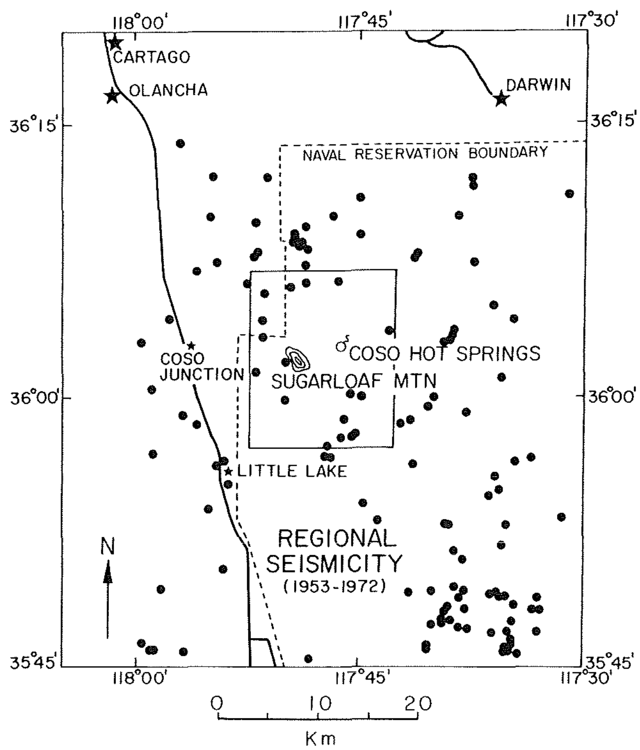

Figure 5. Regional seismicity as indicated by the epicenters for earthquakes of magnitude ≥3, located by the California Institute of Technology Seismological Network, 1953–1972 (modified from Hileman, Allen, and Nordquist, 1973).

of the immediate area of the geothermal activity, as may be noted in the area demarcated by a rectangle in Figure 5.

INSTRUMENTATION AND FIELD PROCEDURE

An array of six Kinemetrics PS-1 portable vertical-component high-grain seismographs (Prothero and Brune, 1971) was established in the Coso geothermal area. Several internal filters provided with the seismographs can be used to shape the system response. Filter 1, peaked at 1 Hz, produced easily discernible first motions, although it probably reduced the number of small local microearthquakes that were recorded since the high-frequency waves from these events are mostly filtered out. Higher resolution of events and well-defined S-P interval times were obtained by using Filter 4 peaked at 20 Hz, which is the predominant frequency for very near microearthquakes. Gain was controlled by attenuating the maximum system sensitivity in 6-dB steps. Stations operated on Filter 4 were attenuated from 24 to 36 dB, whereas the same stations could be operated on Filter 1 with about 12 dB less attenuation. Recording was accomplished at 1 mm/sec with smoked-paper drum recorders.

Kinemetrics Ranger seismometers with a natural frequency of 1 Hz were used. The average generator constant for these seismometers was 100 V-sec/m. External resistors damped the system at 0.7 critical. Timing for the recording units was provided by a temperature-compensated, crystal-controlled unit with an accuracy of ±0.3 ppm over the temperature range of 0 to 50°C. Timing was reestablished daily at each station by superimposing the National Bureau of Standards' WWV radio time code with the internal clock-markings on each record. The drum speed and accurate timing permitted P-arrivals to be picked to 0.1 sec. Without horizontal instruments, S-phases could not be clearly distinguished from multiple crustal P-phases and therefore were not used in hypocentral locations.

Five of these smoked-paper drum recorders were installed on June 13 and 14 while a sixth was installed on June 20, 1974. All of these recorders were picked up on the 25th of June, 1974. Out of the twelve days of recording, ten included information which was sufficient to determine the initial character of the microearthquake activity in the area.

During the period July 5 to July 27, 1974, nine custom-made, three-component, high-gain magnetic tape-recorder type seismographs were installed in the area. Six of these instruments were placed at the locations occupied by the original smoked-paper seismographs. Each system consisted of three Texas Instruments seismometers to measure the vertical and two orthogonal horizontal components of ground motion, and a magnetic tape recording unit. The seismometers were critically damped, and resonant frequencies were 2 Hz for the vertical instrument and 2.5 Hz for the horizontal instruments. Each seismometer was equipped with a preamplifier with a flat gain response of 400 between the 0.5 Hz to 40 Hz pass band. Input noise was less than 0.5 μV in the pass band of 2 to 20 Hz.

The recording units were built at The University of Texas at Dallas. Each unit recorded six channels in analog format on standard 8.9 cm or 12.7 cm reels of magnetic tape via a Norton Industries tape head. The outer two channels record coded time signals from an internal digital clock. This is done to insure that a timing signal is recorded, and to correct for timing errors due to tape skewness. The internal clocks were accurate to about 0.1 ppm, or one second per month. One of the four inner channels was used to record a time segment from radio WWV and a portable traveling clock at the beginning and end of each tape. This established an absolute time base and allowed for correction of internal clock drift. The remaining three channels were used for recording the seismic signals from the three seismometers.

The seismic amplifiers in the recording units have a continuously variable gain from 1 to 100. Gain was set at the recording site so that the peak-to-peak ground noise was approximately 1 mV. The amplified seismic signal is mixed with an 800 Hz bias signal with amplitude set at 1.2 V.

We recorded for 23 days and obtained usable data from eight of these three-component magnetic tape units. The important differences between the two types of seismographs are (1) three-component (one vertical and two horizontal) versus a single component (vertical) installation; and (2) the magnetic tape recorders versus the smoked-paper drum recorders. The three components provided for excellent resolution in the picking of the S-wave arrivals and, consequently, the S-P time intervals. The magnetic tape enabled us to play back the records at different speeds to provide for more distinct P- and S-wave arrivals.

RESULTS AND INTERPRETATION

We have conducted both active and passive field work in the area. From these studies we wanted to determine the background level of seismicity associated with the Coso geothermal area prior to the onset of potential effects caused by future production and reinjection of fluids into presumed geothermal reservoirs. In addition, from the microearthquake activity and precise hypocentral estimates, it is possible to determine any active fault zones in the area which may be functioning as subsurface conduits. Finally, the present microearthquake survey will be used to speculate on the subsurface physical characteristics of the Coso geothermal system.

The microearthquake activity changed considerably over these periods of recording, including some days which had only a few events while others included as many as 100 or more distinct local events per day. In order to quantify the seismicity of the Coso geothermal area, we counted events with S-P times of less than 3 sec for the station near Cactus Peak (Station No. 2 in Fig. 6). Intermittent high noise during the local daytime made event counting less certain; therefore, we have plotted only the number of events per day for the 12-hour period between 2100 and 1900 local time (Fig. 7). Strain release in the Coso geothermal area seems to occur primarily in swarm-type sequences as can be noted by the continuous occurrence of microearthquakes, whereas earthquakes outside the area occur primarily as mainshock-aftershock sequences. The area is definitely undergoing current tectonism.

During laboratory studies of microfracturing, Mogi (1963) and Scholz (1968) noted that stress inhomogeneities, related to either inhomogeneous materials or concentrated sources, are correlated with high *b* values and with swarm-like sequences. Thus, earthquake swarms associated with geothermal areas may be indicative of magmatic activity in progress. That is, swarms may reflect either magmatic activity that does not reach the ground surface as volcanic eruptions, or hydrothermal processes that trigger tectonic strain release.

Rinehart (1972) has suggested that deformational strain generated by earth-tidal forces in geyser basins could be expected to influence heat-flow variation resulting in crack and fissure dilatation allowing convective geothermal fluids to permeate the surrounding material. This mechanism could account for the formation of steam and increased water temperature in the subsurface that would in turn decrease the effective stress enough to allow fractures and to produce small earthquakes.

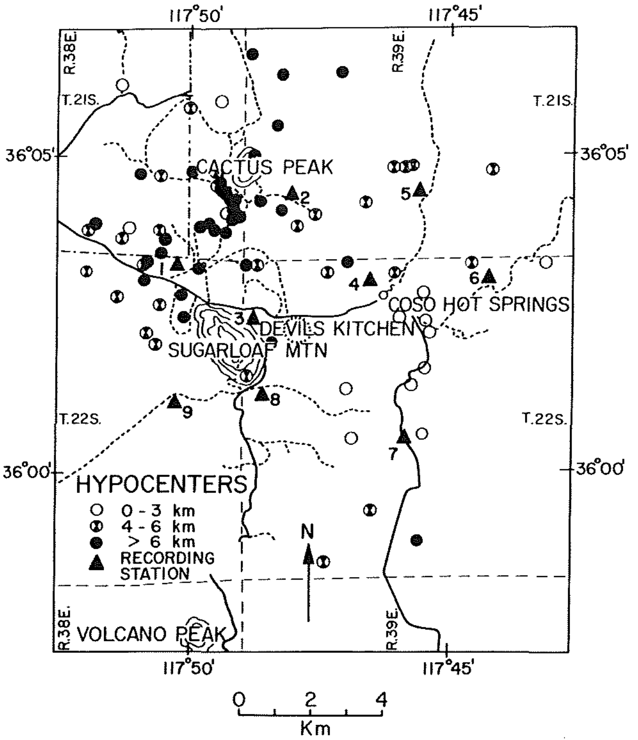

Figure 6. Epicenters of 78 microearthquakes associated with the Coso geothermal area.

To provide a more realistic subsurface velocity model and to aid in the determination of the accuracy of the microearthquake hypocenters, calibration shots provided by personnel of the Naval Weapons Center were analyzed. The shots were located within 250 m. The resulting time-distance plot (Fig. 8) indicates an essentially constant P-wave velocity of 4.75 km/sec, which is in excellent agreement with the seismic refraction studies of Zbur (1963) in the Indian Wells Valley immediately to the south. From a combination of our data, the refraction data of Zbur (1963), and the crustal model of Prodhel (unpub. data) derived from a reversed refraction profile from China Lake to Mono Lake, we obtained a crustal model which consists of a 5.0-km thick layer with a velocity of 4.75 km/sec overlying a half-space of 6.0 km/sec. On many of the seismograms, the S-arrival is impulsive and clear while the P-arrival is emergent. The background noise is more pronounced in the spectral band of P-waves compared to that for S-waves. Therefore, it is advantageous to be able to use the S-phase with some confidence as to its velocity of propagation. The S-velocity can be obtained from the P-velocity through the well-known Wadati diagram (Kisslinger and Engdahl, 1973). Wadati diagrams (S-P times plotted against P-arrival times) were originally drawn to find Poisson's ratio for rocks under

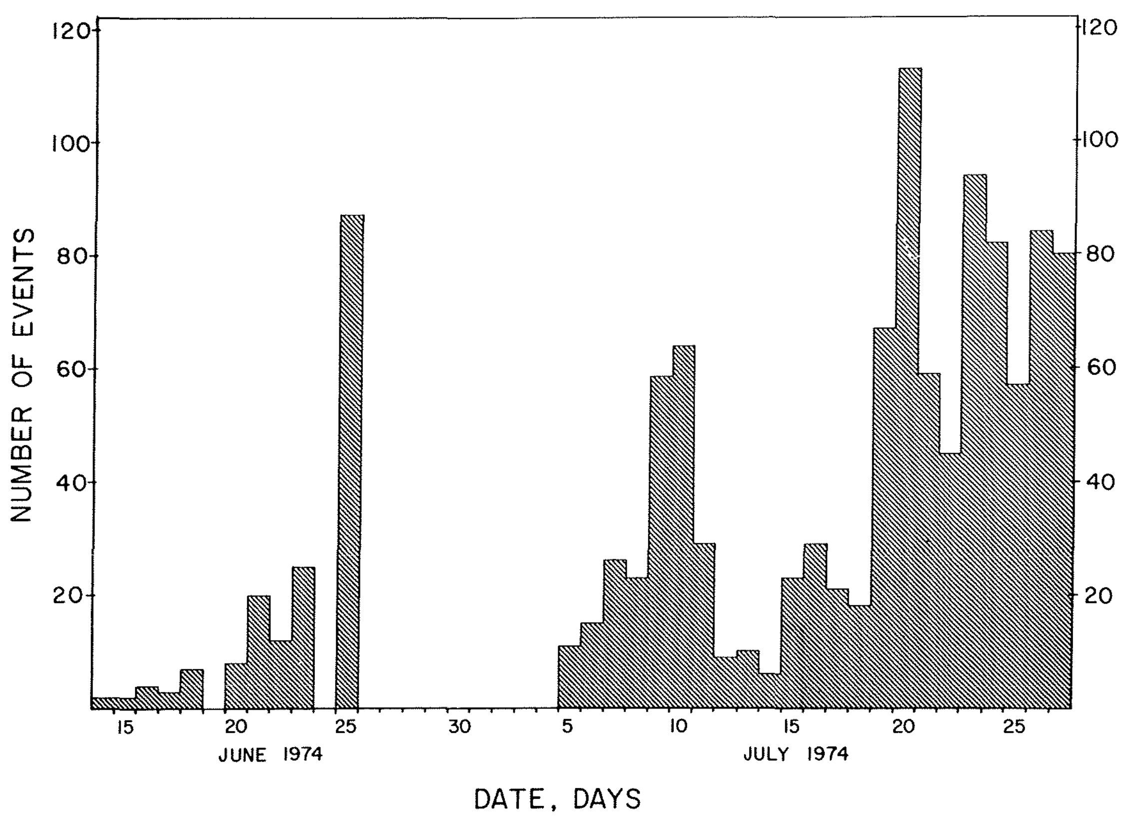

Figure 7. Seismicity of the Coso geothermal area. Number of events with S-P times of less than 3 sec for station No. 2 near Cactus Peak for the 12-hour period between 2100 and 0900 local time.

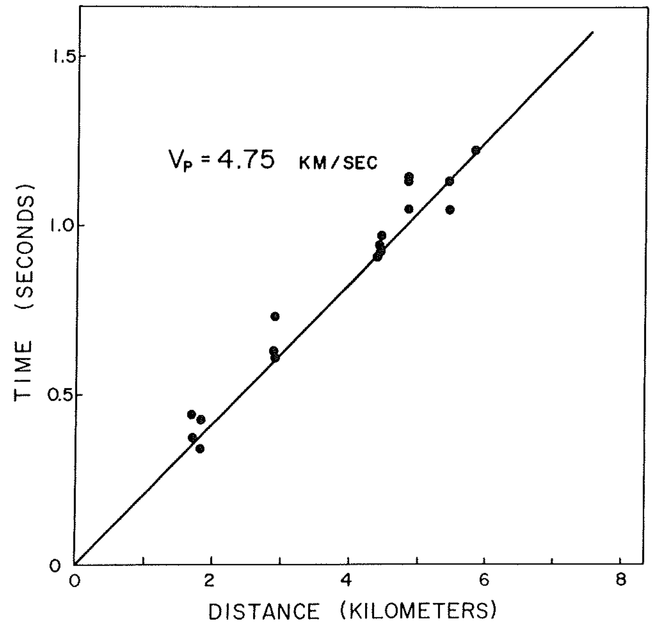

Figure 8. Time-distance curve for calibration blasts.

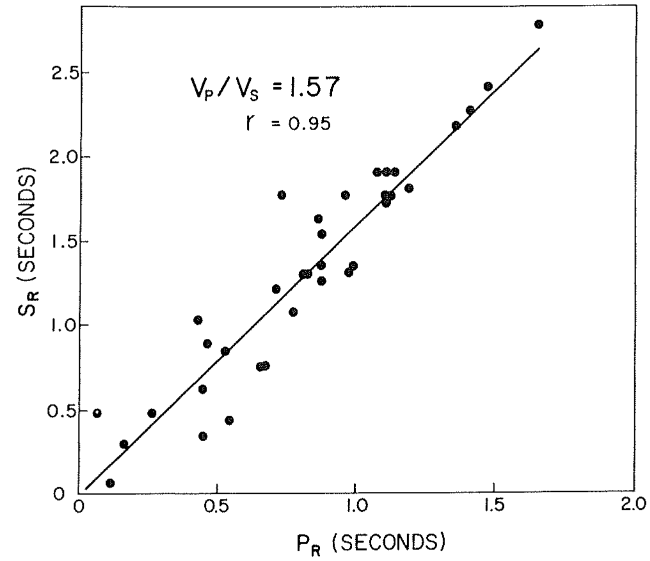

Figure 9. Reduced Wadati diagram. All values of S-arrival time and P-arrival time for several events are reduced to one station and plotted as reduced S-arrival time, S_R, versus reduced P-arrival times, P_R.

stress. The graph was then extrapolated to an S-P time of zero which yields the earthquake origin time.

In equation form, we have for the Wadati diagram,

$$S\text{-}P = (P\text{-}O)(K\text{-}1) \tag{1}$$

where

S = S-wave arrival time
P = P-wave arrival time
O = Origin time

and

$$K = V_P/V_S$$

where

V_P = P-wave velocity
V_S = S-wave velocity

Note that S-P time plotted against P-wave arrival time yields a straight line with a slope K-1. Normally, in the construction of a Wadati diagram, the data from one event recorded at many stations are used. By expanding equation (1), we obtain an equation of the form

$$S = PK - O(K\text{-}1) \tag{2}$$

In this form, where S-arrival time is plotted against P-wave arrival, if we drop the second term, we get the reduced Wadati diagram. For the reduced Wadati diagram, all of the values of S-arrival time and P-arrival time for several events are reduced to one station. We have plotted reduced S-arrival time, S_R, versus reduced P-arrival time, P_R, for a number of events (Fig. 9). From a least squares linear regression analysis, we obtain a slope of 1.57. The ratio of V_P to V_S is therefore equal to 1.57 compared to values of 1.73 to 1.87 which are usually obtained in laboratory and field investigations. Using the P-wave velocity of 4.75 km/sec determined from the calibration blasts, we obtained an S-wave velocity of 3.30 km/sec. These velocities infer a Poisson's ratio of 0.16 compared with values 0.25 to 0.30 which are normally observed.

In a series of carefully performed laboratory experiments, Nur and Simmons (1969) have observed the effect of saturation on seismic velocity in low-porosity rocks. They found that fluid saturation greatly influences the effective bulk modulus of rocks while the shear modulus is almost independent of fluid inclusions. In other words, the shear-wave velocity is almost unchanged when the air in cracks is replaced by water, whereas the compressional wave velocity may increase by as much as 40% for rocks with porosities of less than 0.01. Furthermore, Nur and Simmons (1969) noted that dry rocks exhibit very low values of Poisson's ratio ($<$0.20) while saturated rocks exhibit normal to high values ($\geq$0.25).

The low value for Poisson's ratio observed for the Coso geothermal area indicates that the shallow subsurface is either deficient in liquid water saturation or more likely that the void spaces (cracks) are filled with steam. These results imply that the Coso geothermal system is a vapor-dominated system rather than a hot-water system.

Using all of the above-mentioned data in a program written by Lee and Lahr (1972), we have located 78 microearthquakes ranging in magnitude from −1.0 to 2.5 out of the hundreds which were recorded (Fig. 6). These 78 microearthquakes include events obtained on both seismograph systems as well as events occurring throughout the total recording interval. Most of the seismic activity occurred between the two young volcanoes, Cactus Peak (97 000 yrs; Lanphere, Dalrymple, and Smith, 1975) and Sugarloaf Mountain (40 000 yrs; Lanphere, Dalrymple, and Smith, 1975), although all surface manifestations are observed around Coso Hot Springs and to the east of Devil's Kitchen. The position of the epicenters with respect to the thermal manifestations should be noted. Events clustered around the Coso Hot Springs and extending to the south are all shallow with focal depths between 1 and 3 km. Focal depths increase from the Coso Hot Springs area toward the west and northwest. Most of the events were located in the western portion of the Coso geothermal area near the zone of volcanic manifestations, that is, near the perlite domes. These events are usually deeper, ranging from 5 to 10 km. There appears to be a positive correlation between areas of high seismic noise (Fig. 3) and areas of microearthquake activity (Fig. 6), as well as an inverse correlation between the focal depth and the amplitude of the noise.

We have obtained a fault-plane solution for the shallow events in the Coso Hot Springs area and those to the south (Fig. 6). The resulting focal mechanism clearly indicates a right-lateral strike-slip fault which has a north-south strike (Fig. 10). Although a unique choice of the fault plane cannot be made from the first motion data, the north-striking plane was chosen due to the alignment of the epicenters.

Finally, microearthquakes clustering around the Cactus Peak area (Fig. 6) were examined in an effort to compare the relative attenuation of events arriving at the seismograph sites along different ray paths (Walsh, 1969). Ray paths between Cactus Peak and seismograph sites Nos. 3, 8, and 7 pass through an anomalously high-temperature, shallow crustal zone, whereas they do not from Cactus Peak to site No. 5 (Combs, unpub. data).

Since P- and S-residuals from well-located microearthquakes usually range from −0.02 to 0.02 sec, anomalous ones are easy to pick. At seismograph station No. 7, the P-arrivals for eight events studied arrived slightly early, while the S-phase was quite late. Site No. 7 is at least 10 km from the hypocentral region for the Cactus Peak events. Ray paths may pass through regions with quite different ratios of V_P to V_S which would explain the P- and S-residuals.

The S-phases are attenuated at sites Nos. 3, 8, and 7, indicating that the elastic waves have passed through a high-temperature, shallow crustal zone (Solomon, 1973). Similar phenomena are not apparent on records obtained at seismograph site No. 5. All of these characteristics indicate a local geologic body with properties different from those

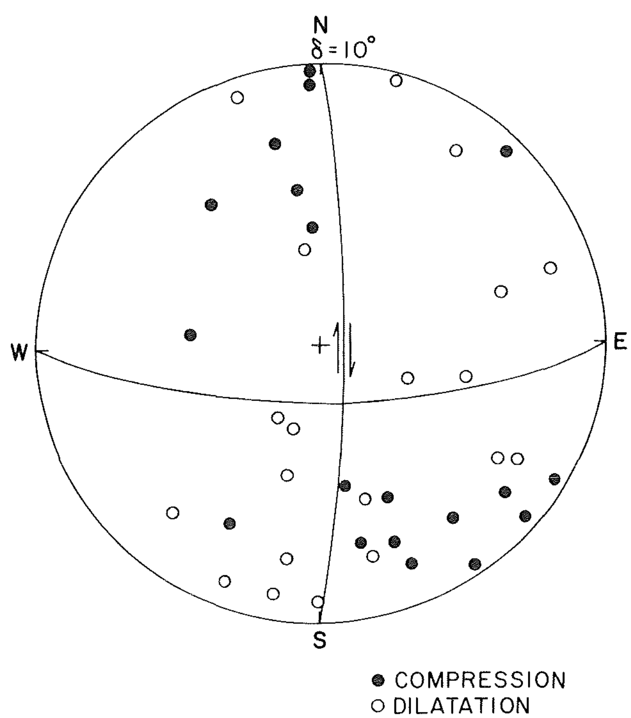

Figure 10. Lower hemisphere equal-area plot of data for fault plane solution of shallow events near Coso Hot Springs.

of its surroundings. These anomalous seismic phenomena substantiate the high heat flow data obtained (Combs, unpub. data).

In conclusion, whatever new data future geophysical work provides, the existence of the large, late-Cenozoic ring structure centered around the active fumaroles and areas of Pleistocene volcanism defined by Duffield (1975), as well as our microearthquake studies, provides a much larger target for geothermal exploration than suggested by the distribution of the young volcanic rocks.

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