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MICROEARTHQUAKE INVESTIGATION OF THE MESA GEOTHERMAL ANOMALY

IMPERIAL VALLEY, CALIFORNIA

by

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Final Report
June, 1974
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ABSTRACT

Microearthquakes associated with the Mesa Geothermal Anomaly, were recorded for five weeks during the summer of 1973, using an array of six portable, high-gain seismographs equipped with vertical-component 1-sec natural period seismometers. Background seismicity of the area is thus determined prior to development for geothermal power and water. The seismicity changed considerably over the period of recording. Most daily activity is characterized by only one or two locatable events, while two microearthquake swarms of two and three day duration, included as many as one hundred or more distinct local events per day.

Hundreds of small events--some clustered in swarms, were recorded by each seismograph; however, most were not obtained on at least four or more seismographs so that an exact hypocenter location could not be determined. Locations were determined for 36 microearthquakes having epicenters situated in the 150 sq km areal extent of the anomaly. Focal depths ranged from near surface to about 10 km. More than half of the located events have hypocenters greater than the 3.5 km which is approximately the depth to crystalline basement.

A new right-lateral strike-slip fault, the Mesa Fault, was defined based on the results of the present study. The northwest-southeast trending Mesa Fault is an active fault functioning as a conduit for rising geothermal fluids of the Mesa Geothermal Anomaly. This investigation is another demonstration that geothermal areas are characterized by high microearthquake activity. Stress, associated with these geothermal anomalies, is relieved by a combination of continuous seismic activity and intermittent microearthquake swarms.

INTRODUCTION

The Imperial Valley of Southern California (Fig. 1) is an area of considerable interest for the exploration and development of geothermal resources. Geothermal anomalies in the valley have been investigated by a variety of geophysical techniques. A fundamental characteristic of most geothermal resource areas is close association with regions of high geological activity manifested most commonly as microearthquakes (Westphal and Lange, 1962; Brune and Allen, 1967; Lange and Westphal, 1969; Ward, Palmason and Drake, 1969; Ward and Bjornsson, 1971; Ward and Jacob, 1971; Hamilton and Muffler, 1972; Ward, 1972). Occurrence of microearthquakes indicates that shear stress has exceeded rock strength at the point of rupture. Earthquakes usually occur along existing zones of weakness and not in areas of previously unbroken rock. Good correlation has been found between zones of rupture and mapped faults where earthquake locations have been determined accurately and in sufficient number to define a pattern. Consequently, seismically active faults can be mapped in three dimensions using microearthquakes. Since active faults channel hot water from the vicinity of deep heat sources to shallow depths, information on active faults is important for geothermal exploration and production.

Studies have shown that faults may vary their normal patterns of earthquake activity if fluid pressures are changed in regions of tectonic stresses. In particular, evidence has accumulated recently showing that shallow earthquakes can be triggered by increases in fluid pressure induced by man. This phenomenon was first observed near Denver, Colorado, when Evans (1966) accidentally noted a correspondence between injection of chemical waste material into a deep

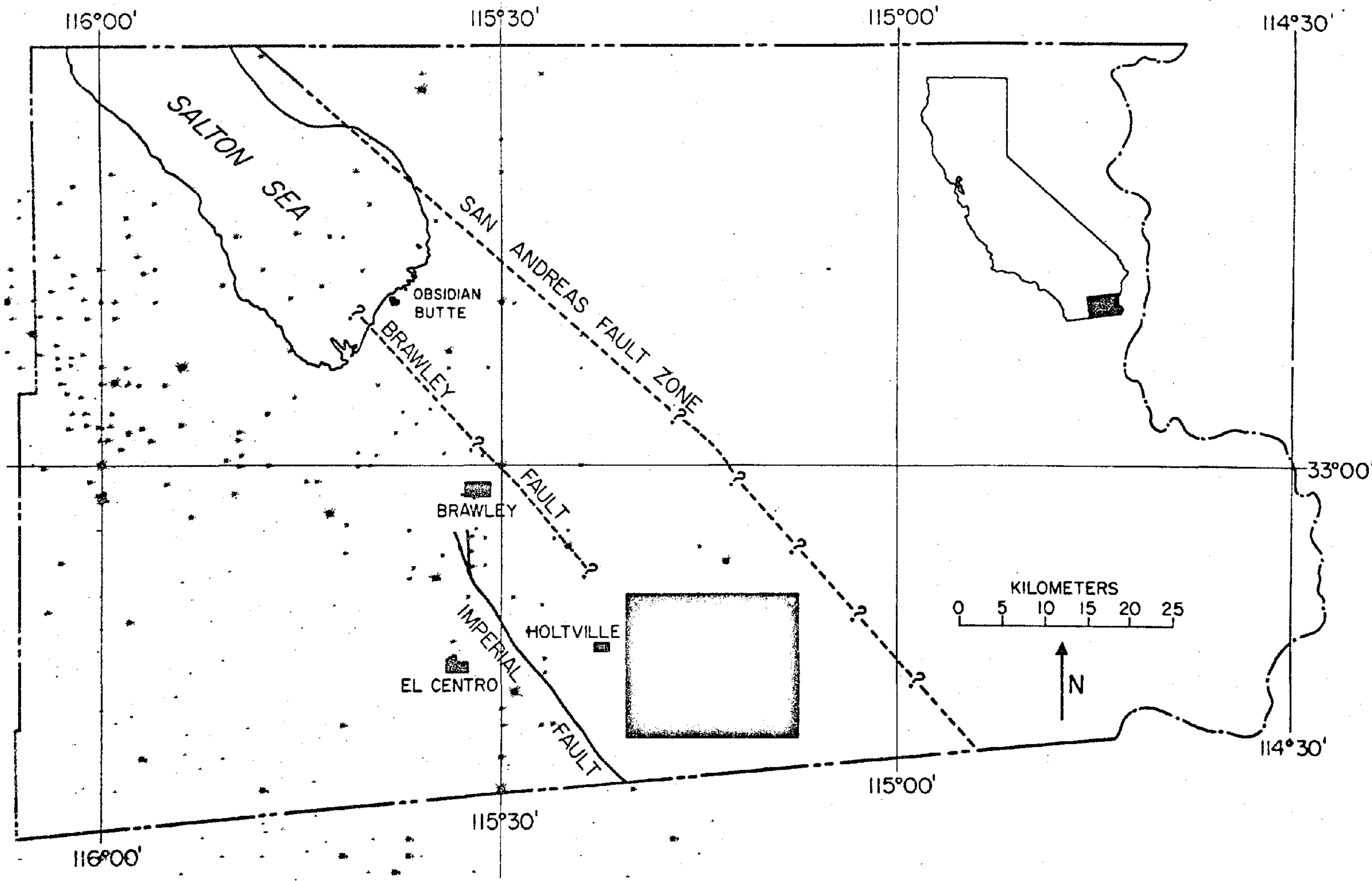


Figure 1. Location map of Imperial Valley, Southern California. Stippled rectangle depicts area of the microearthquake investigation including the Mesa Geothermal Anomaly. Star-shaped symbols represent earthquake epicenters from the CIT seismograph network for 1961 to 1971. Size of the symbol denotes number of events.

disposal well and the level of earthquake activity in the Denver area. The time-space correlation of seismic activity, compared with the location and rates of injection into this disposal well, clearly demonstrated a causative relation between the earthquakes and fluid injection at this site (Healy, et al., 1968).

The effect of fluid pressure on rock strength to explain large thrust faults was first proposed by Hubbert and Rubey (1959). The physics of their observations is simple. The frictional forces that resist sliding along a fault plane are proportional to a coefficient of friction and the normal stress acting across the fault plane. Fluid pressure reduces this normal stress and therefore weakens the rock. These observations have lead directly to the conclusions that changes in fluid pressure may control the timing of seismic activity, and the possibility that a change in subsurface fluid pressure caused by reinjection of geothermal fluids, could lead to a change in seismic activity associated with a geothermal field.

In order to assess the effects of variations in fluid pressures, monitoring stations to gather seismic data should be established in geothermal areas prior to the onset of the potential effects purportedly caused by production or reinjection. That is, seismic monitoring stations should be established near productive geothermal areas to determine if patterns emerge that appear to be related to the removal of fluids from geothermal reservoirs, or the reinjection of fluids into these geothermal reservoirs.

The object of the present study was to detect and accurately locate discrete seismic events (microearthquakes and nanoearthquakes) associated with the

Mesa Geothermal Anomaly. In other words, in order to delineate any seismically active faults and to characterize the background seismicity of the area in advance of withdrawing fluids from, or injection of fluids into, the potential geothermal reservoir, the Mesa Geothermal Anomaly was monitored. Microearthquakes associated with the area were recorded for five weeks during the summer of 1973, using an array of six portable, vertical-component seismographs. Hundreds of small events (nanoearthquakes) were recorded by each recording system; however, most events were not obtained on at least four or more seismographs so that an exact hypocenter location could not be determined. Locations were determined for 36 events having epicenters situated in the areal extent of the anomaly.

The seismicity changed considerably over the period of recording. The activity of most days was characterized by only one or two locatable events per day, while two microearthquake swarms of two and three day duration included as many as one hundred or more distinct local events per day.

With the completion of each new microearthquake study, there is a more obvious correlation between earthquake swarms and subsurface thermal features, i.e., geothermal activity. A causal relationship between swarms and magmatic, volcanic, or hydrothermal activity still remains unresolved. However, by finding these microearthquake swarms, an efficient method of detecting ongoing volcanic, hydrothermal, and/or magmatic processes in potentially valuable geothermal areas may eventually be developed.

GENERAL GEOLOGY AND REGIONAL STRUCTURE

The Imperial Valley of Southern California (Fig. 1) is an extensive sedimentary basin characterized by high heat flow. The geology of the Imperial

Valley, which is part of a structural depression known as the Salton Trough that extends from the Gulf of California, has been described by Dibblee (1954). Several other geological investigations deal with specific areas and problems of the area. Much of the geological work has been summarized in the California Division of Mines and Geology 1:250,000 scale geological map sheets - Santa Ana, Salton Sea, and San Diego/El Centro.

The Salton Trough is delimited by a framework of mountains consisting of Mesozoic and older granitic and metamorphic rocks. The late Tertiary and Quaternary sediments filling the depression include predominately unconsolidated sand, silt, and clay with some gravel. The accumulated thickness is estimated to be as much as 6 km based upon seismic refraction data of Biehler, et al., (1964). Furthermore, the sediments are saturated to within a few meters of the land surface, and therefore, constitute a considerable reservoir of subsurface water.

The structure of the Imperial Valley is controlled by numerous strike-slip faults of the San Andreas-San Jacinto fault system (Dibblee, 1954; Biehler, et al., 1964) on which considerable right slip has occurred (Sharp, 1967). Some of the faults have been active in historic times (Richter, 1958; Allen, et al., 1965; Brune and Allen, 1968).

The Imperial Valley appears to contain one or more centers of either spreading or crustal extension (Lomnitz, et al., 1970; Elders, et al., 1973). These centers are bounded by strike-slip faults (Hamilton, 1961). It is important to ascertain if the earthquake swarms in the Imperial Valley are located along centers of rifting, and not along strike-slip faults similar to the relation found by Sykes (1970) for some 20 earthquake swarms detected from the mid-Atlantic ridge and from other parts of the mid-ocean ridge system.

The Mesa Geothermal Anomaly is on the east flank of the Salton Trough. Seismic refraction profiling indicates that basement at depth is at least 3.5 km (Kovach, et al., 1962). Based on the results of the present study, a new right-lateral strike-slip fault, the Mesa Fault, was defined. The Mesa Fault is an active fault functioning as a conduit for rising geothermal fluids of the Mesa Geothermal Anomaly.

Two wildcat oil wells were drilled to depths of 2.44 and 3.24 km in the immediate area. Both wells penetrated predominantly deltaic sediments and neither well reached basement. Electric logs from these wells indicate interbedded sand and clay, with minor silt beds. Two geothermal wells, USBR Mesa #6-1 and USBR Mesa #6-2, drilled on the Mesa Geothermal Anomaly, indicate the same subsurface geology with the upper stratigraphic sequence consisting of more than 50% clay which functions as a cap rock for the geothermal reservoir.

PREVIOUS INVESTIGATIONS

Three stations in the microearthquake survey (0<M<3) of Southern California conducted by Brune and Allen (1967), were located within the Imperial Valley. At Obsidian Butte during the first two day period of operation, a rate of 128 earthquakes per day was obtained; however, later occupation of the site for a period of five days indicated an average rate of about 32 per day. Brune and Allen (1967) postulated that, although Obsidian Butte is a Quaternary volcanic plug associated with marked local thermal anomalies, the distribution of microearthquakes represents the regional stress system associated with the San Jacinto Fault, and is not solely the result of localized volcanic or thermal activity at depth.

Two other stations, Painted Canyon and East Mesa, both located on the extension of the San Andreas Fault, detected no events with S-P time intervals less than 3 seconds during two-day recording intervals. The East Mesa station of Brune and Allen (1967), located at 33° 00.4'N and 115° 18.0'W, was only 20 km north of the present Mesa Geothermal Anomaly array.

During the summer of 1971, the U. S. Geological Survey monitored for three weeks in the East Mesa Area, including the region covered by the present array. They did not detect any microearthquakes within their seismic network, and it was suggested that perhaps a longer recording period would have some success, since microearthquake activity is often sporadic (R. M. Hamilton, personal communication, 1971).

The California Institute of Technology (CIT) catalog, of earthquakes in Southern California from 1932 through 1972, shows a dense pattern of magnitude 3 or greater earthquakes within the Imperial Valley (Hileman, et al., 1973). Epicenters from the CIT seismograph network for the period 1961 to 1971, are superimposed on the location map of the Imperial Valley (Fig. 1). Note that during the ten year period, three microearthquakes of magnitude greater than 3.0 occurred in the area of the Mesa Geothermal Anomaly.

In April 1973, a 16-station seismograph network was installed in the Imperial Valley to improve the resolution of earthquake locations since this region has high tectonic activity and known geothermal resources (D. P. Hill, personal communication, 1973). This network is part of a cooperative effort between CIT and the USGS. Data from the network were used in this study.

Richter (1958) first discussed the occurrence of swarm sequences in the Imperial Valley. During a seismic investigation of an oceanic ridge earthquake swarm in the Gulf of California, Thatcher and Brune (1971) summarized four swarm sequences. These swarms occurred in 1963, 1965, 1968, and 1969 in the Obsidian Buttes area near the south end of the Salton Sea. Two swarms were recorded during the present investigation.

INSTRUMENTATION

The microseismic array consisted of six stations. Each station was equipped with a portable, vertical-component, high-gain Kinemetrics PS-1 seismograph which has been described in detail by Prothero and Brune (1971). Several internal filters provided with the seismographs, can be used to shape the system response (Fig. 2). 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 ink systems. A representative one-day record, using filter 4, is presented in Figure 3.

Kinemetrics Ranger SS-1 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

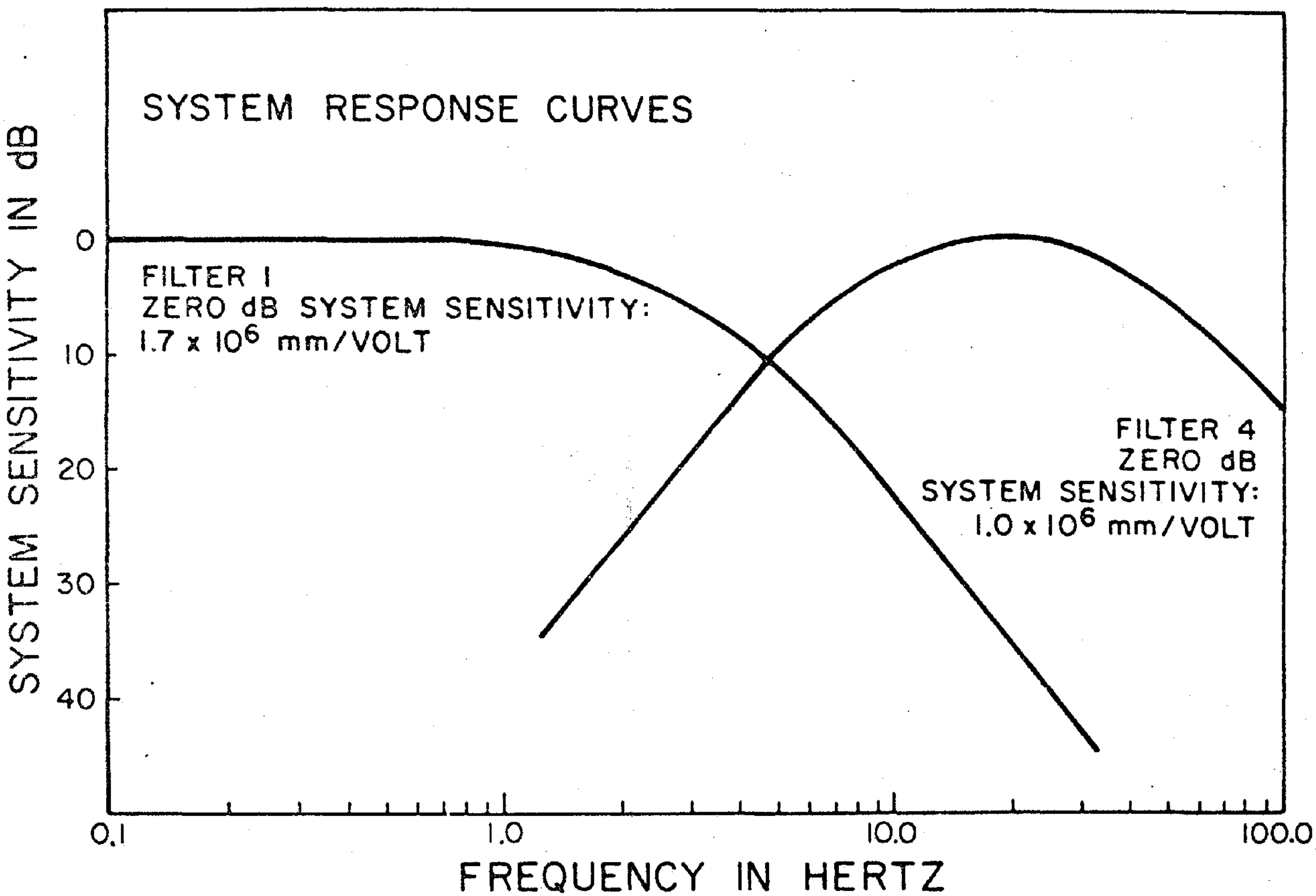


Figure 2. Response curves for microseismic recording systems used in present study.

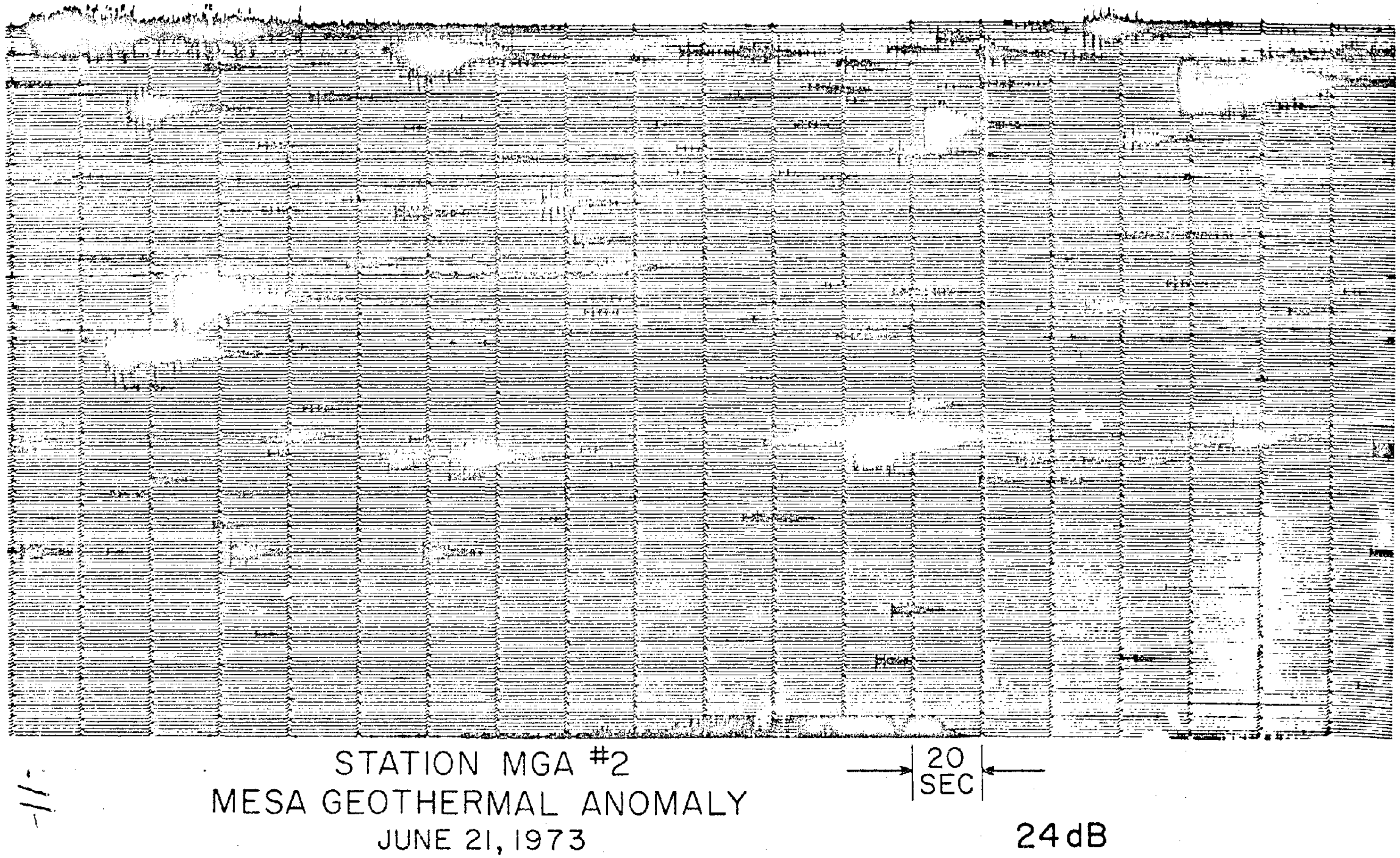


Figure 3. Representative one-day record with seismic recording system peaked at 20 Hz. Recording was done at 60 mm/min.

of 0°C to 50°C. Each recording site was visited daily, and a 60-kHz time code receiver was used to re-establish and coordinate time on the stations using the National Bureau of Standards WWV broadcast system. Timing accuracy is better than 0.05 sec. The drum speed and accurate timing permitted P arrivals to be picked to 0.1 sec. S arrivals could not be picked with similar accuracy, and therefore were not used in the location of events.

HYPOCENTER LOCATIONS AND CRUSTAL MODEL

Microearthquakes located during this study were recorded by the array of six stations described in Table 1. Hypocenter locations were determined using a stepwise multiple regression computer program (Lee and Lahr, 1972). A series of iterations is performed, with adjustments in the trial hypocenter location, until the root mean square (RMS) error in travel time is minimized, or the specified number of iterations is exceeded. Greater than 80% of the located events have RMS residual travel times less than 0.1 sec and 90% have less than 0.2 sec. The quality of the location for events outside the array, is not as good as for those within, as the error increases with distance.

To provide a velocity model for the shallow subsurface portions of the Mesa Geothermal Anomaly, a calibration blast of 180 kg of high velocity seismic gel was exploded. The results of the refraction profile are shown in Figure 4. Location of the shot point is plotted in Figure 5. The near-surface refraction line was directly west of, and extended from, the shot point.

The crustal structure shown in Figure 4, and detailed in Table 2, is an average for the entire area, and does not correspond to the actual crustal structure which is more complicated. For example, small velocity reversals with depths were found on sonic logs for the American Petrofina Salton Trough

TABLE 1. STATION LOCATIONS AND STATION TRAVEL TIME CORRECTIONS

Station*	Latitude (N)	Longitude (W)	Elevation (meters)	Station Delay (seconds)	Average Attenuation Filter 4 (db)
MGA #1	32° 49.79'	115° 09.73'	11	0.13	24
MGA #2	32° 51.25'	115° 12.69'	19	0.05	24
MGA #3	32° 48.62'	115° 15.72'	11	0.03	30
MGA #4	32° 46.89'	115° 11.65'	23	0.0	30
MGA #5	32° 44.72'	115° 07.53'	35	0.0	36
MGA #6	32° 44.31'	115° 14.75'	14	-0.21	36

* All microearthquake stations were located in Quaternary alluvium consisting of water-borne and wind-borne unconsolidated to poorly consolidated sediments.

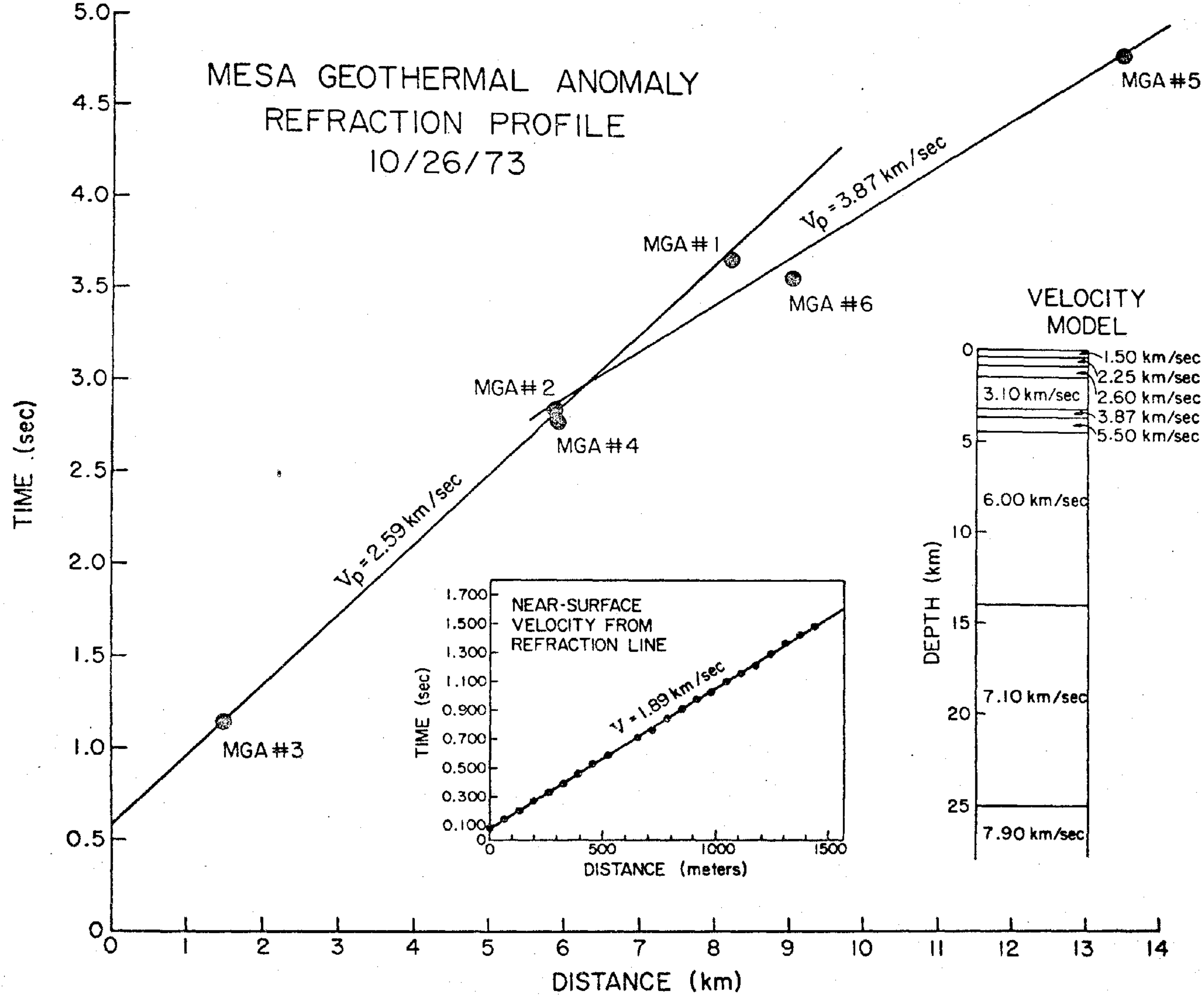


Figure 4. Seismic refraction profile and crustal velocity model. Location of shot point noted on Figure 5. Near-surface refraction line was west of, and extended from, the shot point.

TABLE 2. CRUSTAL STRUCTURE

Velocity in Layer (km/sec)	Depth to Top of Layer (km)
1.50	0.0
2.25	0.40
2.60	0.90
3.10	1.50
3.87	3.20
5.50	3.70
6.00	4.50
7.10	14.00
7.90	25.00

Prospect No. 27-1, the U. S. Bureau of Reclamation Mesa #6-1, and the Texas Company Grupe-Engebretson No. 1 wells. Velocities are similar to those obtained by Kovach, et al., (1962) for their seismic profile 3, located less than 10 km north of the Mesa Geothermal Anomaly. The crustal velocity below 3.7 km is a modified version of Hamilton's (1970) velocity model for the Borrego Mountain Area on the west side of the Imperial Valley.

Several different layered velocity models were used in an attempt to improve the precision of the hypocenters. However, gross changes in the models seldom changed horizontal locations by more than 2 km. Location of the calibration explosion was made to determine the probable precision of the microearthquake hypocenters. The computed location was within 0.20 km in the horizontal plane and 0.10 km in depth of the actual shot point (see Table 3). The typical hypocenter uncertainties for located events are less than 1 km.

MICROSEISMICITY

The epicenter positions of all microearthquakes located in this study are illustrated in Figure 5. Hypocenters, as well as other pertinent data for each of the 36 events, are presented in Table 4. The location errors for horizontal position and focal depth are less than 1 km for events within the seismometer array, and less than 2 km for events just outside the array.

The epicenters define an elongated zone of seismicity that extends westward from the central part of the Mesa Geothermal Anomaly. Ninety percent of the microearthquakes are located within a 3 km wide zone that appears to continue toward the west. Since the locational accuracy of events outside the array decreases very rapidly with distance from the array, earthquakes west of

TABLE 3. CALIBRATION BLAST ON MESA GEOTHERMAL ANOMALY, OCTOBER 26, 1973

Actual Origin Time	10/26/73 - 00:42:05.33 GMT
Calculated Origin Time	10/26/73 - 00:42:05.39 GMT
Actual Location	32° 48.63'N 115° 14.79'W
Calculated Location	32° 48.61'N 115° 14.68'W
Actual Depth	0.04 km
Calculated Depth	0.14 km
RMS	0.02 sec
Error in Depth	0.10 km
Error in Location	0.20 km
Charge Size	180 kg

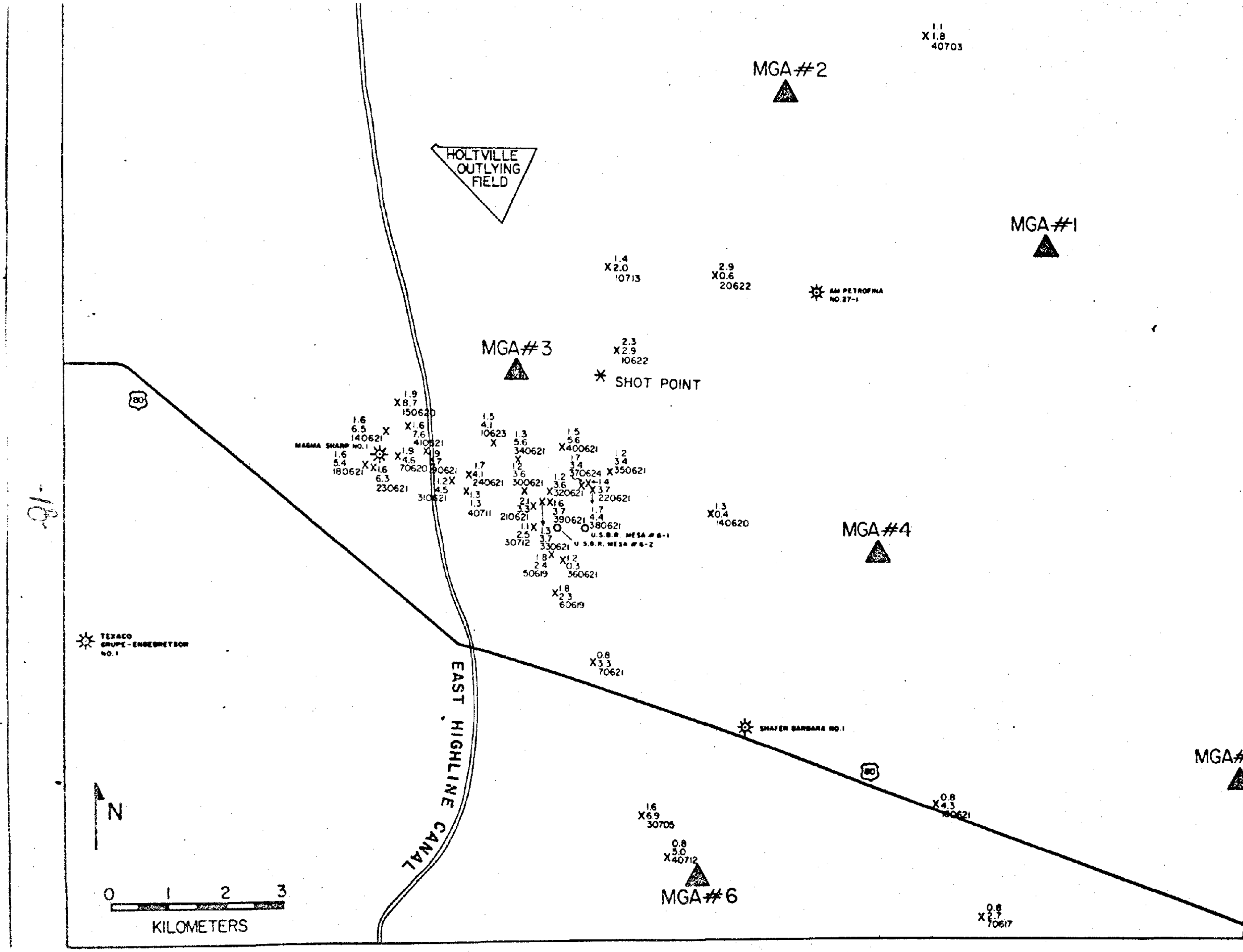


Figure 5. Map of seismograph recording sites and epicenter locations. The upper number beside each epicenter is its magnitude, middle number is focal depth in kms, and lower number is the event identification code, see Table 4. Note location of calibration shot point about 1.5 km east of station MGA #3.

TABLE 4. HYPOCENTERS OF MESA GEOTHERMAL ANOMALY MICROEARTHQUAKES
JUNE 10 TO JULY 15, 1973

Event*	Latitude (N)	Longitude (W)	Depth (km)	Magnitude	No. of Stations	Quality
70617	32° 42.12'	115° 10.45'	2.7	0.8	4	Fair
50619	32° 46.58'	115° 15.56'	2.4	1.8	4	Good
60619	32° 46.16'	115° 15.59'	2.3	1.8	4	Good
70620	32° 47.37'	115° 18.46'	4.6	1.9	5	Fair
140620	32° 47.08'	115° 13.60'	0.4	1.3	5	Good
150620	32° 47.73'	115° 18.37'	8.7	1.9	6	Fair
70621	32° 44.56'	115° 15.37'	3.3	0.8	5	Good
140621	32° 47.58'	115° 19.00'	6.5	1.6	5	Fair
160621	32° 43.76'	115° 10.70'	4.3	0.8	5	Good
180621	32° 47.24'	115° 19.11'	5.4	1.6	5	Fair
190621	32° 47.42'	115° 18.17'	7.0	1.9	5	Fair
210621	32° 46.94'	115° 16.31'	3.3	1.9	5	Good
220621	32° 47.15'	115° 15.51'	3.7	1.4	5	Good
230621	32° 47.18'	115° 19.20'	6.3	1.6	5	Fair
240621	32° 47.22'	115° 17.12'	4.1	1.7	5	Good
300621	32° 47.10'	115° 16.72'	3.6	1.2	5	Good
310621	32° 47.14'	115° 17.57'	4.5	1.2	5	Fair
320621	32° 47.11'	115° 15.82'	3.6	1.2	5	Good
330621	32° 46.92'	115° 16.00'	3.7	1.3	5	Good
340621	32° 47.32'	115° 16.73'	5.6	1.3	4	Good
350621	32° 47.28'	115° 15.27'	3.4	1.2	4	Good

Event	Latitude (N)	Longitude (W)	Depth (km)	Magnitude	No. of Stations	Quality
360621	32° 46.57'	115° 15.37'	0.3	1.2	4	Good
370621	32° 47.15'	115° 15.67'	3.4	1.7	4	Good
380621	32° 47.10'	115° 15.47'	4.4	1.7	4	Good
390621	32° 46.95'	115° 15.98'	3.7	1.6	4	Good
400621	32° 47.49'	115° 16.07'	5.6	1.5	4	Good
410621	32° 47.62'	115° 19.02'	7.6	1.6	4	Fair
10622	32° 48.76'	115° 14.56'	2.9	2.3	4	Fair
20622	32° 49.46'	115° 13.54'	0.6	2.9	6	Good
10623	32° 47.62'	115° 17.21'	4.1	1.5	6	Good
40703	32° 50.99'	115° 11.44'	1.8	1.1	4	Fair
30705	32° 43.99'	115° 14.58'	6.9	1.6	5	Fair
40711	32° 47.43'	115° 16.28'	1.3	1.3	4	Fair
30712	32° 46.95'	115° 15.46'	2.5	1.1	5	Good
40712	32° 43.10'	115° 14.04'	5.0	0.8	5	Fair
10713	32° 49.49'	115° 14.66'	2.0	1.4	5	Good

* The event number 70617 indicates the seventh event recorded on four or more stations from the June 17, 1973 record.

115° 20'W were not included. However, almost no events occurred in the central or eastern part of the array or in the area immediately east of the array. The main concentration of activity is along a fault zone passing through the location of the two geothermal wells, USBR Mesa #6-1 and USBR Mesa #6-2.

The earthquake cluster in Figure 5 is part of an earthquake swarm. An earthquake swarm (Richter, 1958) is defined as a distinctive sequence of earthquakes, closely grouped in time and space, with no one outstanding main event. Swarms account for most of the microearthquake activity observed on the Mesa Geothermal Anomaly; the events concentrated in the area of highest heat flow.

The level of seismic activity was typically about one or two locatable microearthquakes per day. During swarms, the activity was sometimes greater than 100 events per day. Two swarms of two and three day duration occurred; one from June 19 to 21, 1973, the other during July 6 to July 9, 1973. The Mesa swarm activity was associated with similar activity on the Brawley and Imperial Faults, i. e., the small events (Fig. 3 and Fig. 6) are located in the Mesa Area, whereas the larger events cluster along the Imperial and Brawley Faults.

Many of the nanoearthquakes recorded at station MGA #3 (Fig. 6 and Fig.7) are of Richter magnitude less than zero and are not recorded on the other stations. These events occur at a rate of at least 100 per day. Note that they occur continuously and are not distinctly associated with stress release on the Imperial and Brawley Faults. During the last two days of recording, all instruments were moved into a 2 km-array around MGA #3, and a few of these nanoearthquakes could be located.

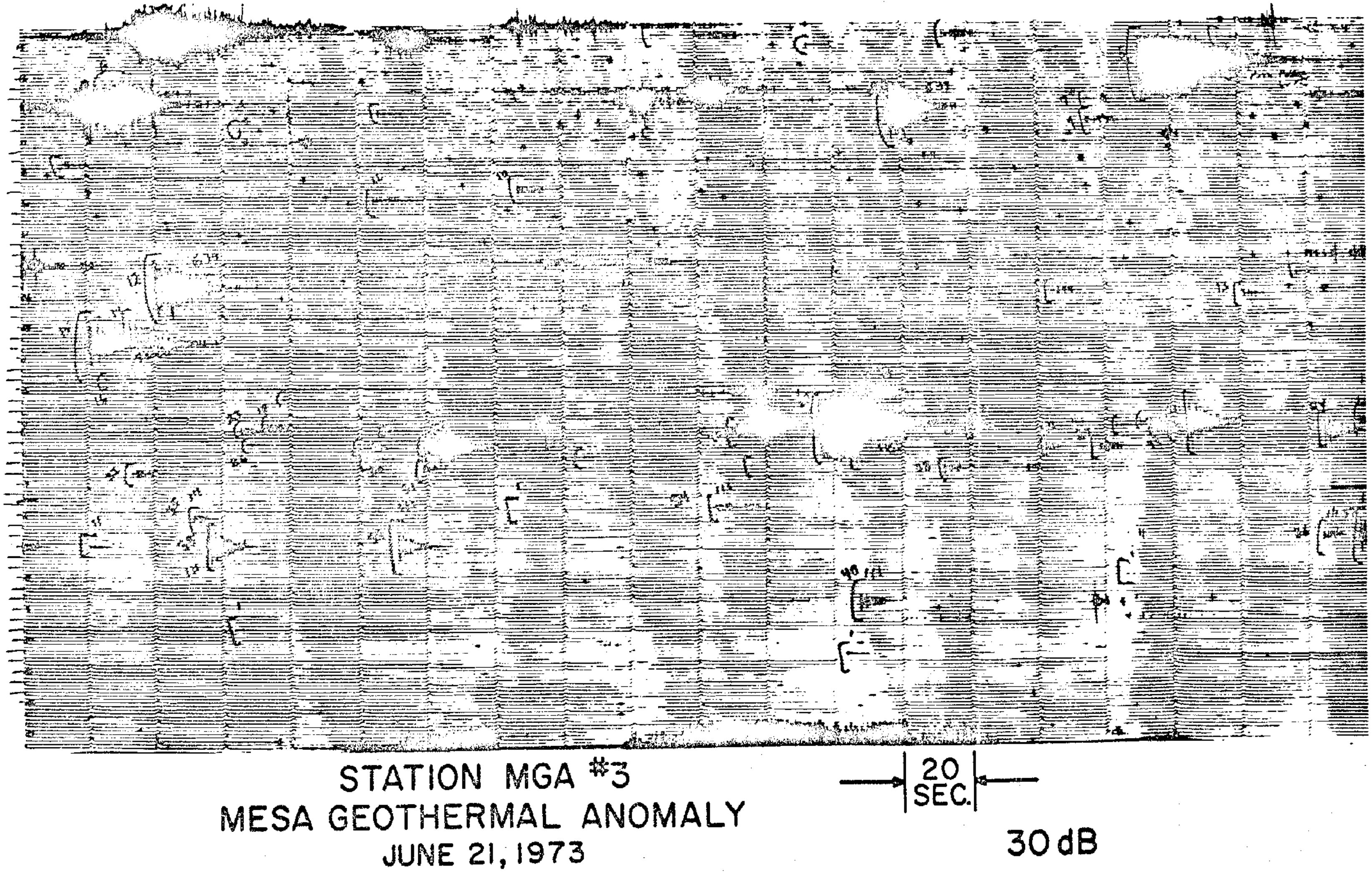


Figure 6. One-day seismogram for station MGA #3 during Imperial Valley swarm of June 19 to 21, 1973. Note the continuous nanoearthquake activity associated with the geothermal area; compare with Figure 3 for station MGA # 2 where no nanoearthquakes were recorded on the same day.

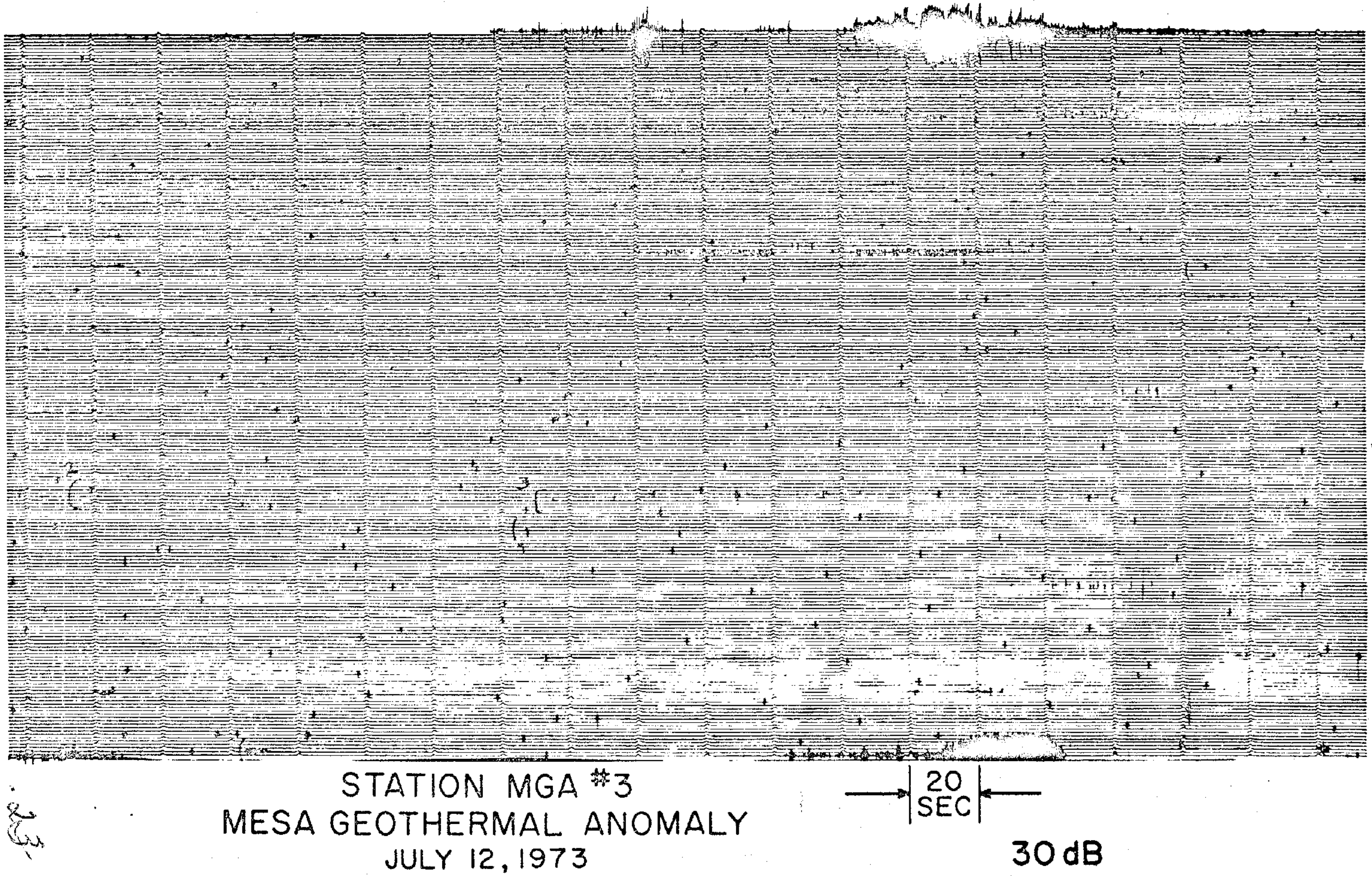


Figure 7. One-day seismogram for station MGA #3 during quiet time. Again note the continuous nanoearthquake activity associated with the geothermal area.

Most of the geothermal earthquakes occur at focal depths of 2 to 5 km. The tectonic events outside the geothermal anomaly extend as deep as 9 km. More than half of the located events have hypocenters greater than the 3.5 km, which is approximately the depth to crystalline basement. Projection of hypocenters into planes transverse and longitudinal to the main trace of the proposed Mesa Fault, demonstrate this phenomenon (Fig. 8). The high temperature gradients confine the accumulation of strain to shallow depths. Temperatures also set an upper limit to the size (Richter magnitude) of the microearthquakes.

MAGNITUDES

The magnitudes of events located in this study were determined by relating total signal duration to Richter magnitude M (1958) with an empirical formula (Hadley, 1973) modified by the results from a San Jacinto Valley microearthquake study (C. Cheatum, personal communication, 1973). The method has commonly been used in microearthquake studies (Lee, et al., 1972; Real and Teng, 1973), because of complications arising in determining magnitudes of events recorded on high-gain instruments.

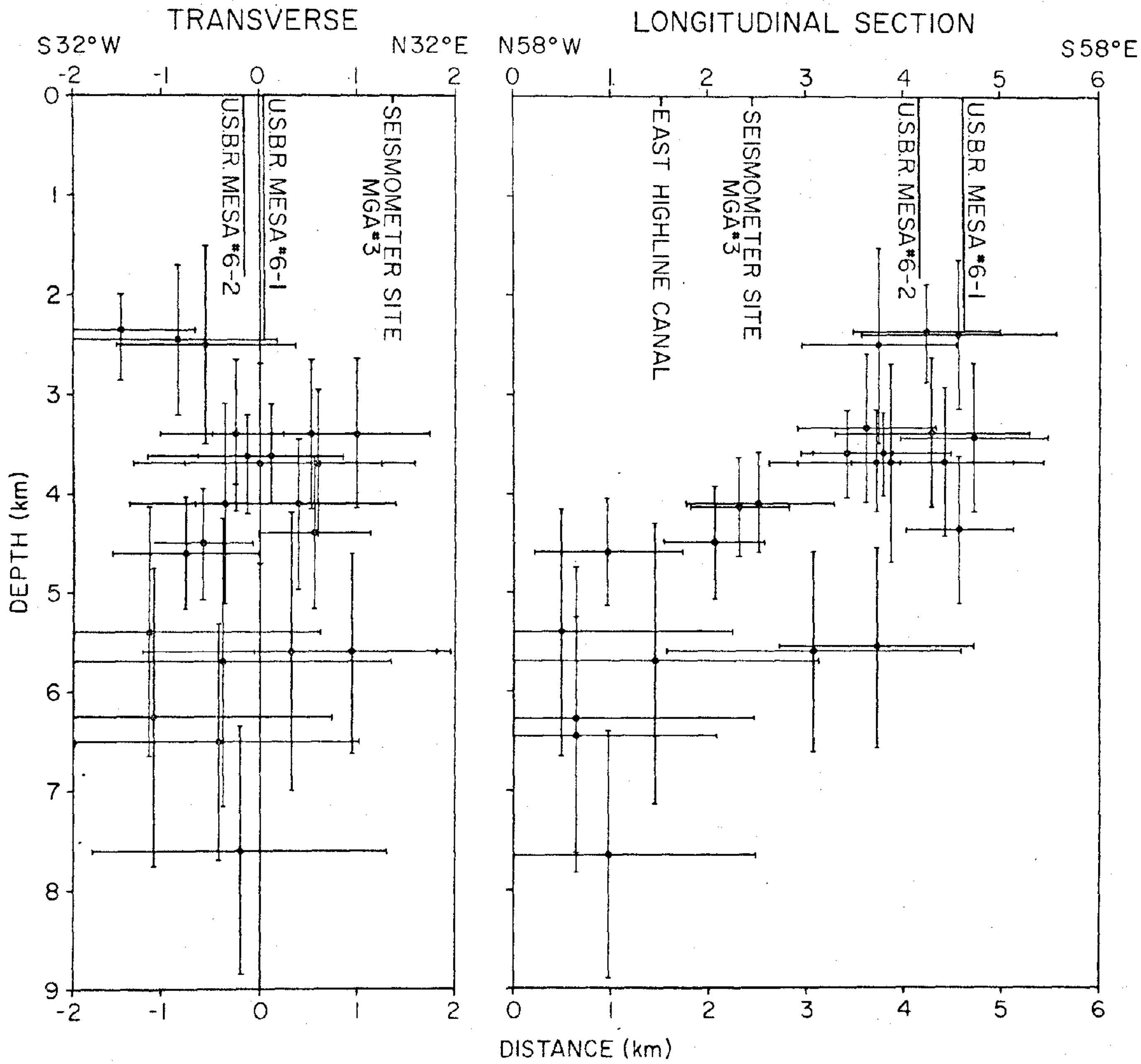
The total signal duration D, measured for each event, was from the P arrival to the location on the seismogram where the signal to noise ratio became 1:1, which was usually less than 20 mm. The empirical relationship from Hadley (1973) is

$$M = 0.057D + 1.43 \qquad (1)$$

and that from Cheatum (personal communication, 1973) is

$$M = -2.1 + 2.35 \log D \qquad (2)$$

where M is the Richter magnitude and D is the signal duration in seconds. Calculated magnitudes, for an event recorded at different stations, varied by as much as 0.4. Therefore, most magnitudes represent a simple average between two or more stations.



MESA GEOTHERMAL ANOMALY MICROEARTHQUAKES JUNE-JULY, 1973

Figure 8. Projection of hypocenters into planes transverse and longitudinal to the main trace of the proposed Mesa Fault. The length of lines indicate the relative error bars.

The frequency of occurrence of earthquakes is generally observed to be related to the magnitude of the events by the relationship (Gutenberg and Richter, 1954)

$$\log N = a - bM \quad (3)$$

where N is the number of earthquakes having magnitudes between M and M + dM. The constant a is an index of the rate of earthquake occurrence and the constant b is an index ranging from 0.4 to 1.8 (Allen, et al., 1965) expressing the relative number of small and large events. Miyamura (1962) and Allen, et al., (1965) have emphasized the possible tectonic significance of regional variations in b. Francis (1968) summarized the possible interpretations for the different magnitude-frequency relations. Using a combination of the techniques of Wyss and Lee (1973), Pfluke and Steppe (1973), and Aki (1965), a value of $b = 0.64 \pm 0.19$ was calculated for the located Mesa events (Fig. 9). Francis (1968) has postulated that b is a function of the type of faulting, large for normal, and small for strike-slip faulting. First motion studies discussed in the next section indicate strike-slip faulting. The value of 0.64 for b is quite similar to values of 0.73 and 0.65 which Tryggvason (1970) found associated with the Reykjanes, Iceland, earthquake swarm of September 28 to 30, 1967.

FIRST MOTION

Focal mechanism solutions can be obtained by plotting the up (compression) or down (dilatation) first motion, as recorded at each station, on an equal area projection of the lower hemisphere of the focal sphere with the hypocenter at the origin (Stauder, 1962). Polarities of the instruments were checked by

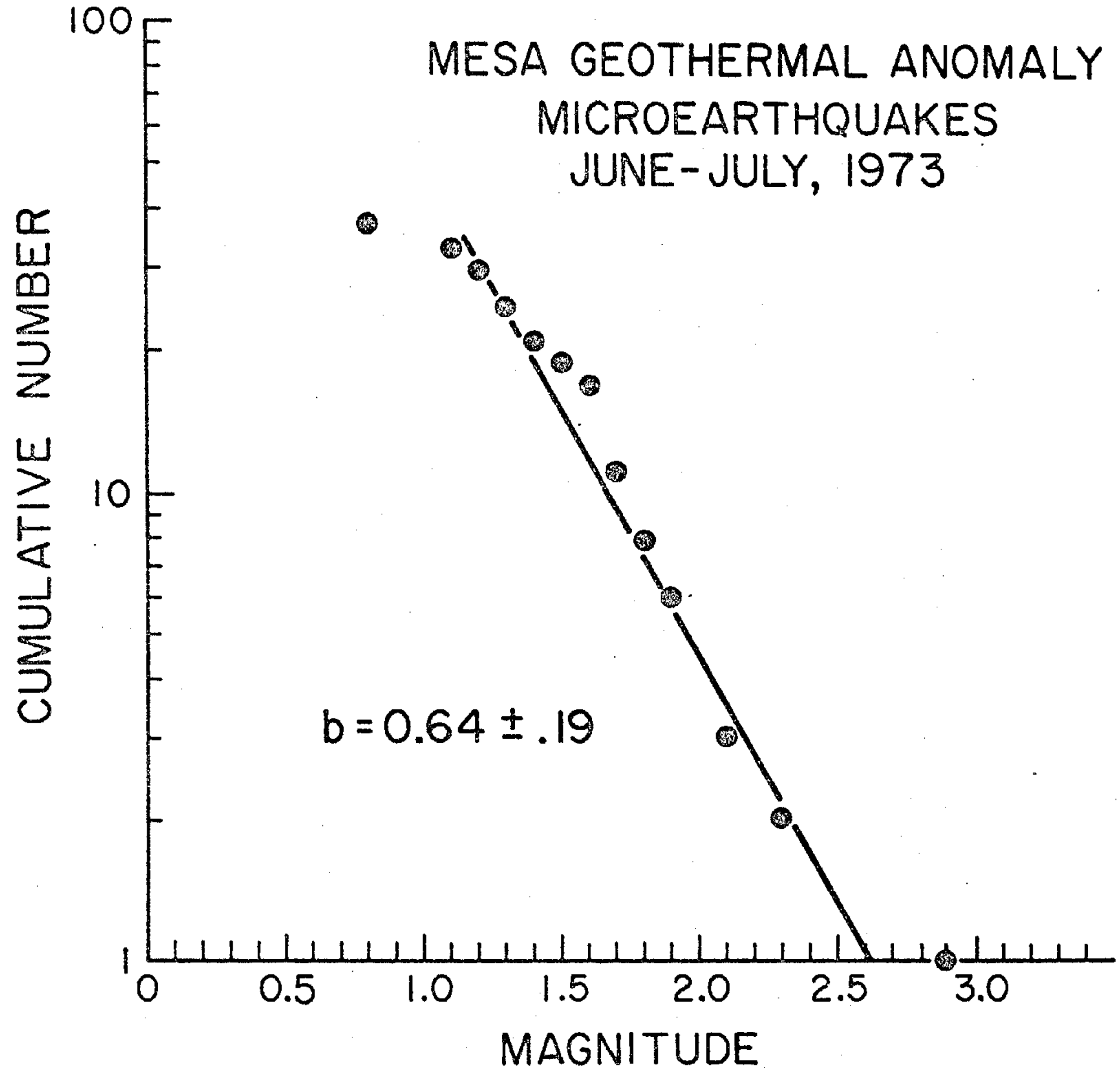


Figure 9. Frequency-magnitude relation for Mesa Geothermal Anomaly microearthquakes.

using a magnitude of 7.5 earthquake in the Aleutions, as well as several southern Nevada events.

Excellent focal mechanism solutions were obtained for two events from the June 19 to 21, 1973 swarm (Fig. 10) located less than one half kilometer from the trace of the proposed Mesa Fault (see Fig. 5). First motions were recorded for five instruments of the Mesa array. In addition, first motions were obtained from several stations of the more widely spaced USGS-CIT Imperial Valley net.

Both solutions indicate a northwest-southeast trending fault of the right-lateral strike-slip type which is designated the Mesa Fault. Although a unique choice of the fault plane cannot be made from the first motion data, the northwest striking plane was chosen due to the alignment of the epicenters. Since the precision in the individual locations is better than 1 km, the northwest-southeast elongated nature of the swarm appears to be a real feature, and not an artifact of the location procedure.

RESULTS AND DISCUSSION

Stress, associated with the Mesa Geothermal Anomaly, is relieved by a combination of continuous seismic activity and intermittent microearthquake swarms. During the five-week recording interval, two earthquake swarms occurred; the first from June 19 to 21, 1973, and the second from July 6 to 9, 1973. The major source of energy release is in the form of continuous nano-earthquake activity centered over the zone of highest heat flow, i.e., inside the 5.0×10^{-6} cal/cm^2-sec isoflux contour of Figure 11. Most of this seismicity was recorded only on station MGA #3 (Fig. 7 and Fig. 11).

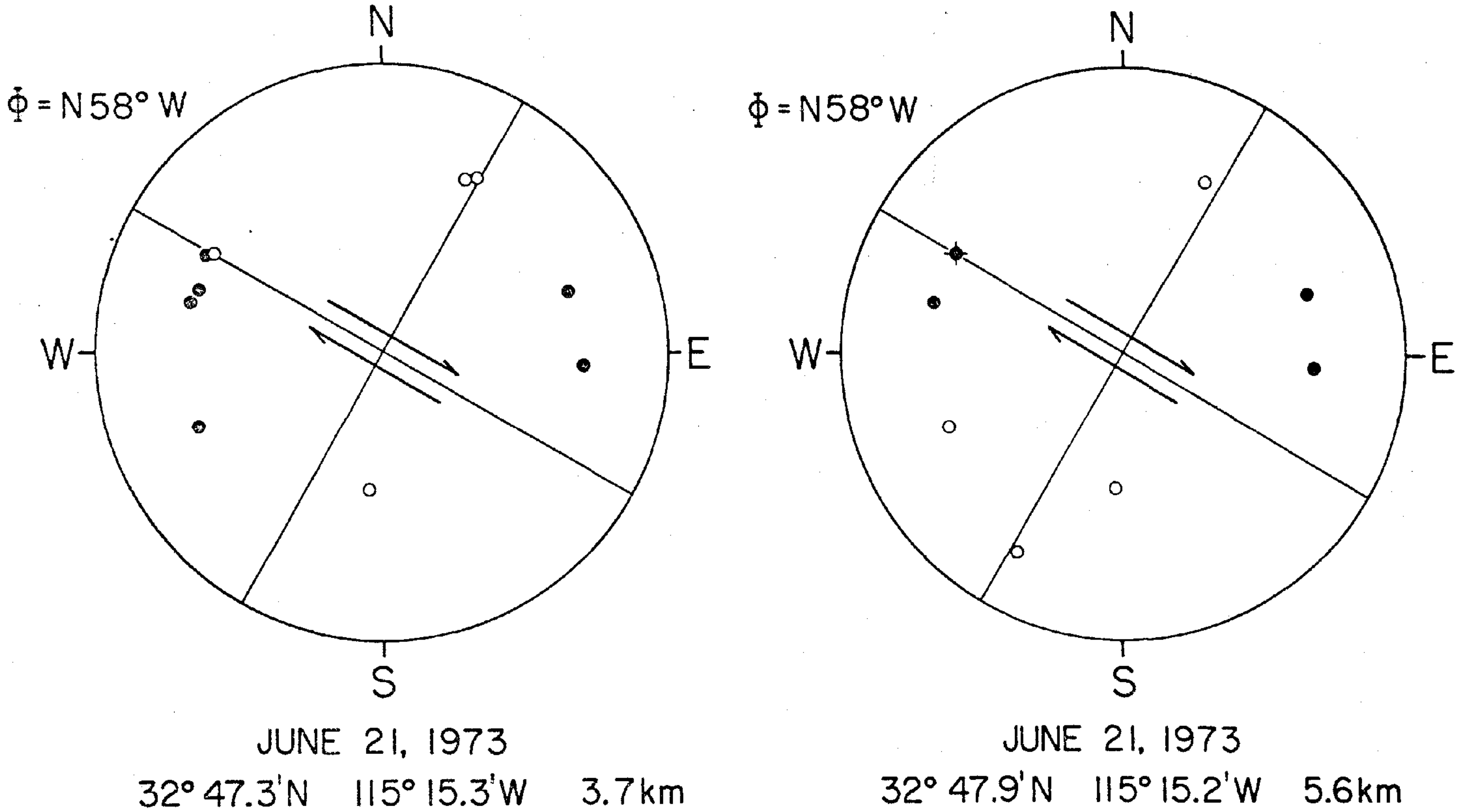


Figure 10. Focal mechanism solutions for two microearthquakes. Open circle is dilatation. Solid circle is compression. Stations are projected on the lower hemisphere. Data is from present array as well as USGS-CIT Imperial Valley array.

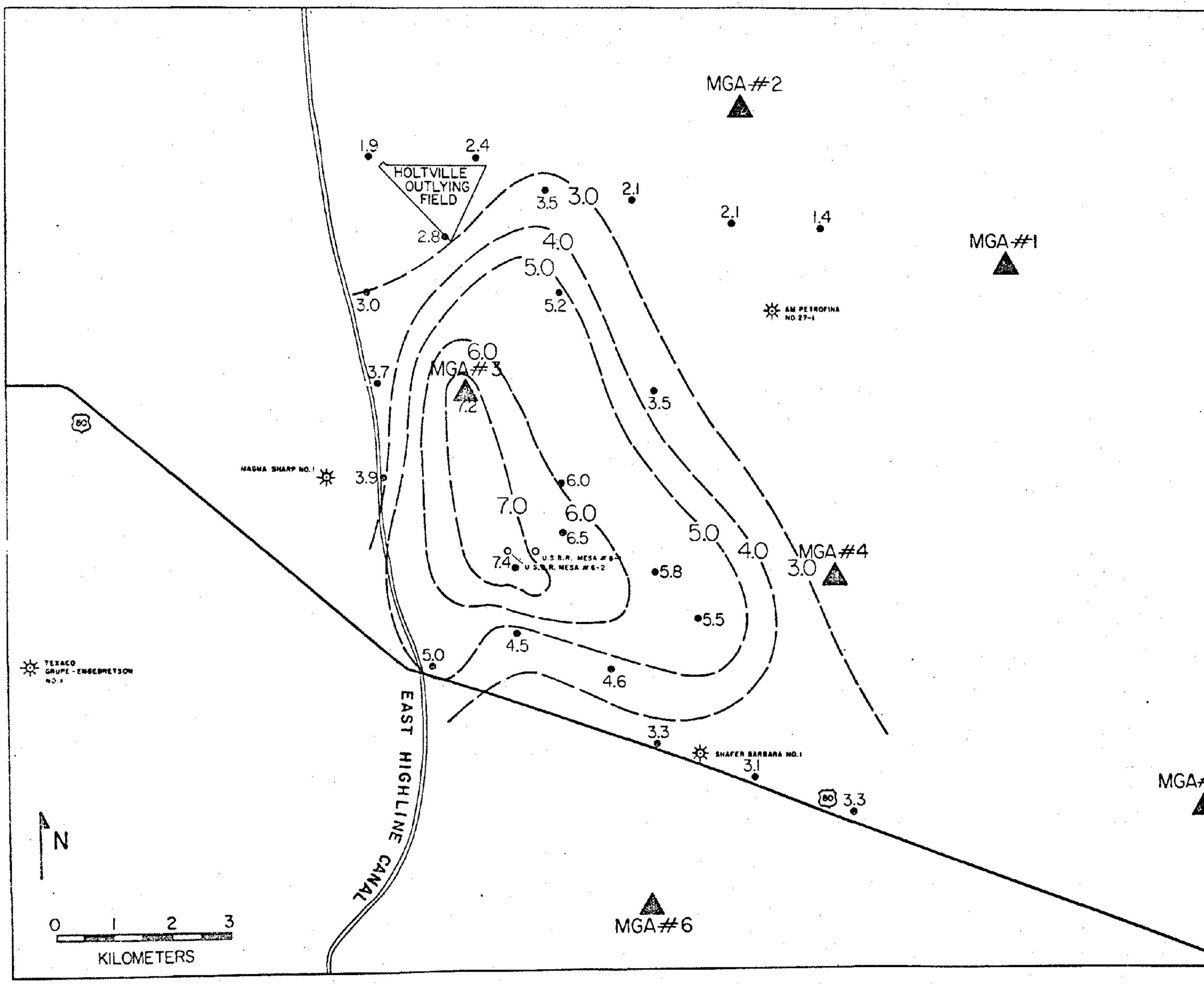


Figure 11. Heat flow contour map in isofluxes of 10^{-6} cal/cm^2-sec. Note the location of the present seismograph network.

Although there does not appear to be a continuous fracture zone, microearthquake swarms in the Imperial Valley appear to migrate from the south to the north. The Imperial Fault and the Mesa Fault seem to respond simultaneously. From the two swarms that were studied, the data is suggestive of a disturbance propogating along a fracture zone at a rate of about 10 to 40 km/day. Thus, the stress release, that is initially associated with swarm activity on the Mesa and Imperial Faults, is transferred in time and space to the Brawley Fault.

Among the several possible mechanisms of swarm generation, Sykes (1970) has pointed out that two are related to volcanism. In one case magmatic activity acts as a concentrated source of stress; whereas in the other, volcanoes are the loci of heterogeneities in physical properties that lead to inhomogeneities in the stress distribution.

Mogi (1963) and Scholz (1968) noted, during laboratory studies of microfracturing, 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 surface of the earth as volcanic eruptions, or hydrothermal processes that trigger tectonic strain release.

A third hypothesis for the generation of swarms has been postulated. In particular, swarms may indicate nonmagmatic mechanisms producing concentrations or inhomogeneities in stress. For example, localized sources of high fluid pressure may lower the effective strength of the rocks and act essentially as concentrated sources of stress. Such a mechanism was undoubtedly a causative agent in the series of earthquakes at the Denver Arsenal (Evans, 1966; Healy, et al., 1968). Similarly, magmas or hydrothermal processes are possible sources of high fluid pressures near volcanoes and some geothermal areas.

There appears to be some resemblance between areas of high seismic noise and areas of microearthquake activity. Results of a seismic ground-noise survey conducted by Teledyne-Geotech (1972) are presented in Figure 12. Contours are total power in decibels relative to 1 $(\text{millimicron/sec})^2$ per Hertz in the passband of 3.0 to 5.0 Hz. The contour interval is equal to 3 db. Epicenters determined, using the Mesa Geothermal Anomaly seismograph network, are indicated by an x. The enhanced seismic ground-noise seems to be seismic wave phenomena associated with the continuously occurring nanoearthquakes.

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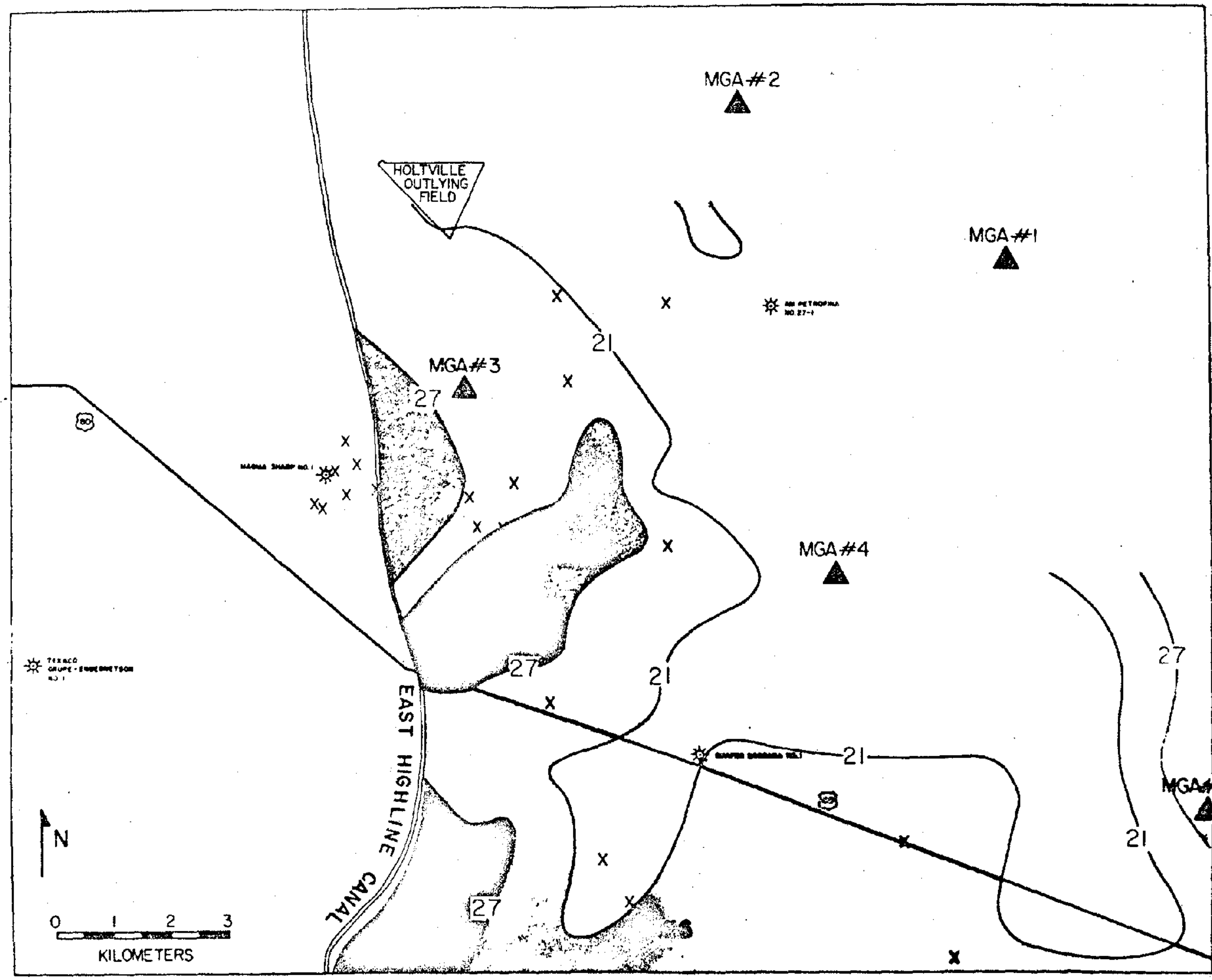

Figure 12. Seismic ground-noise map of the Mesa Geothermal Anomaly. Contours of total power are given relative to 1 $(\text{millimicron/sec})^2$ per Hertz in the passband of 3.0 to 5.0 Hz (after Teledyne Geotech, 1972). Note microearthquake epicenters plotted as x.

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