EAST MESA SEISMIC STUDY

REPORT NO. 3

T.V. McEvilly and B. Schechter

Seismographic Station
Department of Geology and Geophysics
University of California
and
Earth Sciences Division
Lawrence Berkeley Laboratory
Berkeley, California 94720

February 1978

Prepared for the U.S. Bureau of Reclamation
under Purchase Order No. 7-01-30-16550

INTRODUCTION

This third report on the seismic study of the U.S. Bureau of Reclamation (USBR) East Mesa network data is presented in two parts. Part A is a routine summary of the seismic activity recorded at East Mesa during the period of days 276-364, 1977. Part B is a general review of the study to date, specifically emphasizing the attempts, both past and present, to determine the level of local seismicity. New data are presented concerning events in 1976, formerly believed to be local microearthquakes, but shown here to be meteorological in origin. The results of past and present studies are compared, with discrepancies examined and possible explanations discussed. Conclusions based on the present study are given, along with recommendations that may lead to resolution of some major contradictions between past and present results.

PART A. RESULTS FOR THE PERIOD OF DAYS 276-364, 1977

No local events were detected within the East Mesa geothermal field during the period. Events from the Brawley swarms of October and November were well-recorded at East Mesa, including events with estimated magnitudes less than 2.0. The fact that no local earthquakes were recorded at East Mesa during the swarm activity is significant in terms of the local seismicity and tectonics (see below and Part B).

TAPE SUMMARY

The data tapes received during the period are listed below:

Tape #	Time on (UTC)		Time Off	
34	276	1757	286	1656
35	286	1725	296	1523
36	296	1541	304	(ran out)
37	304	1657	314	1935
38	314	1953	325	1558

Tape #	Time On (UTC)		Time Off	
39	325	1614	335	1831
40	335	1845	346	
41	346	1615	356	1600
42	356	1620	364	2330

NETWORK PERFORMANCE

With the exception of a few continuing problems, network performance was satisfactory during the period. Station 4H (tape channel #5) was not recording during the first half of the period but is now operating. The problem of relatively high gain at station 9Z has been corrected. However, the odd response characteristics of MBR stations 3Z and 8Z remains, as depicted in Figure 5 for a Brawley earthquake of $M_L = 4.0$. Note the loss of low-frequency response of these stations relative to the other vertical-component stations.

Although this problem does not affect our determination of the hypocenters (the relatively high frequency P-wave first arrivals appear unaffected), it becomes important in spectral analysis and coda-length magnitude determinations. It would appear to be a mechanical problem in the seismometer suspensions, whereby the effective natural frequency is increased due to stiffening of the suspensions (e.g., by the mass resting at the stops, fungus, mold, or spider webs in the suspension, etc.). Station 9Z has also succumbed recently to this malady.

THE BRAWLEY SWARM

The Brawley swarms of October-November 1977 were well-recorded at East Mesa. In December 1977 at the AGU Meeting in San Francisco, Dr. Carl Johnson of the Seismological Laboratory at Caltech presented the preliminary results for the swarm activity, based on the data from the Imperial Valley U. S. Geological Survey and California Institute of Technology (USGS-CIT) seismic array. We report here only on those aspects of the swarms of interest in the present field-specific study. With one exception (discussed below), no earthquakes were detected during the swarm activity at East Mesa by either the USGS-CIT or East Mesa arrays.

As seen on the regional map (Figure 1), several stations of the USGS-CIT Imperial Valley array lie in close proximity to East Mesa (two more stations are just off the map to the North). Considering the station deployment, it would appear that any significant seismic activity at East Mesa would also be recorded at these stations, although it is not inconceivable that highly localized, low magnitude activity would pass undetected. A search of the USGS files for the period of days 178-364, 1977, yielded the following events within a range of 32°40'-32°52' north latitude and 115°05'-115°21' west longitude:

Event (Map Symbol)	Day	Origin Time (UTC)	Lat	Long	Depth (km)	Qual
A	202	0517 04.4	32°41.8'	115°14.1'	5.0	3
B	278	1446 25.7	32°45.3'	115°15.4'	4.9	4
C	315	2155 02.1	32°50.5'	115°09.1'	5.0	4
D	318	0311 24.4	32°44.4'	115°20.3'	5.1	4
E	318	0416 17.6	32°42.3'	115°16.7'	5.0	4

All events, except A, have a quality factor of 4 which indicates only a rough location (not known within 15 km). Events B-E were examined in further detail.

Event B. As shown on Figure 2, the signal-to-noise ratio of this event is unusually low, especially for a local event well-recorded by the USGS-CIT array (although effects of attenuation and local ground noise should be considered). Using the S-P distance contraints of MBR stations 3 and 9, probable locations for this event at fixed focal depths of zero and 4 km are shown on Figure 1 (labeled B_o and B_4, respectively). Since a focal depth of 4 km seems more likely, based on USGS-CIT results, it appears that this event is actually associated with the Imperial fault.

Event C. Based on the East Mesa records, this event does not appear to be seismic in origin. Only slowly traveling surface waves propagating west to east are apparent.

Events D and E. These were well-recorded (both P- and S-waves) and were relocated as shown on the map at D' and E' (with error bars for latitude and longitude). The new locations clearly associate these events with the Brawley/Imperial fault system.

Thus, within the sensitivity of the USGS-CIT array, no events appear to have occurred in the immediate vicinity of the East Mesa geothermal field during the period, supporting the conclusion reached from a study of the East Mesa array data.

Note: A magnitude 2.8 event, which occurred on day 230, 1977 (see Figure 1 in report No. 2, UCID-4029), is also plotted in Figure 1, the USGS-CIT location at point J and the East Mesa solution at J' (shown with standard error bars for latitude and longitude). This appears to be the largest event located east of the Brawley/Imperial fault ozone and close to East Mesa detected by the Imperial Valley array since the start of the present study, with a minimum S-P time of approximately 3.0 seconds observed at MBR station 7.

COMBS-HADLEY HYPOTHESIS TESTED

On the basis of their 1973 study, Combs and Hadley (1977) located microearthquakes within the East Mesa geothermal field for the period June-July 1973 and reported that they appeared to be tectonically associated with the more extensive and simultaneous swarm activity occurring along the Brawley/Imperial fault system. The larger events occurred on the Brawley fault and the smaller events occurred at East Mesa and were associated with the Mesa fault.

During the same time period no earthquakes were detected at East Mesa by the USGS-CIT network although, as Hill (1975) points out, most of the events discussed by Combs were too small to be detected on four or more stations of the Imperial Valley array. However, the East Mesa array used by Combs was more spread out than the present one, and thus was in even closer proximity to the Imperial Valley array. Thus the question arises whether the microearthquakes actually occurred at East Mesa or farther west along the Brawley fault (see Part B).

To test the Combs-Hadley hypothesis of Brawley-E. Mesa interaction, a 7-hour period of high activity, characterized by a large occurrence ratio of small to large events, was examined in detail. The period studied runs between 0720-1420 (UTC) on day 293. Forty-three events were identified on the visual records, which is a complete sample of the data since the signal-to-noise ratio observed on these records normally exceeds that of the data tape. The magnitudes of the events ranged from $M_L = 4.0$ to $M_L < 2.0$. All of the larger events with S-P times greater than 3 sec (as determined by visual inspection) were discarded. All others were played out and analyzed. The events fell into 3 categories:

1. large events clearly associated with the Brawley/Imperial fault;
2. small events clearly associated with the Brawley/Imperial fault;
3. small events, usually recorded only on stations 3Z and 9Z, which could not be located.

Figures 3-6 illustrate each type of event. Every locatable event was found to originate along the Brawley/Imperial fault. The locations of the smallest events (see Figure 6) with magnitudes probably on the order of zero are unresolved.

Attempts to increase the sensitivity of the records by means of filtering have been only partially successful. A comparison of the filtered versus unfiltered signals from station 7H in Figure 4 shows a considerable amount of ground noise in the 4-10 Hz bandwidth, a characteristic of S-wave arrivals.

One possible way to reduce the surface noise is to install 4.5 Hz 3-component geophones into new or existing boreholes within the geothermal field area. Even a single such station would provide an S-P distance constraint more sensitive than is now possible, for use in locating these small events. Alternatively, surface array of 4.5 Hz geophones, both vertical and horizontal components in a cross pattern 100-200 m in diameter with 18 or 36 geophones each leg, would go far in reducing noise levels while enhancing signal levels.

In summary, no local seismic events were detected at East Mesa by either the USGS-CIT Imperial Valley or the USBR East Mesa seismic arrays, down to estimated thresholds of at least $M_L = 2.0$ and $M_L = 1.0$, respectively, during the recent Brawley swarm activity. This contradicts the observations of Combs and Hadley (1977) and may indicate that the East Mesa geothermal field is not tectonically linked with the Brawley/Imperial fault system. The location of smaller events detected at East Mesa remains unresolved, but normal seismicity characteristics suggest extremely low activity at East Mesa. It is quite possible that previous investigators, confusing secondary P arrivals on vertical components as S-waves, mislocated Brawley or Imperial fault events at erroneously short distances (see Part B).

OTHER ASPECTS OF THE BRAWLEY SWARM (as recorded at East Mesa)

Several interesting observations, apparent in studying records of Brawley earthquakes, may be of use in subsequent work.

Multiple arrivals

Many earthquakes show large amplitude multiple arrivals on both vertical and horizontal records (see Figures 7,8, and 9) although they are not characteristic of all earthquakes (Figure 10) and appear to be totally absent from the smallest records (Figure 6).

Figures 7 and 8 present in reduced travel time form a typical event from the Brawley swarm. The secondary P phase (P_{sec}) propagates at the same apparent velocity across the array as the initial P phase with a constant time delay of approximately 2.3 seconds. This secondary P phase appears to be characteristic of many earthquakes in the area and is observed throughout the Imperial Valley up to a distance of 60 km with the time difference between P_{sec} and P constant and independent of distance (Hill, et al. 1975). The velocities assigned to later P-wave arrivals, which may number three or more, are assigned somewhat more arbitrarily due to the complexity of the arrival patterns and the limited range of distances between observations. Figure 7 shows such an arrival with a velocity of 2.6 km/sec assigned to it. In Figure 9 the multiple P-wave arrivals are indicated by arrows, with no attempt made to assign velocities. Figure 8 clearly shows the arrival of a secondary S-wave phase, also traveling at the same apparent velocity as the initial S-waves with a time lag of about 6.1 seconds, constant and independent of distance.

Hill interprets the initial P-wave as a down-going wave from a focus near the base of the sediments, critically refracted at the sediment-basement interface, while the secondary P-wave is an upgoing wave reflected off the free surface, then critically refracted along the sediment-basement interface. This interpretation is also consistent with the S-wave data and requires the source to be located either within the sediments or within the basement close to the sediment-basement contact.

Johnson and Hadley (1976) found that the focal depths for most events of the 1975 Brawley swarm ranged from 4-8 km, falling within two kilometers above or below the presumed depth of the sediment-basement contact -- results consistent with the above interpretation.

Using a reasonable and uniform velocity model, it is then possible to make an independent determination of the focal depth, since the time difference between arrivals, both P_{sec}-P and S_{sec}-S, is a function of depth only. The important P- and S-wave ray paths are shown in Figure 10 for a representative regional velocity model along with depth determination schemes. Two distinct cases are considered -- sources within the sediments and sources within the basement rock. For sources within the sediments, both P_{sec} and S_{sec} waves are generated as well as possible converted P-wave waves at shallow depths within the sedimentary section. In this simple model, however, no true P_{sec} and S_{sec} waves, as defined above, are generated for sources within the basement. Secondary phases may arise as the result of S- to P-wave conversions at the basement-sediment interface, with SP and SP_{sec} generated as shown in Figure 10b. The time difference $T_{SP} - T_P$ is a function of the depth of source below the interface and thus the focal depth may be calculated if the P and SP arrivals are observed. As indicated in the figure, the time difference between the P- and SP_{sec}-wave arrivals must be at least 2-6 seconds for basement sources.

These depth determination schemes as presented in Figure 10 are complicated by the fact that the depth to the basement is not well-determined. East Mesa is situated on the eastern flank of the Salton trough; consequently, the basement contact slopes generally towards the west for these ray paths. Also, there are indications of basement topography variations, particularly in the seismically and geothermally active areas (Savino et al. 1977).

Thus, the depth to the basement, critical to these focal depth determinations is not well-defined. However, the fact that $T_{P_{sec}} - T_P$ typically appears to be less than 3.0 seconds (see Hill et al. 1975 and also Figures 7 and 9, this report) argues in favor of sources either within the deep sediments or shallow basement.

S-to-P conversions

Theoretical studies of earthquake sources show that energy transmitted by the S-wave is many times greater than for the P-wave. Thus, S- to P-wave conversions, in addition to those already discussed, may be important in the local wave propagation. For example, the postulated 2.6 km/sec arrival seen in Figure 7 could result from an S-to-P conversion at the interface between layers (1) and (2) within the sedimentary section. The ray paths for this and other possible converted waves are shown in Figure 10. An example of an earthquake where S-to-P conversions appear not to have been as important is shown in Figure 11. Note the large amplitude

S-waves and the relatively small amplitude secondary P phases (compared with P). Contrast these relative amplitudes with those in Figure 9 where the P_{sec} arrivals appear enhanced and the S-waves diminished relative to the P arrivals.

The major factors controlling wave conversion thus appear to be location (i.e., structure between source and receiver), depth of source, and focal mechanism.

It is conceivable that these secondary phases could prove valuable in mapping attenuation or velocity anomalies at specific depths in the shallow section, and thus contribute to the reservoir delineation aspects of geothermal exploration in the Imperial Valley. Further study is warranted.

PART B. REVIEW OF PAST AND PRESENT SEISMIC STUDIES AT EAST MESA

In this section we present a review of the previous seismic studies at East Mesa, emphasizing the conclusions reached pertaining to the local seismicity and comparing them with our results. The discussion is divided into six sub-sections:

1. General seismicity -- prior to 1973.
2. Results of the USGS-CIT Imperial Valley array.
3. Results of the 1973 microearthquake studies at East Mesa.
4. Results of the 1974-1975 microearthquake studies at East Mesa.
5. Events of Feb. 15, 1976 -- a reinterpretation.
6. Results of the present study.

The section closes with conclusions and recommendations for resolving outstanding problems.

GENERAL SEISMICITY -- PRIOR TO 1973

Prior to the installation of the USGS-CIT Imperial Valley network in April 1973, minor earthquakes in the region could only be located roughly. Despite the low sensitivity of the systems before 1973, major swarm activity was detected in 1934, 1940, 1950, and 1955. The Imperial Valley earthquake of 1940, the largest event ever recorded in the region (located about 20 km west of East Mesa) broke the ground for over 60 km along what has become known as the Imperial fault. A maximum ground displacement of almost 6 m was reported (Richter, 1958).

Of more immediate interest is a swarm of events in 1938, roughly located 10 km north of East Mesa, with the largest event of magnitude 5.0, and two events occurring in 1972 with magnitudes 2.9 and 3.1 located about 15 km east and 20 km west of East Mesa, respectively.

Two microearthquake studies in the Imperial Valley in 1967 and 1971, with 2 days and 3 weeks recording time, respectively, in the East Mesa region, failed to detect any local sismic activity. However, the 1967 study revealed intense swarm activity in the Obsidian Buttes region near the then-inferred Brawley fault. The East Mesa station in 1967 was located about 25 km north of the present array (Brune and Allen, 1967).

THE USGS-CIT IMPERIAL VALLEY ARRAY

A network of 16 high-gain vertical seismic stations was installed throughout the Imperial Valley in April 1973, with a good coverage in all directions around East Mesa. The results of the first year of operation have been summarized by Hill (1975).

The major events of the first year were four earthquake swarms in June and July 1973, which occurred along the Brawley/Imperial fault system. Combs (1974) and Combs and Hadley (1977) reported microearthquake activity at East Mesa coincident with the Brawley swarm. Hill noted that most of the events reported by Combs (1974) were too small to be located by the USGS-CIT network, for which coverage was considered uniform for events down to about $M_L = 2.0$. A small event ($M_L = 1.5$-2.5) was located at East Mesa, as indicated by Hill (1975).

Swarm activity along the Brawley/Imperial fault zone has been detected by the USGS-CIT network in every year subsequent to 1973, but no significant seismic activity has been located at or associated with the East Mesa KGRA.

It is interesting to note that, while Hill reported earthquake activity at the Salton Sea and Brawley geothermal fields (associated with the Brawley fault), no evidence for seismic activity at the Dunes and Glamis KGRA's was apparent.

RESULTS OF THE 1973 MICROEARTHQUAKE STUDY AT EAST MESA

The results of a 5-week microearthquake study at East Mesa in 1973 have been reported by Combs (1974) and Combs and Hadley (1977). Their array consisted of 6 high-gain, portable, vertical seismometers deployed in roughly the same locations as the present array, although the station separation was somewhat larger.

The normal background seismicity was characterized by one or two locatable events per day (recorded on at least 4 stations), and one hundred or more small events during days of swarm activity.

The pattern of seismicity suggested the existence of a fault (the Mesa fault) running WNW through the geothermal field across the zone of highest heat flow. Focal mechanism studies, coupled with the coincidence of swarm activity at both East Mesa and the Brawley/Imperial fault zone, indicated that the Mesa fault was linked tectonically to the more extensive fault system (see Elders et al. 1972, for a discussion of the regional tectonics).

Continuous nanoearthquake activity (events too small to be located) was recorded at a site close to the present MBR STA 9, persisting even during "quiet" times.

The magnitudes of microearthquakes at East Mesa during the June-July activity, as determined by coda length, ranged up to an $M_L = 2.9$ event with roughly half of the events having a magnitude ≥ 1.5. It is not immediately clear why the bulk of this activity was not better recorded by the USGS-CIT array, with 6 stations in the vicinity of East Mesa.

RESULTS OF THE MICROEARTHQUAKE STUDY AT EAST MESA, 1974-1975

An array of nine 3-component seismographs was deployed at East Mesa from December 1974 to December 1975, recording microearthquake activity before, during, and after withdrawal and injection of geothermal fluids. Combs (1976) reported no significant change in seismicity throughout the entire period. The pattern of seismicity was found to be essentially the same as that found during the 1973 study -- several locatable microearthquakes per day plus intermittent periods of swarm activity.

The seismicity is divided into discrete events and swarm activity. Discrete events are further subdivided, based on characteristic S-P times, as shown in the table below:

S-P Time(sec)	Type of Event	Location	Depth(km)	No. per day
< 1.5	nanoearthquake	not locatable	-	10's - 100's
1.5 - 3.0	microearthquake	in field	2 - 4	~ 5
3 - 10	" "	outside field	4 - 10	~ 5
> 10	" "	regional	-	a few

Combs noted several differences between events appearing to originate within the field and those from without:

1. arrivals for local events appear more emergent and are lower frequency than external "tectonic" events;
2. local events appear to originate at shallower depths than tectonic events;
3. Brawley earthquakes show significant attenuation of high frequency content as the wavefront travels across the array (through zone of high heat flow).

EVENTS OF FEBRUARY 13, 1976 -- A REINTERPRETATION

Several events recorded by the East Mesa seismic array in the early hours of February 13, 1976, initially interpreted as seismic events, are now shown to be meteorological in origin, resulting from local thunderstorm activity (Witherspoon et al., 1976). Approximately 23 events, extending from 1055 to 1125 UTC have been reexamined in detail.

Initial Observations

The events recorded on day 44, 1976, were initially interpreted as microearthquakes, with several of the better-recorded events being located within the geothermal field. The events were correlated with the occurrence of an anomalous 3 psi increase in water pressure at well 8-1, also located within the geothermal field. The pressure rose impulsively, beginning at approximately 1110 UTC, and returned to normal (within the normal fluctuation) about 2 hours later. The pressure at well 6-1, located less than 1 km NW of well 8-1, showed no anomalous activity during the same period of time (see Figure 15).

Two unusual observations are immediately apparent from the East Mesa seismic records (see Figures 12-14). First is the occurrence of a large pulse, recorded simultaneously at all stations (when visible at all), which precedes subsequent ground motion on most events. Second is the very slow apparent velocities ($V_{max} \sim 0.6$ km/sec) of the first arrivals, characteristic of Rayleigh waves rather than the P- or S-wave velocities expected for seismic events.

The large pulse was originally attributed to tape stretching incurred during initial playback of the events.

New Observations

The current lack of apparent seismic activity at East Mesa has rekindled interest in these events. Several lines of evidence indicate that they are not seismic in origin and that the pressure anomaly initially associated with these events is neither the cause nor an effect of them:

1. The large pulses are not recorded on the channels of STA 6H and 7H that were not operational at the time, thus excluding the possibility of tape stretching as a cause (these channels lie approximately in the center of the tape). In other words, the pulses are actual recorded events.

2. A prominent "phase" with an apparent velocity of 0.33 km/sec (the speed of sound) has been identified on most records and has been used to locate the source of many events.

3. Weather records indicate heavy rain and thunderstorm activity in the region (thunderstorm activity at Yuma, Arizona, less than 60 km east of East Mesa, and rain throughout the Imperial Valley) during the morning hours.

The large pulses are interpreted as lightning-induced radio interference and accurately define the origin times for all events. The subsequent ground motion represents a complex assemblage of air-caused Rayleigh waves, possibly some rapidly attenuating P- and S-waves, and a true "air-wave" arrival, all generated by the expanding air shock wave (thunder) associated with each stroke of lightning.

The actual air-wave, easily detected on most records (see Figure 15), is characterized by high frequency (≥ 20 Hz), large amplitude on both vertical and horizontal components, and an apparent velocity of 0.33 km/sec across the field.

The location of a given event is easily found once the "air-wave" is identified on each record. Taking the time difference from large pulse to air wave arrival as the travel time ΔT and 0.33 km/sec for the velocity, the distance to i^{th} station is given by

$$\Delta_i = v \times \Delta T_i .$$

The intersection of arcs swung from each station yields the location, with the convergence of arcs surprisingly good for those events located within or close to the geothermal field.

The location procedure is complicated in some instances by the rapid rate of occurrence (which tends to mix the codas) and the fact that stations 7H, 6Z, and 6H were not operating. Also, the records of Station 7Z were obscured by a large amplitude, low frequency oscillation, which was partially eliminated by filtering.

The locations of events are listed in Table 1 and plotted on the map (Figure 1) as open circles. The quality of each location is estimated by the relative degree of arc convergence as follows:

very good - location probably correct to within 0.5 km.
good - " " 1.0 km.
fair - " " 2.0 km.
poor - rough location.

The quality of the locations generally increased as the distances involved decreased. The pattern shown on the map clearly shows an east to west trend of events with time. The storm appears to have died out approximately over East Mesa as no events were recorded west of the array and no well-defined events were detected subsequent to event #23.

A final question remains: what caused the pressure anomaly at well 8-10 during the storm? One plausible explanation, in view of this new interpretation, is that the pressure recording instrumentation at the well site was affected by the local lightning activity.

The fact that no pressure anomaly was recorded at well 6-1, coupled with the close proximity of that well to well 8-1, indicates that the actual anomaly occurred not within the geothermal fluids, but rather in the instrumentation itself.

A look at the map shows that event #8, which occurred at 1108 UTC, was located in the immediate vicinity of the wells. The dotted vertical line on Figure 16 shows the correspondence of this event in time with the onset of the pressure anomaly. We may thus speculate that this event, properly occurring in space and time, may have been the trigger responsible for the observed pressure anomaly.

Table 1. Location of events of Day 44, 1976 (Feb. 13)

Event	Origin Time (UTC)	Latitude (N)	Longitude (W)	Quality
1	1055 37	32° 44.8'	115° 00.8'	fair
2	1058 17	32° 46.0'	115° 00.9'	"
3	1059 39	32° 45.0'	115° 03.8'	"
4	1100 24	32° 44'	115° 04'	poor; rough location
5	1103 04	32° 45.8'	115° 08.5'	fair
6	1104 45	32° 43.2'	115° 06.0'	"
7	1105 54	32° 46.5'	115° 09.2'	"
8	1108 27	32° 46.9'	115° 15.0'	fair; closest event to well 8-1
9	1109 08	32° 44.2'	115° 07.0'	fair
10	1110 24	32° 38.6'	115° 11.1'	good; although far from other events, convergence was good
11	1112 10	32° 45.6	115° 09.1'	fair
12	1113 16	32° 47.8'	115° 10.0'	"
13	1114 00	32° 43.7'	115° 09.0'	"
14	1115 03	32° 47.1'	115° 09.6'	"
15	1116 04	32° 47.8'	115° 10.5'	"
16	1117 23	32° 46.8'	115° 11.5'	good
17	1118 39	32° 47.5'	115° 11.3'	good
18	1119 26	--	--	phases of events 18 & 19 overlap
19	1119 38	32° 44'	115° 12'	poor
20	1122 00	32° 46.7'	115° 13.0'	very good
21	1122 46	32° 46.3'	115° 13.7'	very good
22	1123 50	32° 45.8'	115° 13.8'	very good
23	1125 21	32° 46.0'	115° 14.8'	very good

RESULTS TO DATE OF THE PRESENT STUDY

The major result of the present study has been the total absence of detected local microearthquakes originating within the East Mesa geothermal field. This is consistent with early microearthquakes in the Imperial Valley and with the findings of the USGS-CIT network, but inconsistent with two microearthquake studies at East Mesa in 1973 and 1974-75.

Several possible explanations could account for the descrepancies:

1. The Mesa fault was active in the period 1973-1975 but has been inactive during the present period of study (July 1977 to present). This does not seem likely, since the local activity was assumed to be tectonically linked to the broader zone of seismicity associated with the Brawley/Imperial fault system, which has continued active throughout the period. One would have expected, under this hypothesis, to see local events during the recent Brawley swarms.
2. The microearthquakes used to define the Mesa fault in 1973 were actually located along the Brawley fault. Only vertical component instruments were available to locate these events. In Report No. 2 we demonstrated the problems of accurately locating events using P arrivals only, especially for events located outside the array. A comparison of station deployment and the epicenter distribution shows the station distribution heavily weighted to the east of epicenters, a situation which could easily lead to mislocations. Relocation of these events farther west would also increase the computed focal depth to values more compatible with those reported by Johnson and Hadley (1976) for Brawley events. Only a re-evaluation of the actual data can resolve this problem.
3. "Geothermal events" may actually be non-seismic in origin. Figures of these events in Combs (1976) appear to be more consistent with air-coupled Rayleigh waves than microearthquakes, featuring emergent, low frequency arrivals and similar waveforms appearing simultaneously on both vertical and horizontal records. The local velocity structure (very low velocities in the near-surface) constrain ray paths, even for local events, to propagate nearly vertically near the surface, clearly separating P- and S-waves as

vertical and horizontal motions, respectively. The "geothermal event" waveforms (Combs, 1976, p. 34), if body waves, are not consistent with such characteristics.

In addition, the manner in which the S-wave arrival is determined is often ambiguous. Improper determination of S-P times, more than any other error, would heavily influence the determination of local seismicity.

The observation that the local seismicity remained unaffected by withdrawal and injection of geothermal fluids could be interpreted as evidence that the observed seismicity is not of local origin. A re-examination of the data appears necessary to resolve these questions. Of specific interest would be the determination of the apparent velocities associated with the "geothermal events" and the temporal correlation of these events with the records of the USGS-CIT Imperial Valley array.

The small events detected at East Mesa during the present study (see Part A and Figure 6) may be analogous to the nanoearthquakes discussed by Combs (1974 and 1976), since they are observed at roughly the same location now as then (MBR STA 9 lies close to Combs' MGA #3), although the S-P time of 1.5 seconds assigned by Combs to these events, indicating a local origin, is not observed (no S-wave arrivals are, in fact, seen for these events). Since these events appear only on MBR 9Z and 3Z, we speculate that they are actually the smallest members of the Brawley earthquake swarms with origins to the NW of East Mesa. One would thus expect the signals to show up also on STA 7Z; however, a map of seismic ground noise (Combs 1974, p. 33) shows high noise levels in the vicinity of MBR 7 relative to levels around MBR 3 and 9. Hopefully, records from the soon-to-be installed 4.5 Hz buried geophones will enable an S-P time to be resolved and the sources of these events to be located unambiguously.

CONCLUSIONS AND RECOMMENDATIONS

1. No local earthquakes have been detected to date at the East Mesa KGRA with the sensitivity of the array sufficient for an estimated detection threshold for local events of at least $M_L = 1.0$.

2. Regional seismic activity, events of magnitude 2.0 or less, is well-recorded at East Mesa and is distinguished from local events by S-P constraints (and less accurately by relative P-wave arrivals). The quality of the data makes accurate locations of the larger ($M \gtrsim 2.0$) events possible, although local station corrections are not determined. Several phases, in addition to the initial P- and S-wave arrivals, are routinely observed.

3. Local atmospheric and man-made disturbances, such as storm activity, drilling, and bombing, are distinguishable from seismic activity based on waveform appearance, frequency content, and apparent velocities. In certain cases the sources have been determined.

4. Based on the results of the present study to date, there appears to be no local seismicity associated with the East Mesa KGRA. The local stress regime, while still undetermined, appears to be independent of the tectonic activity associated with the Brawley/Imperial fault zone.

   Continued observation with the present system is not expected to modify this conclusion.

5. The origin of small events remains unresolved. Installation of a 4.5 Hz 3-component geophone into a 300-ft borehole may aid in determining the source of these events and may also result in detection of small "geothermal events" not presently observable, due to the high level of surface noise in the seismic bandwidth. At least one order of magnitude improvement in threshold of detectability is required for serious study of the field seismicity, given the available time scale for monitoring and the usual $\log N = a - b M_L$ earthquake occurrence rates, with $b \approx 1.0$.

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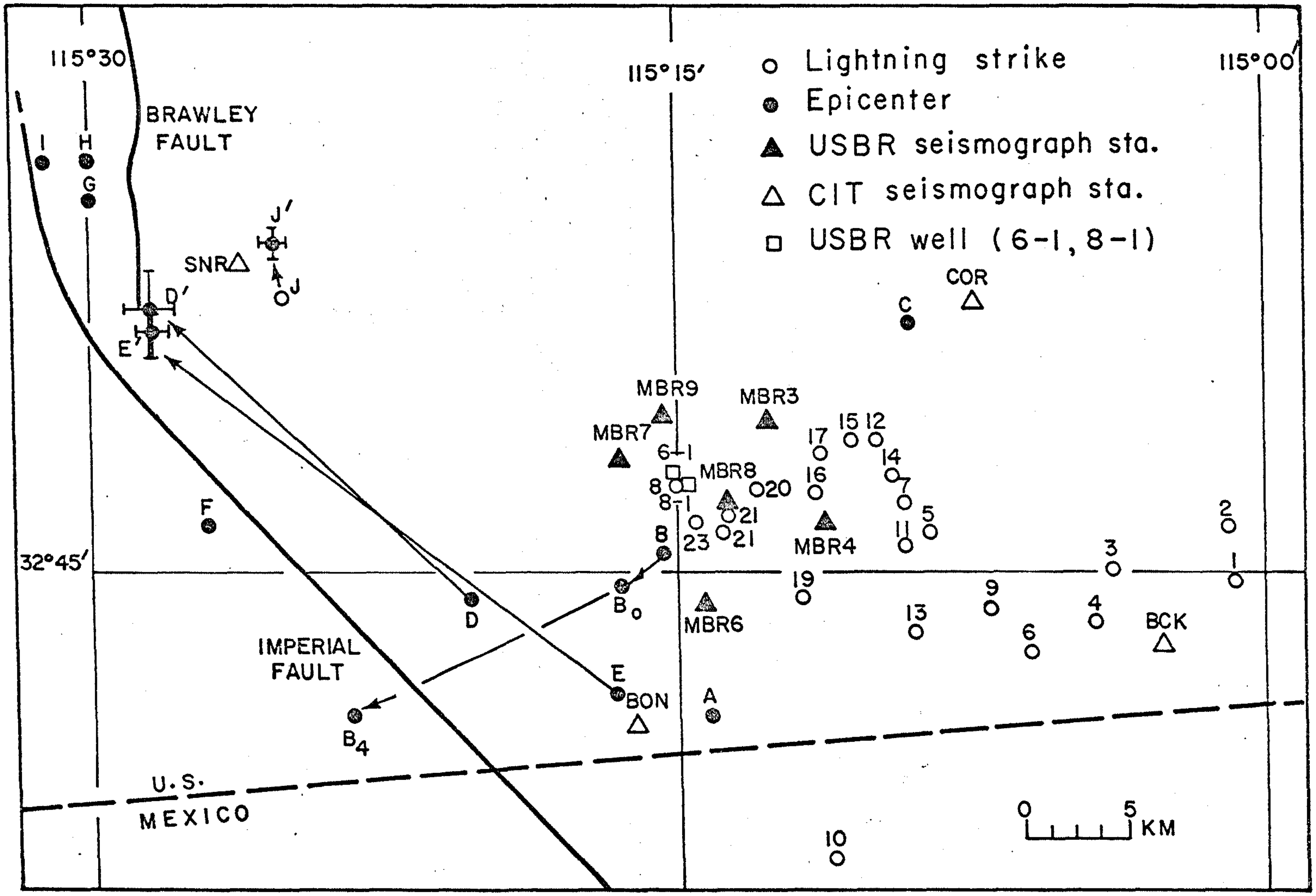
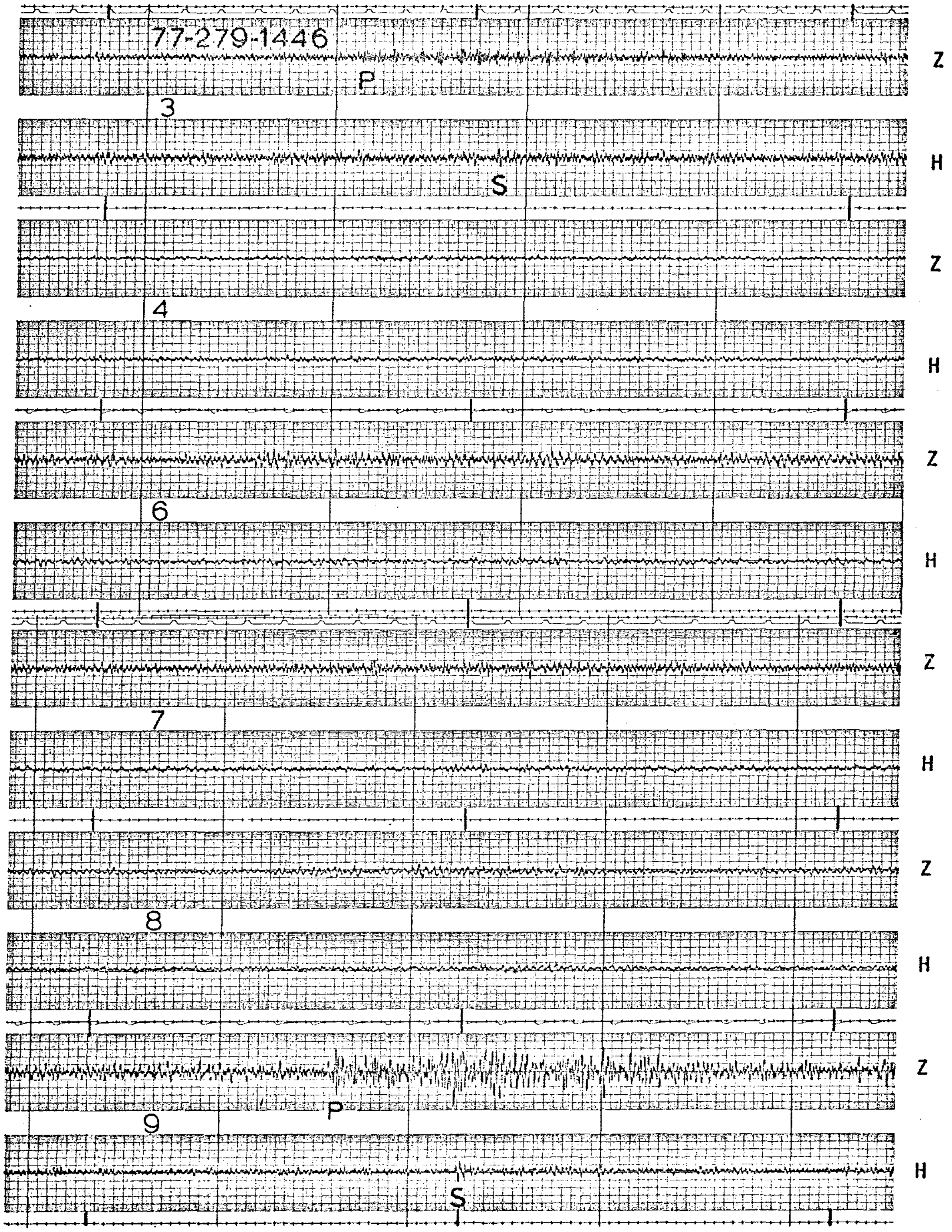
This report was done with support from the U. S. Bureau of Reclamation. Any conclusions or opinions expressed in this report represent solely those of the authors and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory, or the U. S. Bureau of Reclamation.



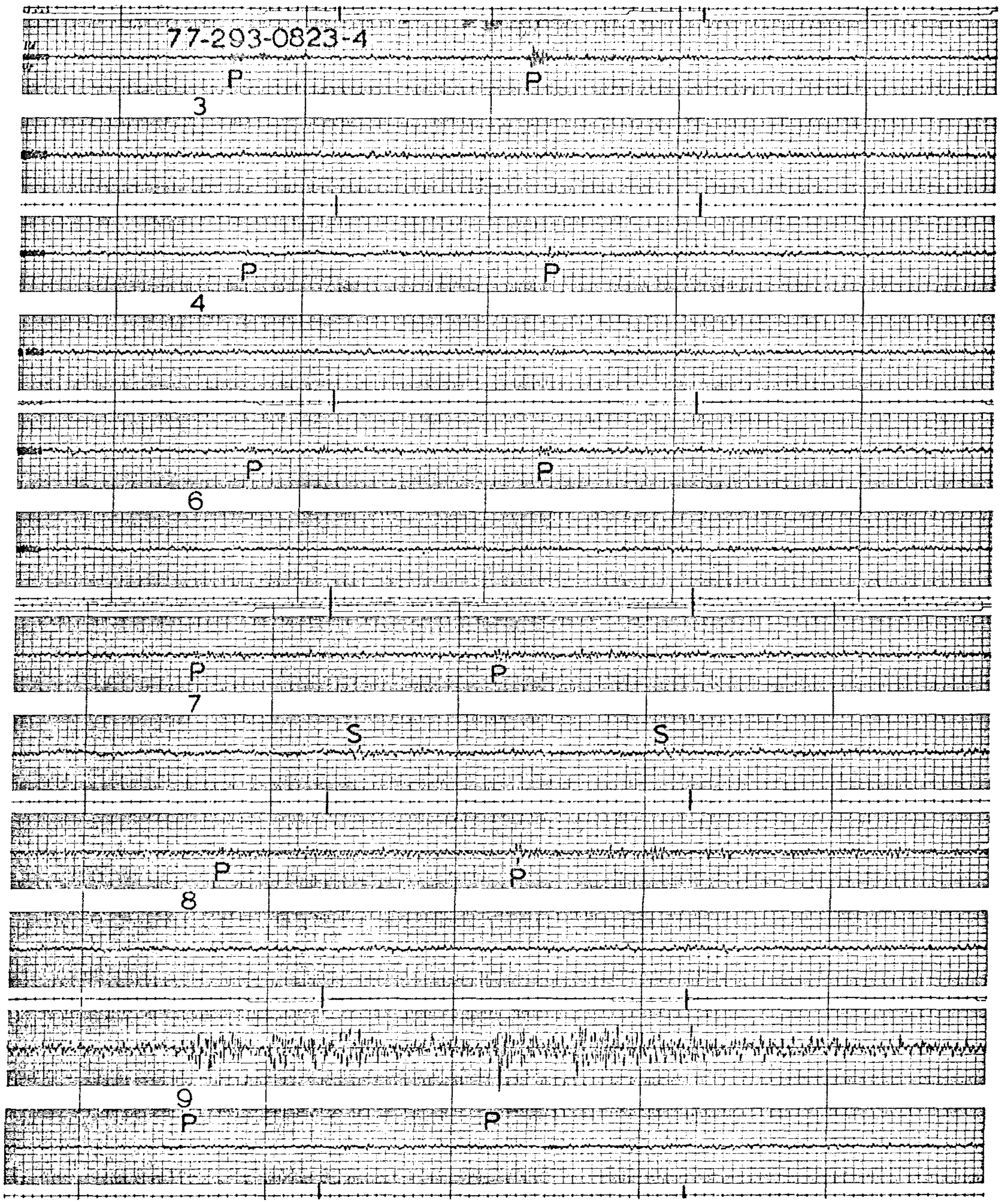
XBL785-795

Figure 1. East Mesa area, showing seismographic stations, wells, and events discussed in the text.



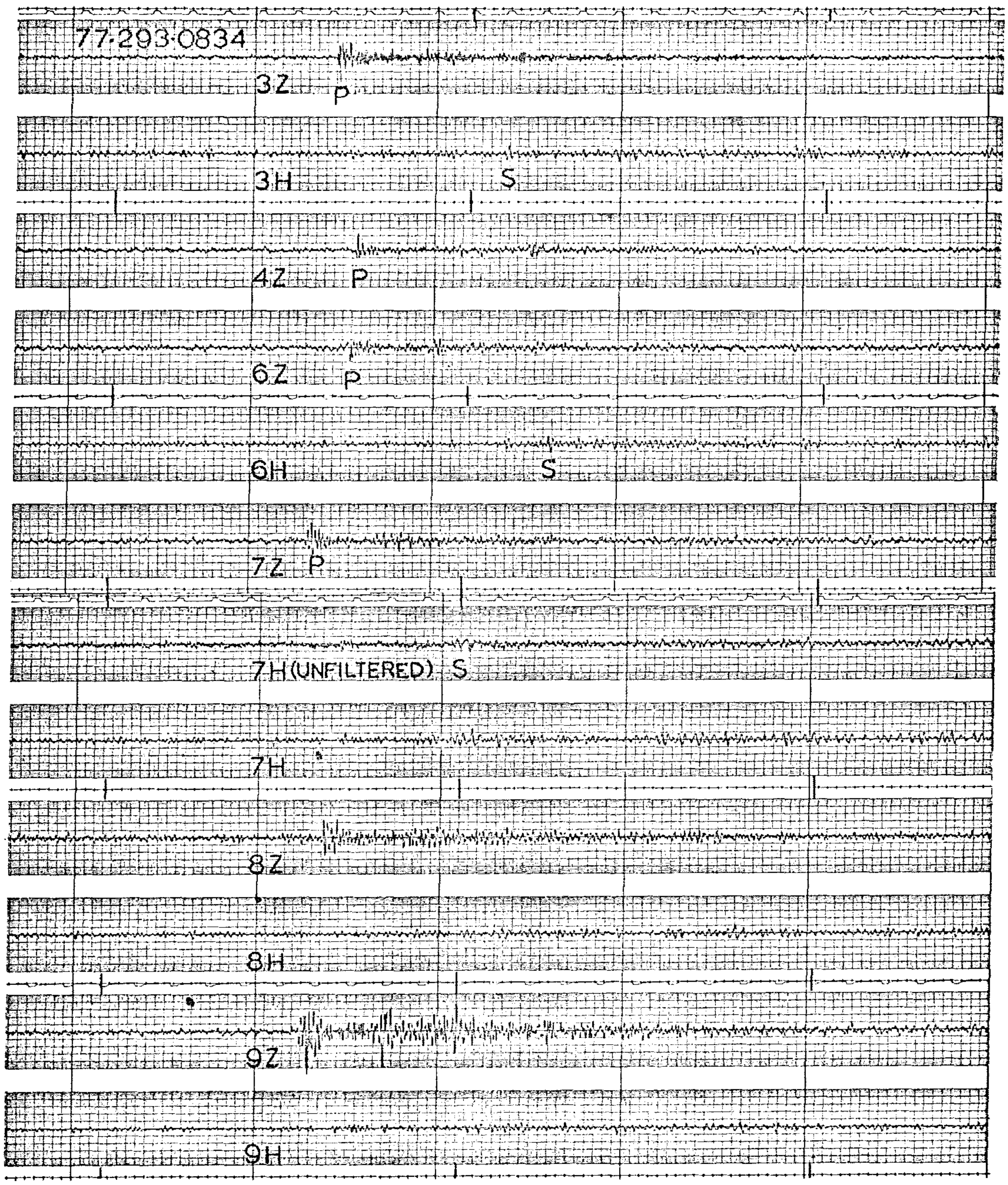
XBL 784-8083

Figure 2. Seismograms for day 279 earthquake, located within East Mesa KGRA by USGS-CIT network. Map symbols B, B∘, B_4 (see text). 3Z, 3H, 6Z, 7Z, 9Z, & 9H high-pass filtered at 4.5 Hz and displayed at 50 mv/div; others not filtered, 100 mv/div. Time line segments at 10 seconds.



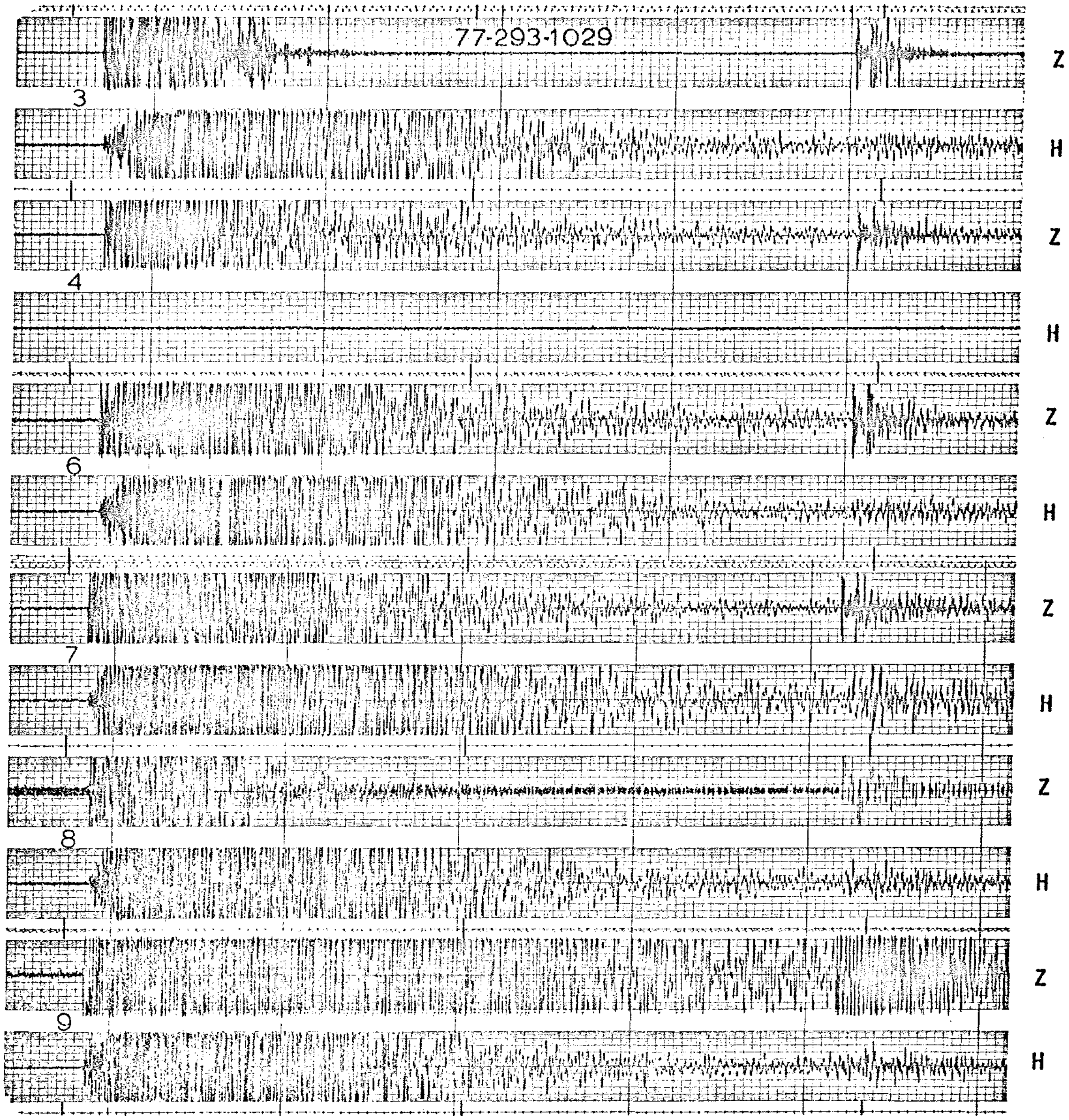
XBL 784-8084

Figure 3. Two small earthquakes in the Brawley swarm. 100 mv/div. These are the smallest locatable events; map symbol H. Time lines 10 sec.



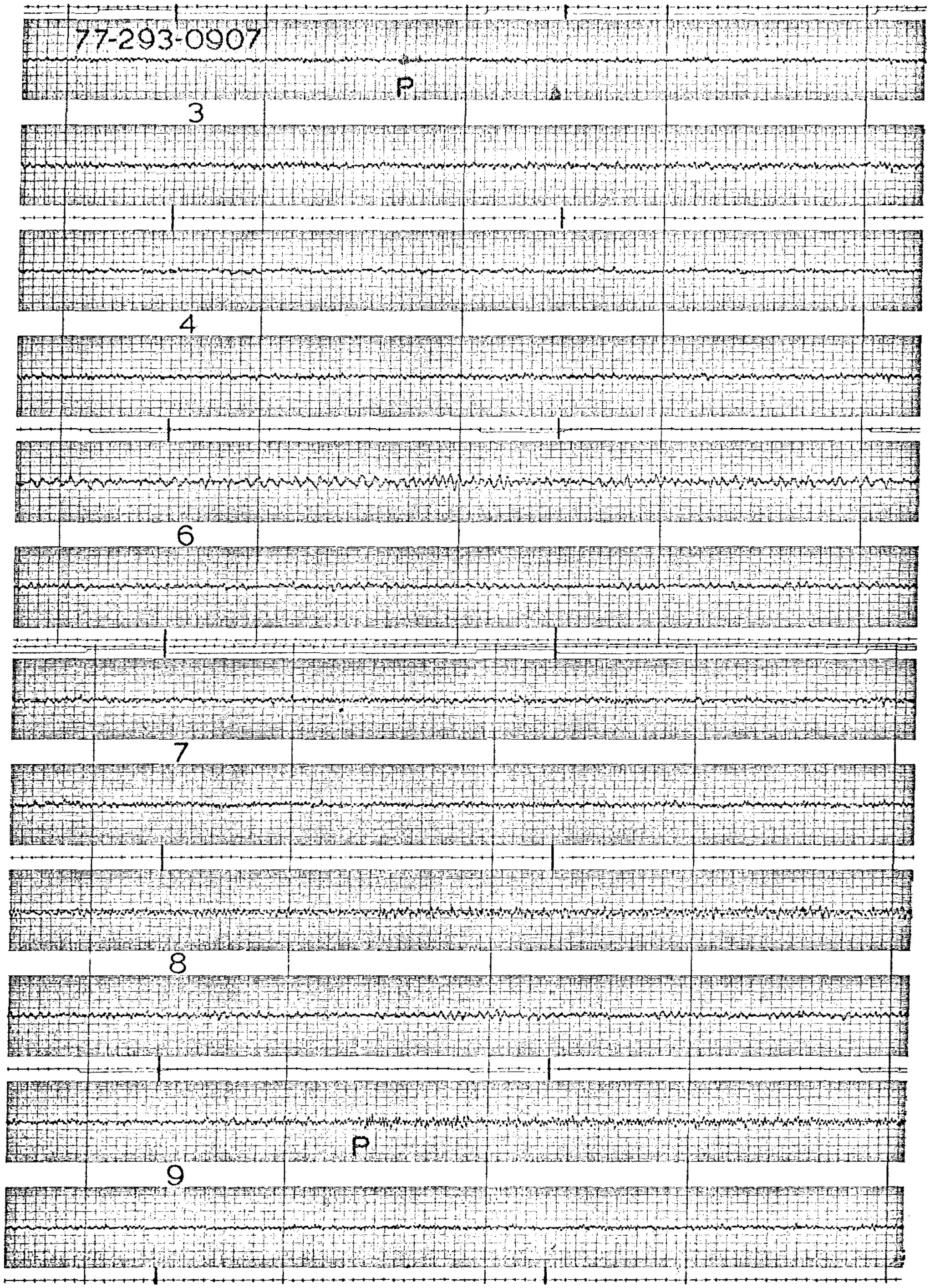
XBL 784-8079

Figure 4. Filter tests on small Brawley swarm event, map symbol 1. Verticals unfiltered at 100 mv/div except 9Z, 200 mv/div. Horizontals at 50 mv/div band-pass filtered 4-10 Hz. Time lines at 10 sec spacing.



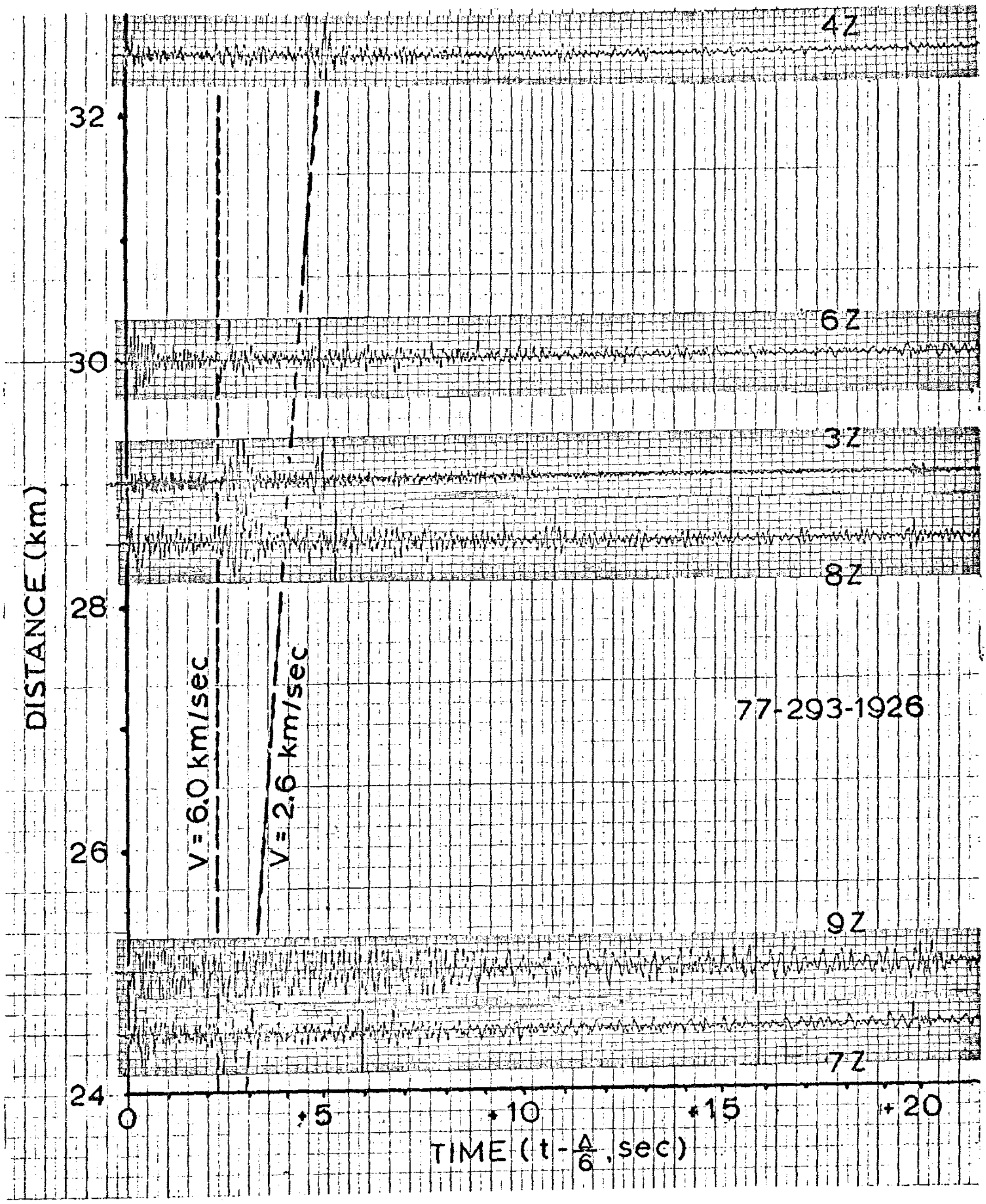
XBL 784-8085

Figure 5. Two Brawley swarm events (first one is magnitude 4.0) illustrating defective vertical seismometers at 3Z and 8Z, reducing low frequency response. Time lines at 1 min spacing. Map symbol G.



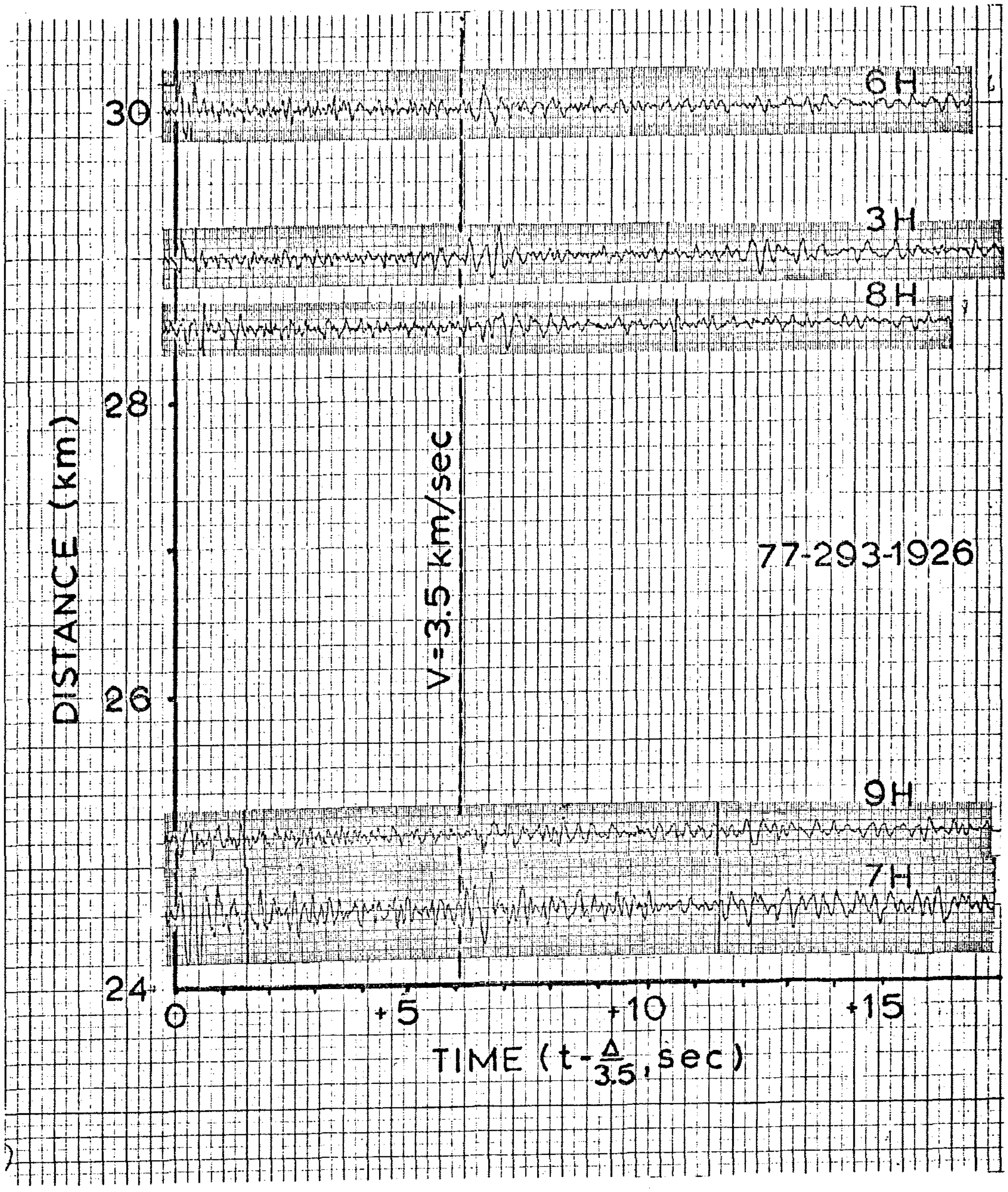
XBL 784-8080

Figure 6. Small event during the 7-hour test period of Brawley swarm (see text), the smallest presently detectable at East Mesa, with visible arrivals only at 3Z and 9Z. 100 mv/div except 9Z at 200 mv/div. 10 sec time marks.



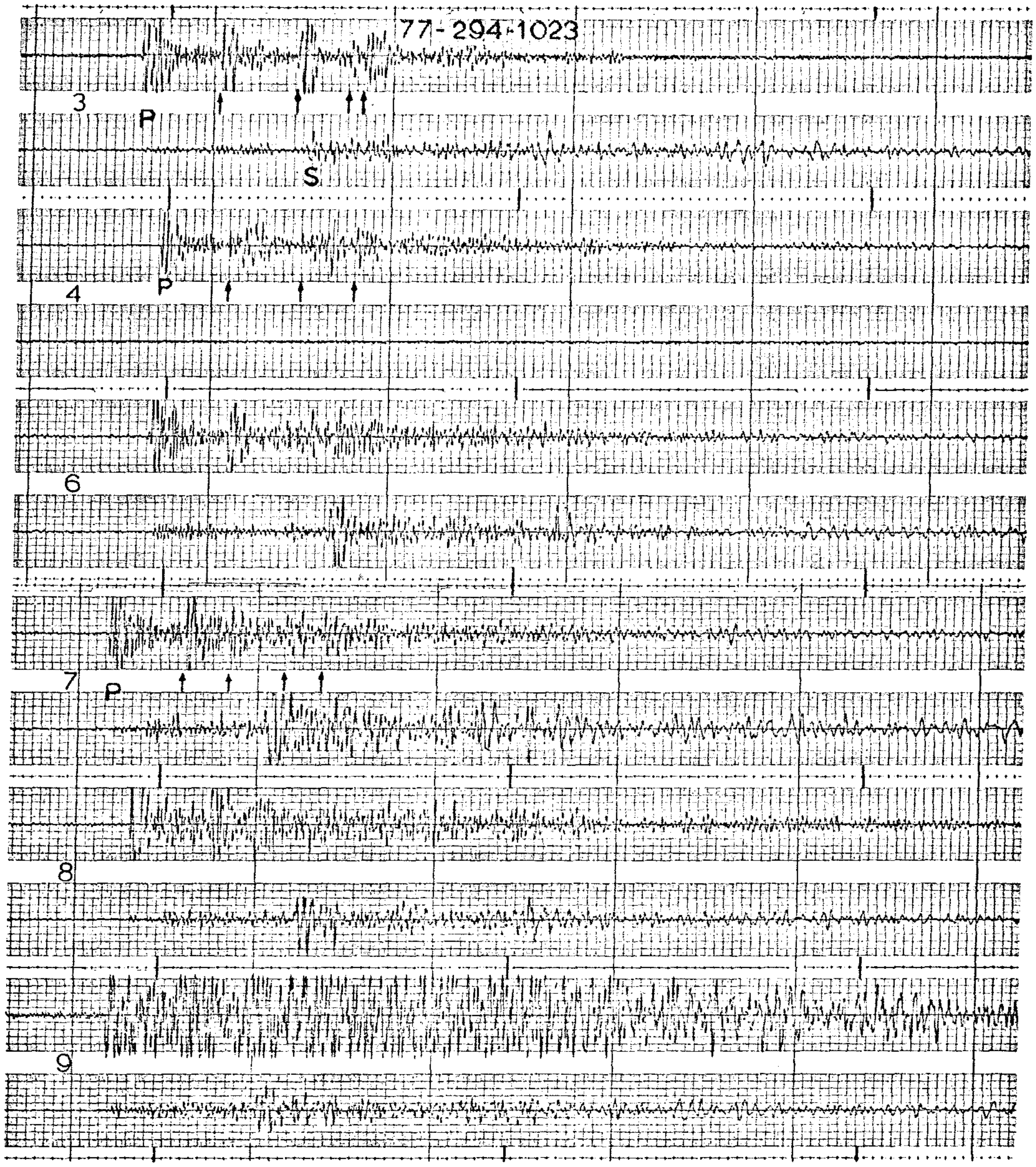
XBL 784-8086

Figure 7. Reduced record section, M=2.8 Brawley event, map symbol G. Vertical components.



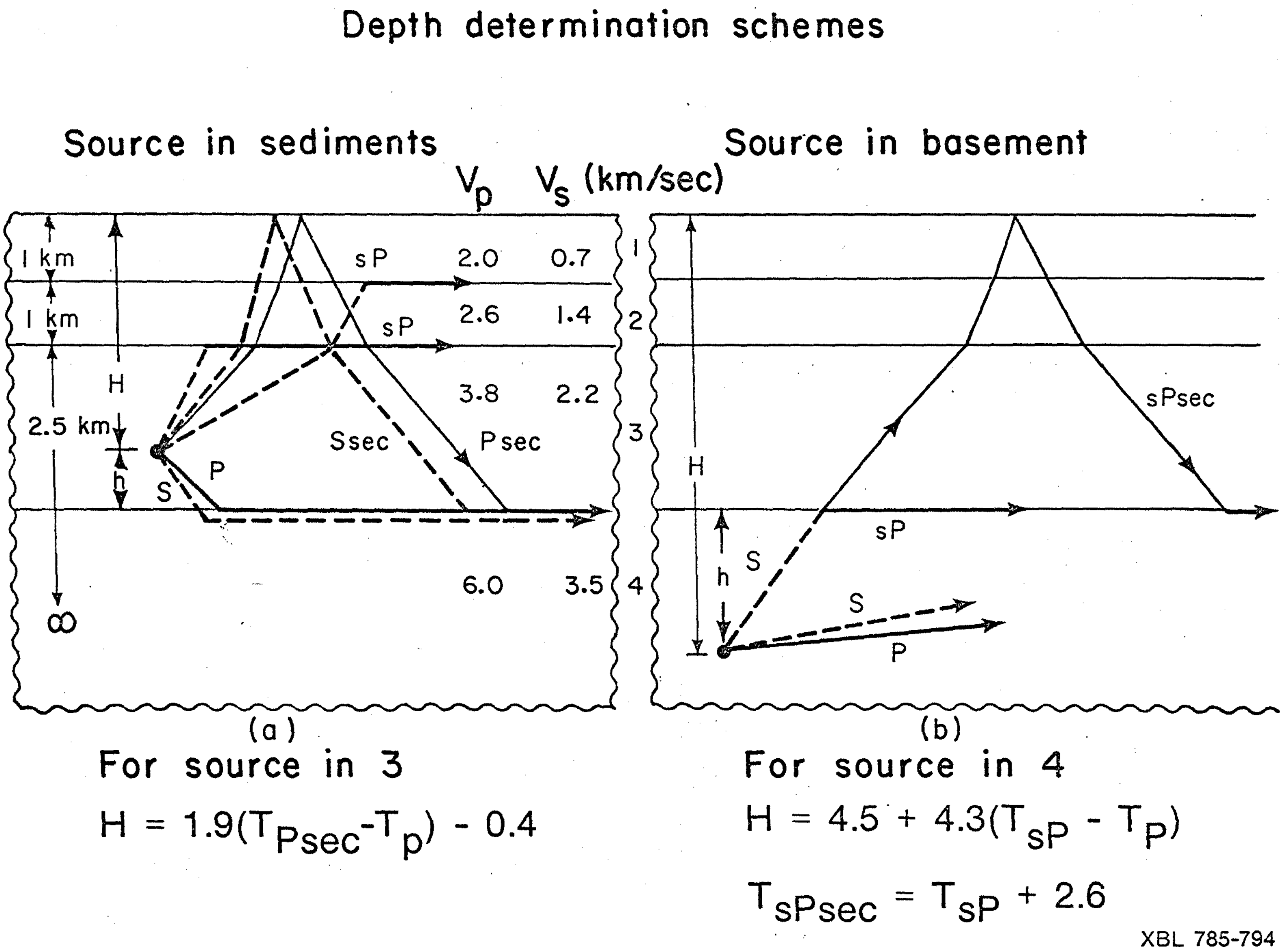
XBL 784-8082

Figure 8. Reduced section as for Figure 7, horizontal components.



XBL 784-8087

Figure 9. Multiple P- and S-wave arrivals for M=2.6 Brawley event, map symbol G.

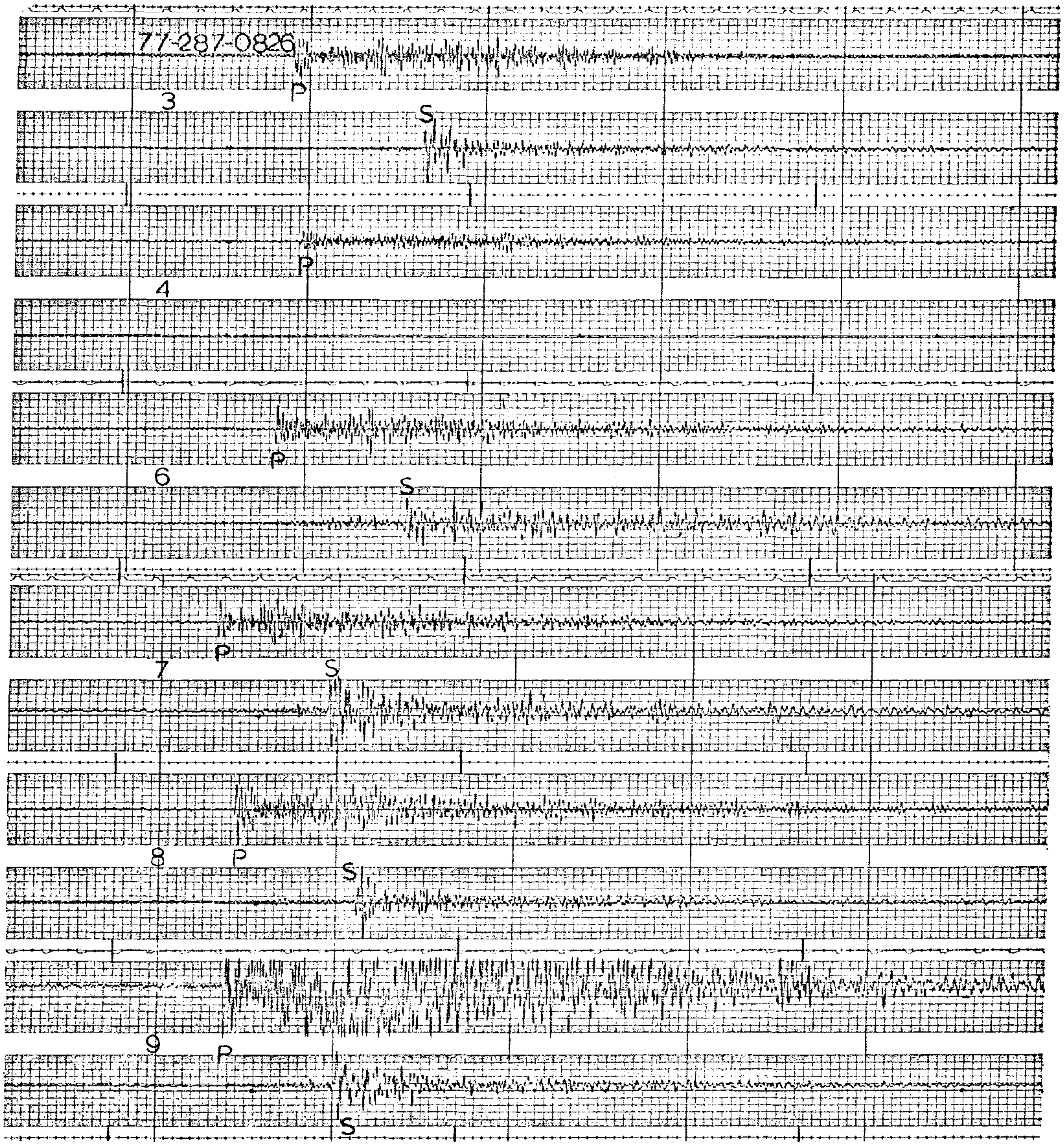


$$H = 1.9(T_{Psec} - T_p) - 0.4$$

$$H = 4.5 + 4.3(T_{sP} - T_P)$$

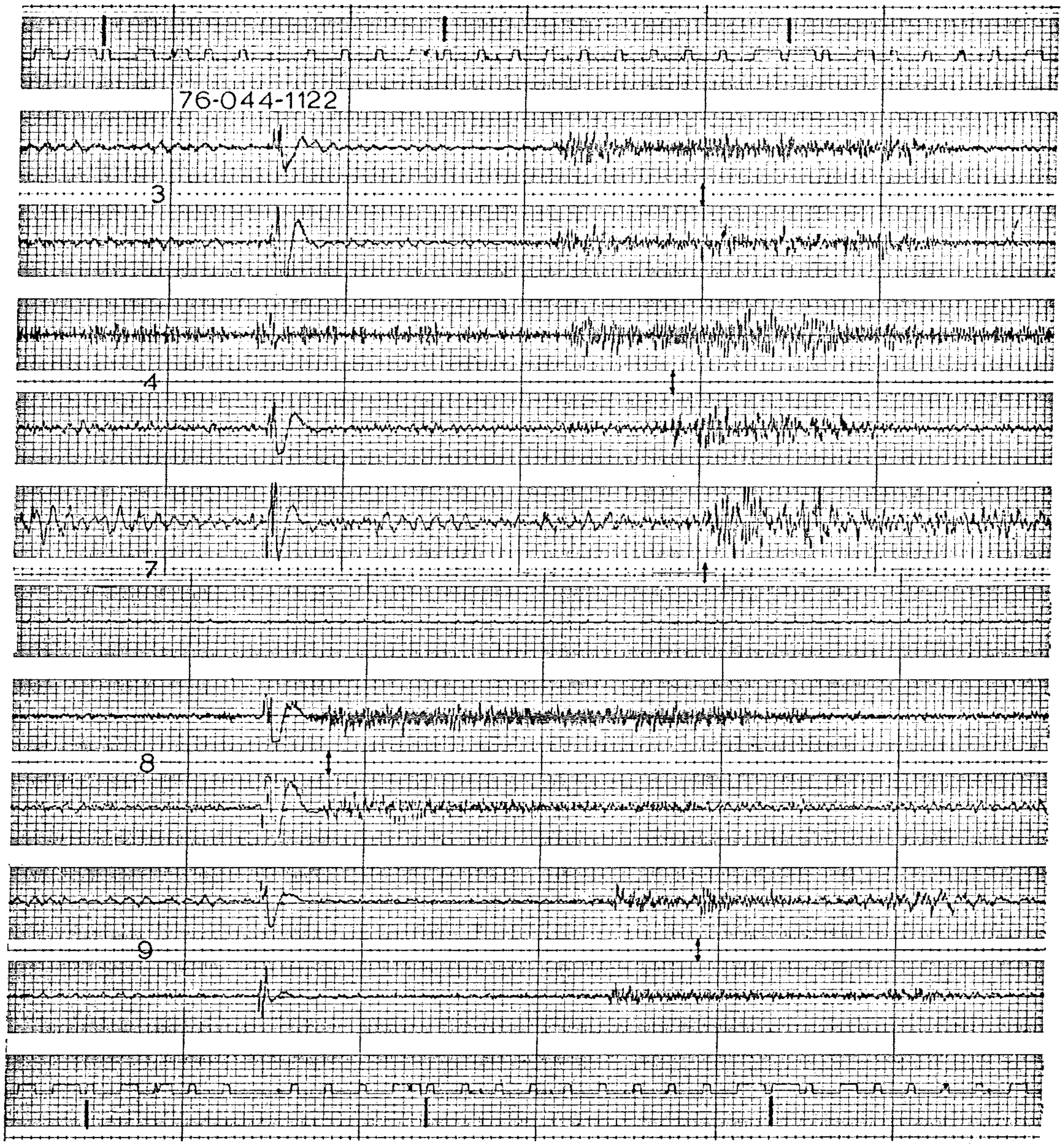
$$T_{sPsec} = T_{sP} + 2.6$$

Figure 10. Possible ray paths and depth relations for secondary arrivals.



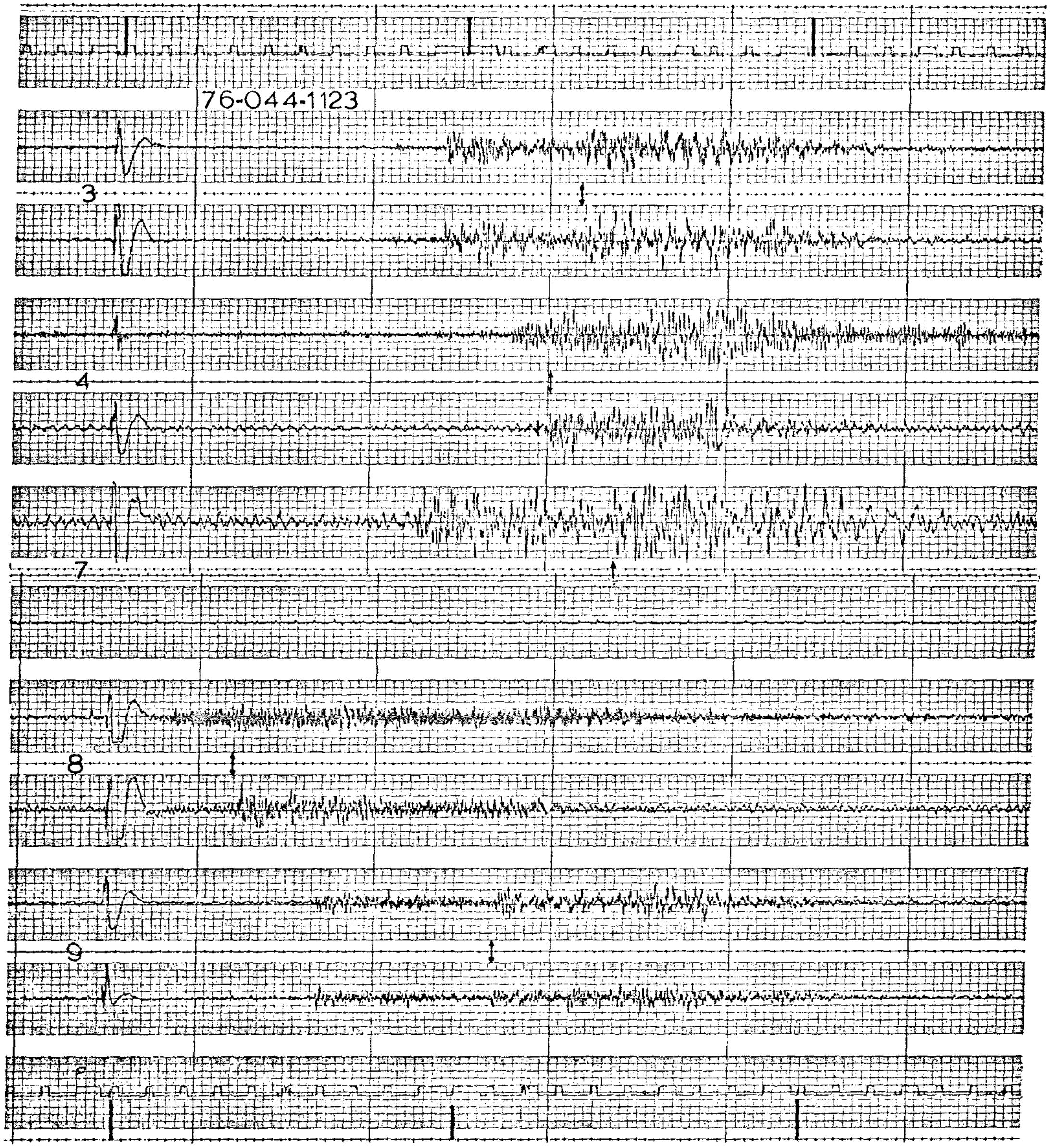
XBL 784-8088

Figure 11. M=2.4 event on Imperial fault, west of East Mesa. Map symbol F.



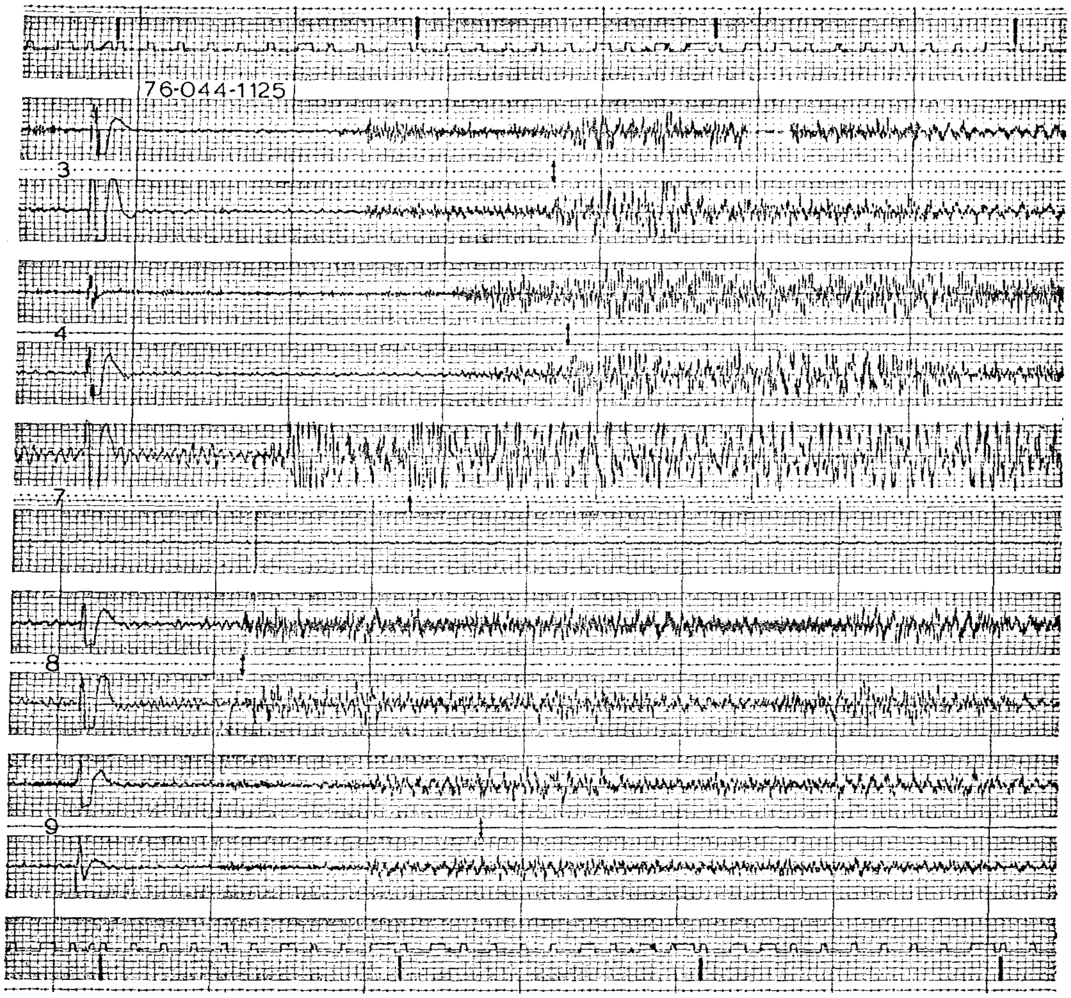
XBL 784-8078

Figure 12. Records for event no. 21 of 13 Feb. 1976 activity, showing RF interference pulses at origin time and arrival of air wave (arrows). 1-sec time code pulses shown top and bottom.



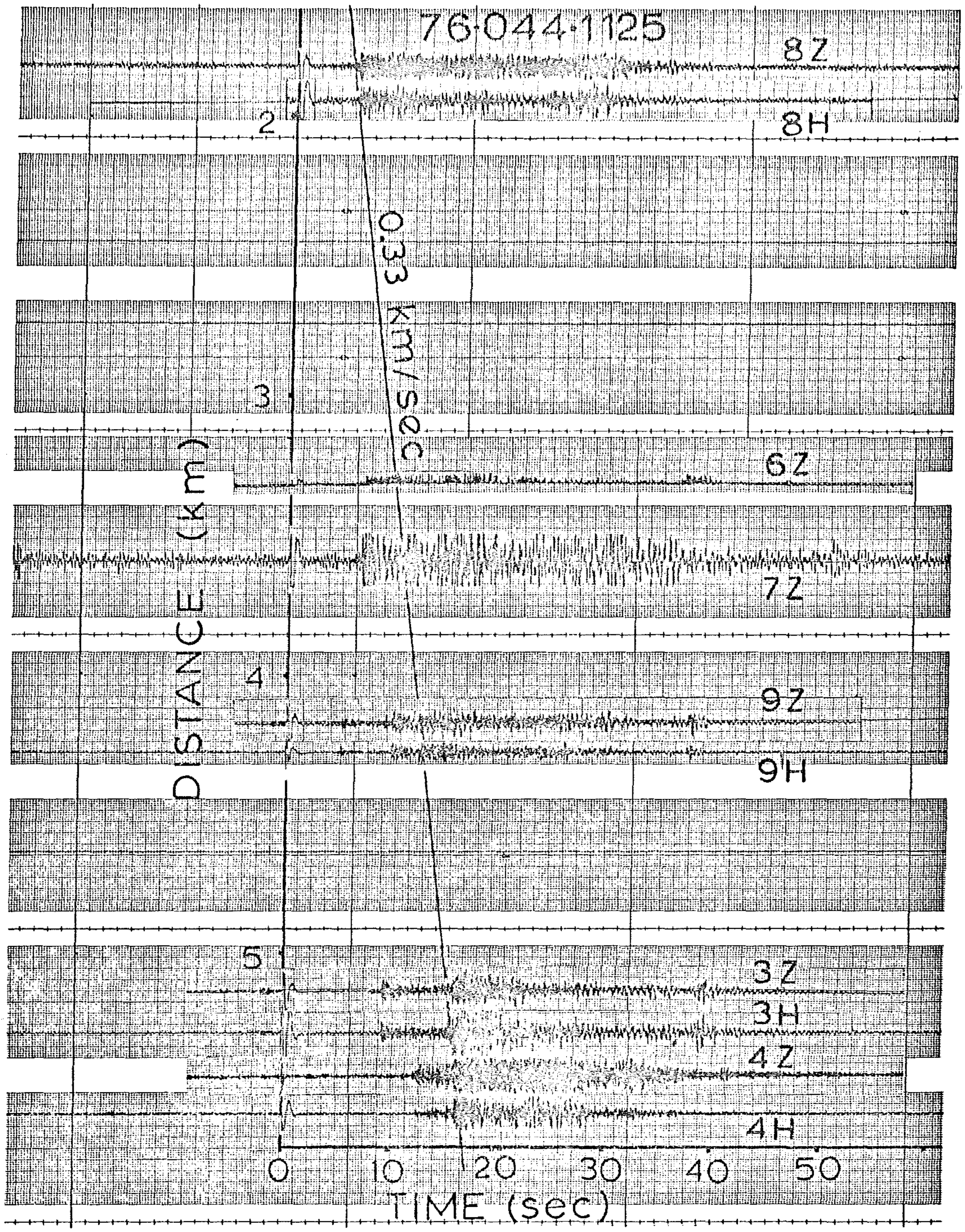
XBL 784-8077

Figure 13. Event no. 22, 13 Feb. 76 activity.



XBL 784-8076

Figure 14. Event no. 23, 13 Feb 76 activity.



XBL 784-8081

Figure 15. Record section for event no. 23, 13 Feb 76, showing apparent air wave at 0.33 km/sec. Played out at 500 mv/div to enhance high frequencies, and at low paper speed to accentuate arrival groups. Compare Figure 14, for same event.

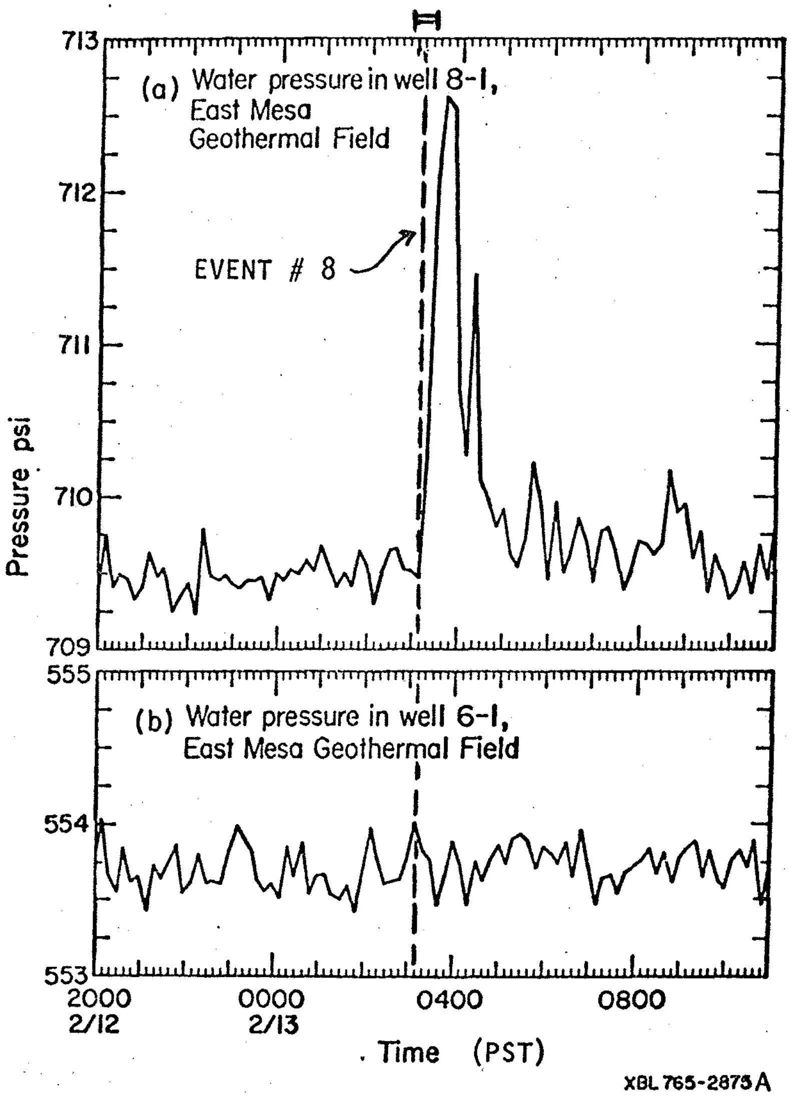


Figure 16. Records of well pressures for wells 8-1 and 6-1 during period of activity on 13 Feb 76. Short bar at top indicates interval of activity recorded on seismic net; vertical dashed line indicates time of event no. 8.