# AN
# INVESTIGATION OF
# THE MILL CREEK EARTHQUAKES OF
# OCTOBER, 1935

by

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fulfillment for the degree of
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## I

## THE PRUPOSE OF THE INVESTIGATION

The purpose of this investigation has been to determine the characteristics of the seismic disturbances which occurred near Mount San Gorgonio, San Bernardino County, California on October 22, October 24, and intermittently thereafter until October 31. The principal shock occurred at 6:47:56.1 Pacific Standard Time on October 24, 1935. Travel-times for several phases have been determined, and the thicknesses of layers for Southern California have been calculated.

## II

## ACKNOWLEDGEMENTS

The writer is grateful for the assistance given to him by Dr. Beno Gutenberg. He wishes also to acknowledge his appreciation to members of the Carnegie Institute Seismological Station staff at Pasadena, California. Dr. Gutenberg personally supervised this study and was in close contact with the work at all times. Messers. Nordquist, Thiele, and Rogers aided the writer in acquainting himself with laboratory technique, the filling systems, and the particular methods used in the routine work at the station. All the data that available in the files was freely used in the investigation.

## III

## DESCRIPTION OF THE SEISMOLOGICAL STATIONS IN SOUTHERN CALIFORNIA

Seismological stations are maintained at Mt. Wilson, Riverside, Santa Barbara, La Jolla, Tinemaha, and Haiwee in addition to the central laboratory at Pasadena as a joint undertaking by the Carnegie Institution of Washington and the California Institute of Technology.

All of the above stations are equipped with vertical Benioff seismometers and with east-west and north-south component Wood-Anderson torsion seismometers. The free periods of the torsion instruments are 0.8 seconds, and the galvanometer period for most instruments is 0.2 seconds. The vertical Benioff instruments have a free period of one to one and a half seconds and have a galvanometer period, in general, of 0.2 seconds. One station, Pasadena, however, has also a galvanometer with a period of thirteen seconds for recording teleseisms. For short waves the magnification on most of the torsion instruments is approximately 3000. About critical damping is used on all instruments. Usually in addition to the regular recording instruments, experimental devices are in operation at Pasadena.

Table I shows the location of the stations and the particular instruments whose records were used in this study. Absolute time signals are recorded at Pasadena three times daily on photographic paper. Time at the other stations is recorded by radio signals from a central broadcasting station.

## TABLE I

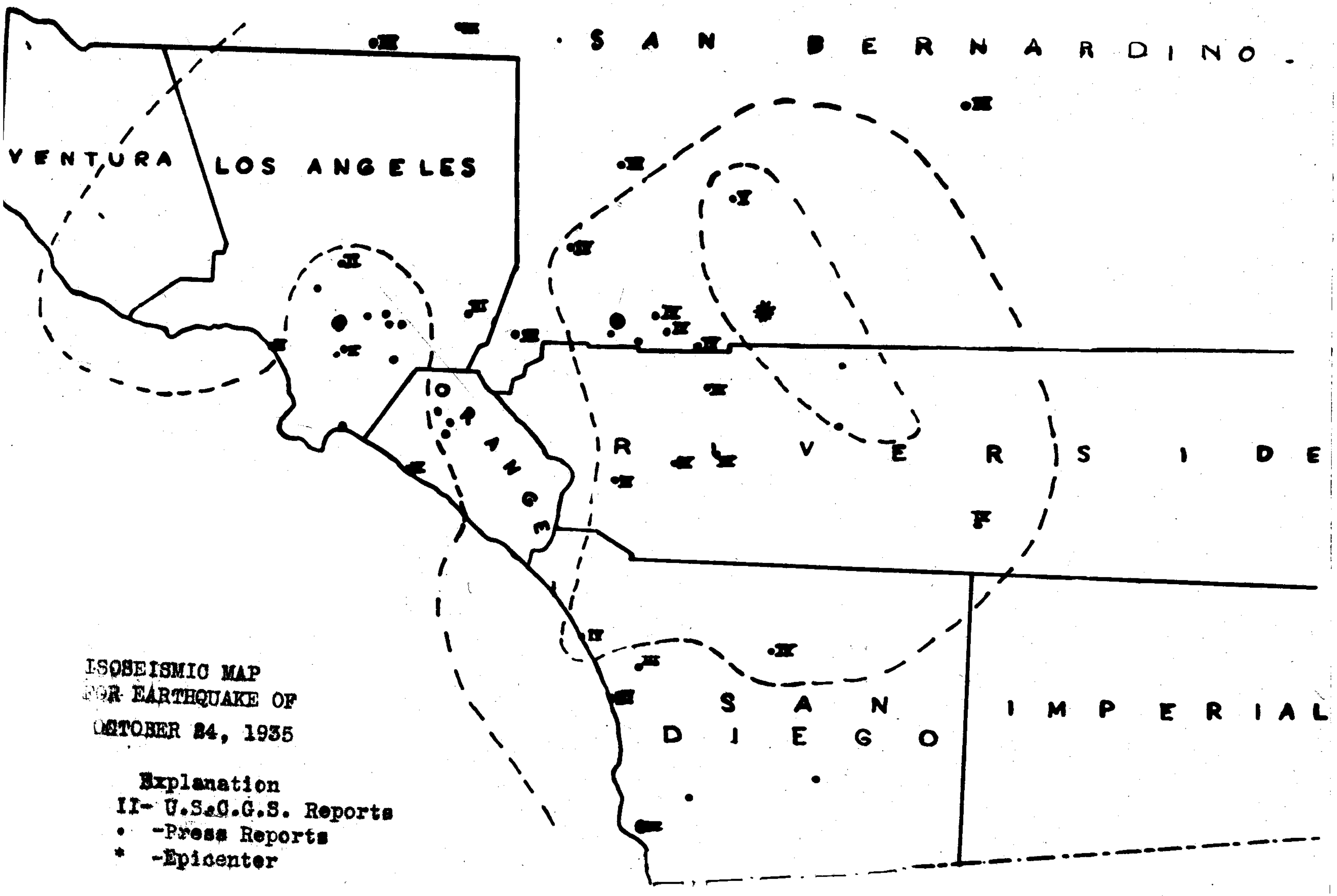
### LIST OF STATIONS AND INSTRUMENTS

| Station | Latitude North | Longtitude West | Elevation (in meters) | Instruments (components used) |
|---|---|---|---|---|
| Pasadena | 34° 08.9' | 118° 10.3' | 295 | North-South |
| Mt. Wilson | 34° 13.5' | 118° 03.4' | 1742 | Vertical |
| Riverside | 33° 59.6' | 117° 22.4' | 250 | Vertical |
| Santa Barbara | 34° 26.6' | 119° 42.8' | 100 | East-West |
| La Jolla | 32° 51.8' | 117° 15.2' | 8 | East-West, North-South |
| Tinemaha | 37° 05.7' | 118° 15.5' | 1180 | Vertical |
| Haiwee | 36° 08.2' | 117° 58.6' | 1100 | Vertical |
| Epicenter | 34° 06' | 116° 48' | | |

## TABLE II

## TABLE SHOWING DISTANCES FROM EPICENTER AND FOUNDATION ROCKS FOR SOUTHERN CALIFORNIA STATIONS

| STATION | DISTANCE FROM EPICENTER (in kilometers) | FOUNDATION ROCK |
|---|---|---|
| Riverside | 55 | Weathered granite |
| Mt. Wilson | 118 | Weathered granite |
| Pasadena | 128 | Weathered granite |
| La Jolla | 144 | Consolidated detrital material |
| Haiwee | 247 | Loosely cemented tuff |
| Santa Barbara | 265 | Alluvium |
| Tinemaha | 355 | Basalt |



ISOSEISMIC MAP
FOR EARTHQUAKE OF
OCTOBER 24, 1935

Explanation
II- U.S.C.G.S. Reports
• -Press Reports
* -Epicenter

# IV

# THE SHOCKS

## A. General Features.

The particular earthquake which is the object of this investigation occurred in a period of seismic activity marked by a number of mild earthquakes. It was preceded by several foreshocks and was followed by a great many aftershocks lasting for several days. All of these shocks exhibit the same general pattern and are distinguished largely by differences of amplitude from the seismograms. The most intense shock of this swarm, occurring at 6:48 Pacific Standard Time on October 24, was studied in detail. A total of at least ninety-eight seperate shocks were observed in this swarm beginning on October 22 and terminating on October 31. No shocks were noted on October 27 or October 29, but one or more shocks were noted on all other days. The greatest number of shocks to occur on a single day, were noted on October 24 when 83 shocks were recorded following the most intense shock. Table III includes all of the important shocks observed in this swarm.

## B. Isoseismic Map.

The information reported to the laboratory by the Coast and Geodetic Survey and the Press Surveys have been useful in plotting an isoseismic map showing the regions of varying intensities of destruction related to the shock.

The most intense disturbance was reported from Lucerne Valley where an earthquake of intensity V (Rossi-Forel Scale) was observed. San Bernardino and Coachella Valley areas reported intensities of IV. In general, the epicenter can be assigned to the San Bernardino Mountain area on the basis of the surveys. The accompanying map shows the approximate boundaries of the zones of increasing intensity toward the epicenter.

C. Epicenter.

A special effort was made to obtain accurate time corections for this shock so that a precise epicenter might be determined. The time of the shock was very favorable for the purpose coming near the time signal.

Mr. Rogers determined the epicenter at 34 degrees and 6 minutes of north latitude and 116 degrees and 48 minutes of south longtitude. This location is estimated to be within 15 kilometers of the epicenter and places the disturbance on the Mill Creek Fault, San Bernardino County, California. The position of this active seismic area suggests that the uplift responsible for Mount San Gorgonio is lifting the highest mountain in Southern California to new heights. All of the shocks have been assigned to the same epicenter.

D. Notes on the geology near the epicenter.

The Mill Creek-Mission Creek Fault is a steep thrust fault according to F.E. Vaughan*. The ridge north of Mill Creek has been displaced, at least, 5000 feet above the floor of the San Bernardino Valley. The present floor of valley is not part of the old surface which was once continuous with the mountains but is heavily alluviated. The old surface is buried beneath alluvium south of the fault. Because of the undetermined thickness of alluvium it is impossible to obtain a satisfactory estimate of the vertical displacement of the uplifted blocks. The fault plane is not well exposed in Mill Creek Canyon and is difficult to trace. The rocks on both sides of the fault are schists. Eastward in the Mission Creek area, there are several good exposures of the fault plane.

The area in which the epicenter lies is practically uninhabited. The ridge forming San Gorgonio and San Bernardino peaks was uplifted by movements on both the San Andreas and Mill Creek faults. To the northwest only the San Andreas fault appears to have been active while south of Dry Morongo Creek the Mission Creek Fault has been the more active in recent times.

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*Vaughan, F.E., "Geology of the San Bernardino Mountains north of San Gorgonio Pass", Univ. of Calif. Publ's. Geol. Sci., Vol. 13, No. 9, pgs. 319-411, 1922.

### E. Foreshocks and aftershocks.

In Table III are listed most of the important aftershocks and foreshocks. The first disturbance was recorded on October 22 at 7:00:41.9 Pacific Standard Time at Pasadena. This was followed by a second shock~~s~~ at 14:37 Pacific Standard Time on the same day. October 23 was relatively inactive. Beginning at 6:48 Pacific Standard Time on October 24 there occurred at least 81 shocks from the same epicenter during the remaining hours of that day. The relative magnitudes* of the principal foreshocks and aftershocks are shown in Table IV. The increasing magnitudes of the foreshocks are followed by the somewhat irregular descending magnitudes of successive aftershocks. The maximum magnitude was observed in the shocks at 6:48 Pacific Standard Time on October 24 and in several shocks shortly thereafter from the same epicenter with magnitudes of 5 and 4½ respectively. A total of 98 seperate shocks were observed from this epicenter from October 22 to October 31.

### F. Periodicity of shocks.

A frequency chart has been plotted showing the number of shocks occurring within successive five minute intervals between 6:50 Pacific Standard Time and 13:00 Pacific Standard Time on October 24. In general, there appears to

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* Richter, C.F., "An Instrumental Magnitude Scale". Bull. Seism. Soc. Amer., Vol. 25, No. 1.

## TABLE LII

## COMPLETE LIST OF SHOCKS FROM THE MILL CREEK EPICENTER FOR OCTOBER

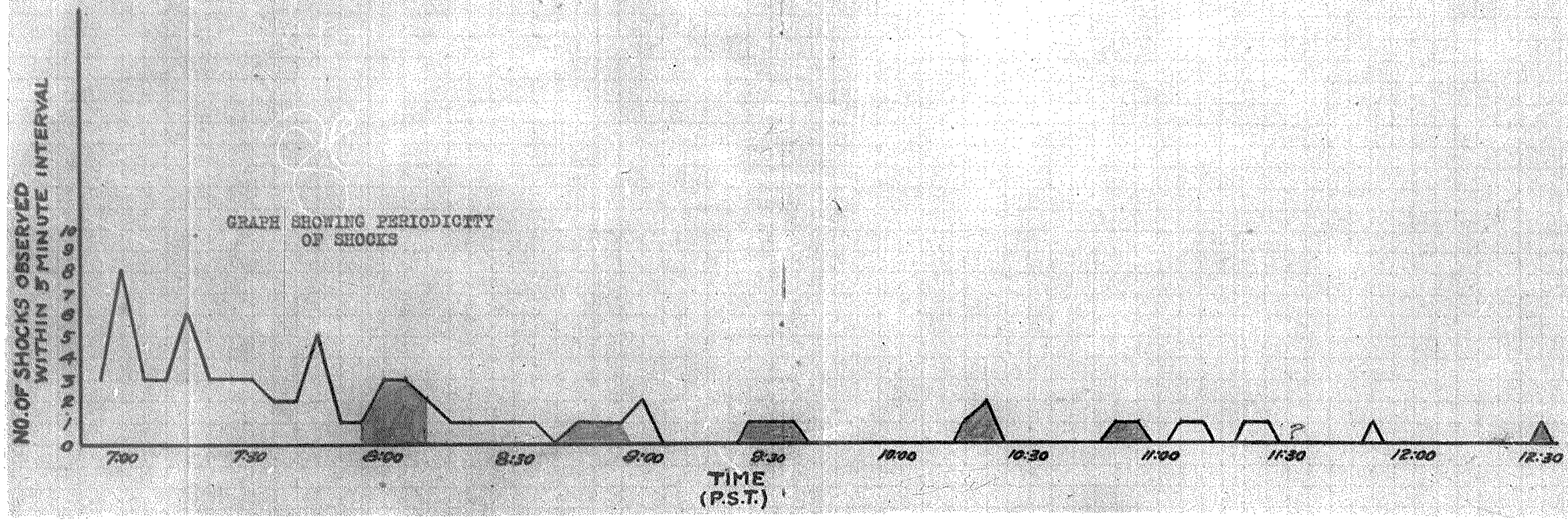
| | Time of Shock (P.S.T.) |
|---|---|
| October 22 | 07:00 |
| | 14:37 |
| October 24 | 06:48 |
| | 06:51 |
| | 06:52 |
| | 06:54 |
| | 06:55 |
| | 06:55 |
| | 06:55 |
| | 06:55 |
| | 06:57 |
| | 06:58 |
| | 06:59 |
| | 06:59 |
| | 07:00 |
| | 07:02 |
| | 07:03 |
| | 07:05 |
| | 07:06 |
| | 07:09 |
| | 07:10 |
| | 07:10 |
| | 07:11 |
| | 07:11 |
| | 07:12 |
| | 07:13 |
| | 07:16 |
| | 07:17 |
| | 07:18 |
| | 07:20 |
| | 07:22 |
| | 07:23 |
| | 07:25 |
| | 07:26 |
| | 07:27 |
| | 07:30 |
| | 07:34 |
| | 07:37 |
| | 07:43 |
| | 07:44 |
| | 07:45 |
| | 07:46 |
| October 24 | 07:47 |
| | 07:48 |
| | 07:52 |
| | 07:55 |
| | 08:00 |
| | 08:00 |
| | 08:01 |
| | 08:01 |
| | 08:02 |
| | 08:05 |
| | 08:06 |
| | 08:10 |
| | 08:13 |
| | 08:16 |
| | 08:21 |
| | 08:28 |
| | 08:31 |
| | 08:35 |
| | 08:48 |
| | 08:52 |
| | 08:57 |
| | 09:03 |
| | 09:04 |
| | 09:26 |
| | 09:31 |
| | 09:35 |
| | 10:18 |
| | 10:20 |
| | 10:24 |
| | 10:54 |
| | 10:56 |
| | 11:07 |
| | 11:24 |
| | 11:11 |
| | 11:28 |
| | 11:52 |
| | 12:30 |
| | 12:54 |
| | 16:12 |
| | 16:22 |
| | 17:23 |
| | 18:02 |
| | 19:10 |
| October 24 | 20:33 |
| | 22:18 |
| | 23:41 |
| | 23:50 |
| October 25 | 00:17 |
| | 00:56 |
| | 02:09 |
| | 03:56 |
| | 04:18 |
| | 04:38 |
| | 04:58 |
| | 08:08 |
| | 08:53 |
| | 12:38 |
| | 12:40 |
| | 12:59 |
| | 23:40 |
| October 26 | 00:01 |
| | 01:14 |
| | 03:47 |
| October 28 | 18:18 |
| October 30 | 08:15 |
| | 22:29 |
| October 31 | 01:20 |

be a marked periodicity of shocks at 43 minute intervals with the beginning centered on 8:05 Pacific Standard Time and lasting until 10:50 Pacific Standard Time. After this hour, the periodicity is no longer evident. Moreover, swarms, exhibiting this characteristic period, last for approximately 15 minutes and are preceded and followed by calm periods. Between 9:30 and 10:30 Pacific Standard Time the best defined period is observed. At other times, irregular frequency maximum are to noted but are difficult to interpret.

## TABLE IV

### PRINCIPAL FORESHOCKS AND AFTERSHOCKS OF THE EARTHQUAKE OF OCTOBER 24

| Date | P.S.T. | Magnitude |
|---|---|---|
| October 22 | 07:00 | 3.5 |
| | 10:37 | 4 |
| October 24 | 06:48 | 5 |
| | 06:51 | 4.5 |
| | 06:52 | 4.5 |
| | 06:57 | 3 |
| | 07:06 | 3 |
| | 07:15 | 3.5 |
| | 07:26 | 3 |
| | 07:27 | 4 |
| | 07:30 | 2 |
| | 07:43 | 2.5 |
| | 07:52 | 2.5 |
| | 08:02 | 2.5 |
| | 08:16 | 3 |
| | 08:35 | 2.5 |
| | 10:24 | 2.5 |
| | 11:11 | 2.5 |
| | 16:22 | 3 |
| | 23:50 | 3 |
| October 25 | 00:17 | 2.5 |
| | 08:53 | 3 |
| October 26 | 01:14 | 2 |
| October 31 | 01:20 | 2.5 |



GRAPH SHOWING PERIODICITY OF SHOCKS

## V

## TRAVEL-TIME CURES FOR WAVES

All observed inflections, marked changes in amplitude, and sudden changes in period are listed in Table V. The direct readings of the seismograms and the corrected P.S.T., of the various tremors are recorded with symbols to indicate the phases determined from the travel-time curves. Minute marks are automatically placed on all of the seismograms, and in reading the records the attempt is made to read the seismograms to the nearest tenth of a second. At the distant stations, the initial impulses of the phases are less definite, and for this reason the seismograms at considerable distances from the epicenter are sometimes very difficult to interpret. On the Santa Barbara records, the phases are the most difficult to recognize for the Mill Creek earthquakes.

| Stations | Distances to Epicenter in Kilometers |
|---|---|
| Riverside | 55 |
| Mt. Wilson | 118 |
| Pasadena | 128 |
| La Jolla | 144 |
| Haiwee | 247 |
| Santa Barbara | 265 |
| Tinemaha | 355 |

A. The $\overline{P}$-waves.

The corrected P.S.T., readings were then plotted against time, and a preliminary travel-time curve obtained. It was found necessary to shift the time scale to a new base, so that travel-time values could be read directly from the graph. Before the second travel-time curve was drawn, an attempt was made to interpret the data. Travel-time curves were drawn for Px, Py, Pm , as well as $\overline{P}$.

The origin time was obtained by dividing the observed travel-times of the $\overline{P}$-waves minus the distance by 5.64 where the distance is expressed in kilometers.

| Station | Distance in Kilometers | $\frac{\Delta}{5.64}$ | P obs. | Pobs.- $\frac{\Delta}{5.64}$ | Dif |
|---|---|---|---|---|---|
| Mt. Wilson | 118 | 20.9 | 28.9 | 8.0 | -0. |
| Pasadena | 129 | 28.9 | ---- | ---- | --- |
| La Jolla | 144 | 25.6 | 33.9 | 8.3 | +0. |
| Haiwee | 247 | 43.8 | 52.4 | 8.6 | +0. |
| Tinemaha | 356 | 63.2 | 71.2 | 8.0 | -0. |
|  |  |  | Average | 8.2 |  |

The average value for P obs. - $\frac{\Delta}{5.64}$, 8.2, is the value which should be used in shifting the time scale to the zero origin time. The differences listed in the last column represent the variations of P obs. - $\frac{\Delta}{5.64}$ from the average value, 8.2.

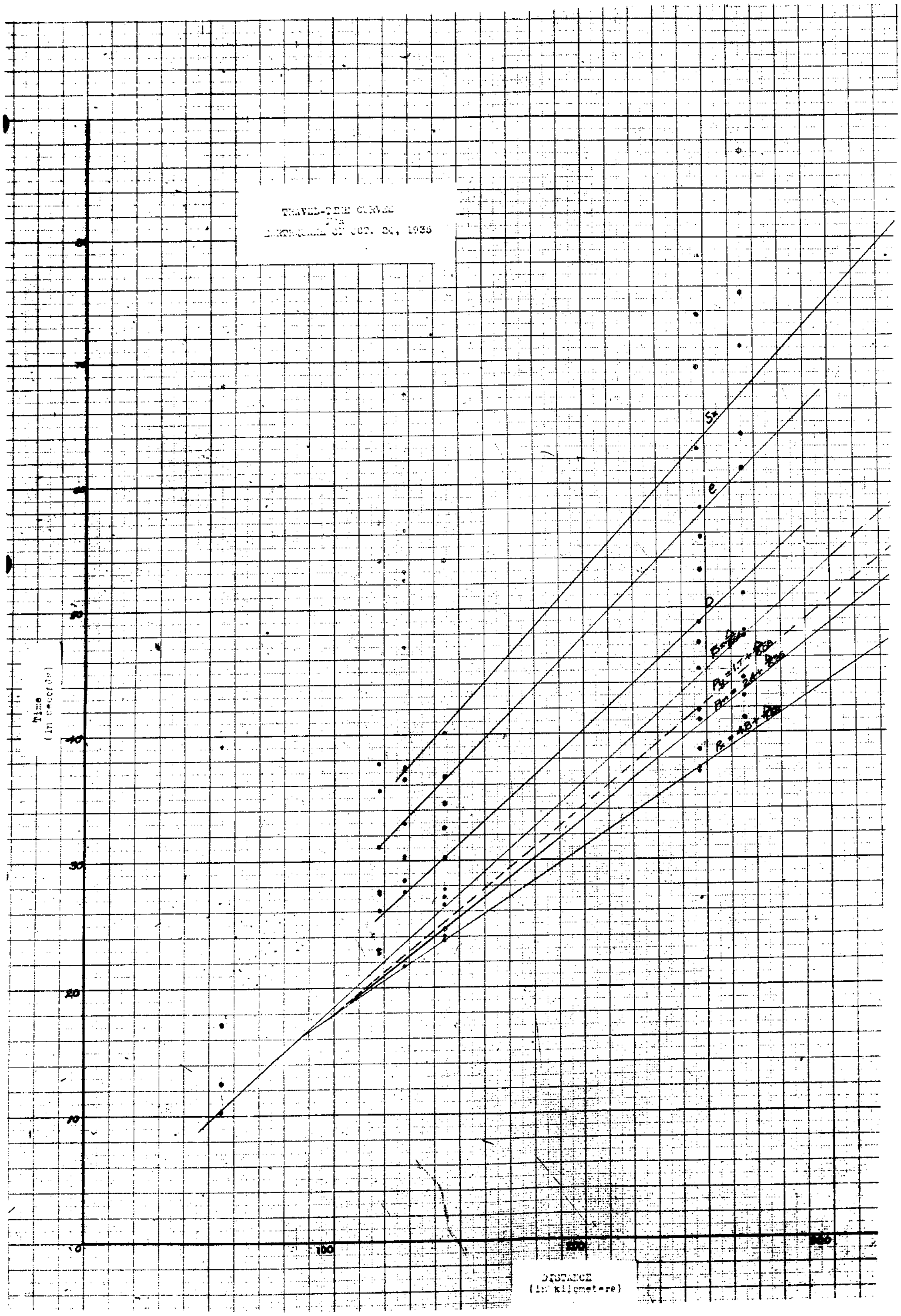
## TABLE V

### DIRECT READINGS AND CORRECTED P.S.T., OF OBSERVED PHASES

### October 24, 1935

| Station | Phase | Direct Reading | Corrected P.S.T. |
|---|---|---|---|
| Riverside | (1) $\bar{P}$ | 07:11:30.3 | 06:48:17.8 |
| | (2) | 07:11:32.6 | 06:48:20.1 |
| | (3) S | 07:11:37.2 | 06:48:24.7 |
| | (4) | 07:11:59.2 | 06:48:46.7 |
| | (5) | 07:12:28.2 | 06:49:15.7 |
| Mt. Wilson | (1) $\underline{P}$x | 06:48:48.1 | 06:48:28.4 |
| | (2) $\underline{P}$y | 06:48:48.6 | 06:48:28.9 |
| | (3) $\bar{P}$ | 06:48:48.9 | 06:48:29.2 |
| | (4) | 06:48:49.9 | 06:48:30.2 |
| | (5) | 06:48:50.2 | 06:48:30.5 |
| | (6) | 06:48:53.3 | 06:48:33.6 |
| | (7) | 06:48:54.6 | 06:48:34.9 |
| | (8) | 06:48:54.8 | 06:48:35.1 |
| | (9) e | 06:48:58.3 | 06:48:38.6 |
| | (10) S | 06:49:02.8 | 06:48:43.1 |
| | (11) | 06:49:04.9 | 06:48:45.2 |
| Pasadena | (1) Px | 06:48:46.5 | 06:48:29.2 |
| | (2) Pm | 06:48:47.1 | 06:48:29.8 |
| | (3) | 06:48:52.3 | 06:48:35.0 |
| | (4) D | 06:48:53.2 | 06:48:35.9 |
| | (5) | 06:48:54.9 | 06:48:37.6 |
| | (6) | 06:48:55.1 | 06:48:37.8 |
| | (7) | 06:48:57.8 | 06:48:40.5 |
| | (8) | 06:49:01.2 | 06:48:43.9 |
| | (9) | 06:49:01.9 | 06:48:44.6 |
| | (10) Sx | 06:49:02.2 | 06:48:44.9 |
| | (11) | 06:49:11.8 | 06:48:54.5 |
| | (12) | 06:49:17.1 | 06:48:59.8 |
| La Jolla | (1) $\underline{P}$x | 07:00:55.4 | 06:48:31.2 |
| | (2) $\bar{P}$ | 07:00:55.7 | 06:48:31.5 |
| | (3) $\underline{P}$m | 07:00:56.2 | 06:48:32.0 |
| | (4) $\bar{P}$ | 07:00:58.2 | 06:48:34.0 |
| | (5) | 07:00:58.8 | 06:48:34.6 |
| | (6) | 07:00:59.4 | 06:48:35.2 |
| | (7) D | 07:01:02.1 | 06:48:37.9 |
| | (8) | 07:01:04.3 | 06:48:40.1 |
| | (9) | 07:01:06.2 | 06:48:42.0 |
| | (10) e | 07:01:08.4 | 06:48:44.2 |
| | (11) | 07:01:11.6 | 06:48:47.4 |
| | (12) S | 07:01:11.8 | 06:48:47.6 |
| | (13) | 07:01:25.6 | 06:49:01.4 |

| Station | Phase | Direct Reading | Corrected P.S.T. |
|---|---|---|---|
| Haiwee | | | |
| | (1) | 07:00:10.0 | 06:48:44.4 |
| | (2) Px | 07:00:10.3 | 06:48:44.7 |
| | (3) | 07:00:11.8 | 06:48:46.2 |
| | (4) Pm | 07:00:14.1 | 06:48:48.5 |
| | (5) $\overline{P}$ | 07:00:14.9 | 06:48:49.3 |
| | (6) | 07:00:18.2 | 06:48:52.6 |
| | (7) | 07:00:20.3 | 06:48:54.7 |
| | (8) | 07:00:21.9 | 06:48:56.3 |
| | (9) | 07:00:26.1 | 06:49:00.5 |
| | (10) | 07:00:88.8 | 06:49:03.2 |
| | (11) e | 07:00:31.1 | 06:49:05.5 |
| | (12) Sx | 07:00:35.7 | 06:49:10.1 |
| | (13) | 07:00:46.8 | 06:49:21.2 |
| Santa Barbara | | | |
| | (1) | 06:26:54.2 | 06:48:48.6 |
| | (2) | 06:26:56.0 | 06:48:50.4 |
| | (3) Pm | 06:26:57.5 | 06:48:51.9 |
| | (4) $\overline{P}$ | 06:27:00.8 | 06:48:55.2 |
| | (5) | 06:27:04.1 | 06:48:58.5 |
| | (6) | 06:27:14.2 | 06:49:08.6 |
| | (7) e | 06:27 27.1 | 06:49:11.5 |
| | (8) Sx | 06:27:24.2 | 06:49:18.6 |
| | (9) | 06:27:28.5 | 06:49:22.9 |
| | (10) | 06:27:35.1 | 06:49:29.5 |
| Tinemaha | (1) Px | 06:19:08.7 | 06:48:59.1 |
| | (2) | 06:19:09.1 | 06:48:59.5 |
| | (3) | 06:19:09.2 | 06:48:59.6 |
| | (4) | 06:19:10.2 | 06:49:00.6 |
| | (5) | .06:19:11.9 | 06:49:02.3 |
| | (6) | 06:19:12.9 | 06:49:03.3 |
| | (7) Py | 06:19:14.0 | 06:49:04.4 |
| | (8) | 06:19:16.8 | 07:49:07.2 |
| | (9) $\overline{P}$ | 06:19:18.6 | 07:49:09.0 |
| | (10) | 06:19:26.2 | 07:49:16.6 |
| | (11) e | 06:19:33.1 | 07:49:23.5 |
| | (12) Sx | 06:19:44.2 | 07:49:34.6 |
| | (13) | 06:19:46.0 | 07:49:36.4 |



TRAVEL-TIME CURVES
for
EARTHQUAKE OF OCT. 24, 1935

The observed differences may be due to inability to determine the precise beginning of shocks at the stations the greatest distances from the epicenter, and they may be complicated by the local geology in the vicinity of the various stations. The seismogram for Riverside is difficult to interpret because of the close proximity of the epicenter. As pointed out by Gutenberg*, $\overline{P}$-waves are late arriving due to sedimentary layers near the coast, and at long distances the waves arrive too early due to the earth's curvature and the increase of velocity with depth. After considering these factors, no further corrections were deemed necessary.

The velocity, 5.64 kilometers per second for $\overline{P}$, compares with 5.55 kilometers per second, a mean value obtained by Dr. Gutenberg for Southern California from a number of observations. He found slightly higher values for shocks away from the coast, usually in excess of 5.6 kilometers per second.

B. Px, Py, and Pm waves.

Three other waves were recognized Px, Py, and Pm. Pn was not evident on most of the seismograms, and therefore it was impossible to plot a travel-time curve for this wave. The Px waves have a large vertical component and, in general, showed

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* Gutenberg, B., "Travel-time curves at small distances and wave velocities in Southern California". Gerlands Beitrage zur Geophysik, Vol. 35, p. 6-50, 1932.

strong movement on the vertical instruments. The travel-time curves are drawn as estimated mean free paths between successive points. The velocity of these waves are determined directly from the slope of the travel-time curves. The equations for all longitudinal waves follow.

$$\bar{P} = \frac{\Delta}{5.64} \qquad Py = 1.7 + \frac{\Delta}{6.08}$$

$$Pm = 2.4 + \frac{\Delta}{6.36} \qquad Px = 4.8 + \frac{\Delta}{7.58}$$

In general, the constant terms are smaller in all of these equations than might be expected from the results of previous investigations.

C. The S-waves and surface waves.

An attempt was made to determine the various S-waves, but it is very difficult to join in a satisfactory manner the points selected as representing new phases since they are superimposed on earlier waves. The only distinct S-wave appears to be Sx whose equation is $4.3 + \frac{\Delta}{4.32}$ ; however both the constant term and the velocity are low for this wave. There are indications that other phases are represented, but it is difficult to work with them since the results generally unsatisfactory. No attempt was made to determine the velocities or equations of the surface waves.

## VI

## THE DEPTH OF FOCUS

The following equations were used to determine the depth of focus, h.

$$h^2 = (tv)^2 + \Delta^2$$

$$t = \frac{\Delta}{v} + d$$

$$\text{or, } h^2 = vd(vd + 2\ ) = \text{Ca. } 2vd$$

Using the appropriate values for Riverside, the nearest station to the epicenter, the depth of focus is 13.6 kilometers.

$$h = \sqrt{2(0.3)(5.64)(56)}$$

$$= 13.6 \text{ kilometers.}$$

$d = 0.3$ seconds

$\Delta = 56$ kilometers

$v = 5.64$ kilometers per second

Gutenberg obtained a mean value of 12 kilometers with which the new value agrees within the limits of error. This depth places the focus near the base of the first granite layer as pointed out in the next section of this paper. Assuming an error of 0.2 seconds in reading the seismograms, the upper and lower limits of the depth of focus are 7.9 and 17.6 kilometers respectively. It may, therefore, be stated that the accuracy of the depth of focus is plus or minus approximately 4½ kilometers.

## VIII

## THICKNESS OF LAYERS IN SOUTHERN CALIFORNIA

If the velocities of waves propagated in successive layers are indicated by $V_1$, $V_2$, $V_3$, ......, Vn, the thicknesses by $d_1$, $d_2$, $d_3$, ......., $d_n$ and assuming constant velocity across each layer, the depth of layers can be calculated suing the following equations.

$$2h_1 - h = \Delta^* \frac{(\frac{1}{V_1} - \frac{1}{V_2})}{\sqrt{\frac{1}{V_1^2} - \frac{1}{V_2^2}}} = \Delta^* \sqrt{\frac{V_1 - V_2}{V_1 + V_2}}$$

where $\Delta^*$ is equal to the distance at which two corresponding travel-time curves intersect; h is equal to the depth of focus; $h_1$ is equal to the depth of the first layer; and i is equal to the angle of incidence.

$$\sin i_1 : \sin i_2 : \sin i_3 : \ldots : 1 = V_1 : V_2 : V_3 : \ldots : V_n$$

$$\Delta_n = (2d_1 - h) \tan i_1 + 2d_2 \tan i_2 + 2d_3 \tan i_3 + \ldots + 2d_{n-2} \tan i_{n-2}$$

$$t_n = \frac{2d_1 - h}{V_1 \text{Cos } i_1} + \frac{2d_2}{V_2 \text{Cos } i_2} + \frac{2d_3}{V_3 \text{Cos } i_3} + \ldots\ldots + \frac{2d_{n-2}}{V_{n-2} \text{Cos } i_{n-2}}$$

$$D_n = \Delta' - t \qquad T_n = t' - t_n$$

t' is equal to the travel-time to a distance $\Delta'$ of a wave with its deepest point in the layer n.

$$d_{n-1} = \frac{(V_n Tn - D_n) \text{ Cos } i_{n-1}}{2\left(\frac{V_n}{V_{n-1}} - \frac{V_{n-1}}{V_n}\right)}$$

If, as is generally assumed, the apparent differences of Py, Pm, $\overline{P}$, and Px are the result of discontinuities of the wave velocity as a function of depth, the following thicknesses of layers are indicated.

| Thickness of layers (in kilometers) | Longitudinal velocity (in kilometers per second) | Depth of layers (in kilometers) | Mean Depth of layers (Gutenberg) |
|---|---|---|---|
| 14.9 | 5.64 $\overline{P}$ | 0-14.9 | 14 |
| 7.57 | 6.08 $P_y$ | 14.9-22.5 | 25 |
| 8.48 | 6.36 Pm | 22.5-30.1 | 31 |
| ---- | 7.58 Px | > 30.1 | 39 |

Comparable figures obtained by Gutenberg are in good agreement with calculated depths of layers. The largest discrepancy is in the second layer, and even in this case the variation can be accounted for by the assumption of an experimental error of less than 0.2 seconds in reading the records. The transverse waves are too indefinite as they are recorded on the seismograms to enable one to distinguish phases, and therefore are unsatisfactory to use in calculating depths of layers.