On Anomalous Time-Distance Curves Observed in Local Earthquakes

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Abstract

The precise observations of local earthquakes were carried out in Wakayama District, Japan, for the purpose of studying the crustal structure and the nature of local shocks.

The travel-time anomalies were detected, and the anomalous time-distance curves were separable into two groups which seemed to be related with the directions of the initial motion of shocks recorded at their respective stations. The causes of the travel-time anomalies may reasonably be attributed to the condition of the hypocentre and mechanism of earthquake occurrence.

1. Introduction

Seismometrical studies on minor earthquakes, as the local shocks and the aftershocks, have heretofore been made by many researchers. Contrary to the case of utilizing artificial explosions, however, the determination of local fine structure of the crust from these shocks of small magnitude seems to be difficult in spite of the various attempts to do so. The artificial explosion method is certainly powerful for ascertaining the underground structure, owing to previous knowledge of the shot point and origin time, but the mechanism of occurrence and the nature of the emitted waves in this case are regarded as being certainly and widely different from the natural earthquake. From such a standpoint, the precise observation of minor shocks frequently occurring in their epicentral region is expected, with great interest, to offer an effective clue to such problems.

2. Observation

The present seismometric observations of local earthquakes were carried out in Wakayama District, western part of the Kii-Peninsula, Honshû, with many sets of high magnification seismometers, for the purpose of studying the unsolved above-mentioned problems of minor shocks and the crustal structure in the district concerned. These observations were pursued in close co-operation with the Earthquake Research Institute of Tokyo University (abbr. E.R.I.), from Nov. 24th to Dec. 2nd in 1954, and from April 10th to 22nd in 1956. Observation stations were installed in a limited region with a 10 km radius having Kainan City as its centre, where local earthquake-swarms have frequently occurred since 1920. Really the number of humanly felt shocks amounted to 250 and those non-felt 865 during one year of maximum seismic activity in this region. The superficial layer in this area consists of metamorphic rocks, termed crystalline shist and phyllite. The locations of all stations and the epicentres of earthquakes mentioned in this paper are shown in Fig. 1. (The co-ordinates of these stations determined from triangula-

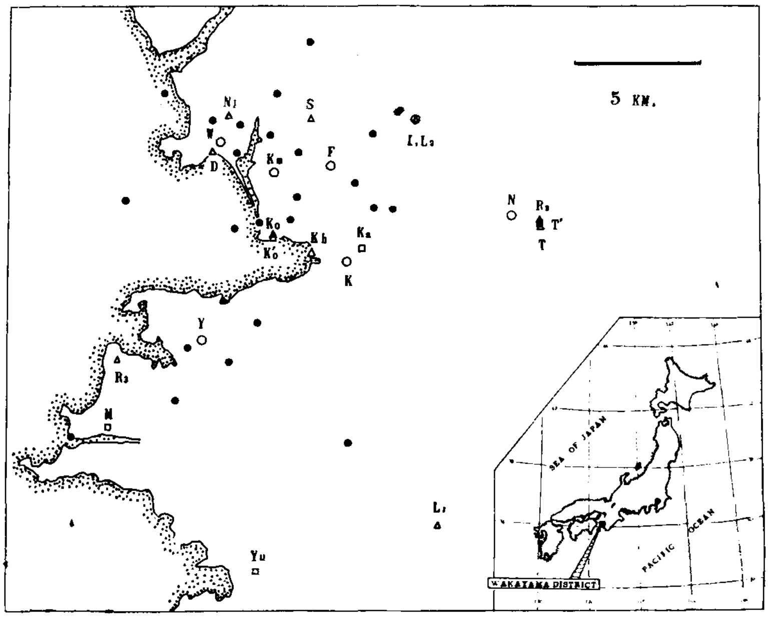

Fig. 1. Positions of the observation stations and the epicentres of the earthquakes concerned.

□ observation station of the E.R.I. with the electromagnetic seismometers
△ observation station of the E.R.I. with the acceleration seismomegraphs
○ observation station of the Kyoto Univ. with the electromagnetic seismometers
● epicentre

tions and aerial photographs by the E.R.I. were used in our analysis by the courtesy of the Institute.)

The instruments used in the present observations were both the vertical and horizontal electromagnetic seismometers of the variable reluctance type. Their natural period and voltage sensitivity are 0.45 sec. and 1.79 volt/kine, respectively. Maximum magnification of these seismometers in direct connection with the galvanometer of 0.35 sec. in free period and 3.11×10^{-8} amp/mm in direct current sensitivity is approximately 80,000 at the optical distance of 1 metre. The three of our stations were fully equipped with three components of these seismometers, and the others with only vertical component. The JJY standard short wave (4 or 8 Mc) was used as the time marker. The paper speed of the oscillogram was nearly 5.0 mm/sec. Most stations of the E.R.I. made an observation with electromagnetic seismometers using a line carrier telerecording or radio telerecording, and the remainder of them with acceleration seismographs.

3. Observed Results and Discussion

The well-recorded 27 earthquakes which seem to have occurred inside or near our observation network were selected from those observed at more than five stations and were used in the present analysis. In the ensuing discussions the data obtained at the stations of the E.R.I. will concomitantly be used with our own.

For the first step usual methods were adopted to determine the focal positions of the previously mentioned shocks, applying the P-S duration times (i.e. S-P time) or the arrival times of the first P-wave at all stations, and assuming the crust in the observed area to be of a uniform medium. And, as a result, their foci were approximately determined by utilizing the S-P times, but those for the major part of the shocks could hardly be determined by the application of arrival times of the P-waves. With respect to this anomalous result some detailed discussion will follow.

(a) Firstly, when a graphical method or a least square method from *the S-P times* clearly recorded at more than four stations was used in determining the hypocentre of each of 17 shocks, the focus could be determined with errors of less than several hundred metres, and the Omori's constants[1] were calculated as values from 5 to 8. However, the plotted points on a time-distance graph taking the hypocentral distance as the abscissa, obtained by the present method excessively diverged in a wide range. The propagation velocities estimated from a mean straight line, provisionally represented as the time-distance curve, have a great diversity in every shock, even in several shocks which occurred at approximately the same position. The deviation of travel times at each station from its line is considered to be beyond the limit of observational errors.

Considering, however, the time-distance curve to consist of minor groups, from another point of view, it can advantageously be divided into two groups accommodating most of the shocks analysed here. The respective groups of the time-distance curve can plausibly be represented as straight lines approximately paralleling each other with the travel-time difference of about ¼ sec., having small deviation of observed values at each station from either line. This fact can be verified for the S-waves as well as for the P-waves. The velocity differences estimated from two straight lines are within 0.1 km/sec., and the propagation velocities themselves obtained from 15 shocks are 4.3~5.3 km/sec. for the P-waves and 2.3~2.8 km/sec. for the S-waves, respectively. These values are not so diverse in every earthquake as they are in the cases of non-separation, and are considered to be reasonable ones for the velocities in the crustal upper layers.

Furthermore, the correlations between the travel times at the stations in each group of time-distance curves and various subjects were examined in all the shocks above treated. It seems, then, in every shock that the arrival times at the respective stations in two groups of the time-distance curves are closely related with the recorded directions of the initial motion at each observatory, but not with the geographical locations of stations, the position of hypocentre, the focal distance etc., as easily seen in Table 1. Namely, the travel times at the stations in the anaseismic region have a tendency to belong to either group on the time-distance graph, and the other group consists of the stations in the kataseismic area. But at the stations near the nodal lines some exceptional cases were found. Two examples of the travel time-distance curves are shown in Fig. 2. In two of 17 shocks the time-distance curve could be represented as a straight line, but the recorded directions of the first movement are anaseismic at all stations.

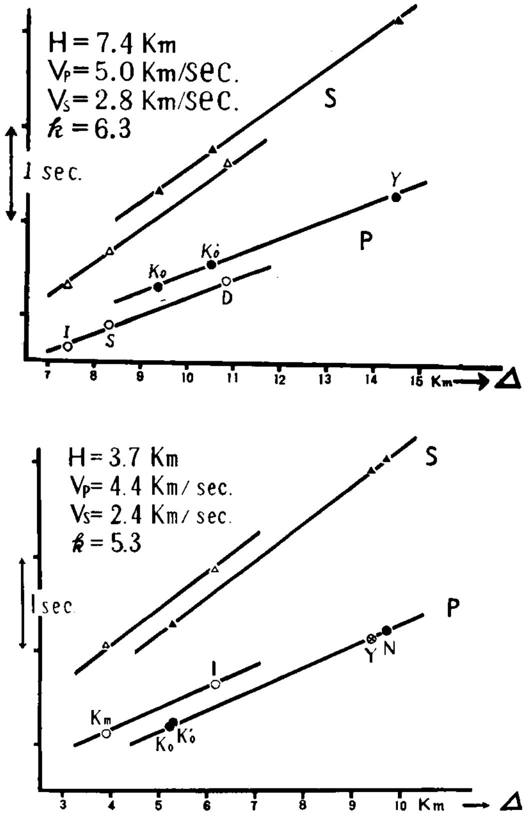

Fig. 2. (a) Time-distance curves (No. 140).
(b) Time-distance curves (No. 122).

(b) Secondly, the arrival times of *the initial wave* at more than five stations were used applying a least square method for estimating the positions of hypocentres. In this case, however, the focus, for most of the shocks, could not analytically be determined with some ex-

[1] The Omori's constant (k) shows the constant combining the S-P time (t) and the hypocentral distance (Δ) under the assumption of a homogeneous medium. This relation is expressed as $\Delta = kt$ and $k = VpVs/(Vp - Vs)$, where Vp and Vs are the velocities of the P- and S-waves, respectively.

ceptions. That is, their focal depths resulted in imaginary values, the velocities were calculated as unreasonable values, or the probable errors in travel-time curves were found to be exceedingly large. In the analysis by this method, the cases in which the focus was determinable were only as follows:

i) When the directions of initial motion recorded at all stations were the same, in other words, only in the anaseismic or kataseismic sense, the hypocentre could be determined with good accuracy, and the time-distance curves could be represented as straight lines with small probable errors and reasonable velocities. Fig. 3 shows an example of the time-distance curves in these 6 cases.

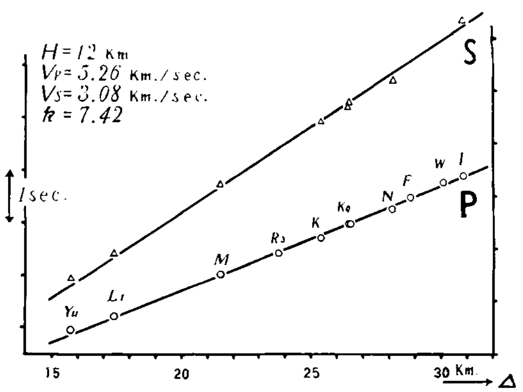

Fig. 3. Time-distance curves (No. 247).

ii) When both the anaseismic and kataseismic first movements were recorded at various stations, the focus was well determined, only when the arrival times at the stations with the same initial direction were used in calculation. On a time-distance graph, the travel times at these stations successfully lie on a straight line with reasonable velocities. But the travel times at other stations with another initial direction, which were excluded from this calculation, deviate from the above-mentioned line, and the straight line suitably connecting these plotted points runs parallel approximately with the former with a time difference of 0.2~0.4 sec. An example of these 7 cases is shown in Fig. 4.

(c) As described in this paragraph, the time-distance curve has an indication both for the P- and S-waves that the travel times are separable into two groups relating to the direction

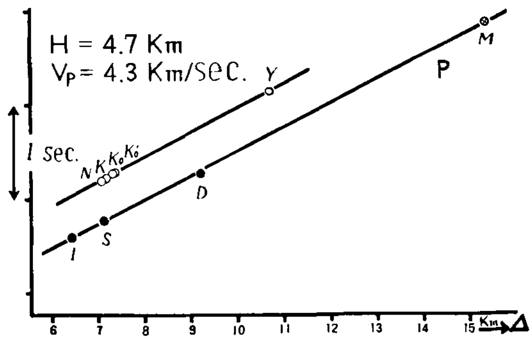

Fig. 4. Time-distance curves (No. 137).

of initial movement of shock at each station, when the arrival times as well as the S-P times were made use of in the hypocentre's determination.

Synthesizing all of 27 shocks analysed here, the time-distance curve could be represented as a straight line in 6 shocks and could be separated into two groups in 21 shocks. In the former instances the recorded directions of initial motion at respective stations are all the same, and in the latter, with regard to 12 shocks among 21, the stations with the initial anaseismic direction belong to a group of the shorter travel time, and the initial kataseismic stations form that of the longer one in 12 shocks, and contrary cases to these were found in 9 shocks. The travel-time difference is in the range from 0.2 to 0.4 sec.

The locations of epicentres, focal depths, velocities of the P- and S-waves, Omori's constants, the travel-time differences between two groups and abbreviations of stations constructing the time-distance curves, in every shock, are tabulated in Table 1. The velocity—focal depth graph in many shocks obtained from calculations under the uniform medium assumption is shown in Fig. 5. The examples of seismograms are shown in Fig. 6.

(d) The various problems in the present analysis will be mentioned and discussed as follows.

First, the time error accompanied by a precise reading of time-marks of every second on the seismograms is considered to be about $^{1}/_{50}$ sec. in good records and less than $^{1}/_{20}$ sec. in other ones, judging from the clearness of the initial P- and S-waves in most of the shocks treated here. Consequently, the travel-time

Table 1. Analyzed results.

X, Y; location of epicentre, Z; focal depth, Analytical method: P-S; using the P-S times, P; using the arrival times of the P-waves, Vp; velocity of the longitudinal waves, Vs; velocity of the transversal waves, k; Omori's constant, (1), (2); groups of travel time, U; initial 'Upward'-motion, D; initial 'Downward'-motion, δT; difference of the travel times between two groups.

The shoulder mark * indicates that the direction of initial motion at the marked station recorded the opposite one or it was not clearly recorded.

The observed data (the arrival times of the initial wave, the P-S times and the directions of initial motion) at the stations of the E.R.I.; R_2, R_3, L_1, L_2, K6, Ko′, Kh, Ka, T, T′, D, S, Ni, M, Yu, were used in our analysis by the courtesy of the institute. Positions of all stations are graphically referred to Fig. 1, and the station W is adopted as the origin point in the present treatment. The positive X, Y and Z indicate the southward, eastward and downward directions, respectively, seen from the origin point.

Shock No.	X (km)	Y (km)	Z (km)	Anal. Method	Vp (km/sec)	Vs (km/sec)	Vp/Vs	k	Time-Distance Curves	δT sec.
121	12.17	5.20	11.20	P-S	4.83	2.58	1.87	5.54	(1) Y, N (D); (2) Km, D, I (U)	0.20
122	0.47	3.15	3.70	P-S	4.36	2.40	1.82	5.34	(1) Ko, Ko′, Y*, N (D); (2) Km, I (U)	0.20
123	2.77	6.20	3.30	P-S	4.25	2.43	1.75	5.68	(1) I, Km*, Y (U); (2) Ko, N (D)	0.35
124	—0.28	6.20	4.40	P-S	5.04	2.52	2.00	4.78	(1) Y (U); (2) I, Ko, N (D)	0.25
135	3.57	0.60	4.60	P-S	4.64	2.47	1.87	5.30	(1) D, Y, S (U); (2) Ko, I, N (D)	0.20
136	7.37	1.50	4.70	P-S	4.62	2.54	1.82	5.65	(1) Y, D*, I (U); (2) Ko, Km, N (D)	0.25
137	2.77	6.95	4.75	P	4.40	—	—	—	(1) I, S, D, M* (D); (2) Km, N, Ko, Ko′, Y (U)	0.40
140	−1.23	7.35	7.40	P-S	5.07	2.81	1.81	6.31	(1) I, S, D (U); (2) Ko, Ko′, Y (D)	0.25
151	1.72	5.40	5.80	P-S	4.73	2.70	1.85	5.88	(1) Km, I, S, D (U); (2) Ko, N, Y* (D)	0.20
201	25.65	5.67	10.30	P	5.11	2.92	1.75	6.84	(1) L_1, Y, R_3, K, Kh, Ko, N, I (U)	—
202	2.45	−3.85	6.20	P	5.10	—	—	—	(1) F, K*, I, N* (U); (2) Ni, Ko, Ko′, R_3*, Kh, L_1 (D)	0.20
206	11.97	−5.98	9.25	P	5.43	3.13	1.74	7.35	(1) M, R_3, Y, Ko, Ko′, Kh, K, W, Ka, L_1, L_2, T′ (D); (2) Yu (U)	0.15
207	2.30	3.05	3.60	P-S	4.31	2.67	1.62	(7.01)	(1) Y, N (D); (2) Ko, Ko′, K, W, I (U)	0.40
217	−0.98	−0.36	7.90	P	5.35	(3.56)	(1.58)	7.64	(1) Ni, W, F, Ko, Ko′, L_2, Y, N, T′ (U); (2) K, Ka, L_1 (D)	0.20
220	−1.20	7.25	5.10	P	4.66	2.85	1.64	7.35	(1) W (D); (2) I, F, N, K, Ko′, L_1 (U)	0.35
222	8.35	−1.25	4.40	P	4.72	2.96	1.60	5.94	(1) Y, Ko, K, W, F*, I, N (U)	—
223	3.35	1.59	5.15	P-S	4.72	2.72	1.73	6.41	(1) Ko, W, Y, I, N (U); (2) F (D)	0.20
224	−0.70	0.65	8.90	P-S	5.38	2.91	1.85	6.35	(1) F, Ko (D); (2) W, I, N (U)	0.25
228	−2.05	−2.30	7.25	P	5.65	3.54	1.60	—	(1) W, Ko, F, I, Y, K, N (U)	—
230	0.45	0.65	8.40	P	5.65	—	—	—	(1) F, I (D); (2) W, Ko, K, N, Y (U)	0.20
236	10.50	−1.75	6.30	P	4.83	2.93	1.65	7.45	(1) L_1, N, R_2 (D); Y, Ko, Ko′, K*, Ka, W, F, I (U)	0.25
247	27.30	4.15	12.00	P	5.26	3.08	1.71	7.42	(1) Yu, L_1, M, R_3, K, Ko, Ko′, N, F, W, I (U)	—
248	−0.17	2.00	4.55	P-S	4.93	2.66	1.87	5.63	(1) W, Y (U); (2) F, Ko, K, I (D)	0.40
249	−1.87	2.30	8.80	P-S	5.33	3.20	1.68	(8.00)	(1) W, F, Ko, N (U); (2) I (D)	0.20
250	3.20	2.80	3.70	P-S	4.26	2.54	1.73	5.97	(1) Ko, Ko′, W, N, R_2* (U); (2) F*, K, Ka, I (D)	0.30
251	8.96	0.46	5.30	P	4.86	—	—	—	(1) Ko, Ko′, F, W, I, N (U)	—
253	−4.10	3.60	6.60	P-S	5.00	2.88	1.80	6.78	(1) I, W, Ko, Ko′, K, N, R_2, Y (U)	—

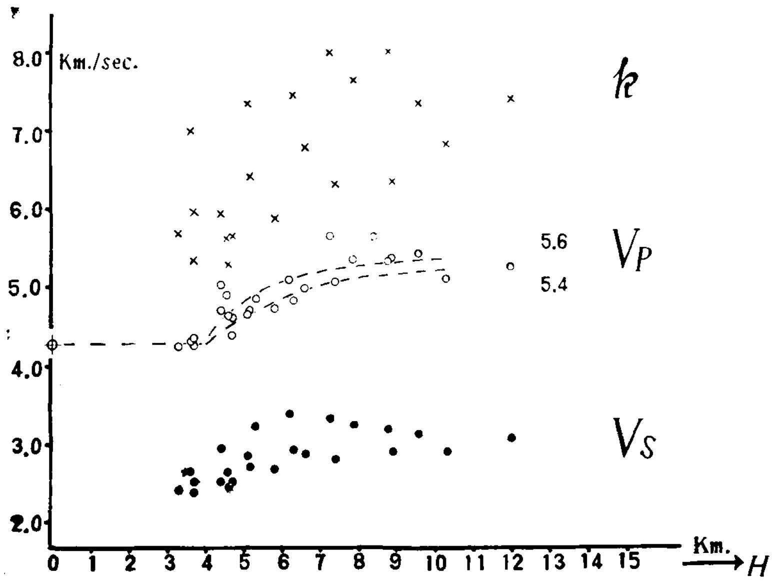

Fig. 5. Velocity — focal depth graph.

anomalies as already stated are not regarded as time errors.

Second, a possibility of mis-discrimination of the initial wave in $^1/_2$ or 1 cycle was examined. But the time error resulted from such a mis-discrimination is insufficient to produce the travel-time difference previously mentioned, considering the wave frequency in the initial part of seismic motions. Taking, also, into consideration the distribution of the recorded initial movements, the clearly recorded first waves at most of the stations used in the analysis and so forth, the cause of separation of the travel-time curves cannot be attributed to the mis-discrimination of the initial wave.

Third, the errors of focal position caused by the observational time errors were estimated under a uniform medium assumption. The uncertainties in the present case are presumed to be less than 1 kilometre, but the general appearance of the time-distance curve is not altered within this range.

Fourth, the effect on travel-time curves was studied, by assuming a horizontally layered structure instead of the homogeneous medium. Such an effect was ascertained to be slight, namely, the large deviations in travel times cannot be explained from the influence resulted by the simple model of crustal structure.

From the various reasons above stated, it may safely be said that the cause of the anomalies in travel times is attributable to the effects of focal conditions, such as the mechanism of earthquake occurrence or the shape of the hypocentral region. The detailed description and discussion of this problem will appropriately be referred to MIKUMO's paper (1956).

4. Crustal Structure in Wakayama District

The structure of the crust in the district concerned was presumed to be composed of horizontal parallel layers.

The propagation velocities of the P- and S-waves in the surface layer consisting of metamorphic rocks and its layer thickness were estimated to be approximately 4.3, 2.5 km/sec. and 4 km, respectively, from the relationship indicated in Fig. 5, and the results of seismic prospecting already carried out.

The longitudinal velocity in the second layer was calculated so as to be adapted to the distribution of the uniformly assumed velocity against the depth shown in Fig. 5, on the basis of the already known thickness and velocities in the surface layer. The velocity of the P-waves was determined to be 5.4~5.6 km/sec., and the corresponding velocity of the S-waves was calculated to be about 3.2 km/sec.

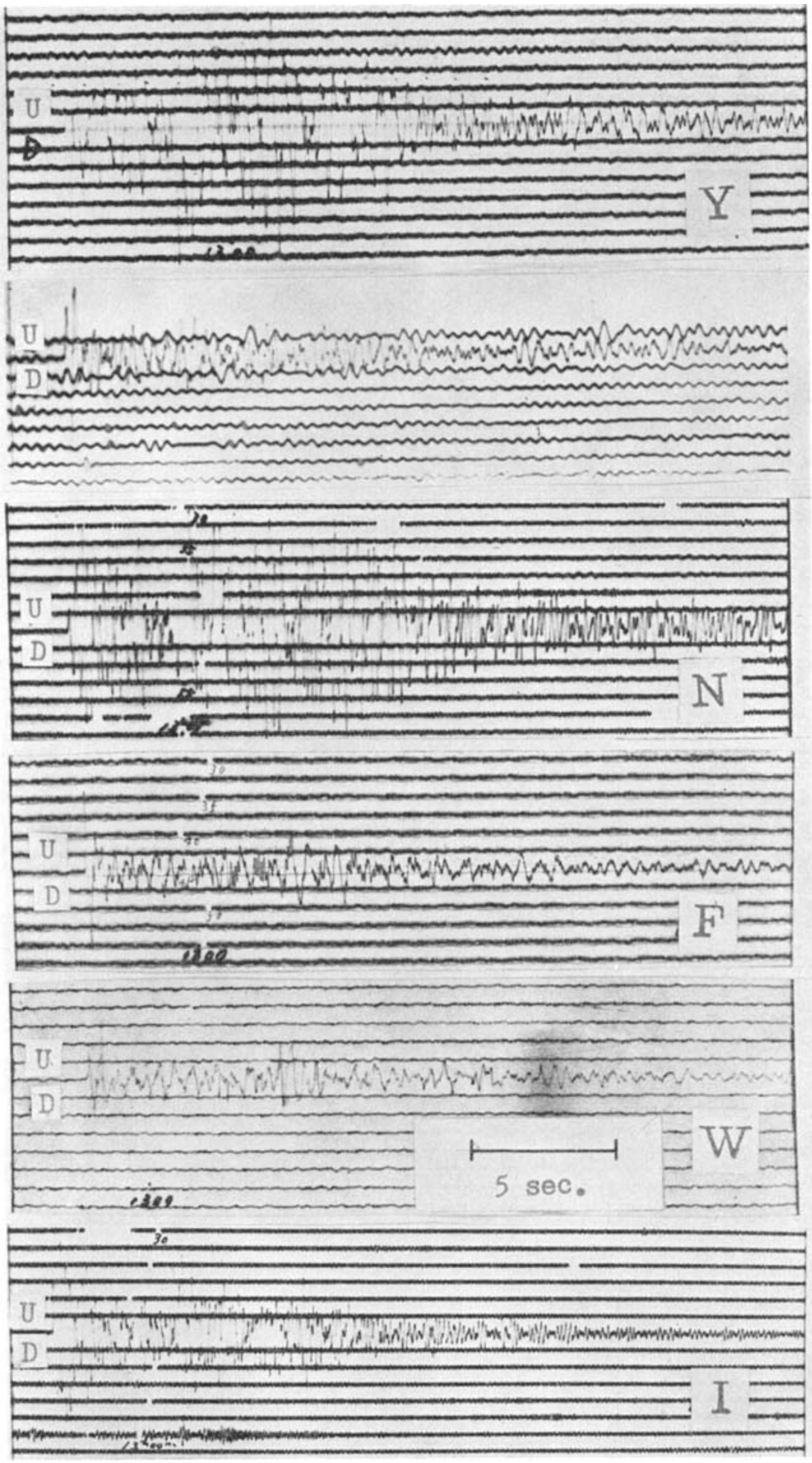

Fig. 6. Examples of seismograms recorded at six station; No. 247, April 22, 1956, 12 h 45 m.

The apparent velocities in the third layer were determined by the data obtained at five temporary stations in Wakayama District in an earthquake which occurred near Kyoto, being 100 km distant and with focal depth of about 11 km. Supposing the thickness of the second layer to be nearly 6 km (NISHIMURA and KISHIMOTO, 1956), the velocities in the third layer were considered to be approximately 6.0 and 3.4 km/sec. respectively for the P- and S-waves.

5. Conclusion

An anomalous nature in the time-distance graph was found by precise seismometric observation of the local earthquakes which frequently occurred in a swarm in a certain limited area within Wakayama District. Namely, the time-distance curve in each shock is necessarily separated into two groups for the P- and S-waves in order to obtain the definite hypocentre and normal velocities. And it was learned that the separation of the stations is intimately related to the distribution of the so-called push- (anaseismic) and pull- (kataseismic) zones of the first motion of the ground in earthquakes at each station. Consequently the obtained values of 0.2~0.4 sec. in a time-gap between two groups are interpreted to suggest numerically the azimuthal difference in mechanism of earthquake occurrence or the deviation of focal region from a sphere. As the earthquakes treated in the present investigation are all local shocks and have a shallow foci of several kilometres, the above obtained value of time-gap may probably be increased in case of large destructive earthquakes with hypocentral region of some ten times that of these local shocks. The time difference stated above may be regarded as affording a powerful clue for detecting the behaviour of focus. From this standpoint, a precise observation with a dense net of stations in the epicentral area of large earthquakes is highly recommended, in future, in the study of the nature and mechanism of occurrence regarding these earthquakes. It should be suggested that precise seismometric observations with the high-sensitive strain seismometers are at present being operated by our institute in the area concerned, and the synthetic treatment of the present problem by the analysis of ground-motion and ground-strain should be expected to advance our knowledge about the nature of earthquakes.

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