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# THE TRAVEL-TIMES OF THE SEISMIC WAVES *P* and *S*

## A Study of Data from the International Seismological Summary, 1930 and 1931

By A. W. LEE, D.Sc.

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*Frontispiece.*

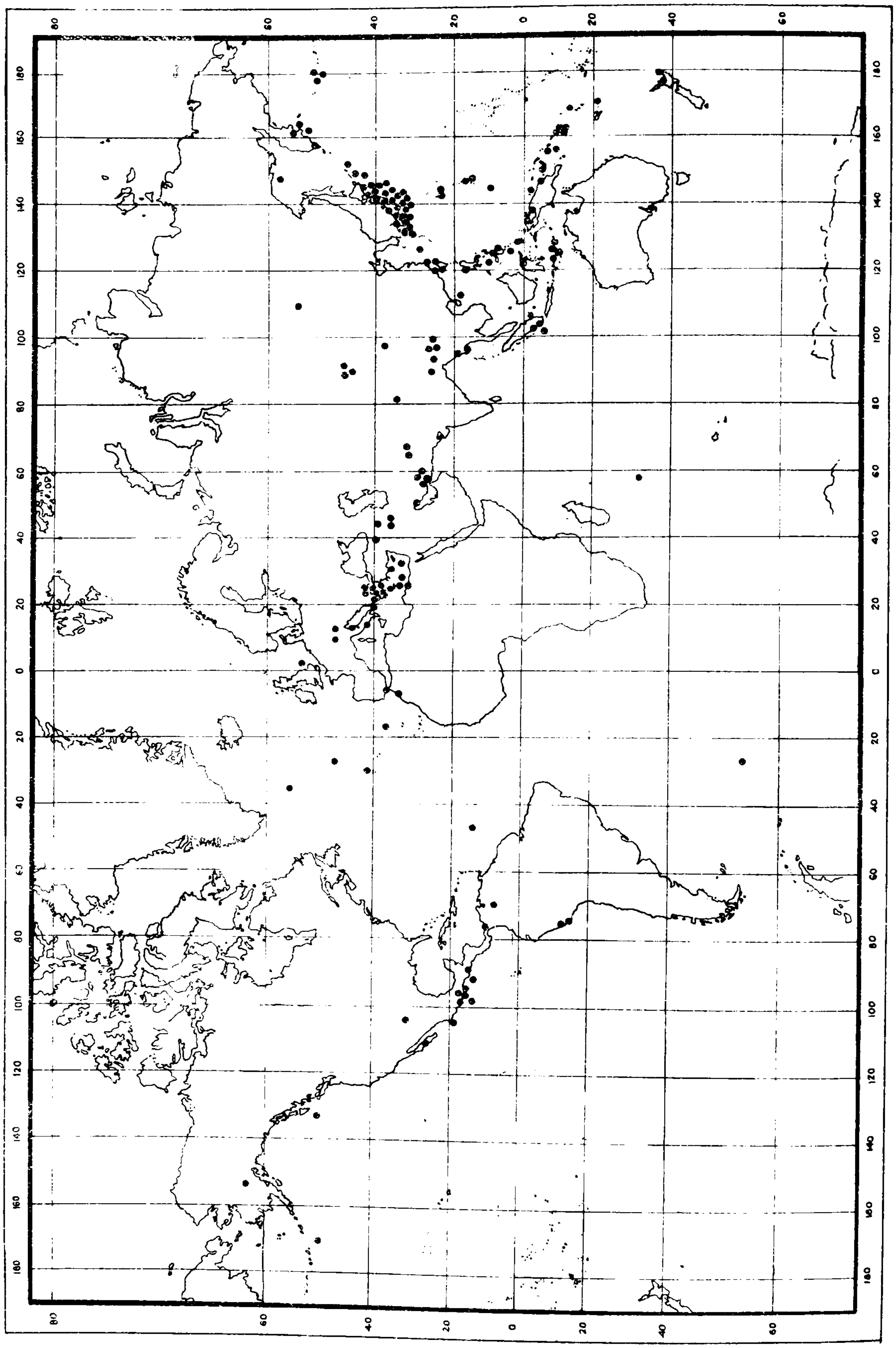


FIG. 1—DISTRIBUTION OF EARTHQUAKES WITH GOOD EPICENTRES, 1930–1.

# THE TRAVEL-TIMES OF THE SEISMIC WAVES *P* AND *S*

## A study of data from the International Seismological Summary, 1930 and 1931

### § 1—INTRODUCTION

The travel-times of seismic waves have been examined in many papers published in the last few years. The investigations have generally followed one or other of the following methods :—

(1) The analysis of a large number of seismograms for selected earthquakes.
(2) Statistical studies based upon the data published in the various bulletins or in the International Seismological Summary (1).*

Recent examples of the first method are to be found in papers by Miss I. Lehmann, J. B. Macelwane, P. Byerly, B. Gutenberg and C. F. Richter, and F. J. Scrase. The second method has been used by the late Professor H. H. Turner, in the monograph by H. Jeffreys and K. E. Bullen (2), and in other papers by Jeffreys. Each method has its merits and its disadvantages ; these have been discussed by Jeffreys and Bullen (2, pp. 15-6). The former method has the advantage of uniformity in tabulation, for with the measurements all made by the same person the seismograms from adjacent stations can be compared. By using the second method the investigator avoids the laborious measurement of the curves and has a great deal more material at his disposal.

The tables prepared by Jeffreys and Bullen were introduced in the compilation of the International Seismological Summary from the beginning of 1930. The data for two complete years, based upon these tables, have now been published, and it is pertinent to examine how closely the observations are in agreement with the new tables.

It was therefore decided to investigate the travel of *P* and *S* waves from the data published for a number of earthquakes during the years 1930–1. An additional improvement, introduced into the International Seismological Summary (I.S.S.) from 1930 is a classification of the quality of the epicentral determinations. Each epicentre is indicated as 1 (good), 2 (moderate), 3 (poor) or X (uncertain). The letters *N* and *R* precede these characterizations to distinguish between " new " epicentres and " repetitions " from earlier shocks. The epicentre is always calculated *ab initio* for the more important earthquakes, and an old position is only retained when the evidence definitely points to repetition. Excluding the deep focus earthquakes there were 146 shocks with " good " epicentres during the years 1930–1. These are the earthquakes used in the present investigation.

### § 2—GEOGRAPHICAL DISTRIBUTION OF THE EARTHQUAKES

The geographical distribution of the epicentres of the 146 earthquakes is shown in Fig. 1 (*frontispiece*). About half of the total number of shocks are located in the great belt of seismic activity which extends from the Kurile Islands, through Japan and round the southern coast of China, to the East Indies and Polynesia ; a quarter of the shocks are in the regions from central Europe across the eastern Mediterranean to south-west Asia. The remaining epicentres are more scattered, but there are groupings in central America and in Burma.

The selection of earthquakes has been made according to quality of the epicentral determinations. Thus, in addition to the large earthquakes, smaller shocks are included for regions where observatories are plentiful. The map gives a rough approximation to the normal distribution of earthquakes, but the importance of

* The numbers in brackets refer to the bibliography given on p. 16.

shocks within some 20° of the European and Japanese stations is overestimated, and the number of shocks in latitudes north of the equator and longitudes east of Greenwich is greater than normal. Dividing the globe into four regions according to whether the latitude is north or south of the equator and the longitude east or west of Greenwich, the percentages of the 146 earthquakes in each region, and the average distribution for the 6,738 earthquakes recorded in the International Catalogue of Epicentres from 1913–30 (3), are :—

| Years | Number of earthquakes | Percentage of earthquakes in region :— | | | |
|---|---|---|---|---|---|
| | | Lat. N. Long. E. | Lat. N. Long. W. | Lat. S. Long. E. | Lat. S. Long. W. |
| 1930–1 .. | 146 | 67 | 15 | 16 | 2 |
| 1913–30 .. | 6,738 | 60 | 16 | 14 | 10 |

Following Jeffreys, we may attribute the small number of utilisable shocks in the last region to the neglect of the departure of the figure of the earth from a sphere.

The I.S.S. classification of the epicentres shows that 52 of the earthquakes could be regarded as " repetitions " from previous epicentres, and that 94 had epicentres which had not previously appeared in the Summary. In the preparation of the Summary the residuals of $P$ are examined for the earthquakes with epicentres of Class I, and the " probable error " of the epicentral distances is estimated ; these so called probable errors are small, being in most cases only a few tenths of a degree.

## § 3—DISTRIBUTION OF RESIDUALS FOR THE $P$ AND $S$ WAVES

The readings identified in the Summary as representing the $P$ and $S$ waves have been used in the examination of travel-times for these waves. The data for the $P$ waves are more reliable than those for $S$ ; the latter waves are frequently difficult to identify in the seismograms, and other pulses may be recorded at nearly the same time as $S$. The tabulations for both classes of waves are liable to errors due to occasional inaccuracies in the measurements or in the timekeeping ; these uncertainties originate at the observatories before the data are forwarded to the compilers of the Summary.

The residuals, for $P$ and for $S$ waves respectively, from the 67 earthquakes of Class 1 which occurred during 1930, are shown in Figs. 2 and 3. The ordinates of these diagrams represent the departures of the observed times of the onsets from the times given in the Jeffreys-Bullen tables. The observations are grouped over two-degree ranges of epicentral distances. The " departures " are in seconds.

Table I is a statistical summary of the observations for the two years. The numbers of observations and the medians of the residuals over two-degree ranges of distances are given for each year. In the data for both years together the quartiles of the residuals are also included to show the scatter of the observations. The observations of $P$ extend from 0° to 110°, and those of $S$ from 0° to 106°. A bar has been inserted in the tabulations for $S$ at 80° to emphasise that, with $SKS$ preceding $S$ at the greater distances, the difficulties of identification are increased.

The medians and quartiles of the residuals for the 146 earthquakes are plotted against epicentral distance in Fig. 4. The lines for $P$ at distances beyond 95°, and for $S$ beyond 87°, are broken to indicate that the values have been computed from less than 100 observations in each two-degree range, and are consequently less reliable than those for the smaller distances.

At distances less than 92° the medians of the $P$ residuals do not exceed $\pm 1$ second, and the observations are in excellent agreement with the tables. From 92° to 110° the medians of the $P$ observations are about 2 seconds later than the calculated times. At these greater distances the distributions of the residuals are skewed ; there is a notable increase in the separation from the medians of the third quartiles,

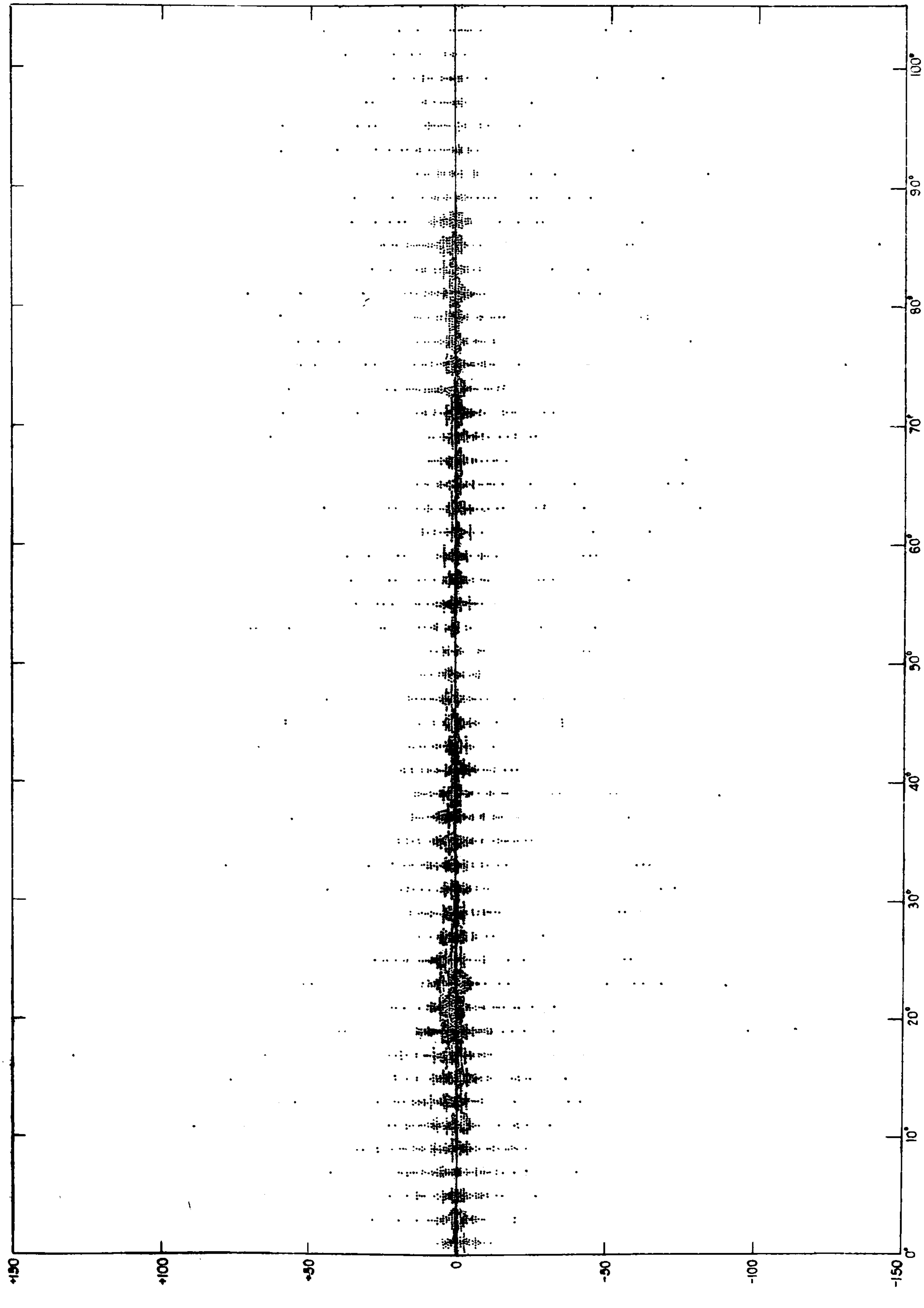



FIG. 2. — DISTRIBUTION OF RESIDUALS OF *P* — I.S.S. 1930.
67 Earthquakes with well-determined epicentres.

(3735)

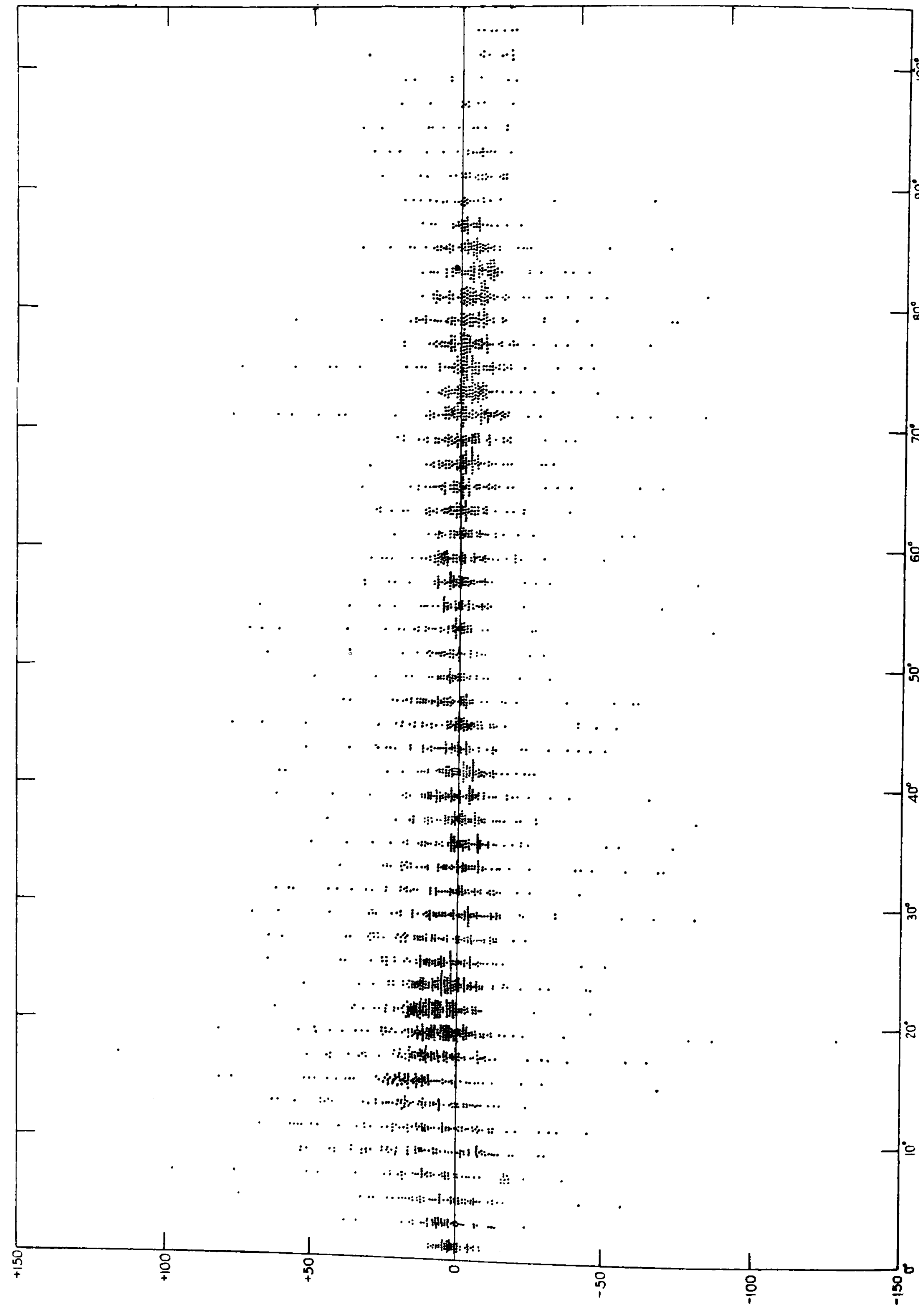



FIG. 3.—DISTRIBUTION OF RESIDUALS OF $\delta$ − I.S.S. 1930.
67 Earthquakes with well-determined epicentres.

## TABLE I—MEDIANS AND QUARTILES OF RESIDUALS FOR *P* AND *S* WAVES

| Δ | *P* | | | | | | | | *S* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1930. | | 1931. | | 1930–1. | | | | 1930. | | 1931. | | 1930–1. | | | |
| | Median | No. of values | Median | No. of values | First quartile | Median | Third quartile | No. of values | Median | No. of values | Median | No. of values | First quartile | Median | Third quartile | No. of values |
| ° | sec. | | sec. | | sec. | sec. | sec. | | sec. | | sec. | | sec. | sec. | sec. | |
| 0·0–1·9 | −1 | 71 | 0 | 246 | −3 | 0 | +2 | 317 | +2 | 52 | +1 | 204 | −2 | +1 | +4 | 256 |
| 2·0–3·9 | −1 | 87 | +1 | 283 | −2 | +1 | +3 | 370 | +4 | 51 | +2 | 173 | −2 | +2 | +6 | 224 |
| 4·0–5·9 | −1 | 80 | 0 | 223 | −3 | 0 | +2 | 303 | +1 | 56 | +5 | 130 | −2 | +4 | +8 | 186 |
| 6·0–7·9 | +1 | 70 | 0 | 187 | −4 | 0 | +4 | 257 | +4 | 55 | +3 | 112 | −7 | +3 | +11 | 167 |
| 8·0–9·9 | +1 | 86 | 0 | 158 | −4 | +1 | +4 | 244 | +7 | 69 | +4 | 112 | −8 | +5 | +15 | 181 |
| 10·0–11·9 | +1 | 104 | 0 | 124 | −3 | 0 | +5 | 228 | +7 | 74 | +6 | 83 | −5 | +6 | +16 | 157 |
| 12·0–13·9 | +2 | 92 | −1 | 103 | −4 | 0 | +5 | 195 | +11 | 68 | +9 | 79 | −1 | +10 | +22 | 147 |
| 14·0–15·9 | −1 | 101 | 0 | 83 | −4 | 0 | +5 | 184 | +13 | 82 | +11 | 68 | +1 | +12 | +19 | 150 |
| 16·0–17·9 | 0 | 118 | 0 | 85 | −3 | 0 | +3 | 203 | +7 | 106 | +7 | 71 | 0 | +7 | +14 | 177 |
| 18·0–19·9 | 0 | 172 | −1 | 88 | −3 | 0 | +3 | 260 | +5 | 150 | +7 | 73 | −1 | +5 | +13 | 223 |
| 20·0–21·9 | +1 | 140 | −1 | 131 | −3 | 0 | +3 | 271 | +7 | 135 | +7 | 118 | +1 | +7 | +13 | 253 |
| 22·0–23·9 | 0 | 137 | 0 | 118 | −2 | 0 | +3 | 255 | +4 | 129 | +6 | 108 | 0 | +5 | +10 | 237 |
| 24·0–25·9 | +2 | 100 | +1 | 151 | −2 | +1 | +4 | 251 | +5 | 88 | +8 | 136 | +1 | +6 | +13 | 224 |
| 26·0–27·9 | +1 | 75 | 0 | 139 | −3 | 0 | +3 | 214 | +6 | 77 | +3 | 122 | −4 | +4 | +12 | 199 |
| 28·0–29·9 | 0 | 94 | 0 | 100 | −3 | 0 | +3 | 194 | −1 | 83 | 0 | 96 | −6 | −1 | +10 | 179 |
| 30·0–31·9 | 0 | 63 | 0 | 107 | −3 | 0 | +4 | 170 | +1 | 64 | −1 | 95 | −5 | −1 | +9 | 159 |
| 32·0–33·9 | +1 | 70 | +1 | 92 | −2 | +1 | +3 | 162 | 0 | 69 | +1 | 86 | −6 | 0 | +10 | 155 |
| 34·0–35·9 | +1 | 90 | 0 | 82 | −3 | 0 | +2 | 172 | −1 | 80 | 0 | 78 | −7 | −1 | +5 | 158 |
| 36·0–37·9 | +1 | 85 | +1 | 63 | −2 | +1 | +4 | 148 | −2 | 77 | +3 | 58 | −5 | +1 | +9 | 135 |
| 38·0–39·9 | 0 | 93 | 0 | 74 | −3 | 0 | +2 | 167 | +1 | 85 | +4 | 73 | −4 | +2 | +8 | 158 |
| 40·0–41·9 | −1 | 99 | −1 | 47 | −3 | −1 | +2 | 146 | −2 | 83 | −3 | 43 | −7 | −2 | +3 | 126 |
| 42·0–43·9 | 0 | 73 | 0 | 60 | −3 | 0 | +3 | 133 | 0 | 65 | +2 | 52 | −4 | +1 | +9 | 117 |
| 44·0–45·9 | 0 | 73 | −1 | 73 | −3 | 0 | +3 | 146 | −1 | 71 | +2 | 64 | −7 | 0 | +6 | 135 |
| 46·0–47·9 | +1 | 70 | −1 | 109 | −3 | 0 | +3 | 179 | +3 | 66 | +1 | 91 | −3 | +2 | +9 | 157 |
| 48·0–49·9 | +1 | 44 | +1 | 86 | −2 | +1 | +3 | 130 | +2 | 44 | +2 | 78 | −2 | +2 | +7 | 122 |
| 50·0–51·9 | 0 | 31 | 0 | 128 | −2 | 0 | +3 | 159 | +2 | 37 | +2 | 113 | −3 | +2 | +9 | 150 |
| 52·0–53·9 | +1 | 48 | 0 | 162 | −3 | 0 | +4 | 210 | +1 | 53 | 0 | 144 | −4 | +1 | +7 | 197 |
| 54·0–55·9 | +1 | 58 | 0 | 114 | −3 | 0 | +4 | 172 | +1 | 50 | +2 | 104 | −5 | +1 | +9 | 154 |
| 56·0–57·9 | −1 | 62 | 0 | 78 | −3 | −1 | +2 | 140 | +1 | 62 | +1 | 78 | −4 | +1 | +7 | 140 |
| 58·0–59·9 | 0 | 64 | −1 | 62 | −4 | −1 | +3 | 126 | +1 | 74 | −1 | 60 | −5 | 0 | +6 | 134 |
| 60·0–61·9 | −1 | 54 | 0 | 47 | −3 | 0 | +2 | 101 | −1 | 50 | 0 | 51 | −6 | −1 | +3 | 101 |
| 62·0–63·9 | 0 | 74 | 0 | 51 | −3 | 0 | +2 | 125 | 0 | 69 | −4 | 47 | −6 | −1 | +3 | 116 |
| 64·0–65·9 | −1 | 69 | −1 | 55 | −5 | −1 | +1 | 124 | −1 | 69 | −2 | 61 | −7 | −1 | +3 | 130 |
| 66·0–67·9 | −1 | 75 | −2 | 64 | −3 | −1 | +2 | 139 | −2 | 75 | −2 | 70 | −6 | −2 | +3 | 145 |
| 68·0–69·9 | −2 | 68 | −1 | 84 | −4 | −1 | +1 | 152 | −1 | 65 | −3 | 86 | −7 | −3 | +4 | 151 |
| 70·0–71·9 | 0 | 104 | −2 | 74 | −4 | −1 | +1 | 178 | −1 | 96 | −4 | 76 | −8 | −2 | +3 | 172 |
| 72·0–73·9 | −1 | 92 | −1 | 98 | −3 | −1 | +2 | 190 | −3 | 91 | −4 | 87 | −8 | −4 | 0 | 178 |
| 74·0–75·9 | 0 | 91 | 0 | 98 | −2 | 0 | +2 | 189 | −2 | 82 | −5 | 80 | −10 | −4 | 0 | 162 |
| 76·0–77·9 | 0 | 81 | 0 | 80 | −2 | 0 | +2 | 161 | −2 | 81 | −5 | 70 | −9 | −4 | 0 | 151 |
| 78·0–79·9 | 0 | 85 | 0 | 128 | −2 | 0 | +2 | 213 | −3 | 72 | −4 | 104 | −9 | −4 | +2 | 176 |
| 80·0–81·9 | 0 | 101 | 0 | 115 | −2 | 0 | +3 | 216 | −4 | 87 | −5 | 100 | −10 | −5 | +1 | 187 |
| 82·0–83·9 | +1 | 76 | 0 | 128 | −3 | 0 | +3 | 204 | −6 | 66 | −5 | 100 | −11 | −6 | 0 | 166 |
| 84·0–85·9 | +1 | 96 | 0 | 158 | −2 | 0 | +3 | 254 | −4 | 69 | −3 | 74 | −9 | −3 | +2 | 143 |
| 86·0–87·9 | +1 | 75 | 0 | 150 | −2 | 0 | +4 | 225 | −2 | 37 | −2 | 76 | −6 | −2 | +2 | 113 |
| 88·0–89·9 | −1 | 39 | 0 | 118 | −3 | 0 | +3 | 157 | −1 | 25 | −6 | 57 | −9 | −3 | +3 | 82 |
| 90·0–91·9 | +1 | 36 | 0 | 95 | −4 | 0 | +4 | 131 | −5 | 25 | −8 | 38 | −10 | −6 | 0 | 63 |
| 92·0–93·9 | +1 | 39 | +2 | 77 | −2 | +2 | +9 | 116 | −5 | 18 | −5 | 25 | −9 | −5 | +3 | 43 |
| 94·0–95·9 | +3 | 26 | +1 | 74 | −3 | +1 | +6 | 100 | +1 | 11 | −3 | 36 | −10 | −3 | +3 | 47 |
| 96·0–97·9 | +1 | 25 | +1 | 62 | −2 | +1 | +7 | 87 | −1 | 10 | −7 | 18 | −12 | −5 | 0 | 28 |
| 98·0–99·9 | +1 | 26 | +3 | 39 | −2 | +3 | +11 | 65 | −1 | 8 | −5 | 13 | −12 | −5 | +11 | 21 |
| 100·0–101·9 | +9 | 18 | +2 | 27 | +1 | +4 | +27 | 45 | −11 | 10 | −3 | 11 | −15 | −8 | +5 | 23 |
| 102·0–103·9 | −1 | 14 | +2 | 33 | −4 | +1 | +12 | 47 | −11 | 7 | −13 | 14 | −17 | −13 | −10 | 21 |
| 104·0–105·9 | −2 | 11 | +3 | 29 | −3 | +1 | +9 | 40 | −11 | 3 | −1 | 5 | .. | −7 | .. | 8 |
| 106·0–107·9 | −1 | 9 | +9 | 12 | −2 | +3 | +17 | 21 | .. | .. | .. | .. | .. | .. | .. | .. |
| 108·0–109·9 | +1 | 17 | +1 | 14 | −4 | +1 | +11 | 31 | .. | .. | .. | .. | .. | .. | .. | .. |

which is not shown in the separation of the first quartiles. The medians for distances beyond 92° are consequently influenced by these additional late readings, which are probably misidentifications of later movements for the onset of $P$, and the results show that the genuine observations are in good agreement with the tables. The Jeffreys-Bullen table for $P$ has therefore been accepted as entirely satisfactory for representing the observations over the whole range of epicentral distances.

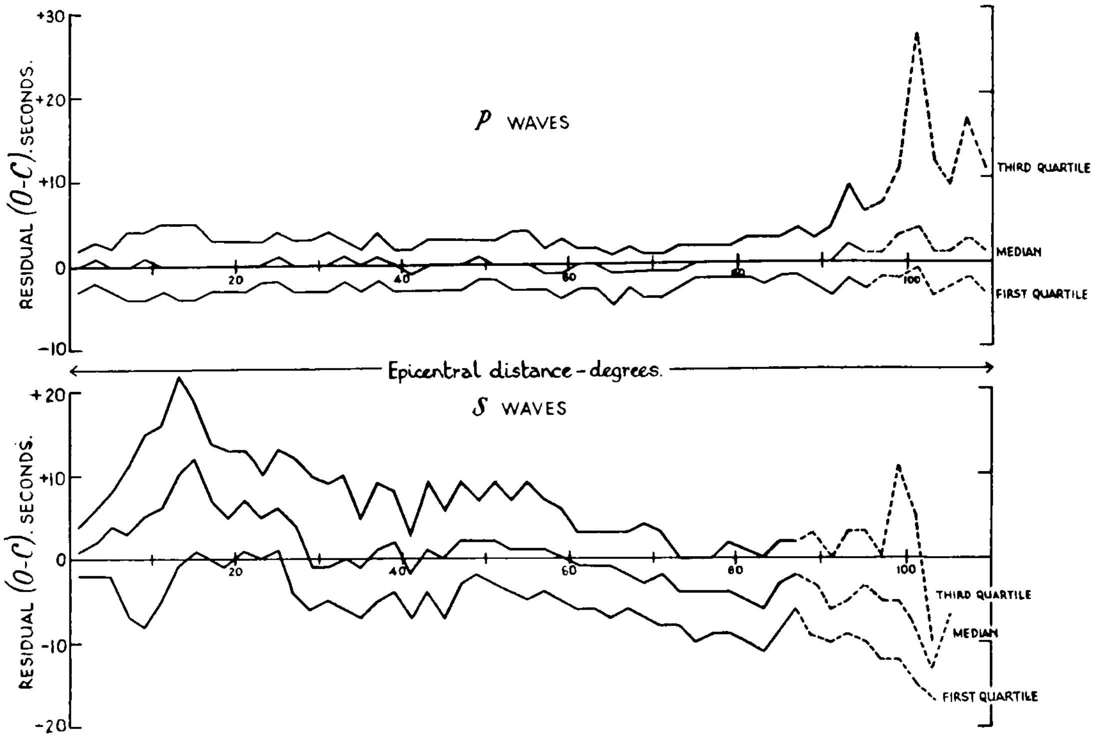



FIG. 4.—MEDIANS AND QUARTILES OF RESIDUALS, 1930-1.
Broken lines indicate that the values are computed from less than 100 observations.

The observations of $S$ are on the average later than the times of the tables at distances less than 28°, and systematically earlier than the tabulated times at distances beyond 60°. These differences are examined more closely in a later section. On the average for $S$ the separation of the quartiles from the medians is larger than for the $P$ data. Curiously enough the separation of the $S$ quartiles diminishes from about 100° showing very consistent observations at the greater distances.

The differences between the observations of $P$ at distances beyond 92° and the tabulated times have been attributed above to systematic errors in the identifications of the $P$ onset. Discrepancies, especially for the $S$ observations, are frequently passed over with an explanation of this sort, and it is necessary to examine how far the distributions of the residuals represent onsets of a single type of wave. The distributions of the residuals for the 146 earthquakes grouped for ten-degree ranges of distance from 0° to 110°, are shown in Fig. 5. The ordinates of the diagrams are the percentage occurrences of each residual from +15 seconds to −15 seconds. The residuals of $P$ appear on the left of the diagram, those of $S$ on the right.

The distributions for $P$ show well-defined maxima centring near the times from the tables, but at distances greater than 90° there are secondary maxima about 10 seconds later. It may be inferred that for distances less than 90° the residuals given in the Summary are usually those for the normal $P$ waves, and that errors in the identifications were rare.

Owing to the greater difficulties of observing, the maxima in the frequencies for $S$ are not so well-defined as those for $P$. The distributions are flattest for distances from 10° to 30°, and the scatter is greatest beyond 90° where the numbers of

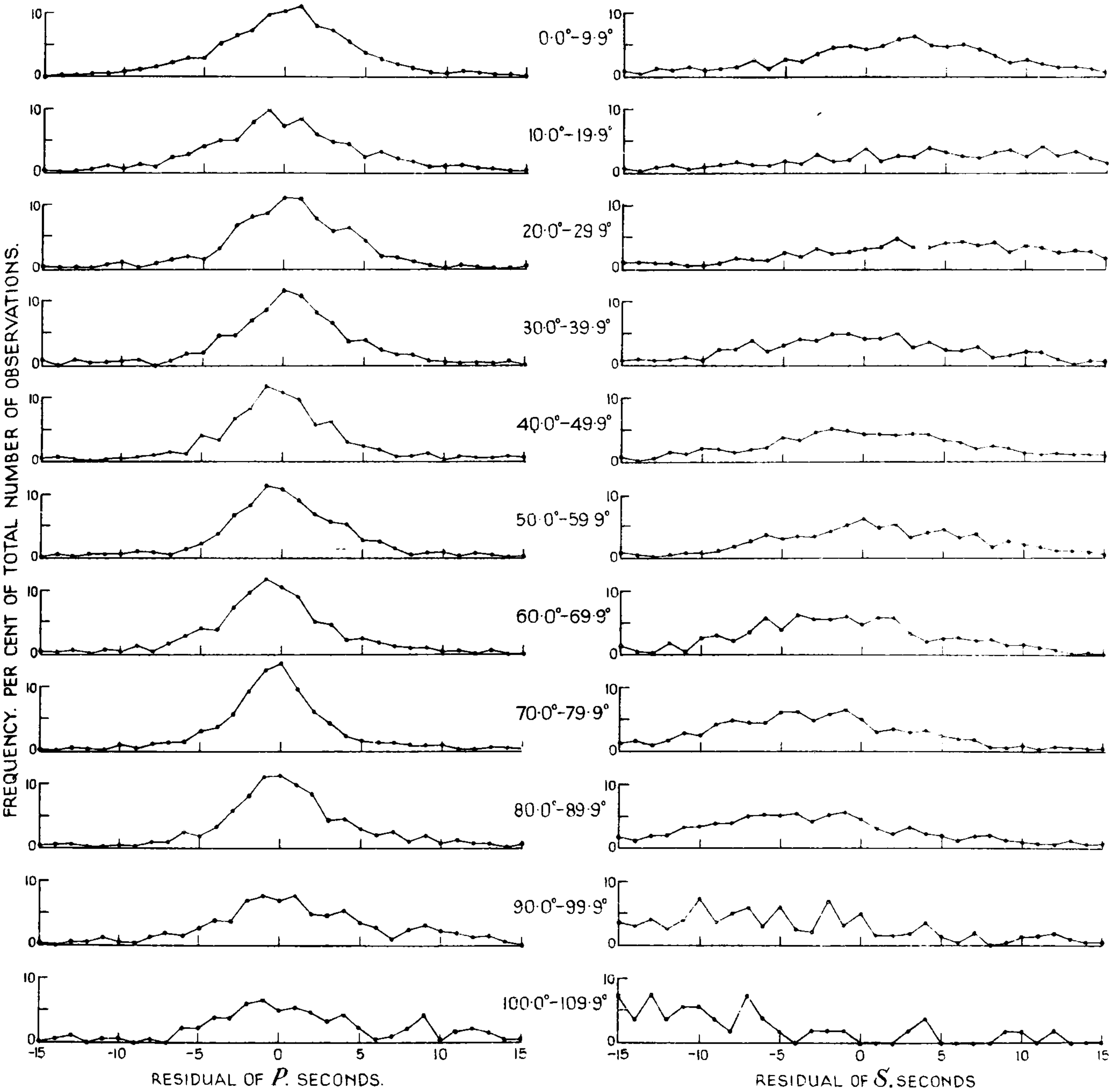



FIG. 5.—FREQUENCIES OF SPECIFIED RESIDUALS FOR *P* AND *S* OVER TEN-DEGREE RANGES OF EPICENTRAL DISTANCES.

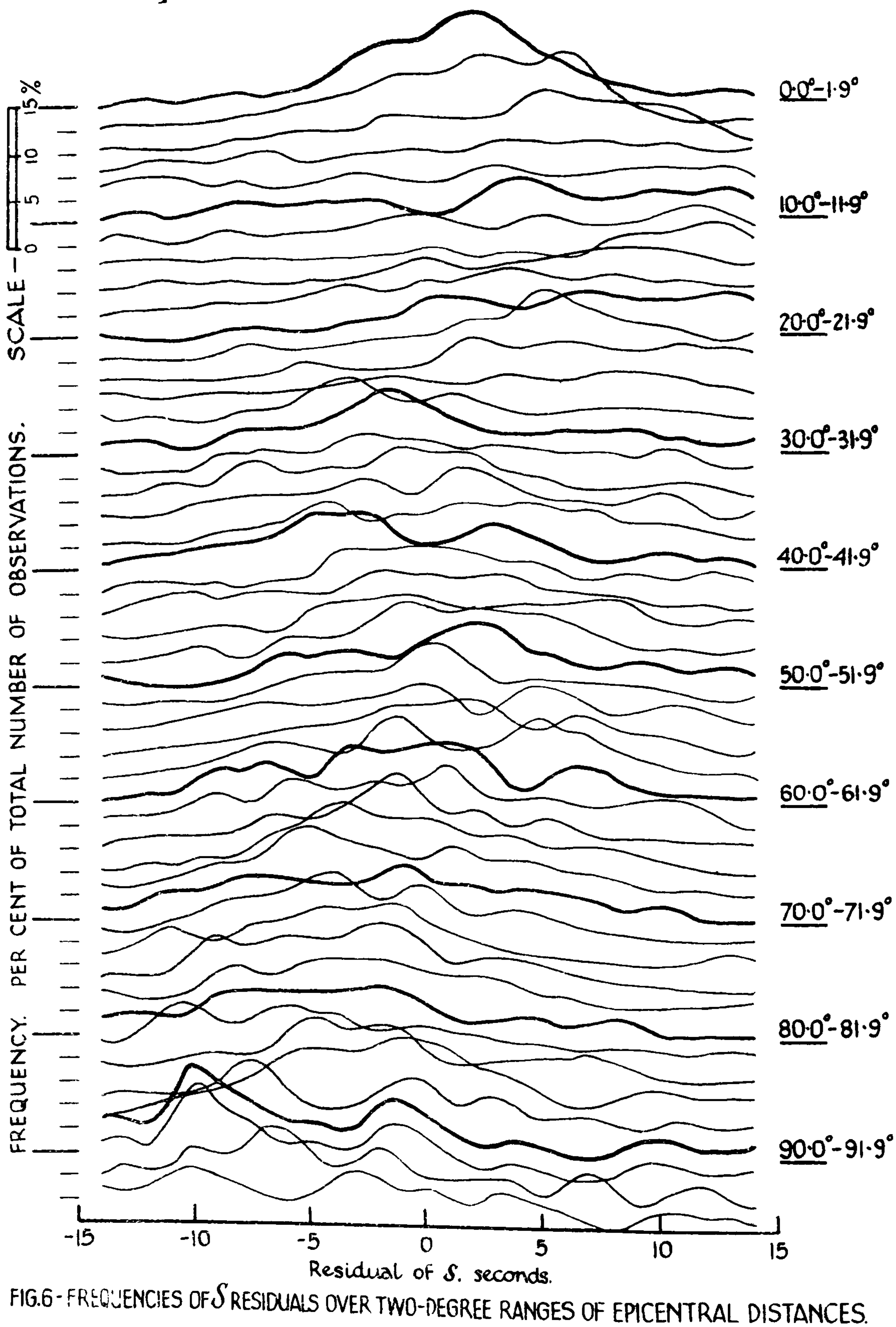



FIG. 6 - FREQUENCIES OF *S* RESIDUALS OVER TWO-DEGREE RANGES OF EPICENTRAL DISTANCES.

observations fall off. Subsidiary maxima are not very prominent but they seem to occur about 4 seconds on either side of the main maximum for distances less than 10°, and 5 or 6 seconds after that for distances from 40° to 50°.

A closer examination of the $S$ residuals, with particular reference to those at distances less than 30°, was clearly called for, and the frequencies for the two-degree ranges were studied. The distributions for these ranges are plotted in Fig. 6. For each range of distances the frequencies of the residuals have been averaged over groups of three consecutive values, the central values being given double weight; these smoothed numbers of occurrences are expressed as percentages of the number of observations. At distances less than about 30° the trend of the curves is notably smoother for negative than for positive residuals; beyond 60° this effect is reversed. The duplication of the maxima in the frequencies may be due to misidentifications. The possibility of such confusion arises :—

(1) At very short distances where some of the observations probably refer to the waves through the upper layers of the earth's crust, $S_g$ and $S^*$.

(2) Around 20° and 40° where waves of type $P_cP$ and $P_cS$ respectively arrive at about the same time as $S$.

(3) Beyond 80° where $SKS$ and the associated movements precede $S$.

To a great extent, however, the complexity of the diagram cannot be explained in this way, and the conclusion is that at most distances the combination of a large number of earthquakes cannot give data for $S$ which are reliable to within a few seconds. It is clear from the diagram that there is less evidence of duplication in the readings from 10° to 30° than for some other distances. It appears therefore that although there may have been some confusion in the identifications at small distances, the large scatter in the observations from 12° to 28° cannot be explained in this way.

## § 4—COMPARISON OF THE OBSERVATIONS WITH OTHER TABLES OF TRAVEL-TIMES

Since the introduction of the Jeffreys-Bullen tables, Dr. Jeffreys has published a number of papers in which the tables have been amended and in which the corrections are worked out for variations in the focal depth. In many cases the corrections are too small to affect the present analysis of the I.S.S. data, and in this work it has been assumed that the earthquakes are all of "normal" focal depth. The comparisons with later tables are therefore made with those derived from a re-discussion of the material used by Jeffreys and Bullen. The corrected tables are published in *Fascicule 14, Travaux Scientifiques de l'Association de Seismologie, U.G.G.I.* (4), and may conveniently be referred to as the J.14 (1936) tables.† The differences between the two sets of tables are shown in Fig. 7, together with the medians of the residuals for the I.S.S. observations.

The differences between the two tables of travel-times for $P$ are very small, and the observations are in good agreement with either of the tables.

The observations of $S$ may be divided into two groups corresponding with distances less or greater than 28°. In the first group the medians of the observations are conspicuously greater than the times given by either of the tables; these differences are examined in § 5. For distances exceeding 28° the medians are closer to the J.14 (1936) curve than to the straight line which represents the J.B. table. The travel-times are adapted to a single focal depth, and for foci within the upper layers the times of $S$ may be later, with respect to $P$, by an amount $Z$ which is independent of the distance. For distances beyond 28° the average departure of the medians from the later table is $1\frac{1}{2}$ sec., and the average $Z$ correction for the 146 earthquakes amounts to $-1\frac{1}{2}$ sec. Allowance for this correction brings the J.14 (1936) curve into fair agreement with the $S$ observations beyond 28°, but there are still some discrepancies.

† The designation J.14 (1936) has been adopted to distinguish between the tables of Fascicule 14, and the tables published by Jeffreys earlier in 1936 which were termed J (1936) in *Geophysical Memoirs*, No. 74.

Similar comparisons have been made between the observations and the tables of travel-times published by J. B. Macelwane (5), by K. Wadati and S. Oki (6), and by B. Gutenberg and C. F. Richter (7), but in no case did the tabulated times agree with the new I.S.S. observations as well as the tables, J.B. and J.14 (1936), examined above. In each case allowance has been made for the fact that the other

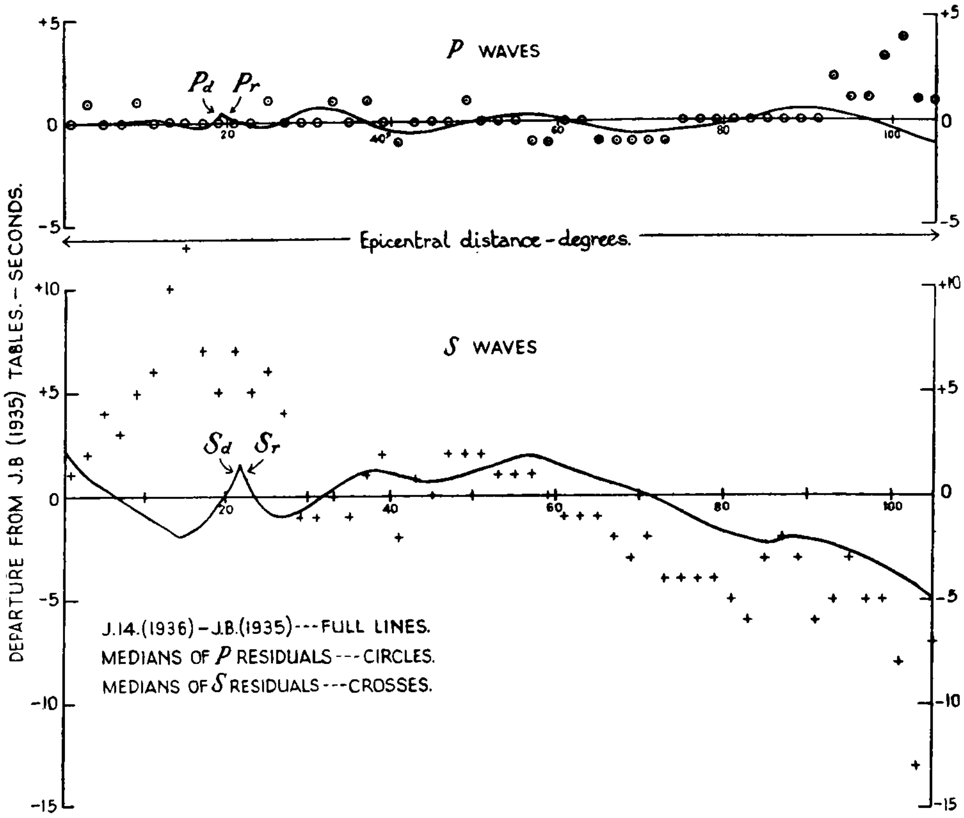



FIG. 7.—DEPARTURES FROM J.B. (1935) TABLES, OF J.14 (1936) TABLES AND OF OBSERVATIONS FROM THE I.S.S.

authors have taken as epoch the time of occurrence of the earthquake at the focus, whereas in the J.B. and J.14 (1936) tables the epoch is the extrapolated time of starting of the normal *P* wave. It may be noted that in his latest paper (8) Jeffreys arrives at tables which are intended to refer to a surface focus and the epoch is the time of occurrence of the earthquake.

## § 5—OBSERVATIONS OF *S* AT DISTANCES UP TO 28°

The large differences between the *S* observations and the tabulated times for distances less than 28° have been studied more closely, and the following possible explanations of the anomaly have been considered :—

(1) Errors in identification, some later onsets being mistaken for the true *S*.
(2) Differences between the focal depths of the 146 earthquakes.
(3) Errors in the *S* table for these distances.

Regarding (1) it must be reiterated that in the records of near earthquakes it may not be possible to discriminate between the onsets of the normal *S* and of waves which have travelled through the outer layers of the earth's crust. It has been shown in § 3 that there may have been some confusion in the identifications up to 12°, but the discrepancy beyond that distance cannot be explained in that way.

The scatter of the observations, represented by the differences between the first and third quartiles (Fig. 4), may be interpreted as evidence that the *Z* corrections of the earthquakes best recorded around 20° are not abnormal. In support of this interpretation it will be noted that the scatter of the *S* observations up to 28° is no greater than that beyond 28°, and further that the scatter of *S*, compared with that of $P$, is no larger from 10° to 28° than at other distances. Consequently it seems unlikely that the large systematic residuals of $S$ in this region can have been due to overweighting of the data by earthquakes at any particular focal depth. Evidence bearing more directly on this question is desirable, and it is hoped that, when changes are next made in the I.S.S., it will be found possible to give an approximate $Z$ correction for each important earthquake.

The accuracy of the $S$ tables from 15° to 25° has been examined critically by Jeffreys (4, p. 35), who concludes that the J.B. times for $S$ are nearly right. In support of this conclusion he gives the residuals of $S$ for five European earthquakes; these residuals are summarised in Table II.

TABLE II—NUMBERS OF OCCURRENCES OF SPECIFIED RESIDUALS OF $S$ FROM FIVE EUROPEAN EARTHQUAKES. H. Jeffreys. (Fascicule 14, p. 40.)

| Epicentral distance | Residual of $S$. seconds | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | −5 | −4 | −3 | −2 | −1 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| ° 0–10 | 0 | 0 | 2 | 2 | 1 | 3 | 2 | 0 | 3 | 5 | 6 | 6 | 1 | 0 | 1 | 1 | 2 | 0 | 0 | 1 | 2 | 1 | 2 |
| 10–20 | 1 | 0 | 1 | 1 | 1 | 2 | 0 | 3 | 2 | 2 | 0 | 2 | 2 | 3 | 1 | 7 | 4 | 2 | 8 | 4 | 3 | 3 | 1 |
| 20–30 | 0 | 0 | 2 | 1 | 2 | 2 | 4 | 3 | 3 | 2 | 4 | 8 | 9 | 4 | 4 | 3 | 8 | 1 | 2 | 1 | 1 | 2 | 3 |
| 30–40 | 0 | 4 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 2 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |

Regarding the figures Jeffreys writes: "It is clear on inspection that there is a maximum of frequency near 0 sec. in nearly all ranges. On the other hand there is a rise of frequency about +9 sec. in most ranges up to 30°, which is strongest in the range 10° to 20°."

To my mind the evidence of Table II does not provide any definite indication that the observations refer to more than one type of wave, and, without a careful examination of the seismograms for these earthquakes, the distributions may be regarded as merely representing the scatter of the $S$ observations.

From her investigation of the travel-times for distances around 20° (9), Miss Lehmann concludes that no normal $S$ was recorded at distances around 15° from the Atlantic earthquake of May 20, 1931, and suggests that the wave might be found at such distances in the records of stronger shocks. I have examined this possibility by comparing the observations of $S$ for two groups of earthquakes with epicentres in the belt from Europe to the Persian Gulf. The one group of five "stronger" shocks includes earthquakes which were all recorded at distances exceeding 90°; the other of "weaker" shocks is restricted to disturbances which were not recorded beyond 50°. Table III gives the medians of the $S$ residuals and the numbers of values for distances from 14° to 26°.

TABLE III—MEDIANS OF $S$ RESIDUALS FOR "STRONGER" AND "WEAKER" EARTHQUAKES

| Group of shocks | Dates of earthquakes | | Distance (degrees) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 14·0—15·9 | 16·0—17·9 | 18·0—19·9 | 20·0—21·9 | 22·0—23·9 | 24·0—25·9 |
| "Stronger" | 1930 May 6, 22h. May 8, 15h. July 23, 0h. Sept. 11, 12h. Oct. 30, 7h. | Median (sec.) | 10 | 8 | 5 | 9 | 5 | 4 |
| | | Number of values | 9 | 13 | 18 | 10 | 18 | 14 |
| "Weaker" | Mar. 6, 8h. Mar. 6, 9h. May 14, 0h. July 5, 23h. Oct. 7, 23h. | Median (sec.) | 8 | 8 | 5 | 6 | 3 | 2 |
| | | Number of values | 6 | 10 | 15 | 9 | 10 | 6 |

The medians for the two groups are in agreement for the ranges of distance from 16·0° to 19·9°, but for distances from 14·0° to 15·9° and from 20·0° to 25·9° the "stronger" shocks yield the larger positive residuals. It appears therefore that at such distances the agreement between the observations and the tabulated times is better for the "weaker" than for the "stronger" shocks.

It is well known that there are rapid changes in the slopes of the travel-time curves near 20°. These have been interpreted by some seismologists as indicating a discontinuity in the structure of the globe at a depth of about 470 Km. Miss Lehmann believes that pulses transmitted just above and just below the discontinuity could be identified in the records she examined of two earthquakes, one in Iceland, (July 23, 1929), the other in the Atlantic between the Azores and Portugal (May 20, 1931). These pulses were distinguished as $P_d$ and $P_r$, $S_d$ and $S_r$; at distances less than between 19° and 20° $P_d$ is supposed to precede $P_r$, and at distances greater than 20°, $P_r$ should precede $P_d$.

Jeffreys and Bullen accepted Miss Lehmann's hypothesis. In their table the run of $P$ and $S$ is smooth near 20° but they give in addition the times of $P_d$ and $S_d$ from 20° to 25°. In his later tables, J.14 (1936), Jeffreys makes discontinuities in $\partial P/\partial \Delta$ and in $\partial S/\partial \Delta$ at about 20° and $22\frac{1}{2}$° respectively. These discontinuities are responsible for the peaks near 20° in the curves of Fig. 7.

In the preparation of the I.S.S. the first pulse reported by a station as $P$ or $S$ is tabulated, so that if Miss Lehmann's hypothesis is adopted it must be supposed that the comparisons are with the waves which are leading at the appropriate distance. The analysis of the data for 1930–1 is not capable of verifying or disproving the hypothesis; it is impossible to say whether the peaks in the curves are necessary to give an accurate representation of the observations.

### § 6—KEW RECORDS OF EARTHQUAKES AT DISTANCES FROM 12° TO 28°

The discrepancy between the $S$ observations from about 12° to 28° and the calculated times arises from a difference of opinion as to the characteristics of the $S$ onset. On the one hand practical seismologists examining the records can easily recognise the large oscillations of the $S$ phase and generally accept the first prominent movement for tabulation; the analysis of the I.S.S. material has shown that half of the observations are consistent within about $\pm 10$ sec. over the difficult region. The tables, on the other hand, have been constructed from selected early readings, in the belief that they represent the true onset which is so small that it is frequently missed altogether. The indications of the earlier sections of the present paper were not in favour of this hypothesis, but before it can be rejected the records of a first class observatory must be studied to see whether the smaller movements can be found at the times given by the $S$ table. For this purpose I have re-examined our seismograms of the 20 earthquakes at distances from Kew of 12° to 28° during the years 1930 and 1931.

Details of the shocks and of the Kew observations are given in Table V. The shock of November 21, 1930 ($\Delta = 17·8°$) is shown with a residual $S$ ($O-C$) of $+21$ sec.; on this occasion only the E component was available and the $S$ phase was small. There is a suggestion of a smaller movement about 10 seconds before that accepted as $S$, but in view of the absence of the other components it has been thought best to omit this earthquake. Earlier movements which might have been selected instead of those tabulated for $S$, were found on re-measurement of the records for three small shocks which showed abnormal residuals. These shocks, and the corrections to the $S$ residuals, are :—

| | | | |
|---|---|---|---|
| February 23, 1930. | $\Delta = 20·5°$ | $S$ ($O-C$) | corrected from $+28$ sec. to $+8$ sec. |
| January 4, 1931. | $\Delta = 21·2°$ | $S$ ($O-C$) | corrected from $+16$ sec. to $+7$ sec. |
| September 11, 1930. | $\Delta = 26·2°$ | $S$ ($O-C$) | corrected from $+28$ sec. to $+9$ sec. |

These corrections have been adopted.

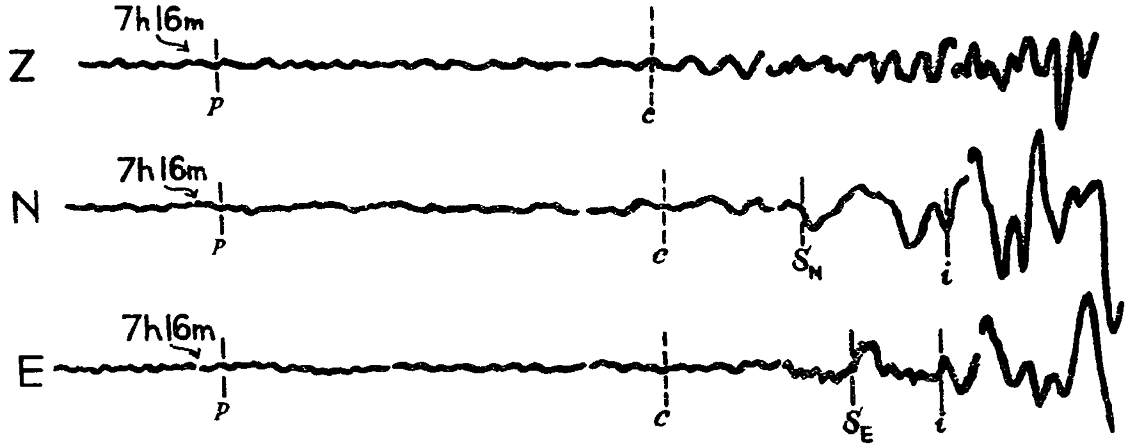
Omitting the shock of November 21, 1930, and also that of October 30, 1930, when (as shown below) the onset of the normal $S$ wave could not be identified at Kew, the $S$ residuals for the 18 surviving shocks are $-4$, 0, $+1$, $+2$, $+4$, $+5$, $+5$, $+6$, $+6$, $+7$, $+7$, $+7$, $+8$, $+9$, $+10$, $+11$, $+11$, and $+14$ sec. The distribution

KEW SEISMOGRAMS. ITALIAN EARTHQUAKE OF OCTOBER 30, 1930.

$\Delta = 12 \cdot 1°$. AZIMUTH = 315°.

$P(O-C) = +4$ sec. $S(O_N - C) = +50$ sec.

$S(O_E - C) = +63$ sec.



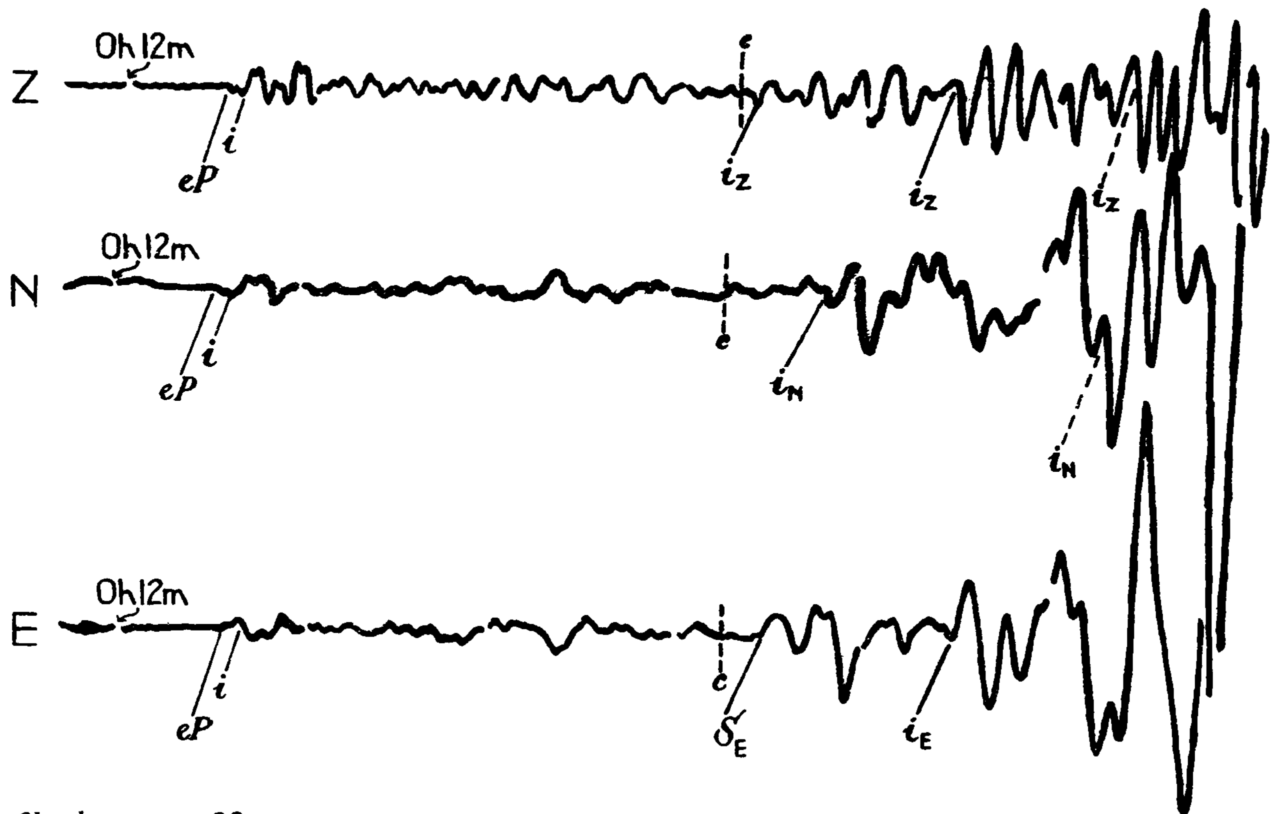

*Clock error: +20 sec.*

The movements on N and E giving residuals of +50 sec. and +63 sec. were tabulated as $S$ in the Observatory bulletin. Later information has shown that the observations given as $S$ and $i$ in the bulletin refer to waves $S^*$ and $Sg$ respectively.

FIG. 8.

*Plate VI.*

KEW SEISMOGRAMS. ITALIAN EARTHQUAKE OF JULY 23, 1930.
$\Delta = 14{\cdot}9^{\circ}$ AZIMUTH $= 319^{\circ}$
$P(O-C) = +1$ sec. $S(O-C) = +11$ sec.




*Clock error: +22 sec.*
Antipathy of N and E in the *P* phases; sympathy in *S* poorly developed.
Z agrees with N throughout.

FIG. 9.

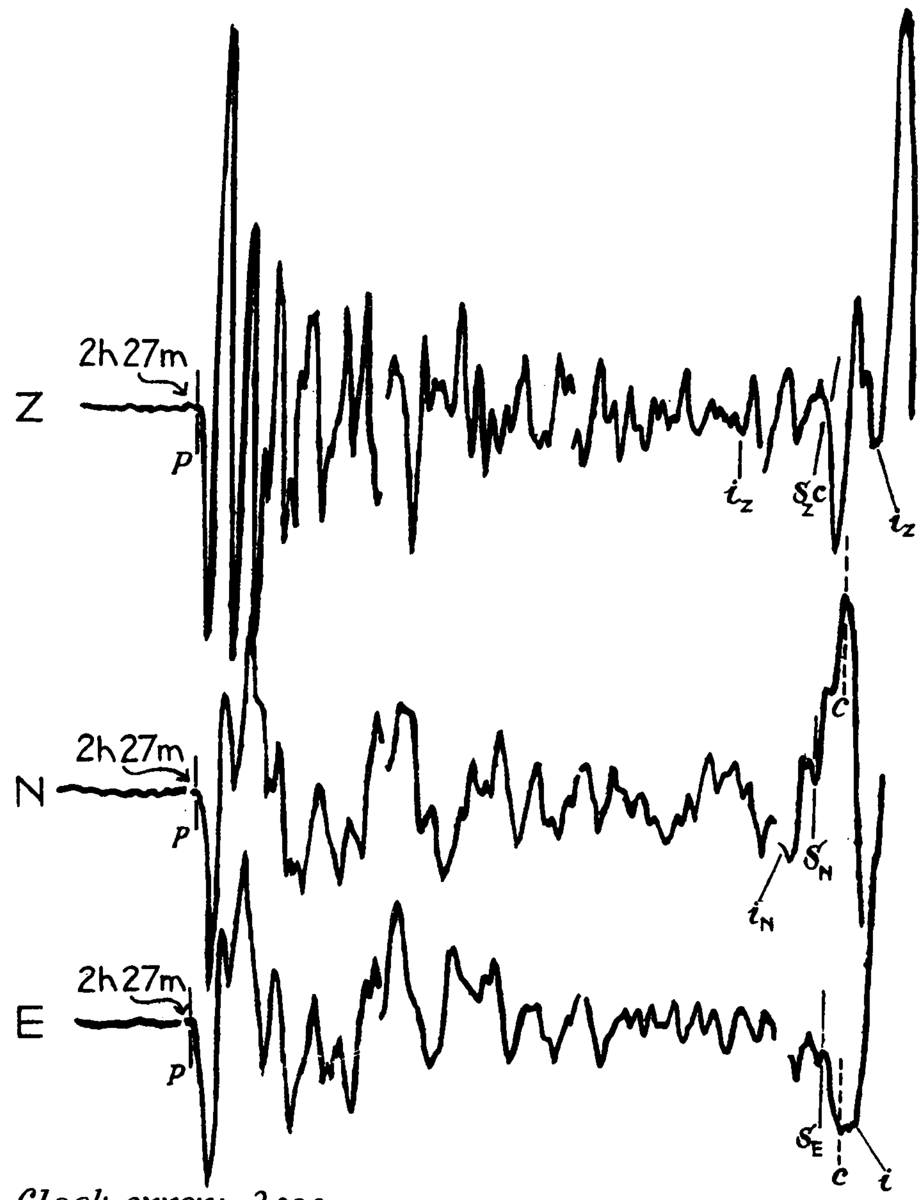
*Plate VII.*

KEW SEISMOGRAMS. ATLANTIC EARTHQUAKE OF MAY 20, 1931.

$\Delta = 17{\cdot}9°$. AZIMUTH = 33°.

$P(O-C) = -1$ sec. $S(O_Z - C) = 0$.

$S(O_N - C) = -6$ sec. $S(O_E - C) = -5$ sec.




*Clock error: +3 sec.*

Sympathy of N and E in the *P* phases changes to Antipathy at *S*: Z agrees with E throughout.

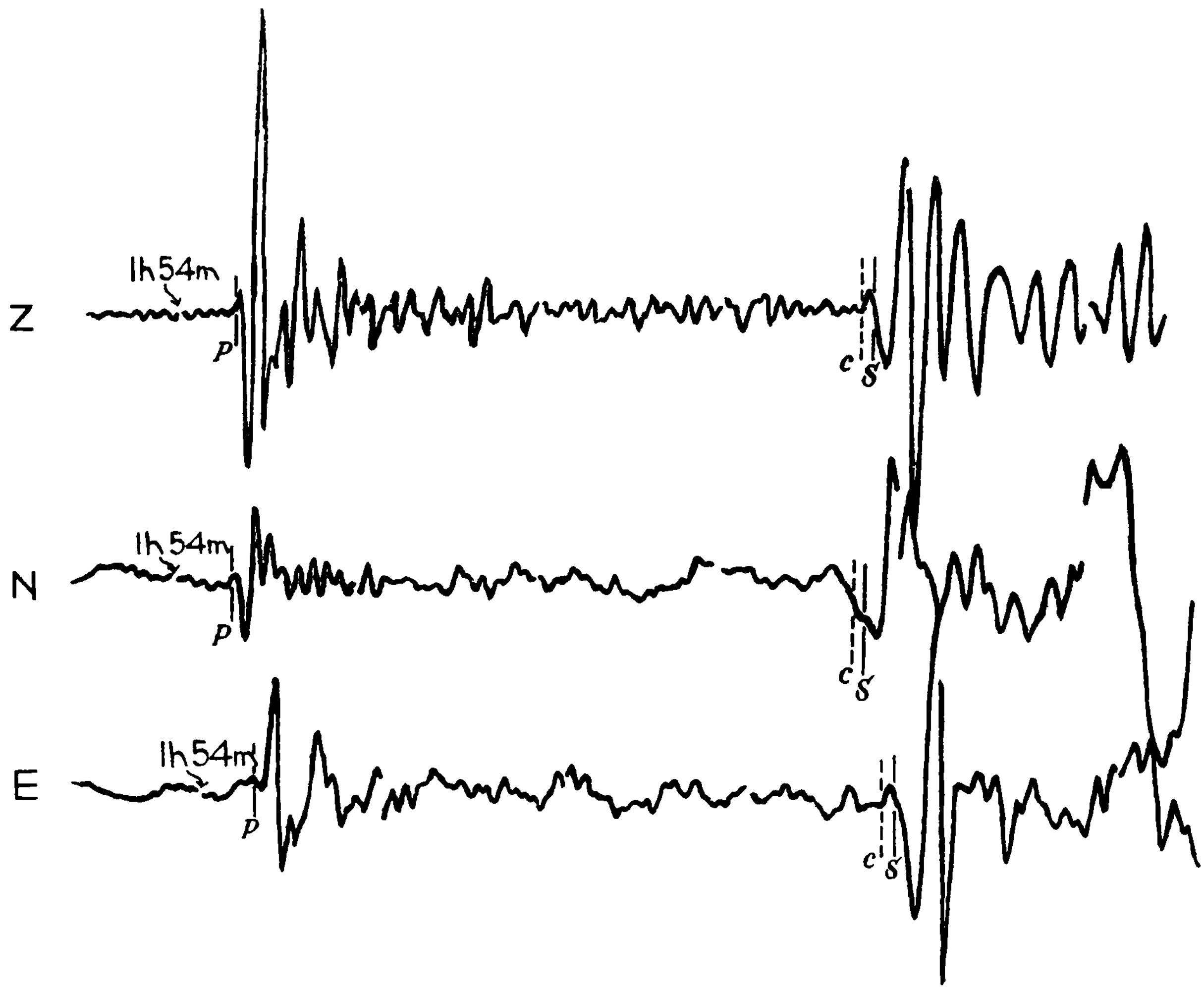
FIG. 10.

*Plate VIII.*

KEW SEISMOGRAMS. MACEDONIAN EARTHQUAKE OF MARCH 8, 1931.

$\Delta = 18{\cdot}8°$ AZIMUTH = 312°.

$P(O-C) = +1$ sec. $S(O-C) = +4$ sec.




*Clock error:–21 sec.*

Antipathy of N and E in the *P* phases changes to sympathy at *S*; Z agrees with N throughout.

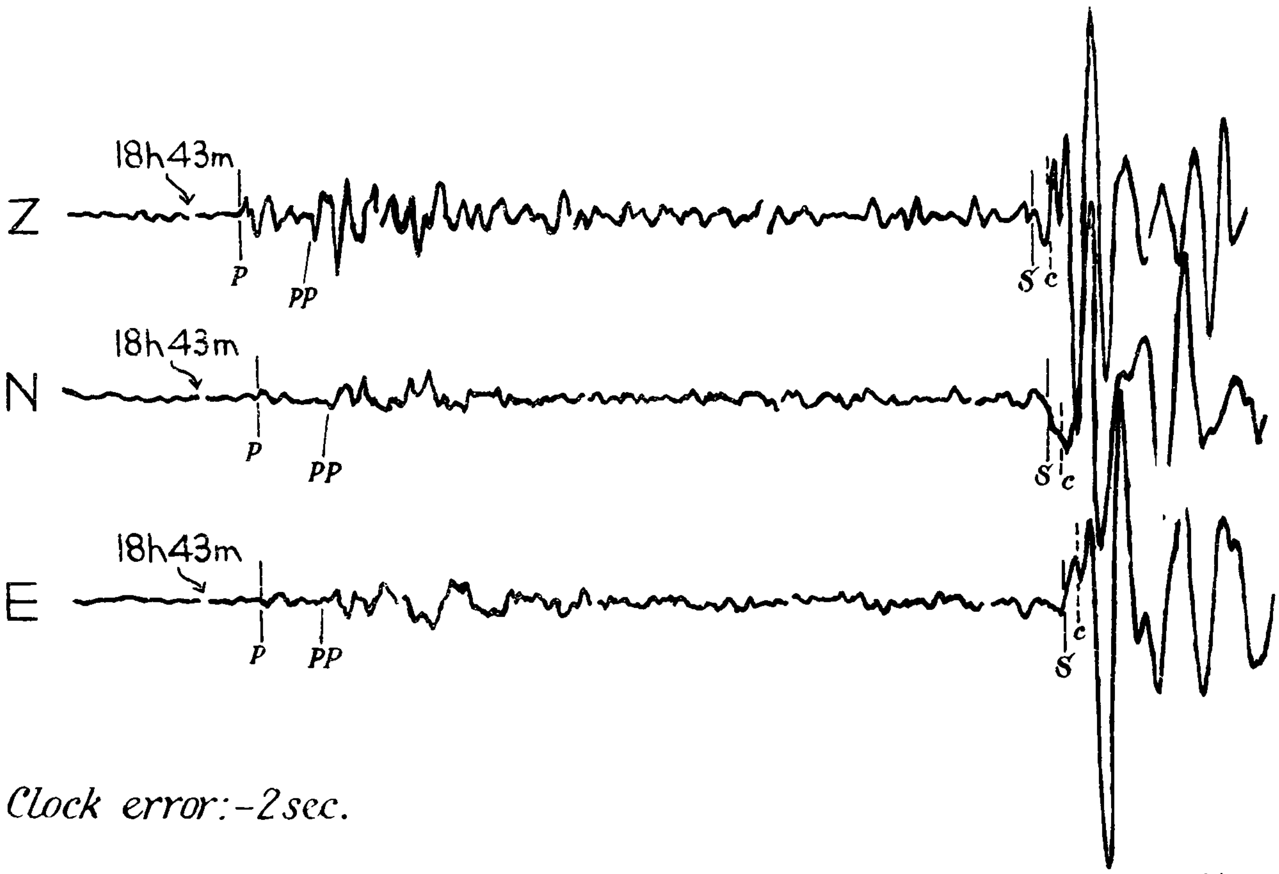
FIG. 11.

*Plate IX.*

KEW SEISMOGRAMS. EARTHQUAKE NORTH OF CRETE ON FEBRUARY 14, 1930.

$\Delta = 23{\cdot}7^\circ$ AZIMUTH $= 318^\circ$

$P(O-C) = +1$ sec. $S(O-C) = -4$ sec.




*Clock error: -2 sec.*

Antipathy of N and E in the *P* phases changes to sympathy at *C*: Z agrees with E in *P* phases.

FIG. 12.

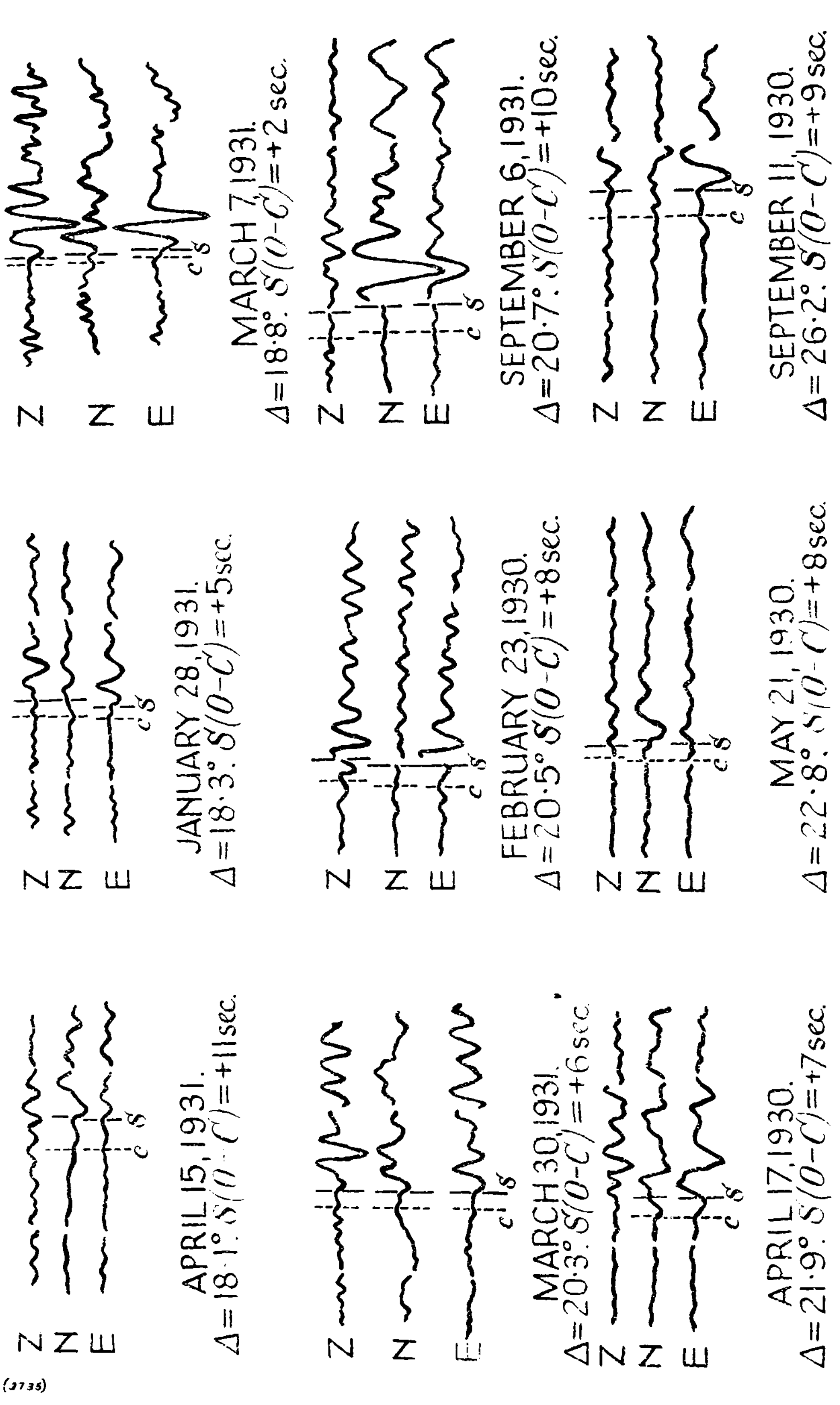



FIG. 13.—KEW RECORDS OF S PHASES FOR EARTHQUAKES AT EPICENTRAL DISTANCES FROM 18° TO 26°.

(3735)

of these residuals shows a maximum in the frequency near +7 sec. and is in striking agreement with that obtained from the I.S.S. observations.

The records of five of the larger shocks are shown in Figs. 8–12, and of the *S* onset for nine smaller shocks in Fig. 13. In these reproductions the direction of recording is from left to right, and upward movements in the diagrams correspond with true earth movements downwards, to the south and to the west. In each diagram *P* and *S* indicate the phases tabulated in the Kew bulletin, and *C* the time of the *S* onset appropriate to the J.B. table.

The difficulty of identification of the normal *S* onset at distances around 12° is brought out from the Kew records of the Italian earthquake on October 30, 1930 (Fig. 8). The movements tabulated as *S* on the two horizontal components differ in time by 13 sec.; probably both these movements refer to the same type of waves, but the onset on the E-W component is obscured by microseisms. A prominent movement about half a minute later was tabulated as " $i_{NE}$ " in the bulletin. Now that the time of origin and epicentral distance are known, it appears that the movements tabulated as *S* are really associated with waves which have travelled through the intermediate layers ($S^*$), and that the later onset, *i*, is $S_g$ the distortional wave through the granitic layer. The travel-times of $S^*$ and $S_g$ to 12·1° being 5 min. 58 sec. and 6 min. 34 sec. (10), the residuals are $S^*$ $(O_N–C)= –3$ sec., and $S_g$ $(O–C)=$ +2 sec. About 8 sec. after *C*, the calculated time for the normal *S* wave, there is some increase in the disturbance of the Z component, but there is no corresponding change in the horizontal components. The onset on Z is very uncertain. This set of records show clearly that misidentifications cannot be avoided at the smaller epicentral distances.

The Italian earthquake of July 23, 1930, 14·9° from Kew, has been studied by Jeffreys (11). The onsets tabulated in the Kew bulletin, and shown in Fig 9, are :—

| | | | |
|---|---|---|---|
| *eP* | at | 0h. 12m. 11s. | G.M.T. |
| *i* | ,, | 0h. 12m. 16s. | ,, |
| $i_Z$ | ,, | 0h. 15m. 0s. | ,, |
| $iS_E$ | ,, | 0h. 15m. 7s. | ,, |
| $i_{ZE}$ | ,, | 0h. 16m. 7s. | ,, |

The movement $i_Z$ at 15m. 0s. is in agreement with the J.B. table, and is the one selected by Jeffreys as the true *S*; it is much smaller than the prominent movement on the E component 7 seconds later, which was given as the *S* in the bulletin. The epicentral distance, 14·9°, is greater than that usually believed to be the range of transverse waves through the crust, but the conspicuous movement, $i_{ZE}$, at 16m. 7s. occurs near the time of $S^*$ and another clear onset (shown by the broken arrow), at 16m. 58s. corresponds with $S_g$.

The so-called Azores earthquake of May 20, 1931 (Fig. 10), is discussed in the paper by Miss Lehmann (9) and in more recent papers by Jeffreys (12, 13). The epicentre accepted for the I.S.S., 37·4° N., 15·9° W., is that given in the earlier paper by Jeffreys; in his later paper the epicentre is corrected to 37·44° N., 16·17° W. For each of these epicentres the distance from Kew is 17·9° to the nearest 0·1°, and the data of the I.S.S. for Kew are not improved by the small change in the epicentre. In selecting the onset for *S* on the N and E components it was noted that the movements of the *P* phases were in sympathy, movements to the north being accompanied by movements to the east and *vice versa*, and that at *S* the sympathy changed to antipathy; this change occurs 5 or 6 seconds before the time of the J.B. table. Miss Lehmann found that onsets several seconds before the time of arrival of *S* were recorded on the seismograms of a number of observatories at distances less than 19°, and suggested that they might be due to a small wave travelling at a somewhat greater speed than the normal *S* wave.

For the Macedonian earthquake of March 8, 1931 (Fig. 11), antipathy of N and E in the *P* phases changes to sympathy at *S*. Small movements near *C* may possibly be associated with the small wave preceding *S* referred to in the above discussion of the Azores earthquake. These movements are small and the selection of the large onset at the point marked *S* seems to be the most reasonable choice for the commencement of the *S* phase.

In the following diagram (Fig. 12) the phases cannot be followed with certainty around *S*, but at *C* the antipathy of N and E in the *P* phases is clearly changed to sympathy; with the sharp onsets at *S*, the observed data must be accepted as satisfactory. The early arrival of *S* around this distance is confirmed from the I.S.S., since 12 of the 18 stations at distances from 20° to 25° gave negative residuals.

The observations of *S* are later than the calculated times for each of the sets of records in Fig. 13. On re-examining the records for earlier movements near the calculated times it is found that such movements can possibly be identified in the records of March 7, 1931, and of April 17, 1930; the small movements on these two occasions are not clearly shown in all three components. In the other seven shocks there are no definite movements preceding *S* to indicate the arrival of an earlier wave. The absence of the earlier movement is especially notable in the large *S* waves of the shock on September 6, 1931.

The main conclusion to be drawn from the re-examination of the Kew records for distances from 12° to 28° is that, at least for some earthquakes, the large *S* onset is preceded by a small movement found more frequently in the vertical than in the horizontal components. The early arrival is inconspicuous in comparison with the large onset which is chosen as the *S* of the Kew seismograms, and which according to the I.S.S. observations is the movement generally selected.

## § 7—NEW *S* TABLE DERIVED FROM THE OBSERVATIONS OF THE INTERNATIONAL SEISMOLOGICAL SUMMARY

The investigation of the data given in the I.S.S. for the 146 earthquakes of 1930–1 has shown that the observations of *P* are in excellent agreement with the J.B. table. The observations of *S* differ from the tables seriously at distances less than 28° and to a lesser extent at the greater distances. According to Jeffreys (11) the times of the *S* tables at distances less than 28° refer to a small movement which indicates the first arrival of waves which have been distortional over the whole of the path from the epicentre to the recording station. The evidence in favour of this conclusion is obtained from his examination of some of the records of the Italian earthquake of July 23, 1930. The residuals he obtains for *S* (11, p. 397) are very scattered. Various suggestions, regarding the nature of the large later movement, are examined in this paper, but he fails to find a satisfactory explanation of its occurrence.

I do not like the hypothesis of a small *S* followed several seconds later by a much larger movement derived from the *S*. The difficulty is that the second movement is so much larger and occurs so much more frequently than the one from which it is supposed to be generated. On the other hand if the large movement is accepted as *S* we are left only with a small subsidiary movement preceding it, and this smaller movement is not prominent enough to be observed frequently. Efforts have been made to develop a satisfactory explanation of this earlier movement as due to transformation of the *S* wave into *P* during some part of its path through the crustal layers, but such an explanation cannot be reconciled with the ordinary laws of refraction for waves passing through homogeneous layers separated by horizontal discontinuities. Actually the properties of the materials in the layers of the earth's crust vary with the depth, the changes from layer to layer occur as gradual transitions rather than as discontinuities, and these transitions may not be horizontal. Under these circumstances the possibility of *S* waves being transformed to *P* in the crust cannot be ignored.

The travel-time tables are required for two purposes:—

(a) for investigating the properties of the material at different depths below the surface of the earth.

(b) for estimation of distances from the records of an earthquake.

(a) requires an accurate knowledge of the travel of the purely distortional waves, but for (b) all that is needed is a table giving the times for the movements most likely to be selected as *P* and *S* by a seismologist whose only information is generally that of the seismograms for a single observatory. For this latter purpose a table of *S* travel-times has been prepared from the medians of the *S* observations for the 146 earthquakes.

The procedure for smoothing the $S$ observations was modified from that utilised in the investigation (14) of the travel of the waves from the Baffin Bay earthquake of November 20, 1933. The epicentral distances studied for the Baffin Bay shock were from 25° to 50°. Over this range the times do not differ greatly from those which correspond with uniform rates of travel over the earth's surface, and all times were accordingly referred to " basic " times progressing uniformly from the J.B. values at 25° to the J.B. values at 50°. Diagrams were then prepared with the abscissae as distances and the ordinates as the differences between the travel-times and the basic times. The travel-time appears as a straight line in a diagram of this sort when the apparent velocity is a linear function of the epicentral distance.

In the present case we have a much wider range of distances and greater departures of the travel from uniform rates. The possibility of taking the basic times as more complicated functions of the distance were rejected since the advantages of linear representation would be lost, and it was decided to divide the observations into four ranges of distance, and to compute basic times from the J.B. values at 0°, 25°, 50°, 75° and 100°. The data for these ranges of distance are set out in the following table :—

| Epicentral distance | Travel-time of $S$ (J.B.) | Range of epicentral distance | Basic time for $S$ |
|---|---|---|---|
| ° | sec. | ° | sec. |
| 25 | 581·0 | 0— 25 | $23{\cdot}240\,\Delta$ |
| 50 | 960·9 | 25— 50 | $201{\cdot}1+15{\cdot}196\,\Delta$ |
| 75 | 1280·1 | 50— 75 | $322{\cdot}5+12{\cdot}768\,\Delta$ |
| 100 | 1536·5 | 75—105 | $540{\cdot}9+\ 9{\cdot}856\,\Delta$ |

The new table for $S$ has been constructed by plotting the departures of the medians of the I.S.S. observations from the basic times and drawing curves as evenly as possible among the points. The curves and observations are shown in Fig. 14. The travel-times of the new $S$ table and of the J.B. table for $P$, rounded to the nearest second, are given in Table IV together with the differences $S$–$P$.

The Kew observations of $P$ and $S$ from the earthquakes of 1930–1 are set out in Table V. The residuals $P$ ($O$–$C$) and $S$ ($O$–$C$) are those for the J.B. tables, while $S$ ($O$–$C'$) refers to the new table for $S$. The numbers of occurrences of each residual are :—

| Residual, seconds | −16 | −15 | −14 | −13 | −12 | −11 | −10 | −9 | −8 | −7 | −6 | −5 | −4 | −3 | −2 | −1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $S$ ($O$–$C$) .. | 1 | 2 | 0 | 2 | 0 | 0 | 0 | 0 | 3 | 1 | 4 | 1 | 8 | 5 | 3 | 3 |
| $S$ ($O$–$C'$) .. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 1 | 1 | 1 | 2 | 5 | 4 | 7 | 6 |

| Residual, seconds | 0 | +1 | +2 | +3 | +4 | +5 | +6 | +7 | +8 | +9 | +10 | +11 | +12 | +13 | +14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $S$ ($O$–$C$) .. | 5 | 1 | 3 | 1 | 4 | 4 | 4 | 5 | 2 | 1 | 1 | 2 | 0 | 0 | 1 |
| $S$ ($O$–$C'$) .. | 5 | 8 | 5 | 4 | 4 | 3 | 4 | 1 | 2 | 2 | 0 | 0 | 0 | 0 | 0 |

It is found that for the 67 earthquakes included in the table, the Kew observations of $S$ are all within $\pm 9$ sec. of the times given in the new table, and within $\pm 3$ sec. on 39 occasions. The corresponding comparisons with the J.B. table show agreement within $\pm 9$ sec. for 58 of the earthquakes, and within $\pm 3$ sec. on only 21 occasions. The residuals of $S$ for the two sets of tables are plotted against the epicentral distance in Fig. 15 ; the scatter of the observations is much less in the lower part of the diagram, which refers to the new table, and the observations are more uniformly distributed about the zero line. It is therefore clear that the Kew observations are a fair sample of the material incorporated in the I.S.S., and that the new table for $S$ has not been overweighted by the inclusion in the summary of data for the numerous observatories with instruments of lower sensitivity.

In conclusion it must be emphasised again that the preparation of the new table is not to be regarded as prejudicing the question whether a wave of $S$ type can occur which passes more rapidly through the earth than the $S$ which has been tabulated. Figs. 8–11 are evidence that this may indeed be the case.

TABLE IV—TRAVEL-TIME TABLES OF $P$ AND $S$

$P$ from J.B. $S$ from I.S.S. Observations, 1930-1.

Epoch: Extrapolated time of starting of $P$.

| Δ | P | | S | | S–P | | Δ | P | | S | | S–P | | Δ | P | | S | | S–P | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ° | m. | s. | m. | s. | m. | s. | ° | m. | s. | m. | s. | m. | s. | ° | m. | s. | m. | s. | m. | s. |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 7 | 32 | 13 | 37 | 6 | 5 | 80 | 12 | 8 | 22 | 11 | 10 | 3 |
| 1 | | 14 | | 26 | | 12 | 41 | | 40 | | 52 | | 12 | 81 | | 13 | | 22 | | 9 |
| 2 | | 29 | | 53 | | 24 | 42 | | 49 | 14 | 7 | | 18 | 82 | | 18 | | 32 | | 14 |
| 3 | | 43 | 1 | 19 | | 36 | 43 | | 57 | | 21 | | 24 | 83 | | 23 | | 43 | | 20 |
| 4 | | 57 | | 45 | | 48 | 44 | 8 | 5 | | 36 | | 31 | 84 | | 28 | | 54 | | 26 |
| 5 | 1 | 11 | 2 | 11 | 1 | 0 | 45 | | 13 | | 51 | | 38 | 85 | | 33 | 23 | 4 | | 31 |
| 6 | | 25 | | 36 | | 11 | 46 | | 21 | 15 | 5 | | 44 | 86 | | 38 | | 14 | | 36 |
| 7 | | 39 | 3 | 2 | | 23 | 47 | | 29 | | 20 | | 51 | 87 | | 43 | | 24 | | 41 |
| 8 | | 53 | | 28 | | 35 | 48 | | 36 | | 34 | | 58 | 88 | | 48 | | 34 | | 46 |
| 9 | 2 | 7 | | 53 | | 46 | 49 | | 44 | | 48 | 7 | 4 | 89 | | 53 | | 44 | | 51 |
| 10 | | 21 | 4 | 19 | | 58 | 50 | | 51 | 16 | 2 | | 11 | 90 | | 57 | | 53 | | 56 |
| 11 | | 35 | | 45 | 2 | 10 | 51 | | 59 | | 16 | | 17 | 91 | 13 | 2 | 24 | 2 | 11 | 0 |
| 12 | | 48 | 5 | 10 | | 22 | 52 | 9 | 6 | | 30 | | 24 | 92 | | 7 | | 11 | | 4 |
| 13 | 3 | 2 | | 36 | | 34 | 53 | | 14 | | 43 | | 29 | 93 | | 11 | | 20 | | 9 |
| 14 | | 15 | 6 | 2 | | 47 | 54 | | 21 | | 57 | | 36 | 94 | | 16 | | 29 | | 13 |
| 15 | | 29 | | 26 | | 57 | 55 | | 29 | 17 | 10 | | 41 | 95 | | 21 | | 37 | | 16 |
| 16 | | 41 | | 49 | 3 | 8 | 56 | | 36 | | 24 | | 48 | 96 | | 25 | | 46 | | 21 |
| 17 | | 54 | 7 | 11 | | 17 | 57 | | 43 | | 37 | | 54 | 97 | | 30 | | 55 | | 25 |
| 18 | 4 | 7 | | 32 | | 25 | 58 | | 50 | | 50 | 8 | 0 | 98 | | 34 | 25 | 3 | | 29 |
| 19 | | 19 | | 52 | | 33 | 59 | | 57 | 18 | 3 | | 6 | 99 | | 39 | | 12 | | 33 |
| 20 | | 30 | 8 | 12 | | 42 | 60 | 10 | 5 | | 16 | | 11 | 100 | | 44 | | 20 | | 36 |
| 21 | | 40 | | 32 | | 52 | 61 | | 12 | | 28 | | 16 | 101 | | 48 | | 28 | | 40 |
| 22 | | 51 | | 51 | 4 | 0 | 62 | | 18 | | 41 | | 23 | 102 | | 53 | | 36 | | 43 |
| 23 | 5 | 1 | 9 | 10 | | 9 | 63 | | 25 | | 54 | | 29 | 103 | | 57 | | 44 | | 47 |
| 24 | | 10 | | 28 | | 18 | 64 | | 32 | 19 | 6 | | 34 | 104 | 14 | 2 | | 52 | | 50 |
| 25 | | 20 | | 46 | | 26 | 65 | | 39 | | 19 | | 40 | 105 | | 7 | 26 | 0 | | 53 |
| 26 | | 29 | 10 | 2 | | 33 | 66 | | 45 | | 31 | | 46 | .. | | .. | | .. | | .. |
| 27 | | 38 | | 18 | | 40 | 67 | | 52 | | 43 | | 51 | .. | | .. | | .. | | .. |
| 28 | | 47 | | 33 | | 46 | 68 | | 58 | | 55 | | 57 | .. | | .. | | .. | | .. |
| 29 | | 56 | | 49 | | 53 | 69 | 11 | 5 | 20 | 7 | 9 | 2 | .. | | .. | | .. | | .. |
| 30 | 6 | 5 | 11 | 4 | | 59 | 70 | | 11 | | 19 | | 8 | .. | | .. | | | | .. |
| 31 | | 14 | | 19 | 5 | 5 | 71 | | 17 | | 31 | | 14 | .. | | .. | | .. | | .. |
| 32 | | 23 | | 35 | | 12 | 72 | | 23 | | 42 | | 19 | .. | | .. | | .. | | .. |
| 33 | | 32 | | 50 | | 18 | 73 | | 29 | | 54 | | 25 | .. | | .. | | | | .. |
| 34 | | 40 | 12 | 6 | | 26 | 74 | | 35 | 21 | 5 | | 30 | .. | | .. | | .. | | .. |
| 35 | | 49 | | 21 | | 32 | 75 | | 40 | | 16 | | 36 | .. | | .. | | .. | | .. |
| 36 | | 58 | | 36 | | 38 | 76 | | 46 | | 27 | | 41 | . | | .. | | .. | | .. |
| 37 | 7 | 6 | | 51 | | 45 | 77 | | 52 | | 38 | | 46 | . | | .. | | .. | | .. |
| 38 | | 15 | 13 | 7 | | 52 | 78 | | 57 | | 49 | | 52 | .. | | .. | | .. | | .. |
| 39 | | 24 | | 22 | | 58 | 79 | 12 | 3 | 22 | 0 | | 57 | .. | | .. | | .. | | .. |

## § 8—SUMMARY

The travel-times of $P$ and $S$ waves are examined, using the data published in the International Seismological Summary of 1930 and 1931 for 146 well-recorded earthquakes; the shocks are all of normal focal depth.

The observations of $P$ are in good agreement with the travel-time table published by Jeffreys and Bullen in 1935. For $S$ the observations are generally later than the tabulated times at distances less than 28°, and earlier than the tabulated times

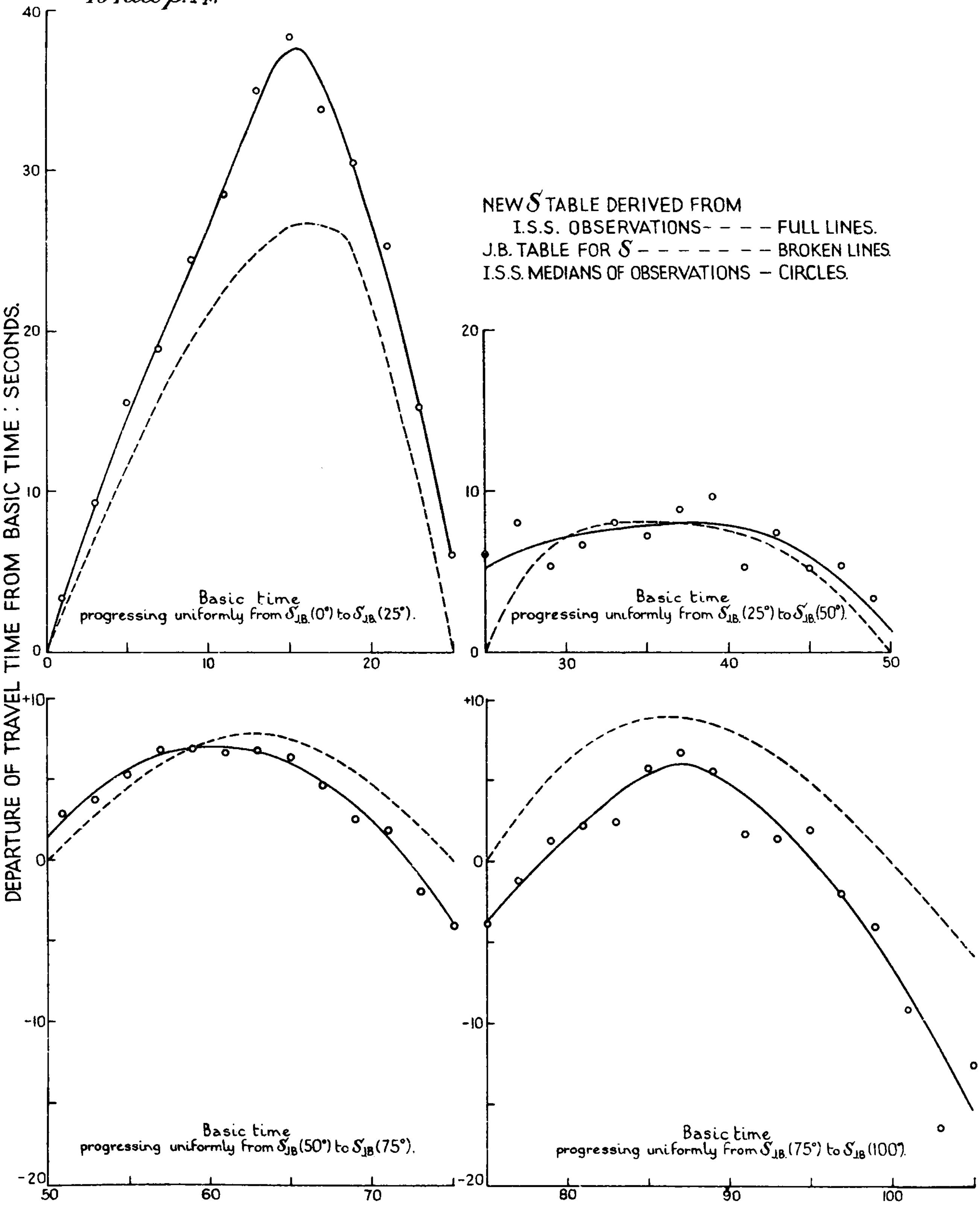



FIG. 14.—DEPARTURES OF TRAVEL TIMES FOR S WAVES FROM BASIC TIMES.

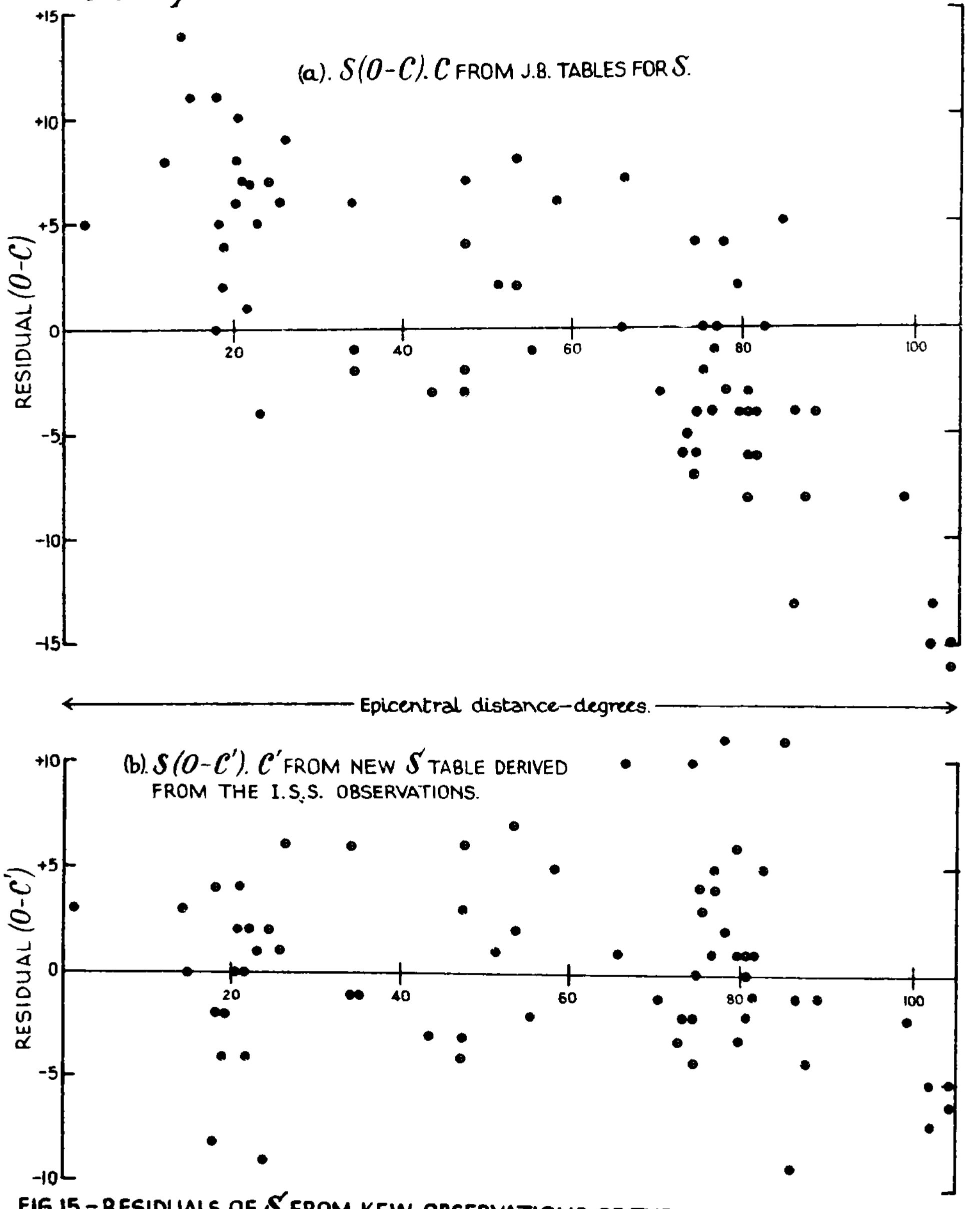



FIG. 15.—RESIDUALS OF S FROM KEW OBSERVATIONS OF THE EARTHQUAKES OF 1930-1.

## TABLE V—KEW OBSERVATIONS OF $P$ AND $S$ WAVES FROM SELECTED EARTHQUAKES OF 1930–1

Tables used :—(a) J.B. for $P$ ($O–C$) and $S$ ($O–C$). (b) New $S$ table (Table IV) for $S$ ($O–C'$)

| Date | Epicentral distance from Kew (I.S.S.) ° | $P$ m. s. | $P$ ($O–C$) s. | $S$ m. s. | $S$ ($O–C$) s. | $S$ ($O–C'$) s. |
|---|---|---|---|---|---|---|
| June 7, 1931 | 2·5 | *i* 0 39 | +3 | *i* 1 9 | +5 | +3 |
| Oct. 30, 1930 | 12·1 | *e* 2 54 | +4 | *e* 6 8* | +63* | +55* |
| July 5, 1930 | 14·2 | .. | .. | *e* 6 10 | +14 | +3 |
| July 23, 1930 | 14·9 | *e* 3 28 | +1 | *i* 6 24 | +11 | 0 |
| May 20, 1931 | 17·9 | *i* 4 4 | −1 | *i* 7 22 | 0 | −8 |
| Apr. 15, 1931 | 18·1 | *i* 4 6 | −2 | *e* 7 38 | +11 | +4 |
| Jan. 28, 1931 | 18·3 | *i* 4 12 | +2 | *i* 7 36 | +5 | −2 |
| Mar. 7, 1931 | 18·8 | *i* 4 15 | −1 | *i* 7 44 | +2 | −4 |
| Mar. 8, 1931 | 18·8 | *i* 4 17 | +1 | *i* 7 46 | +4 | −2 |
| Mar. 31, 1930 | 20·3 | *e* 4 35 | +2 | *e* 8 18 | +6 | 0 |
| Feb. 23, 1930 | 20·5 | *i* 4 38 | +3 | *i* 8 24 | +8 | +2 |
| Sept. 6, 1931 | 20·7 | *e* 4 38 | +1 | *e* 8 30 | +10 | +4 |
| Jan. 4, 1931 | 21·2 | .. | .. | *e* 8 37 | +7 | 0 |
| July 12, 1931 | 21·8 | *i* 4 49 | 0 | *e* 8 43 | +1 | −4 |
| Apr. 17, 1930 | 21·9 | *i* 4 52 | +2 | *i* 8 51 | +7 | +2 |
| May 21, 1930 | 22·8 | *e* 4 57 | −2 | *i* 9 6 | +5 | +1 |
| Feb. 14, 1930 | 23·7 | 5 8 | +1 | *i* 9 14 | −4 | −9 |
| Mar. 6, 1930 | 24·1 | *e* 5 34 | −4 | *e* 9 32 | +7 | +2 |
| Mar. 6, 1930 | 25·6 | .. | .. | 9 57 | +6 | +1 |
| Sept. 11, 1930 | 26·2 | *e* 5 29 | −2 | *e* 10 11 | +9 | +6 |
| May 6, 1930 | 34·2 | *i* 6 42 | 0 | *e* 12 15 | +6 | +6 |
| Apr. 27, 1931 | 34·4 | *i* 6 44 | 0 | *i* 12 11 | −1 | −1 |
| May 8, 1930 | 34·5 | *i* 6 48 | +3 | *e* 12 12 | −2 | −1 |

| Date | Epicentral distance from Kew (I.S.S.) ° | $P$ m. s. | $P$ ($O–C$) s. | $S$ m. s. | $S$ ($O–C$) s. | $S$ ($O–C'$) s. |
|---|---|---|---|---|---|---|
| Sept. 2, 1930 | 43·9 | *i* 8 5 | +1 | *e* 14 31 | −3 | −3 |
| May 11, 1930 | 47·5 | *i* 8 34 | +2 | *e* 15 30 | +4 | +3 |
| May 12, 1930 | 47·5 | *i* 8 34 | +2 | *e* 15 33 | +7 | +6 |
| Aug. 17, 1930 | 47·5 | *i* 8 34 | +2 | *e* 15 23 | −3 | −4 |
| Aug. 23, 1930 | 47·5 | *i* 8 33 | +1 | *i* 15 24 | −2 | −3 |
| Feb. 28, 1930 | 51·2 | *e* 8 58 | −2 | *e* 16 20 | +2 | +1 |
| Aug. 24, 1931 | 53·5 | *i* 9 23 | +5 | *i* 16 57 | +8 | +7 |
| Aug. 27, 1931 | 53·5 | *i* 9 17 | −1 | *i* 16 52 | +3 | +2 |
| Aug. 18, 1931 | 55·3 | *e* 9 32 | +1 | *i* 17 12 | −1 | −2 |
| Sept. 1, 1930 | 58·2 | *e* 9 52 | 0 | *e* 17 58 | +6 | +5 |
| July 13, 1930 | 65·9 | *e* 10 43 | −2 | *e* 19 31 | 0 | +1 |
| July 15, 1931 | 66·3 | .. | .. | *e* 19 43 | +7 | +8 |
| July 2, 1930 | 70·4 | *i* 11 14 | +1 | *i* 20 23 | −3 | −1 |
| Sept. 22, 1930 | 72·9 | *i* 11 28 | 0 | *e* 20 50 | −6 | −3 |
| July 18, 1931 | 73·4 | *i* 11 29 | −2 | *e* 20 56 | −5 | −2 |
| Aug. 16, 1931 | 74·4 | *e* 11 35 | −2 | *e* 21 17 | +4 | +8 |
| Jan. 27, 1931 | 74·6 | *e* 11 38 | 0 | *i* 21 8 | −7 | −4 |
| Mar. 8, 1930 | 74·7 | *i* 11 36 | −3 | *i* 21 11 | −6 | −2 |
| May 12, 1931 | 74·8 | *i* 11 39 | 0 | *e* 21 14 | −4 | 0 |
| Apr. 28, 1930 | 75·2 | *i* 11 42 | +1 | *i* 21 22 | 0 | +4 |
| Sept. 21, 1930 | 75·4 | *e* 11 44 | +1 | *e* 21 23 | −2 | +3 |
| Feb. 2, 1930 | 76·8 | *e* 11 37 | −13 | *e* 21 37 | −4 | +1 |
| Apr. 26, 1930 | 76·8 | *i* 11 51 | +1 | *e* 21 40 | −1 | +4 |

| Date | Epicentral distance from Kew (I.S.S.) ° | $P$ m. s. | $P$ ($O–C$) s. | $S$ m. s. | $S$ ($O–C$) s. | $S$ ($O–C'$) s. |
|---|---|---|---|---|---|---|
| May 20, 1930 | 76·8 | *e* 11 52 | +2 | *e* 21 41 | 0 | +5 |
| June 13, 1930 | 77·7 | *e* 11 54 | −2 | *e* 21 55 | +4 | +9 |
| July 14, 1930 | 78·3 | *e* 11 58 | −1 | *e* 21 54 | −3 | +2 |
| Jan. 5, 1930 | 79·6 | *e* 12 7 | +1 | *e* 22 13 | +2 | +6 |
| Dec. 3, 1930 | 79·9 | *i* 12 10 | +3 | *i* 22 11 | −4 | +1 |
| Apr. 23, 1930 | 80·0 | *e* 12 9 | +1 | *e* 22 8 | −8 | −3 |
| Apr. 9, 1931 | 80·5 | *i* 12 11 | +1 | *i* 22 17 | −4 | 0 |
| May 5, 1930 | 80·7 | *i* 12 13 | +1 | *i* 22 17 | −6 | −2 |
| Jan. 15, 1931 | 80·9 | *i* 12 11 | −2 | *i* 22 22 | −3 | +1 |
| May 16, 1931 | 81·4 | *i* 12 14 | −1 | *e* 22 27 | −4 | +1 |
| Nov. 2, 1931 | 81·4 | *e* 12 22 | +7 | *i* 22 25 | −6 | −1 |
| Mar. 9, 1931 | 82·5 | *i* 12 25 | +4 | *i* 22 42 | 0 | +5 |
| Jan. 2, 1931 | 84·9 | *i* 12 35 | +2 | *i* 23 12 | +5 | +9 |
| June 23, 1931 | 86·0 | *i* 12 39 | +1 | *e* 23 5 | −13 | −9 |
| Nov. 25, 1930 | 86·4 | *e* 12 45 | +5 | *e* 23 17 | −4 | −1 |
| May 1, 1930 | 87·4 | *i* 12 50 | +5 | *e* 23 24 | −8 | −4 |
| Aug. 20, 1930 | 88·8 | *e* 12 54 | +2 | *i* 23 41 | −4 | −1 |
| Mar. 11, 1931 | 99·0 | *e* 13 57 | +18 | *e* 25 10 | −8 | −2 |
| Feb. 10, 1931 | 102·1 | *e* 14 0 | +7 | *e* 25 32 | −13 | −5 |
| Sept. 25, 1931 | 102·1 | *e* 13 54 | +1 | *e* 25 30 | −15 | −7 |
| Oct. 24, 1930 | 104·6 | *e* 14 23 | +18 | *i* 25 52 | −15 | −5 |
| Oct. 28, 1930 | 104·6 | .. | .. | *e* 25 51 | −16 | −6 |

* See Fig. 7 ; the onset tabulated is of $S^*$.

NOTES.—Six earthquakes, giving abnormal $S$ residuals for Kew, have been omitted from the table. These occurred on May 9, 1930, May 31, 1930, Nov. 21, 1930, June 17, 1931, July 12, 1931 and Aug. 10, 1931. The last of these is the Mongolian earthquake for which the seismograms are complicated owing to duplication of the shock (see R. Stoneley, British Association, Report of the Committee for Seismological Observations, 1937). It has been found on re-examination of the seismograms for the other shocks that the onsets of $S$ were very small and could not be timed with sufficient accuracy.

The $S$ times for three earthquakes have been corrected from remeasurement of the records ; the corrections, which have been incorporated in the table, amount to −20 sec. on Feb. 23, 1930, −19 sec. on Sept. 11, 1930, and −9 sec. on Jan. 4, 1931.

beyond 60°. For distances beyond 28° the observations support the amended table given by Jeffreys in 1936.

The departures of the *S* observations from the tables at distances less than 28° are discussed. It is found that there may have been some confusion in the identifications of *S* up to about 12°, but at the greater distances the discrepancy cannot be explained in that way. Re-examination of the Kew records for a number of earthquakes at distances from 12° to 28° shows that, at least for some shocks, the arrival of *S* is preceded by a small movement, but this is so inconspicuous that it cannot be mistaken for the large onset generally accepted as *S*.

A new table of travel-times for *S* has been constructed from the I.S.S. observations of the 146 earthquakes. The interpretation of the observations from the Kew seismograms is improved by the use of this new table.

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