VI. *The Characteristics of a Deep Focus Earthquake: a Study of the Disturbance of February* 20, 1931.

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[Plates 10 and 11.]

1. *Introductory.*

In a previous paper* an account was given of a study of the characteristics of earthquakes with abnormal focal depth. It was shown that echoes should be produced by reflexion of waves at points near the epicentre and evidence in support of this idea was obtained from observations in the International Seismological Summary and also from seismograms registered at Kew and Eskdalemuir Observatories. To carry the work a step further, it was desirable that a detailed study should be made of records from a large number of stations of a well-observed deep focus earthquake; this has been done in the present investigation.

In the earlier paper, it was mentioned that it should be possible to recognise a deep focus earthquake from the records of a single station and to make an estimate of the depth. A favourable opportunity occurred on February 20, 1931, when a disturbance which was recorded at Kew Observatory showed quite definitely the abnormalities associated with a deep focus. On the day that the shock occurred, and from the Kew records alone, it was possible not only to locate the epicentre but also to obtain an estimate of the focal depth. The information so derived was published in the Kew Seismological Bulletin for February, 1931, and also in 'Nature.'† Reports subsequently obtained from other stations confirmed the fact that the shock was very deep seated, so this disturbance has been selected for the detailed study and records from a large number of stations have been examined.

* 'Proc. Roy. Soc.,' A, 132, p. 213 (1931).
† 'Nature,' vol. 127, p. 487 (1931).

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2. *Depth of Focus from Records at a single Station.*

Before discussing the detailed investigation of the earthquake it may be of interest to recall briefly how the early information about the abnormal focal depth of the shock was obtained from the Kew records. In the first place it was noticed that the long waves were very feebly developed compared with the preliminary phases which, though small, were quite sharp and well defined, as may be seen in Plate 10. This characteristic of deep focus earthquakes has been discussed by STONELEY.* For normal earthquakes the ratio of the maximum amplitude (as it appears on a Galitzin seismogram) of the surface waves to the amplitudes of the preliminary impulses is about 30 ; for the disturbance in question, the ratio is only about unity.

The second characteristic of the records was the appearance of well-defined impulses closely following the P and S phases. It was clear that these impulses were much too early for normal reflected waves ; they were more likely to be due to waves reflected from points close to the epicentre. Such supplementary phases were discussed in the previous paper and calculated times of arrival were given for three different depths of focus. The fit of the observed time intervals between the initial impulse, P, and the other phases was tried on the three sets of calculated time curves and it was found that the observations corresponded very closely with the times for an epicentral distance of $77 \cdot 5°$ and a depth of focus of $0 \cdot 06$ R (R being the earth's radius) greater than normal. Had the shock been treated as a normal one, the S–P interval would have indicated a distance of $71 \cdot 9°$. The amplitudes of the initial impulses on the three components enabled a rough determination of the azimuth to be obtained and the epicentre was then estimated to be near 39° N., 126° E., *i.e.*, near the Sea of Japan. As will be seen later, information received from other stations indicates that the true position was 900 km. N.E. of this, but the error in the Kew estimate lies mainly in the azimuth determination and not in the epicentral distance or in the depth of focus.

3. *Final Determination of the Epicentre.*

Actual records or copies of records were obtained from 72 stations, whilst readings for a further 18 stations were supplied by Miss E. F. BELLAMY, of the University Observatory, Oxford, from bulletins collected for the International Seismological Summary. From the records the times of well-defined movements were read, no reference being made to calculated times.

It was found that several pairs of well-distributed stations received the P phase, and also the S phase, practically simultaneously, and it was decided to make use of these stations for the accurate determination of the epicentre. The stations actually used are as follows :—

* 'Gerlands Beitr.,' vol. 29, p. 417 (1931).

TABLE I

Pairs of Stations.		P.	S.
		h. m. s.	h. m. s.
A	Pasadena	5 44 44	5 54 2–3
	Oxford	44 44–45	54 0–2
B	Bidston	44 38	53 49
	Haiwee	44 38	53 50
C	Tucson	45 15	55 2
	Melbourne	45 14	55 3
D	Ksara	44 23	53 20
	Vienna	44 22–23	53 23
E	Kobe	35 45	37 35–37
	Zinsen	35 44–45	37 31–34

For each pair of stations the equation for the locus of points equidistant from each station was obtained and the co-ordinates of the intersections of the various loci were then calculated. Intersections of small angle were rejected; the positions of those actually used are given in the following table :—

TABLE II

Pairs of Stations.	Epicentral	
	latitude, N.	longitude, E.
	° ′	° ′
A and C	44 12	135 33
A and D	44 30	135 33
A and E	43 45	135 21
B and C	44 25	135 5
B and D	44 39	135 17
C and D	44 2	135 58
C and E	44 15	135 40
D and E	44 24	135 51

The centre of gravity of these positions is 44·3° N., 135·5° E., and this has been accepted as the epicentre. This method of obtaining the epicentre has the advantage of being independent of any time-tables and the determination is not affected by the depth of focus.

The epicentre of the disturbance was in the Maritime Province of Siberia, about 30 km. inland from the Sea of Japan and about 300 km. N.E. of Vladivostock. The position determined above is in good agreement with the preliminary estimate, 44° N. 135° E., given in the Supplementary Bulletin of the Jesuit Seismological Association.

The shock is also mentioned by K. WADATI,* who gives the epicentre as being near 44·0° N., 138·0° E., and the depth of focus as 400 km.; he points out that these estimates are not accurate as he was restricted to Japanese stations.

It is noteworthy that the shock occurred near the north-west end of the deep focus earthquake belt discussed by WADATI.† This belt crosses the general earthquake zone of Japan at right angles and extends into Siberia (fig. 1). Of previous disturbances with approximately the same epicentre, five near 45° N., 135° E. have been included in the International summary since 1918 and two of these had abnormal focal depths, viz., 0·05 R and 0·03 R; the other three were very small shocks and possibly the observations were too meagre in these cases to indicate whether the focal depths were abnormal. According to SIEBERG‡, Eastern Siberia is comparatively free from earthquakes.

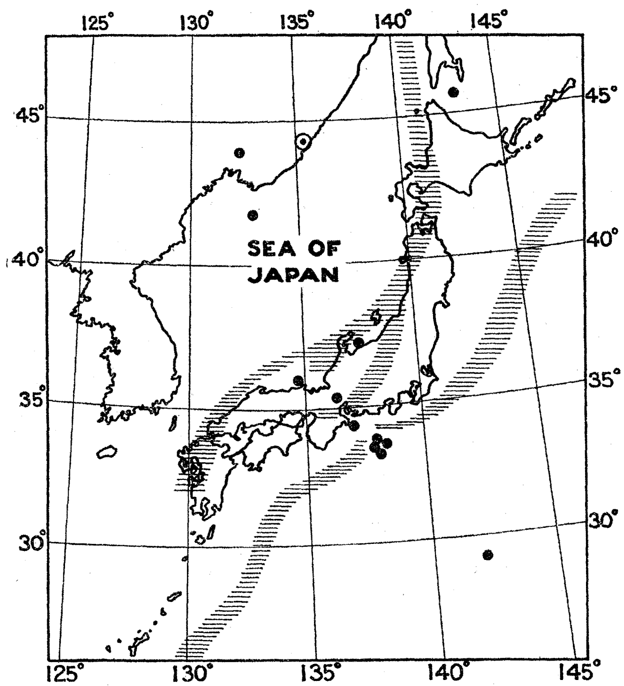


FIG. 1.—Map showing the position of the epicentre and the deep and shallow earthquake zones of Japan.

⊙ Earthquake of February 20, 1931. • WADATI's locations of deep earthquakes. ≡ Normal earthquake zone.

WADATI* mentions that the shock of February 20, 1931, was felt in many parts of Japan, and as far away as 1,300 km. from the epicentre. On the other hand, the disastrous Tokyo earthquake of September, 1923, which was very much more violent, was not perceived at all at distances greater than 800 km. This difference is, of course, in

* 'Geophys. Mag.,' Tokyo, vol. IV, 4, p. 231 (1931).

† 'Geophys. Mag.,' Tokyo, vol. I, 4, p. 162 (1928).

‡ 'Erdbebenkunde,' Jena, 1923.

accordance with the idea that the shock of February, 1931, was of considerably deeper focus than the Tokyo earthquake.

4. *Time of Occurrence.*

In view of the uncertainty associated with the application of the tables of the times of transmission of P and S of normal earthquakes to the case of abnormal focus it seemed desirable to obtain a value of the time of occurrence, T_0, independently of these tables. This was done by plotting the observed S-P intervals against the times of arrival of P and extrapolating the curve to the time at which S-P is zero. The curve is given in fig. 2. Unfortunately, lack of observations near the epicentre makes this procedure rather difficult, but the error in T_0 is thought to be not greater than $\pm$ 2 seconds. The extrapolation leads to a time of occurrence of 5h. 33m. 26s. and this has been accepted for the subsequent computations.

The upper curve in fig. 2 is derived from JEFFREYS's tables* for normal earthquakes ;

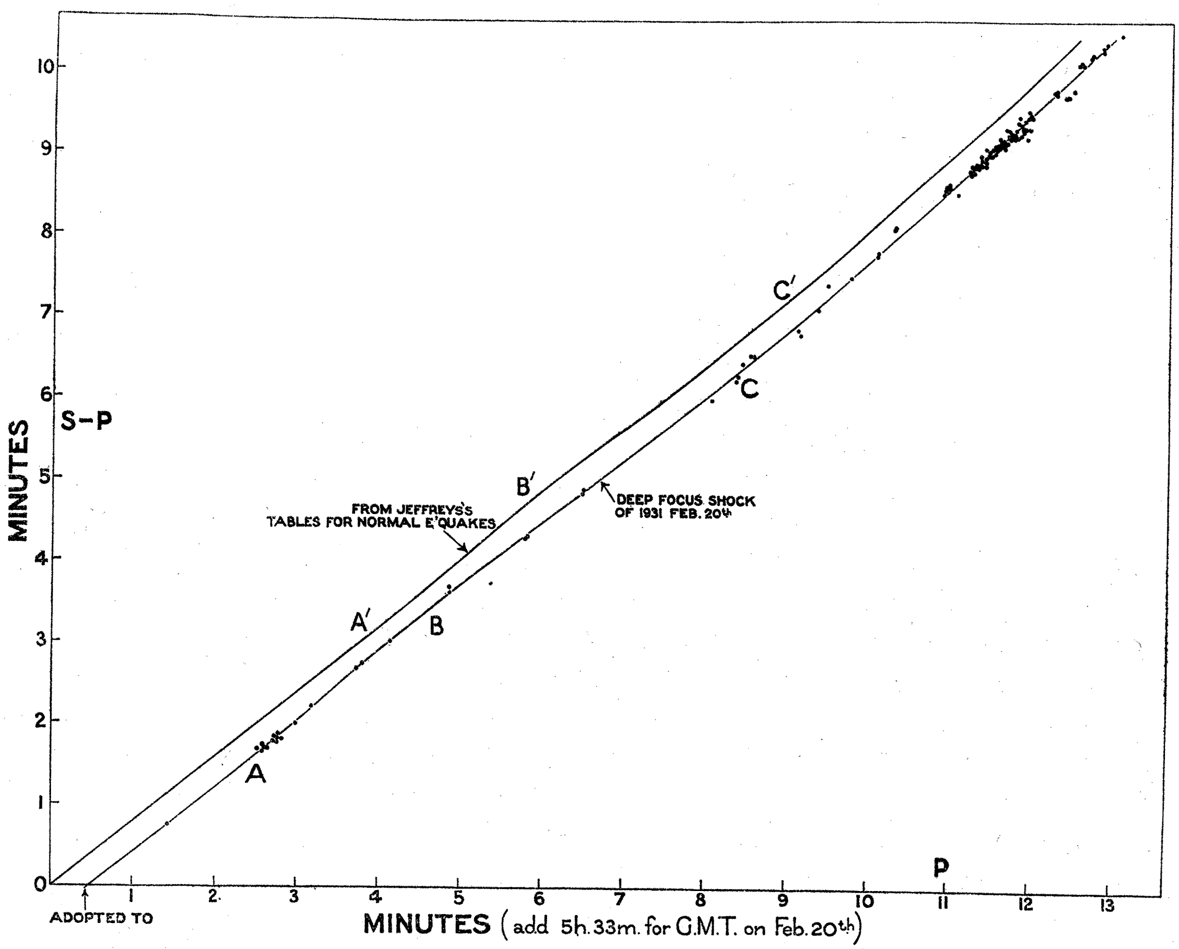


FIG. 2.—Graph of (S–P) and P ; (*a*) from deep focus observations, (*b*) from JEFFREYS's tables for normal earthquakes.

* 'British Association, Gray-Milne Trust Publication,' 1932.

the zeros of the two curves are separated arbitrarily in order to avoid confusion. It will be noticed that the slight changes in curvature on the normal curve are repeated in the deep focus observations, but they occur earlier in the latter ; maximum deviations from the straight lines which are considered to correspond to each other are indicated by the pairs of letters A and A′, etc. These deviations imply changes in the value of POISSON's ratio with depth. For a given maximum depth the ray from a normal focus traverses a longer path than the ray from a deep focus. Thus the effect of a change in POISSON's ratio, as indicated by a change in the slope of the S-P/P curve, appears at lower values of S-P or P on the deep focus curve than it does on the normal focus curve. The difference becomes less marked as the times increase and the paths from deep and normal foci become more nearly coincident.

5. *Observations of Times of Travel.*

The epicentral distances of the stations have been computed to the nearest tenth of a degree and the times of arrival of the phases have in most cases been read to the nearest second. The observed times of travel, reckoned from our adopted time of occurrence, 5h. 33m. 26s. G.M.T., are given in Table IV (appendix); they are also plotted against epicentral distance in fig. 3, but in order to keep the scale of the diagram as large as possible the L and M phases are omitted. The three stations at epicentral distances greater than 145° are omitted from this diagram for the same reason and they are plotted separately in fig. 4 ; no stations were available between 102° and 145°. The full-line curves in figs. 3 and 4 give the calculated times for a depth of focus 0·060 R below normal ; a full explanation of the method of deriving these curves was given in the previous paper. The times for P and S and the reflected waves which do not strike the earth's central core are derived from the ZÖPPRITZ-TURNER tables by making use of KNOTT's paths* for P and S. From the small diagrams in figs. 3 and 4, showing the paths of the waves through the earth, it can be seen that the rays which strike the core leave the focus at inclinations which are very nearly vertical. The times taken by these waves differ from those of the corresponding rays of a normal earthquake, therefore, by an amount which is practically constant at all the distances for which these phases can be observed. The difference is, in fact, within one or two seconds of the time of travel along the vertical path from the deep focus to the normal depth. By extrapolating KNOTT's table Professor TURNER† inferred that the times taken in travelling vertically from a depth of 0·06 R to the normal depth are 46 sec. in the case of P waves and 86 sec. in the case of S waves. To derive the times of the core waves these values have been applied to the times for the corresponding waves of normal earthquakes given by GUTENBERG.‡ The corrections are subtracted for direct waves and added for those waves which undergo reflexion near the epicentre.

* 'Proc. Roy. Soc., Edin.,' vol. 39, p. 157 (1919).

† 'Mon. Not. R. Astr. Soc., Geoph. Suppl.,' vol. I, p. 1 (1922).

‡ 'Handbuch der Geophysik,' vol. IV, p. 216, Berlin (1929).

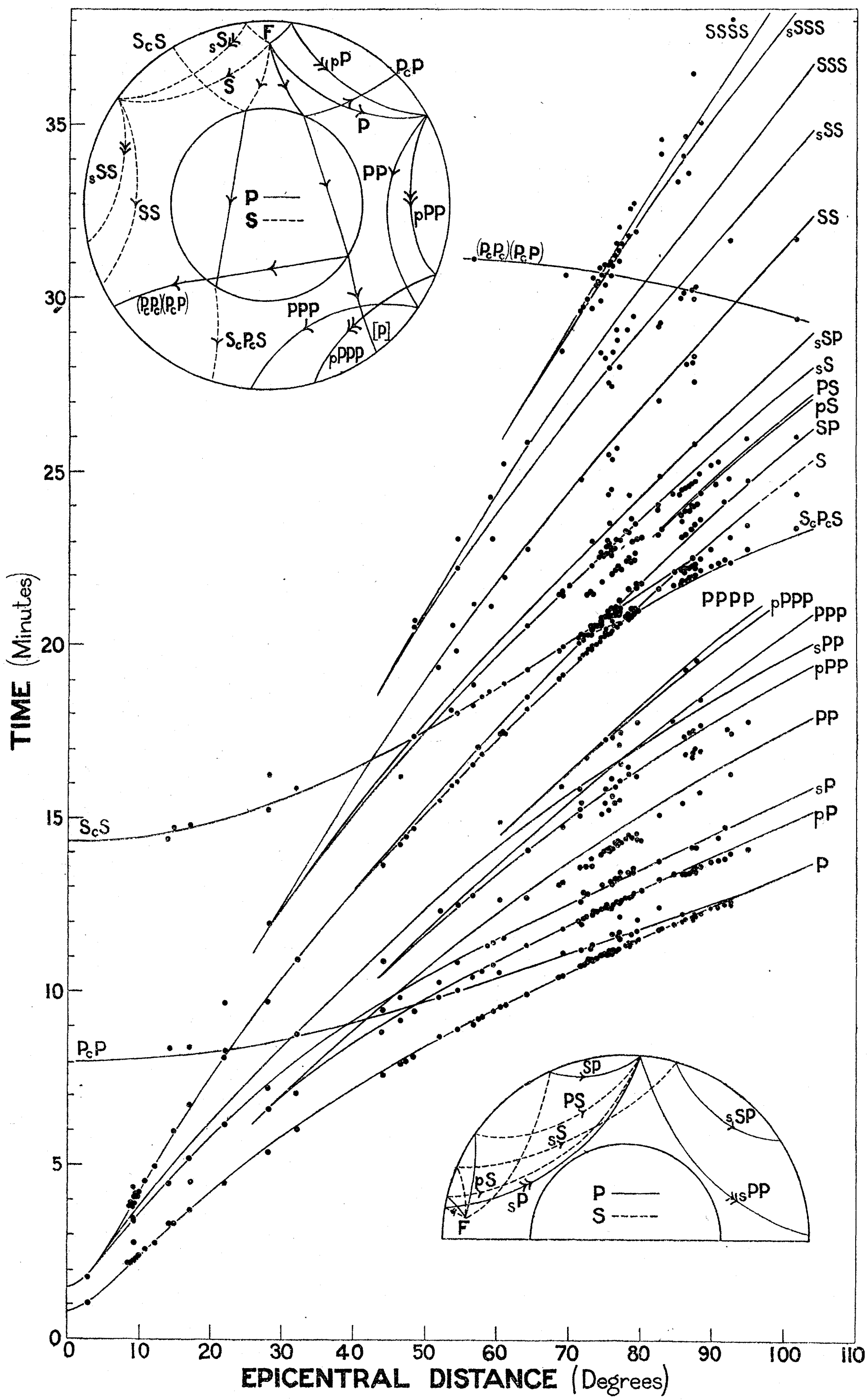


FIG. 3.—Time-distance observations and calculated curves for a focus 0·06 R below normal (Δ < 102°) ; diagrams showing paths of the waves.

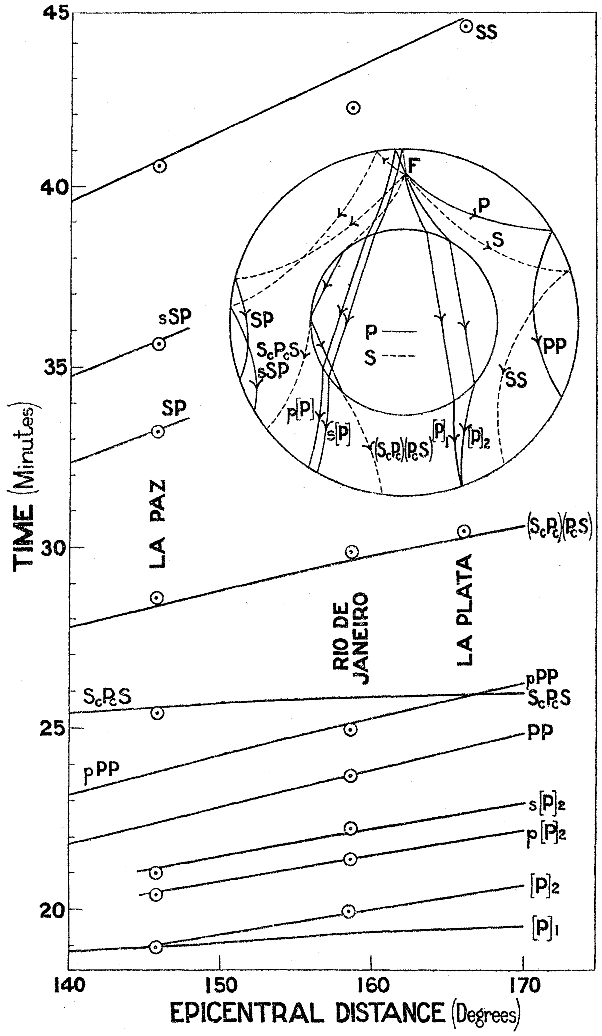


FIG. 4.—Time distance observations and calculated curves for a focus 0·06 R below normal (Δ > 140°) ; diagram showing paths of the waves.

It will be seen that most of the observations fit in with the calculated curves and it is clear that the depth of focus cannot be far removed from 0·060 R below normal. Before attempting a closer estimate of the depth some of the main features of the observations will be discussed.

The P phase was recorded at nearly every station, but at distances greater than 85° it was very weak and liable to be missed. On the other hand, *p*P was well recorded as far as 95°, having about the same amplitude as P up to about 85° and a larger amplitude than P at greater distances. In the Buffalo record shown in Plate 11, for example, P is barely distinguishable from the large microseisms which occur throughout the record, whereas *p*P is large and sharp. The other branch of the singly-reflected longitudinal waves, PP, is not very prominent at distances less than 60°, though there are plenty of observations at greater distances. Both branches should merge into each other at about 26°, but the observations at about this distance are not sufficiently numerous for this to be shown.* The Tokyo (9·2°) and Zi-ka-Wei (17·1°) records which are reproduced in Plate 11 show a phase which follows within a minute of P; this has not been identified, for *p*P and PP cannot occur at such small distances. The *s*P phase can be traced back to comparatively short distances; it is not as well defined on the records as *p*P and the observations therefore show more scatter. A number of impulses have been observed between PP and S on the records of the more distant stations, but it is difficult to separate all these impulses into definite phases. The earlier ones are undoubtedly *p*PP and the later ones most probably represent threefold reflexions.

There was no difficulty in recognising S at all distances up to 101° and S_cP_cS appeared after about 76°. Although observations of *s*S are fairly abundant, the phase is not so prominent as *p*P. SP follows S by intervals which are practically the same as for normal earthquakes. On the other hand, *p*S and PS are about a minute later than SP; they are practically coincident except at great distances, and they make a first appearance at about 72°, which is about 10° shorter than the calculated curve indicates. The minimum distance increases rapidly with depth of focus and a small error in the depth would account for the difference. The three later observations near the *p*S curve are probably sS_cP_cS. Four observations which follow *s*S appear to be *s*SP.

* *Note added November 29th*, 1932.—In my previous paper (loc. cit. p. 215) the distinction between *p*P and PP was made to turn alternatively on two ideas, (1) that the point of reflexion of the *p*P wave is at a less distance from the epicentre than that of the ray which leaves the focus horizontally and (2) that the reflexion for *p*P takes place at a shorter distance than that for PP with the same range. To these may be added another distinction, (3) that *p*P arrives before PP. STECHSCHULTE ('Bull. Seis. Soc. Amer.,' vol. 22, p. 83, 1932) has pointed out that the two earlier definitions are not consistent. Apparently he would allow two *p*P phases in the same seismogram. It seems better to adopt the second definition (which is consistent with the third); the ray which leaves the focus horizontally will in that case arrive as PP.

Of the phases which are reflected at the boundary of the earth's central core S_cS is quite prominent; there are also a fair number of observations of P_cP, but at some distances they are liable to be confused with other phases arriving at about the same times. Both phases can be traced back to 15°; the Zi-ka-Wei record, reproduced in Plate 11, is a good example in which S_cS appears as a well-defined movement in the coda. From the existence of these reflected waves we infer that the change in properties at the boundary of the core is sharp and not gradual. S_cS and P_cP are not so well developed in normal earthquakes. The reflexion at the convex surface of the core causes a large amount of spreading and a consequent rapid fall off in amplitude as the rays approach the surface of the earth. In deep focus earthquakes the body waves carry a relatively much larger proportion of the energy compared with the surface waves, and are therefore more conspicuous. S_cS is more prominent than P_cP, probably because the core only transmits compressional waves; for waves reaching the core the proportion of incident energy reflected back would be greater in the case of S. There are no observations which can be definitely identified as P_cS or S_cP.

The reflected wave SS is fairly well defined on most records and *s*SS can also be recognised. The most definite phase after these two is what appears to be *s*SSS or SSSS. The minimum distance for triple reflexions is about 60° and they are practically coincident up to about 80°. The phases are not sharp, but the amplitudes are relatively large; good examples are shown on the Stuttgart E record and the Stonyhurst record reproduced in Plate 11, and on the Kew records in Plate 11. Readings at two or three stations appear to correspond to $(P_cP_c)(P_cP)$, the compressional wave which enters the core and suffers one internal reflexion before leaving it.

Of the observations at the three most distant stations shown in fig. 4, those from La Plata were taken from a bulletin, but those for La Paz and Rio de Janeiro were read at Kew. The first phase recognisable on the two latter seismograms is P_cP_cP, *i.e.*, [P] in British notation. The occurrence of two branches, $[P]_1$ and $[P]_2$, with a focussing effect at about 143° was predicted by GUTENBERG* and definitely established for normal earthquakes by Miss LEHMANN†. La Paz is at about the distance where the focussing occurs, so the initial impulse may be $[P]_1$ or $[P]_2$. On the Rio de Janeiro record the first definite impulse is $[P]_2$; there is, however, a trace of irregular movement for some seconds before this, but it is too small for any definite commencement to be recognised. Both stations received the echoes, *p*[P] and *s*[P] of the initial impulse. La Paz recorded SP and what appears to be *s*SP while all three stations recorded (S_cP_c) (P_cS).

Although the general agreement between the observations and the calculated curves for a focal depth of 0·06 R is remarkably good, there are some cases where considerable discrepancies occur; for example, PP is systematically early. Before discussing differences between observed and calculated times it is desirable to obtain a more accurate estimate of the depth of focus.

* "Nachr., Ges. Wiss, Göttingen," p. 125 (1914).

† 'Gerlands Beitr.,' vol. 26, p. 402 (1930).

6. *Estimates of the Depth of Focus.*

The depth of focus is best estimated from the time intervals between the direct waves and their echoes since these intervals vary rapidly with depth. Reliable values of these time intervals are provided by the very abundant series of observations between 70° and 80° ; most of the European, United States and Australian stations fall within this range. The observations have been drawn on an extended scale in fig. 5 ; the curves in the diagram have been drawn to fit the points and are not based on calculated times. It will be seen that the intervals between the direct waves and the echoes do not vary much with distance over the range in question and accurate measurements of the intervals can be made from the curves near the middle of the range. From the

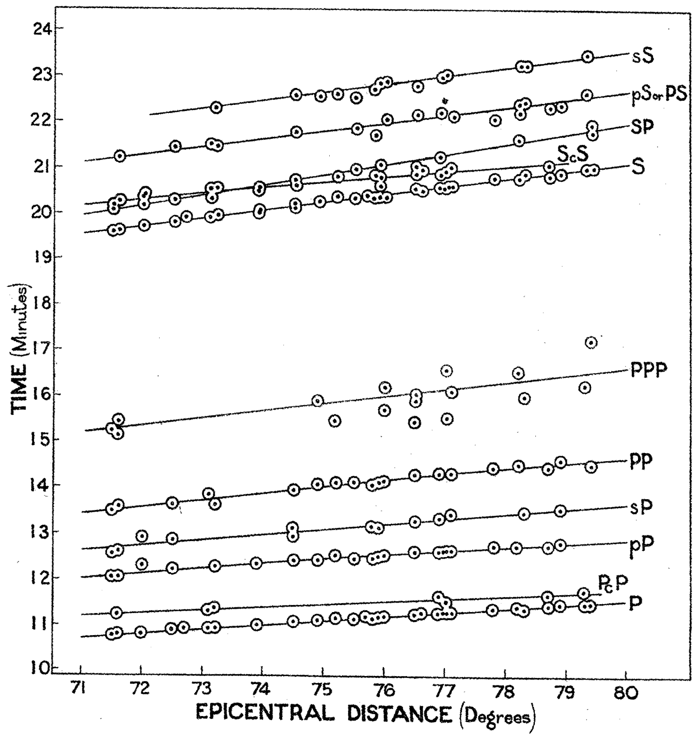


Fig. 5.—Observed time-distance curves for Δ 70° to 80°.

previous paper, we know the calculated times for focal depths of 0·03, 0·06 and 0·09 R below normal and by interpolation the depth of the disturbance can be estimated. Table III includes some values of the focal depth obtained in this manner.

Observations at other distances were also used and the mean value of the focal depth obtained in the above manner is 0·058 R or 370 km. below normal. It must be remembered that as the calculated time intervals ultimately depend on the Zöppritz-Turner tables for P and S they are subject to the errors which are known to exist in these tables. The Z-T times for P and S at short distances imply too small a velocity, by about 8 per cent., immediately below the surface layers and Knott's paths, which were used in obtaining the calculated times in the previous paper, have, therefore, too steep

TABLE III.—Time Intervals for $\Delta : 76°$

Phases.	(a) Calculated for Focal Depths below normal.			(b) Observed.	Estimated Focal Depth below normal.	
	0·03 R.	0·06 R.	0·09 R.			
	sec.	sec.	sec.	sec.	R.	km.
*p*P — P	45	84	120	80	0·057	365
*s*P — P	64	122	176	122	0·060	380
*s*S — S	75	147	210	144	0·058	370

an inclination near the surface. On this account the above estimates of the depth are too large by roughly 8 per cent. If this is taken into account, the mean estimate of the depth becomes about 0·054 R or 340 km. below normal.

To make use of more recent values of the velocities in the upper layers is not easy except in the case of rays having vertical paths. As STECHSCHULTE* has pointed out, a knowledge of, say, *p*P-P for a vertical path gives us directly the time taken by P to travel from the focus to the epicentre (this, of course, assumes that reflexion takes place at the outer surface); then knowing the velocity of P and its rate of change down to the focus we can derive the depth. Time intervals for vertical paths can be obtained by extrapolation from the observed intervals at the more distant stations; after about 60° the intervals increase but very slowly with distance. In this way we find that the time of P from focus to epicentre is 44 sec. and the corresponding time of S is 80 sec., these figures being correct to within about 1 sec.

Now in using these figures for determining the focal depth it is necessary to make some assumptions about the depths of the surface layers. We may, in the first instance, assume that a continental type of structure exists below the epicentre and use the data provided by JEFFREYS's studies of near earthquakes.† In this type of structure a granitic layer extends practically from the surface to about 10 km. depth; below this is the intermediate layer about 20 km. in thickness and under this lies the ultrabasic layer. The seismic body waves travel with different velocities in the three layers. JEFFREYS obtained the values 5·5 and 3·3 km./sec. for compressional and distortional waves respectively in the granitic layer and 6·25 and 3·7 km./sec. for the corresponding waves in the intermediate layer. His revision of seismological tables‡ shows that at the top of the ultrabasic layer the velocities of P and S are 7·8 and 4·35 km./sec. respectively; for our purpose we may assume that these velocities increase uniformly with depth in the top 500 km. and that the rates of increase are about 0·3 and 0·2 km./sec. per 100 km. depth.

* 'Nature,' vol. 128, p. 673 (1931).

† "The Earth," 2nd edition, Camb. Univ. Press.

‡ 'Mon. Not. R. Astr. Soc., Geoph. Suppl.,' vol. II, p. 329 and p. 399 (1931).

It is a simple matter to apply the above data to our times for vertical paths and obtain the depth of focus below the surface, H, by means of the following expression :

$$T = \frac{d_1}{u_1} + \frac{d_2}{u_2} + \frac{1}{b} \log_e \left[1 + \frac{b}{u_3} (H - d_1 - d_2) \right],$$

which may also be written

$$T = d_1 \left(\frac{1}{u_1} - \frac{1}{u_3} \right) + d_2 \left(\frac{1}{u_2} - \frac{1}{u_3} \right) + \frac{H}{u_3} - \tfrac{1}{2} \frac{(H - d_1 - d_2)^2 b}{u_3^2}.$$

Here T is the time from focus to epicentre, d_1 and d_2 are the thicknesses of the upper layers and u_1 and u_2 are the velocities in them, u_3 is the velocity at the top of the ultra-basic layer and b is its rate of increase with depth (assumed linear). The estimates of H obtained in this manner are 352 km. (0·055R) from the P time of 44 sec. and 365 km. (0·057 R) from the S time of 80 sec. If the granitic layer is entirely absent, these estimates would be increased by 1·5 per cent., while if the granitic and intermediate layers are double the thickness that we have assumed the estimates would be diminished by 3 per cent. The correct values of b are not likely to differ from those we have assumed by more than 50 per cent., but even a difference as large as this would only affect our results by 3 per cent. We may regard the mean of the two estimates, 360 km. (0·056 R) as accurate to within about 5 per cent.

The fact that this mean value of the depth below the surface is not very different from the mean estimate of the depth below normal makes it quite certain that normal earthquakes must originate within a few tens of kilometres below the surface.

The depth of the focus in relation to the magnitudes of the surface and upper crustal features may be visualised from fig. 6. This is a rough scale drawing of a section of the upper layers of the earth across the Sea of Japan in the region of the earthquake ; the depths of the granitic and intermediate layers are assumed to be about the same as the estimates obtained for continental areas. The focus of the disturbance is seen to be well down in the ultra-basic layer and the depth is comparable with the width of the Sea of Japan. According to the International Seismological Summary about 30 earthquakes of abnormal focal depth occurred in the Japanese zone during the ten years 1918–27 ; about 70 per cent. of these originated at about the same focal depth as the disturbance of February, 1931.

7. *Comparison of Observations with Calculated Times.*

Although our determinations show that the depth of focus is a little less than 0·060 R, the calculated curves for this depth given in fig. 3 will serve to show up any large systematic errors and any differences in slope. Calculated curves for a depth of 0·056 R would differ from those for a depth of 0·060 R by not more than 3 sec. in the case of phases commencing as longitudinal waves and by not more than 6 sec. in the case of phases commencing as transverse waves. Fig. 3 shows that discrepancies exceeding these amounts occur in some places and that the observations do not everywhere follow the slopes of the curves.

The discrepancies can, in most cases, be traced back to errors in the ZÖPPRITZ-TURNER tables on which the calculated curves are based. JEFFREYS* has investigated these errors and finds that they are greatest at about 35° and after 85°. The effects of the errors are shown in fig. 7A in which the differences between the observed times, O_D, of P and S and the Z-T times, C_N, uncorrected for depth of focus are plotted against epicentral distance. Fig. 7B gives the corresponding differences from JEFFREYS'S times (also uncorrected for depth of focus). In both cases the observed times are reckoned from the adopted T_0 of 5 h. 33 m. 26 s. which is 9 sec. later than the T_0 obtained from the Z-T tables ; this accounts for the Z-T differences being, on the whole, about 9 sec. greater than the JEFFREYS'S differences. It is obvious from fig. 7 that JEFFREYS'S tables give a much smoother fit to the observations by eliminating the bends which occur in the Z-T curves at about 40° and 75°. For distances exceeding 86°, however, the JEFFREYS'S residuals as well as the Z-T residuals for S increase appreciably. The Z-T tables at these distances are definitely wrong. JEFFREYS'S figures indicate that the slope of the S curve between 86° and 100° corresponds to 6·5° per min. ; our observations, which are plotted on a large scale in fig. 8 (the curves being drawn to fit the points), give a slope of 7·2° per min., the slope between 80° and 86° being 5·9° per min. In a study of a normal earthquake Miss I. LEHMANN† noticed a bend in the S

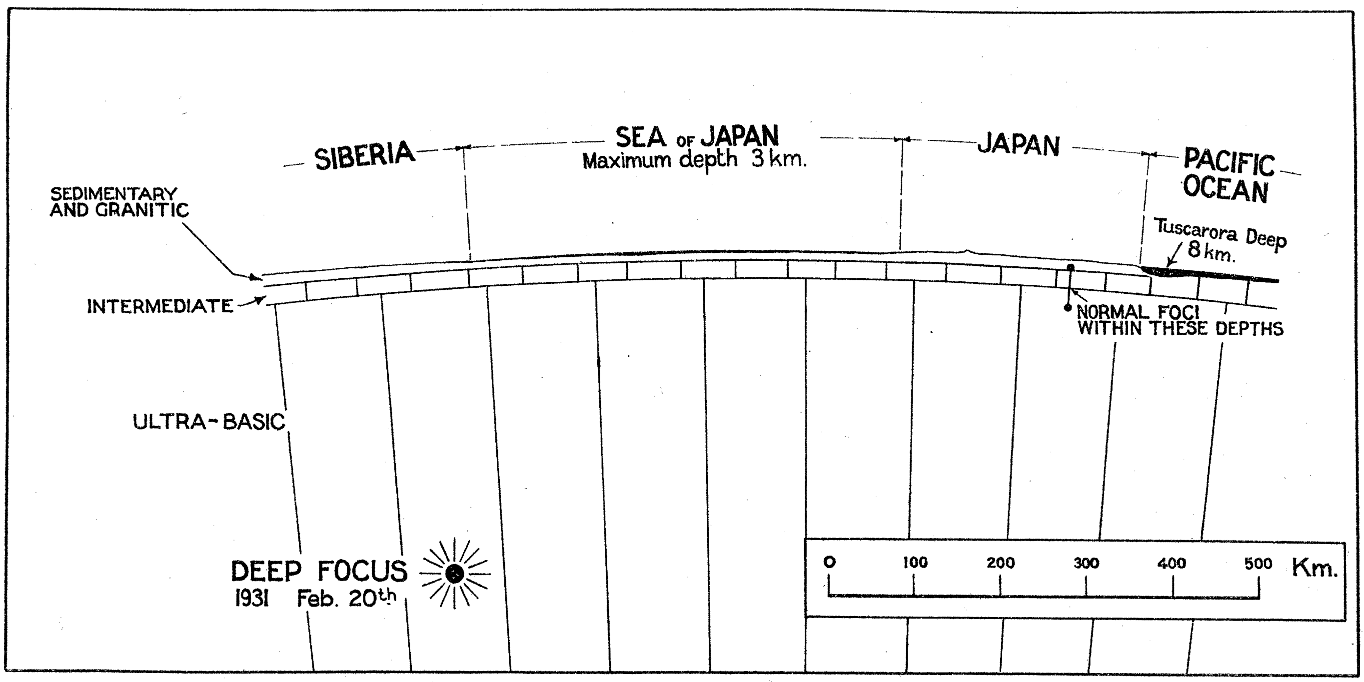


FIG. 6.—Depth of focus in relation to the surface features and the upper layers.

* 'Mon. Not. R. Astr. Soc., Geoph. Suppl.,' vol. II, p. 329, and p. 399 (1931).

† 'Gerlands Beitr.,' vol. 28, p. 151 (1930).

curve at 89°, the change in slope being from 5·6° per min. to about 7·3° per min. Our observations between 80° and 100° are therefore in better agreement with those of Miss LEHMANN than with the corresponding data of JEFFREYS's tables. The fact that the kink occurs at 86° in our case and 89° in Miss LEHMANN's observations is of course

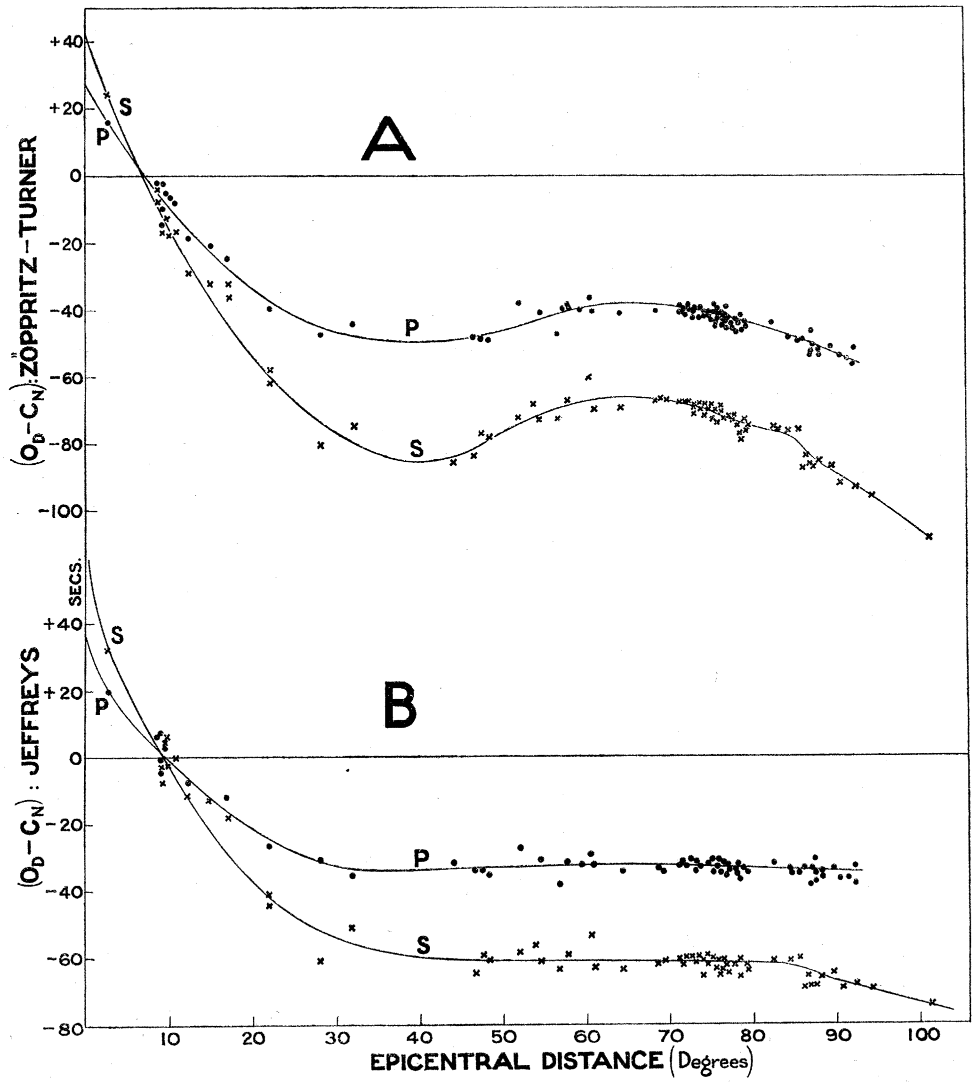


FIG. 7.—P and S ; observed times minus calculated times ($O_D - C_N$), the calculated times being uncorrected for depth of focus.

explained by the difference in focal depth. A corresponding bend should occur in the *s*S curve at about 93°, but the observations fail at about this distance.

The errors, amounting to about 19 sec., in the Z-T tables at about 35° should be repeated at slightly greater distances in the *p*P and *s*P phases ; this accounts for our observations at about 45° being about 15 sec. in advance of the curves. In the cases of PP, *p*PP, *s*PP, SS and *s*SS the errors should be doubled at about 70° ; the PP phase shows the effect very markedly, the errors being about 25 sec. It was suggested in the earlier paper that the large negative residuals of PP indicated that reflexion takes place at a discontinuity below the surface; it appears, however, that the errors are almost certainly due to those of the Z-T tables.

The observed S_cP_cS curve in fig. 8 has practically the same slope as GUTENBERG's curve for normal earthquakes, and our observations are all about 80 sec. in advance

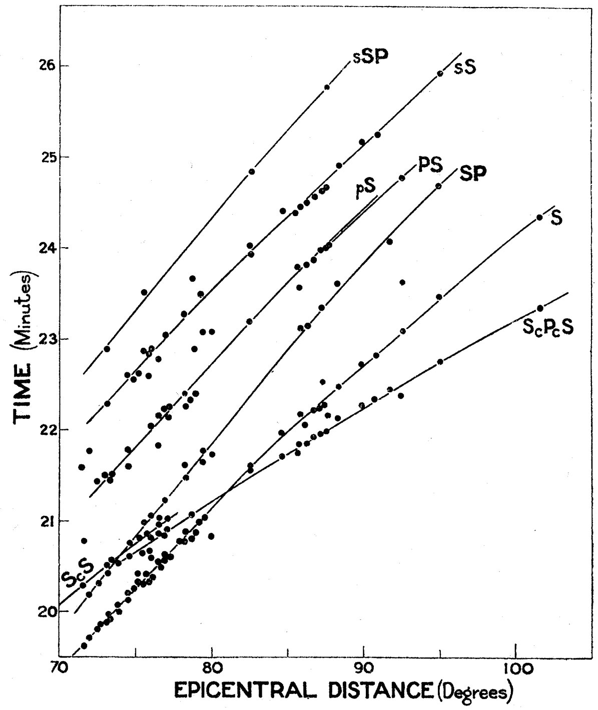


FIG. 8.—Observed time-distance curves for Δ 70° to 100°.

of GUTENBERG's times. This time difference fits in with our estimate of the focal depth. Owing to the overlapping of the three phases SP, S_cS and S_cP_cS at about 75°, it is difficult to see exactly where the latter phase starts; it almost certainly goes back as far as 76°.

8. *Surface Waves.*

JEFFREYS* has pointed out that according to a general reciprocal theorem in dynamics the surface waves of deep-focus earthquakes should be very weak, if not almost completely suppressed. A number of observers have noted that this is borne out in practice, and STONELEY† has discussed the question in some detail. STONELEY remarks that where observers have interpreted phases as L and M in very deep-focus earthquakes the observations actually refer to reflected transverse waves or else to GUTENBERG's early long wave, for which almost complete extinction is not to be expected as the period is very long.

* 'Mon. Not. R. Astr. Soc., Geoph. Suppl.,' vol. 1, p. 518 (1928).

† 'Gerlands Beitr.,' vol. 29, p. 417 (1931).

The present investigation has shown that if one is intent on finding long waves on the records it is very easy to mistake the later reflected S waves for the commencement of the L phase. In a normal earthquake transverse waves which have suffered three reflexions are not very conspicuous, but in a deep focus shock most of the energy is carried by the body waves, and all these are therefore more prominent. The large number of observations which were eventually interpreted as *s*SSS or SSSS were originally taken to be the commencement of LOVE waves, because the amplitudes are comparatively large (see the Stuttgart E. record in Plate 11, and the Kew records in Plate 10,) and the time-distance curve approximates to a straight line. It was decided, however, that these observations could not represent the L phase since they would have indicated a velocity of 4·7 km. per sec., which is greater than that of the fastest LOVE waves which have been observed; further, the periods were considerably smaller than those associated with early long waves and the phase was well recorded on vertical component seismographs, whereas LOVE waves have no vertical component.

A further search was made on the records for indications of surface waves. On about 60 per cent. of the records the characteristics usually associated with surface waves were entirely absent. In records of a normal earthquake the commencement of LOVE waves is usually recognised by the appearance on the horizontal components of large and somewhat irregular oscillations having a long period of the order of 60 sec. The RAYLEIGH waves are more regular and have bigger amplitudes and smaller periods; as a rule they form the most prominent part of the record. On the records examined in the present investigation no prominent movements occur after the reflected waves SSSS, and although it has been possible to obtain readings of what are thought to be L or M for about 30 stations, there is considerable doubt in many of these readings. The maximum amplitude of the M phase rarely exceeds that of the S phase. On the Kew records, for example, the M phase gave a trace amplitude of 4mm., whereas the horizontal impulse of the S gave 9 mm. (the P gave 1·5 mm.); a normal earthquake at about the same distance and having preliminary phases of the same amplitudes has trace amplitudes in the maximum phase of about 35 mm. This almost complete suppression of the surface phase was remarked upon either in bulletins or in the letters accompanying the records by observers at many of the stations. The La Paz Z seismogram reproduced in Plate 10, is of interest since it contains not only a record of the deep-focus shock, but also a record of a normal earthquake at approximately the same epicentral distance. This normal shock occurred at about 17h. 40m. 17s. near 7° S., 100° E. Judging by the amplitudes of the [P] impulses the normal shock was of considerably less intensity, yet the long waves are very much more prominent.

Such observations of L and M as it has been possible to obtain are plotted in fig. 9. The L readings plotted as points without circles are extremely doubtful, and they have been ignored in drawing the straight line through the observations. This line corresponds to a velocity of 3·6 km. per sec. It is doubtful if we are justified in continuing the line back to the time axis, which it cuts at about 1·2 min. This is about the time taken by the S waves to read the epicentre, and if our extrapolation is justified it suggests that the L waves are generated by the arrival of S at the epicentre and not, as Professor TURNER* concluded, at a considerable distance from the epicentre.

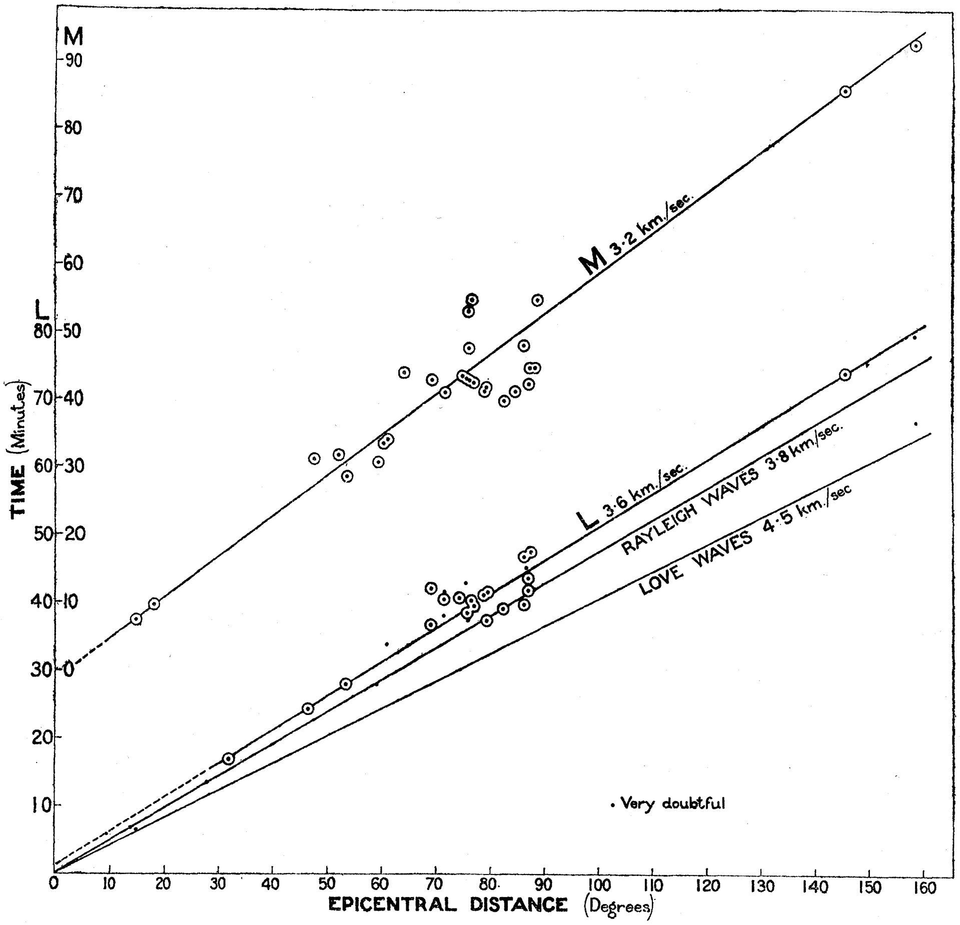


FIG. 9.—Time-distance observations for the L and M phases.

As STONELEY has pointed out, it is almost certain that the readings which TURNER used did not, in most cases, represent L at all, but really referred to the later body waves, which are comparatively well developed in deep-focus shocks. Our mean velocity of L of 3·6 km. per sec. is slightly less than the most frequently observed velocity of RAYLEIGH waves of normal earthquakes, which TURNER found to be about 3·8 km. per sec. For stations at distances greater than about 50° the period at the commencement of the L phase was on the average about 21 sec., but it varied from one station to another in a very irregular manner between 11 sec. and 30 sec. In none of the records is there any sign of a long wave with a period exceeding about 30 sec. Very long LOVE waves, which in normal earthquakes travel at about 4·5 km. per sec.,

* 'International Seismological Summary,' April (1927).

appear to be entirely absent, although theory indicates that it is these waves which should suffer the least extinction. The waves that have been observed appear to be very weak RAYLEIGH waves, since they are shown on the vertical component seismograms in some cases, but it is very probable that the oscillations in the later parts of the records, where surface waves should normally occur, are largely due to the gradual dying out of the body waves.

The observations of M show considerable scatter where they are most abundant, and very few of them represent conspicuous maxima. The average period of M at stations at distances exceeding 50° was 19 sec., but it varied irregularly, from one station to another, between 11 sec. and 30 sec. The velocity given by the straight line drawn through the points in fig. 10 is 3·1 km. per sec.; this is about the same as for normal earthquakes. GUTENBERG* gives 3·2 km. per sec. for M with a period of 20 sec. along continental paths, and BYERLY† found a value of 3·3 km. per sec. in the case of the Montana earthquake.

9. *Conclusions.*

A detailed study has been made of a large number of seismograms of the deep-focus earthquake which occurred near Vladivostock on February 20, 1931. The following determinations have been made :—

Epicentre	44·3° N., 135·5° E.
Time of occurrence	5h. 33m. 26s. G.M.T.
Depth of focus	360 km. below the surface.

The epicentre lies near the north-western end of the Japanese deep earthquake belt which was discussed by WADATI.

The results of the analysis confirm the ideas expressed in a previous paper, viz., that in addition to the phases accompanying normal earthquakes, echoes of these phases can occur when the focus is deep, these echoes being produced by reflexion at points near the epicentre.

All of the preliminary phases are relatively prominent, whereas the surface waves are extremely feeble. This is in accordance with the idea that most of the energy of a deep-seated shock goes into the body waves and that comparatively little energy is available for the surface waves.

The *p*P phase is almost as prominent as the P phase, and the other echoes, *s*P, *s*S, etc., are easily recognisable on most of the seismograms. The time-distance curves of the preliminary phases are reasonably close to those calculated for a depth of 0·060R below normal; the larger discrepancies are mostly due to errors in the calculated curves which are derived from the ZÖPPRITZ–TURNER tables. Most of the discrepancies should disappear when calculated curves based on JEFFREYS'S tables are available;

* 'Lehrbuch der Geophysik,' Berlin (1927).

† 'Bull. Seis. Soc. Amer.,' vol. 16, p. 209 (1926).

the observations of S between 90° and 100°, however, appear to be discordant with the corresponding data of JEFFREYS's tables.

The feebleness of the L and M phases made it very difficult to obtain reliable information as to their times of travel. The amplitudes rarely exceed those of the transverse waves. There appears to be no sign of a long-period LOVE wave at all; the earliest long waves have a velocity of about 3·6 km. per sec., and their period is about 21 sec.

10. *Acknowledgments.*

I wish to express my thanks to Mr. A. W. LEE, who checked my readings of the seismograms, and to Dr. F. J. W. WHIPPLE, Superintendent of Kew Observatory, for suggesting improvements in the paper. I wish also to express my appreciation of the courtesy of the directors of seismological stations who have been so kind as to lend their seismograms or to send copies.

Summary.

A previous investigation had indicated that the seismograph records of a deep-focus earthquake should show certain characteristic features. In order to confirm the existence of these features, a detailed study has been made of the records from a large number of stations of an earthquake which occurred near Vladivostock on February 20, 1931. A preliminary examination of the Kew seismograms had shown that the disturbance originated at a great focal depth.

When an earthquake focus is abnormally deep, phases additional to those associated with normal earthquakes are produced by reflexions at points comparatively near the epicentre; these echoes arrive soon after the direct waves. Further, the surface waves are feebly developed and a much greater proportion of energy is carried by the body waves than is the case in normal shocks; on this account the preliminary phases are comparatively prominent.

Most of the records examined show these characteristics remarkably well. The singly reflected echoes are especially well developed, and the time intervals between these and the direct waves provide reliable data for the computation of the depth of focus when the velocities in the upper layers are known. The focal depth has been estimated as 360 km. below the earth's surface.

The time-distance observations of the phases have been compared with the calculated curves based on the ZÖPPRITZ–TURNER tables of the times of transmission of longitudinal and transverse waves; most of the discrepancies are explained by the errors which are known to exist in these tables. When allowance is made for the abnormal depth of focus the observed times of travel of the direct waves are in much better agreement with JEFFREYS's revised tables, but at distances greater than 85° JEFFREYS's times for transverse waves appear to be too great.

The surface waves are very difficult to recognize in most of the records and there is no trace at all of very long LOVE waves.

APPENDIX.—

No.	Station and Component.		Δ	P.	P_cP.	pP.	sP.	PP.	pPP.	S.	S_cP_cS.	S_cS.
			°	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.
1	Vladivostock ...	N, E	2·8	1 0	—	—	—	—	—	—	—	—
2		Z	—	0 59	—	—	—	—	—	1 44	—	—
3	Toyooka ...	N, E	8·7	2 9	—	—	—	—	—	3 48	—	—
4		Z	—	2 10	—	—	—	—	—	3 52	—	—
5	Heizo	N, E	9·0	2 12	—	—	—	—	—	3 54	—	—
6	Tokyo	N	9·2	2 9	—	—	3 28	—	—	3 53	—	—
7		E	—	2 5	—	—	—	—	—	—	—	—
8		Z	—	(1 56)	—	—	3 23	—	—	3 51	—	—
9	Keizo	N, E	9·2	2 17	—	—	—	—	—	4 4	—	—
10	Zinsen	N, E	9·6	2 18	—	—	—	—	—	4 9	—	—
11		Z	—	2 19	—	—	—	—	—	4 11	—	—
12	Kobe	E	9·6	2 19	—	—	—	—	—	4 5	—	—
13		Z	—	2 19	—	—	—	—	—	4 8	—	—
14	Sumoto ...	—	10·0	2 23	—	—	—	—	—	4 11	—	—
15	Koti	—	10·8	2 33	—	—	—	—	—	4 32	—	—
16	Nagasaki ...	—	12·3	2 44	—	—	—	—	—	4 57	—	—
17	Tsingtao ...	N, E	14·1	(3 22)	(8 22)	—	4 25	—	—	6 7	—	14·4
18	Chiufeng ...	N, E	14·9	3 17	—	—	—	—	—	5 58	—	14 42
19	Zi-ka-Wei ...	N, E	17·1	3 42	8 26	—	5 18	—	—	6 44	—	—
20		Z	—	3 40	8 34	—	5 18	—	—	6 48	—	—
21	Irkutsk ...	N, E	22·0	4 27	—	—	6 7	—	—	8 5	—	—
22		Z	—	4 27	—	—	6 13	—	—	8 15	—	—
23	Hongkong ...	N	28·1	5 21	—	6 39	7 15	—	—	9 39	—	15 11
24		E	—	5 22	—	6 38	7 15	—	—	9 41	—	15 11
25	Manila	N	32·1	6 3	—	7 4	8 46	—	—	10 56	—	—
26		E	—	6 3	—	—	—	—	—	10 55	—	15 52
27	Alipore	N	44·1	7 37	—	8 48	9 30	—	—	13 37	—	—
28	Sverdlovsk ...	N	46·6	7 56	—	9 10	9 48	—	—	14 14	—	—
29		E	—	7 55	—	9 10	9 50	—	—	14 10	—	—
30		Z	—	7 55	—	9 9	9 49	—	—	—	—	—
31	Tashkent ...	N, E	47·3	8 0	—	—	—	—	—	14 28	—	—
32	Amboina ...	N	48·4	8 6	—	—	—	—	—	14 40	—	17 21
33		E	—	8 7	—	9 27	—	—	—	14 40	—	—
34	Medan	N	52·0	8 41	—	—	—	—	—	15 33	—	—
35		E	—	8 42	9 52	9 52	10 18	—	—	15 30	—	—
36	Sitka	N	53·7	—	—	—	—	—	—	15 57	—	—
37	Hyderabad ...	E	54·5	8 55	10 4	—	10 53	—	12†31	16 2	—	18 2
38	Batavia ...	N	56·7	9 3	—	—	—	—	—	16 30	—	18 0
39		E	—	9 3	—	—	—	—	—	16 28	—	18 13
40		Z	—	9 3	—	10 24	—	—	12†48	—	—	—
41	Malabar ...	—	57·3	9 14	—	—	—	—	—	—	—	—
42	Abisko	N	57·9	9 19	—	—	—	—	—	16 50	—	18 30
43		E	—	9 19	—	10 34	—	—	—	16 51	—	18 32
44		Z	—	9 18	—	10 35	—	—	—	—	—	—
45	Honolulu ...	—	58·9	—	—	—	11 22	—	—	17 6	—	18·7
46	Pulkovo ...	N, E	59·4	9 27	—	10 48	11 24	—	—	†	—	—
47	Baku	N, E	60·4	9 38	10 35	—	—	—	—	17 27	—	—
48	Colombo ...	E	61·0	9 38	—	—	11 34	—	—	17 26	—	18 53
49	Upsala	—	64·2	9 57	—	11 19	—	12 42	14† 2	18 5	—	19 12
50	Lemberg ...	E	68·6	10 27	—	—	—	13 5	—	19 1	—	19 49

Table IV.

SP.	*p*S or PS.	*s*S.	SS.	*s*SS.	*s*SSS or SSSS.	L.	M.	Additional Readings.				No.
m. s.	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.		m. s.		m. s.	
—	—	—	—	—	—	—	—	—	—	—	—	1
—	—	—	—	—	—	—	—	—	—	—	—	2
—	—	—	—	—	—	—	—	—	—	—	—	3
—	—	—	—	—	—	—	—	—	—	—	—	4
—	—	—	—	—	—	—	—	—	—	—	—	5
—	—	—	—	—	—	—	—	*i*	2 44	*e*	2 55	6
—	—	—	—	—	—	—	—	*e*	2 52	—	—	7
—	—	—	—	—	—	—	—	*i*	4 19	—	—	8
—	—	—	—	—	—	—	—	—	—	—	—	9
—	—	—	—	—	—	—	—	—	—	—	—	10
—	—	—	—	—	—	(5·9)	—	*e*	5 7	—	—	11
—	—	—	—	—	—	—	—	—	—	—	—	12
—	—	—	—	—	—	—	—	—	—	—	—	13
—	—	—	—	—	—	—	—	—	—	—	—	14
—	—	—	—	—	—	—	—	—	—	—	—	15
—	—	—	—	—	—	—	—	—	—	—	—	16
—	—	—	—	—	—	(6 54)	—	—	—	—	—	17
—	—	—	—	—	—	(6 37)	7 15	—	—	—	—	18
—	—	—	—	—	—	—	—	*i*	4 31	—	—	19
—	—	—	—	—	—	—	9·7	—	—	—	—	20
—	—	9 36	—	—	—	—	—	—	—	—	—	21
—	—	9 45	—	—	—	—	—	—	—	—	—	22
—	—	11 59	11 59	—	—	—	—	*i*	16 19	—	—	23
—	—	11 57	11 57	—	—	(13 30)	—	—	—	—	—	24
—	—	—	—	—	—	—	—	—	—	—	—	25
—	—	—	—	—	—	16·9	—	—	—	—	—	26
—	—	—	—	—	—	—	—	*e*	10 54	—	—	27
—	—	16 12	—	—	—	24·4	—	—	—	—	—	28
—	—	16 8	—	—	—	24·2	—	—	—	—	—	29
—	—	—	—	—	—	—	—	—	—	—	—	30
—	—	—	—	—	—	—	31·1	—	—	—	—	31
—	—	—	—	20†29	—	—	—	† or SSS	—	—	—	32
—	—	—	—	20 43	—	—	—	—	—	—	—	33
—	—	—	19 18	—	—	—	31 48	*e*	12 21	—	—	34
—	—	—	—	—	—	—	—	—	—	—	—	35
—	—	18 5	20 34	—	—	28·1	28·6	—	—	—	—	36
—	—	—	19 49	22 13	—	—	—	† or PPP	—	—	—	37
—	—	18 49	21 12	—	—	—	—	*e*	9 52	—	—	38
—	—	—	—	—	—	—	—	(P_cP_c) (P_cP)	31 10	—	—	39
—	—	—	—	—	—	—	—	*e*	9 54	† or PPP	—	40
17 4	—	—	—	—	—	—	—	—	—	—	—	41
—	—	—	—	—	—	—	—	—	—	—	—	42
—	—	—	—	—	—	—	—	—	—	—	—	43
—	—	—	—	—	—	—	—	—	—	—	—	44
—	—	—	—	—	—	—	—	*e*	9 44	SSS	24·3	45
—	—	—	21·1	23·1	—	(28)	30·9	† S lost in changing record.				46
—	—	—	—	—	—	—	33·8	*i*	12 42	*i*	14 54	47
—	—	—	21 56	—	—	(33·9)	34·1	SSS	25 11	—	—	48
18 29	—	20 30	22 43	—	—	—	44	SSS	25 48	† or PPP	—	49
—	—	21 26	—	—	—	—	—	—	—	—	—	50

Table IV

No.	Station and Component.		Δ	P.	P_cP.	pP.	sP.	PP.	pPP.	S.	S_cP_cS.	S_cS.
			°	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.
51	Copenhagen ...	N	69·1	10 29	11 8	11 50	—	13 10	—	19 7	—	19 52
52		E	—	10 29	—	11 50	—	13 10	—	19 7	—	19 54
53		Z	—	10 29	—	11 48	—	—	—	—	—	—
54	Potsdam ...	N	71·5	10 46	—	12 3	—	13 29	—	19 (36)	—	20 10
55		E	—	10 46	—	12 3	12 (34)	—	15†16	19 (36)	—	—
56	Hamburg ...	N	71·6	10 48	—	—	—	—	—	19 (37)	—	—
57		E	—	10 48	11 14	11 59	12 33	—	15†27	19 37	—	20 17
58		Z	—	10 47	—	12 6	12 39	13 35	15† 8	—	—	—
59	Berkeley ...	N	72·0	10 48	—	—	—	—	—	19 42	—	20 21
60		E	—	10 50	—	—	12 55	—	—	19 43	—	—
61		Z	—	10 49	—	—	—	—	—	—	—	—
62	Dyce	N	72·5	10 54	—	12 13	12 52	13 38	—	19 48	—	—
63	Lick	N	72·7	—	—	—	—	—	—	19 51	—	—
64		E	—	10 55	—	—	—	—	—	—	—	—
65	Ksara	N	73·1	10 57	—	—	—	—	—	19 52	—	—
66		E	—	10 57	11 18	—	—	13 52	—	19 54	—	20 32
67	Vienna	N	73·2	10 57	11 23	12 18	—	13 37	—	19 57	—	20 33
68		E	—	10 57	—	12 15	—	—	—	19 57	—	—
69		Z	—	10 56	—	12 17	—	—	—	—	—	—
70	Göttingen ...	—	73·2	10 54	—	12 16	—	—	—	19 55	—	20 26
71	Belgrade ...	NW	73·9	10 58	—	12 21	—	—	—	20 5	—	20 30
72		NE	—	11 1	—	12 21	—	—	—	20 3	—	20 34
73		Z	—	11 0	—	—	—	—	—	20 5	—	—
74	Edinburgh ...	E	73·9	—	—	—	—	—	—	19 59	—	—
75	De Bilt	N	74·5	11 4	—	12 25	13 7	13 57	—	20 12	—	20 37
76		E	—	11 5	—	12 27	13 7	13 57	15 9	20 11	—	20 37
77		Z	—	11 4	—	12 23	—	13 57	—	20 12	—	—
78	Durham ...	N	74·5	11 4	—	—	—	—	—	20 8	—	20 36
79	Frankfurt ...	N	74·9	11 7	—	12 (26)	—	14 4	—	20 15	—	—
80	Zagreb	NW	75·2	11 11	—	12 32	—	—	15†27	20 19	20 25	—
81		NE	—	11 10	—	12 32	—	14 6	—	20 19	20 26	20 49
82	Stonyhurst ...	E	75·5	11 8	—	12 29	—	14 8	15 15	20 19	20 39	—
83	Haiwee	N	75·7	11 12	—	—	—	—	—	20 24	—	—
84	Stuttgart ...	N	75·8	11 9	—	12 27	13 10	14 5	—	20 21	—	20 52
85		E	—	11 10	—	12 28	13 10	14 4	—	20 22	—	20 51
86		Z	—	11 9	—	12 29	—	14 4	—	20 19	—	20 49
87	Uccle	N	75·9	—	—	—	—	—	—	—	—	20 51
88		E	—	11 11	11 44	12 31	—	14 7	—	20 22	—	20 50
89		Z	—	11 8	—	12 29	13 8	—	—	20 23	20 40	—
90	Santa Barbara...	N	75·9	11 14	—	12 25	—	—	—	—	20 35	—
91		E	—	11 15	—	—	—	—	—	—	—	—
92	Bidston ...	N	76·0	11 12	—	12 32	—	14 9	15 41	20 23	—	—
93	Strasbourg ...	N	76·5	11 17	—	12 35	—	—	—	20 (33)	—	—
94		E	—	11 17	—	12 39	—	14 16	—	20 (33)	—	20 51
95		Z	—	11 13	—	12 36	13 17	14 19	15 25	20 34	—	—
96	Graz	—	76·6	11 15	—	—	—	14 15	—	20 30	—	20 59

(continued).

SP.	*p*S or PS.	*s*S.	SS.	*s*SS.	*s*SSS or SSSS.	L.	M.	Additional Readings.				No.
m. s.	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.		m. s.		m. s.	
—	—	21 25	—	—	28·5	36·8	42·5	PPP	14 45	—	—	51
—	—	21 27	—	—	—	—	43·6	(P_cP_c) (P_cP)	30·6	—	—	52
—	—	—	—	—	—	42	42·7	PPP	14 50	—	—	53
—	—	—	—	—	—	40·6	—	*e*	21 36	—	—	54
20 4	—	—	—	—	29 38	(38·2)	41·1	*e*	21 38	† or PPP	—	55
—	—	—	24 47	—	29·7	—	—	*i*	15 54	*i*	20 47	56
—	—	—	—	—	29·6	—	—	† or PPP	—	—	—	57
—	—	—	—	—	29·7	(41·5)	—	*i*	20 46	† or PPP	—	58
—	—	—	—	—	29·3	—	—	*i*	21 47	—	—	59
20 11	—	—	—	—	29 36	—	—	*e*	21 46	—	—	60
—	—	—	—	—	—	—	—	Large microseisms.				61
20 18	21 26	—	—	—	30† 0	—	—	*i*	16 48	† Very sharp.		62
—	—	—	—	—	—	—	—	—	—	—	—	63
—	—	—	—	—	—	—	—	—	—	—	—	64
20†18	21 29	—	—	—	—	—	—	*s*SP	22 54	† or S_cP_cS	—	65
—	21†32	—	—	—	—	—	—	† Well marked.				66
—	—	—	—	—	31	—	—	—	—	—	—	67
—	21 28	22 18	—	—	—	—	—	—	—	—	—	68
—	—	—	—	—	—	—	—	—	—	—	—	69
20 26	—	—	—	—	29 40	—	—	—	—	—	—	70
20 30	—	—	—	—	30·5	—	—	*i*P	11 2	—	—	71
20 34	—	—	—	—	30·5	—	—	—	—	—	—	72
—	—	—	—	—	—	—	—	*i*P	11 3	—	—	73
—	—	—	—	—	30 24	—	—	Large microseisms.				74
20 37	21 47	22 33	—	—	30·1	—	—	SSS	28 33	—	—	75
20 37	—	22 39	—	—	29·8	—	—	SSS	28·4	—	—	76
20 45	—	—	—	—	30·9	40 48	—	SSS	28 19	—	—	77
20 36	—	—	—	—	30 37	—	—	—	—	—	—	78
—	—	22 34	—	—	30 23	—	43·6	PPP	15 53	SSS	28 17	79
—	—	22 38	—	—	30·9	—	—	† or PPP	—	—	—	80
20 49	—	—	—	—	31·0	—	—	*e*	17 21	SSS	28 48	81
20 58	—	22 52	25 29	28 1	31·0	(43)	43·5	*s*SP	23 32	*e*	24 14	82
—	—	—	—	—	—	—	—	—	—	—	—	83
—	—	—	—	27 24	—	(39·0)	43	*i*	28 48	—	—	84
—	—	—	—	—	31 4	—	54	—	—	—	—	85
—	—	—	—	—	31 2	—	52	*i*	24 29	—	—	86
—	—	22 36	—	—	—	—	—	—	—	—	—	87
—	—	22 52	—	—	31 3	—	—	*e*	17 23	—	—	88
21 3	—	—	—	—	—	39·3	47·7	*i*P	11 10	—	—	89
—	—	—	—	—	—	—	—	—	—	—	—	90
—	—	—	—	—	—	—	—	—	—	—	—	91
—	22 4	22 53	25 22	—	30 38	—	—	PPP	16 11	SSS	28 25	92
21 2	22 10	—	—	—	31·1	40·4	—	SSS	29 4	—	—	93
21 3	—	22 47	—	—	31·3	—	—	*i*	16 1	—	—	94
—	—	—	—	—	31 17	—	54 52	*i*P	11 15	*s*PP	15 54	95
—	—	—	25 39	—	32	—	—	SSS	28 46	—	—	96

TABLE IV

No.	Station and Component.		Δ	P.	P_cP.	pP.	sP.	PP.	pPP.	S.	S_cP_cS.	S_cS.
			°	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.
97	Kew	N	76·9	11 17	11 38	12 38	13 18	14 19	—	20 35	—	20 51
98		E	—	11 18	—	12 38	13 22	—	—	20 35	—	20 52
99		Z	—	11 14	—	12 35	13 18	14 21	—	20 35	—	20 52
100	Oxford	N	77·0	11 19	—	12 35	—	—	—	20 36	—	20 55
101		E	—	11 18	—	12 40	—	—	—	20 33	—	—
102	Pasadena ...	N	77·0	11 22	—	—	—	—	—	20 37	—	—
103		E	—	11 18	11 32	—	—	—	—	20 36	—	—
104		Z	—	11 18	—	12 (39)	—	—	15 31	—	—	—
105	Zurich	N	77·1	11 18	—	12 (37)	—	—	—	20 37	—	—
106		E	—	11 18	—	—	13 29	—	—	20 37	—	21 2
107		Z	—	11 17	—	12 40	—	14 19	—	—	—	—
108	Neuchatel ...	N	78·0	11 21	—	12 42	—	14 27	—	20 47	—	—
109		E	—	11 23	—	12 43	—	—	—	20 48	—	—
110		Z	—	11 23	—	12 45	—	14 27	—	—	—	—
111	Parc St. Maur ...	N	78·2	11 25	—	12 44	—	14 31	—	20 46	—	—
112		E	—	11 25	—	12 44	—	—	—	20 47	—	—
113	Perth	N	78·3	11 22	—	—	13 29	—	—	20 53	—	—
114	Helwan ...	E	78·7	11 27	11 40	12 46	—	14 28	—	20 49	21 4	—
115	Florence ...	N	78·9	11 30	—	12 57	13 26	—	—	—	—	—
116		E	—	11 30	—	12 48	—	—	—	20 52	—	—
117		Z	—	11 26	—	12 51	13 29	—	—	20 54	—	—
118	Adelaide ...	N	79·3	11 29	11 46	—	—	—	—	21 0	—	—
119	Sydney	N	79·4	11 29	—	—	—	14 32	—	21 2	—	—
120		E	—	11 29	—	—	—	—	—	21 1	—	—
121		Z	—	11 30	—	—	—	—	—	—	—	—
122	Denver	—	80·0	—	—	12 59	—	14 20	—	—	20 50	—
123	Melbourne ...	E	82·5	11 48	—	—	—	15 8	—	21 37	—	—
124	Tucson	N	82·5	11 49	—	13 18	—	—	—	21 36	—	—
125		E	—	11 49	—	13 12	13 47	—	—	21 36	—	—
126	Barcelona ...	N	84·6	11 57	—	—	—	—	—	21 59	21 43	—
127		E	—	11 57	—	13 25	—	—	—	21 58	21 42	—
128	Chicago ...	—	85·7	—	—	—	—	—	—	—	21 46	—
129	Tortosa ...	N	85·8	12 2	12 16	13 27	—	15 28	—	22 12	21 52	—
130	Ottawa	N	86·2	12 8	—	13 25	—	—	16 51	22 4	21 52	—
131		E	—	—	—	13 24	—	—	—	22 4	—	—
132	Toronto... ...	—	86·7	—	—	13 25	—	—	—	22 14	21 56	—
133	Florissant ...	N	87·2	12 6	—	13 31	14 7	—	16 49	22 15	21 59	—
134		E	—	12 6	—	13 29	14 10	—	16 49	22 15	21 59	—
135		Z	—	12 11	—	13 30	14 11	—	16 50	22 32	—	—
136	St. Louis ...	N	87·4	12 11	—	13 29	—	—	16 59	22 17	21 59	—
137		E	—	12 15	—	—	14 11	—	16 51	22 18	22 0	—
138	Buffalo	Z	87·6	12 12	—	13 35	—	—	—	22 11	—	—
139	Toledo	NW	88·3	12 15	—	13 37	—	15 51	16 58	22 30	22 9	—
140		NE	—	12 15	—	13 38	—	15 47	—	22 29	22 10	—
141		Z	—	12 13	—	13 40	—	15 47	—	—	—	—
142	Little Rock ...	N	89·8	12 24	—	13 46	—	—	—	22 45	22 19	—
143		E	—	12 24	—	—	—	—	—	22 45	22 16	—
144	Fordham ...	—	90·8	12 26	—	13 48	14 28	—	—	22 50	22 21	—
145	Georgetown ...	—	91·7	12 30	—	13 51	14 45	—	—	—	22 27	—
146	Wellington ...	N	92·5	12 (37)	—	—	—	—	—	23 7	22 22	—
147		E	—	12 (38)	—	—	—	—	17 26	23 5	22 24	—
148		Z	—	12 32	—	14 2	—	16 19	17 28	—	—	—
149	Colombia ...	—	94·9	—	—	14 8	—	—	17 46	23 27	22 45	—

(continued).

SP.	*p*S or PS.	*s*S.	SS.	*s*SS.	*s*SSS or SSSS.	L.	M.	Additional Readings.				No.
m. s.	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.		m. s.		m. s.	
—	—	23 4	—	—	31†24	—	42 23	*e*	17 9	†SSSS	32 0	97
21 14	—	23 1	—	27 59	31 40	—	—	—	—	—	—	98
21 15	22 14	—	—	—	—	—	—	*i*P	11 16	*e*	17 9	99
—	—	23 3	—	—	31 34	—	—	*i*	17 31	—	—	100
—	—	23 4	—	—	31 34	39·7	—	—	—	—	—	101
—	—	23 3	—	—	—	—	—	—	—	—	—	102
—	—	—	—	—	—	—	—	PPP	16 35	—	—	103
—	—	—	—	—	—	—	—	—	—	—	—	104
—	22 9	—	—	—	—	—	—	*i*	12 11	*s*PP	16 6	105
—	—	—	—	—	—	—	—	*i*	12 10	—	—	106
—	—	—	—	—	—	—	—	*i*P	11 19	—	—	107
—	—	—	—	—	—	—	—	*i*P	11 24	SSS	29 4	108
—	—	—	—	—	—	—	—	—	—	—	—	109
—	—	—	—	—	—	—	—	—	—	—	—	110
21 38	22 25	23 17	—	—	31·7	—	—	PPP	16 31	—	—	111
21 38	—	—	—	—	31·9	—	—	—	—	—	—	112
—	22 29	23 16	—	—	—	—	—	*s*PP	16 18	—	—	113
—	22 20	23 40	—	—	32·5	41·2	41·3	*i*	34 4	—	—	114
—	—	—	—	—	32 42	—	—	*i*	15 5	SSS	29 26	115
—	—	—	—	—	—	—	—	*i*	15 2	*i*	22 54	116
—	22 24	—	—	—	—	—	—	—	—	—	—	117
—	22 59	23 30	—	—	31·9	41·6	41·9	*i*	13 15	*s*PP	16 14	118
21 47	—	—	—	—	—	—	—	*i*	12 5	*e*	23 5	119
21 40	—	—	—	—	—	37·3	—	*e*	17 47	—	—	120
—	—	—	—	—	—	—	—	*e*	17 46	—	—	121
21 44	—	—	—	—	—	—	—	sS_cP_cS	23 6	—	—	122
—	23 12	24 2	27 4	29 9	32 16	39·2	39·9	*i*	12 28	—	—	123
—	—	23 56	—	29 16	34·3	—	—	*s*SP	24 52	—	—	124
—	—	—	—	—	34·9	—	—	—	—	—	—	125
—	—	—	—	—	—	—	41·1	—	—	—	—	126
—	—	24 25	—	—	—	—	—	—	—	—	—	127
—	23·8	24·4	—	30·1	33·4†	—	—	†*s*SSS	—	—	—	128
23 8	23 34	24 28	—	30 7	34·1	—	—	—	—	—	—	129
23 11	23 50	24 31	28 6	—	34·7	47·1	48·1	*es*PP	17 23	*i*	19 18	130
—	23 50	24 31	28 5	—	—	39·8	48·1	—	—	—	—	131
—	23 53	24 34	—	—	—	45·2	—	*es*PP	17 (25)	—	—	132
23 22	23 59	24 38	28 6	29 58	—	43·9	44·8	*i*P	12 10	—	—	133
—	24 1	24 38	28 5	30 13	36 31	42·0	42·3	*i*P	12 10	—	—	134
23·3	—	—	28 23	—	36·4	—	—	*es*PP	17 31	—	—	135
—	23 59	24 39	28·4	30·3	—	47·7	—	*es*SP	25 48	—	—	136
—	24 2	24 41	28 11	30·3	—	—	—	—	—	—	—	137
—	24 2	—	—	—	—	—	—	*ip*PPP	19 31	—	—	138
—	—	24 55	—	—	35·0	—	54·9	*e*PPP	18 26	—	—	139
23 38	24 27	—	—	—	35·1	—	54·8	*es*PP	17 40	—	—	140
—	—	—	—	—	—	—	—	—	—	—	—	141
—	—	25 9	—	—	—	—	—	—	—	—	—	142
—	—	25 10	—	—	—	—	—	—	—	—	—	143
—	—	25 15	—	—	—	—	—	—	—	—	—	144
24 5	—	—	—	—	—	—	—	—	—	—	—	145
—	—	—	—	—	—	—	—	sS_cP_cS	24 46	—	—	146
—	—	—	—	31 39	37·9	—	—	*i*	23 39	sS_cP_cS	24 48	147
—	—	—	—	—	—	—	—	—	—	—	—	148
24 42	—	25 56	—	31·6	—	—	—	—	—	—	—	149

TABLE IV

No.	Station and Component.		Δ	P.	P_cP.	*p*P.	*s*P.	PP.	*p*PP.	S.	S_cP_cS.	S_cS.
			°	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.
150	Tananarive ...	N	101·6	—	—	—	—	—	—	24 21	23 22	—
151		E	—	—	—	—	—	—	—	24 23	23 23	—
				[P]		*p*[P]	*s*[P]					
152	La Paz	N	145·8	18 57	—	20 24	—	—	—	—	—	—
153		E	—	18 56	—	—	—	—	—	—	25 24	—
154		Z	—	18 56	—	20 22	20 57	—	—	—	—	—
155	Rio de Janeiro...	N	158·6	19 58	—	21 24	—	23 41	24 57	—	—	—
156		E	—	—	—	—	22 14	—	—	—	—	—
157	La Plata ...	—	166·1	—	—	—	—	—	—	—	—	—

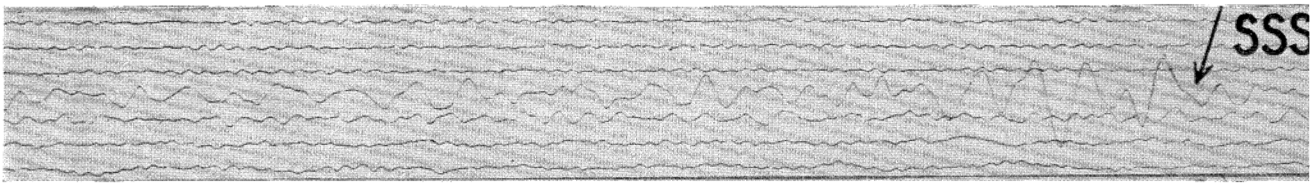
(continued).

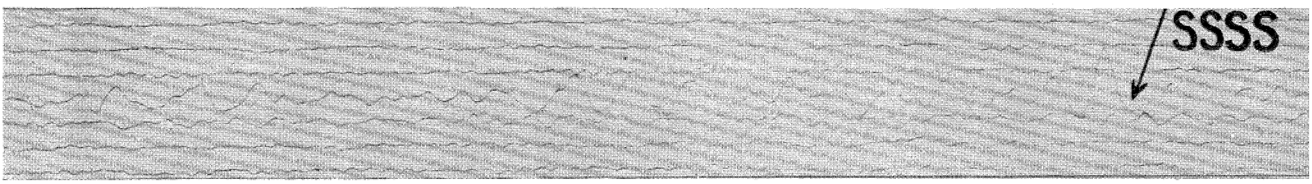
SP.	*p*S or PS.	*s*S.	SS.	*s*SS.	*s*SSS or SSSS.	L.	M.	Additional Readings.				No.
m. s.	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.	m. s.		m. s.		m. s.	
26 2	—	—	31 41	—	—	—	—	—	—	—	—	150
25 57	—	—	31 43	—	42·8	—	—	(P_cP_c) (P_cP)	29 25	—	—	151
—	—	—	—	—	—	(72)	86	(S_cP_c) (P_cS)	28 36	—	—	152
—	—	—	40 33	—	—	74·1	(85)	*e*	60·7	—	—	153
33 12	—	—	—	—	—	74·3	86	*s*SP	35 37	—	—	154
—	—	—	—	—	—	(79·8)	92·9	(S_cP_c) (P_cS)	29 52	—	—	155
—	—	—	42 11	—	—	(67·0)	—	—	—	—	—	156
—	—	—	44·5	—	—	—	—	(S_cP_c) (P_cS)	30 26	—	—	157

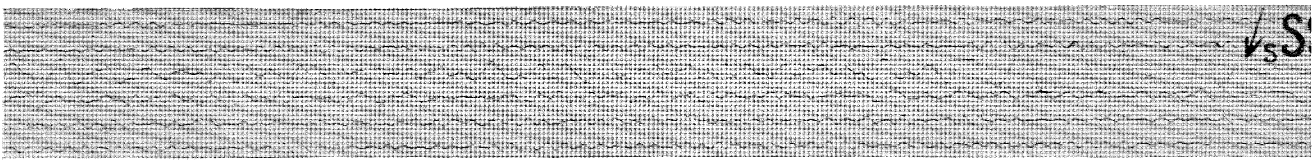
DESCRIPTION OF PLATES.

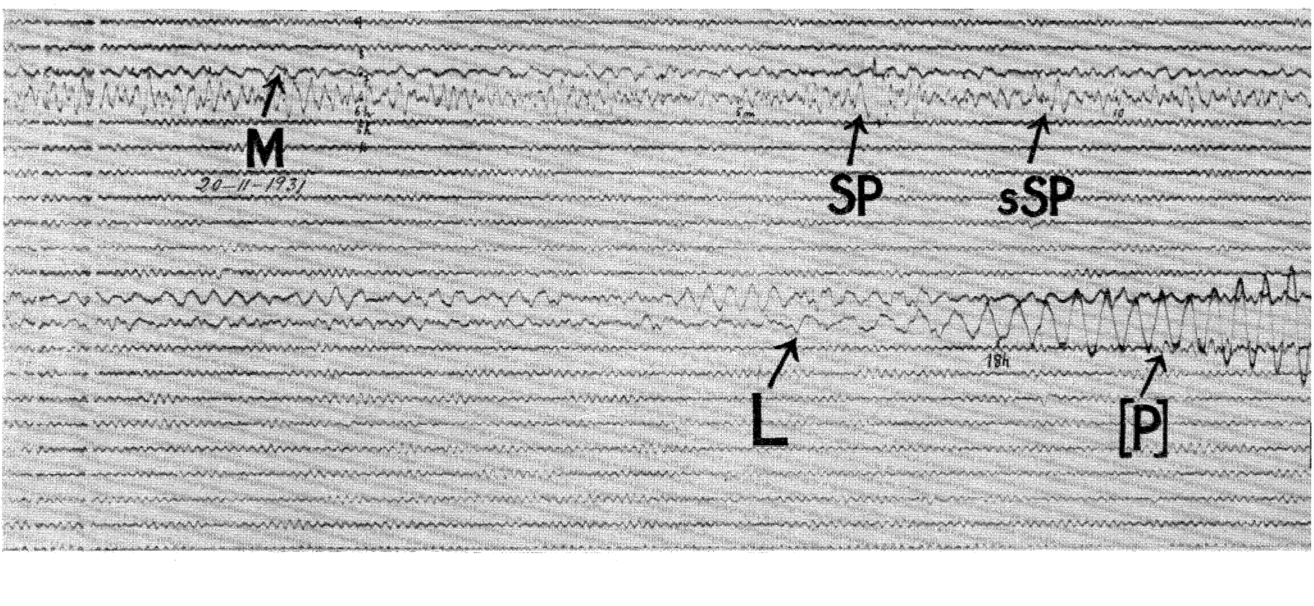
PLATE 10.—Some records of the earthquake	Kew ...	... N.
	Kew ...	... E.
	Kew ...	... Z.
	La Paz ...	... Z.
PLATE 11.—Some records of the earthquake	Stuttgart	... N.
	,,	... E.
	,,	... Z.
	Tokyo ...	... N.
	Stonyhurst	... E.
	Zi-ka-Wei	... N, E.
	Buffalo ...	... Z.

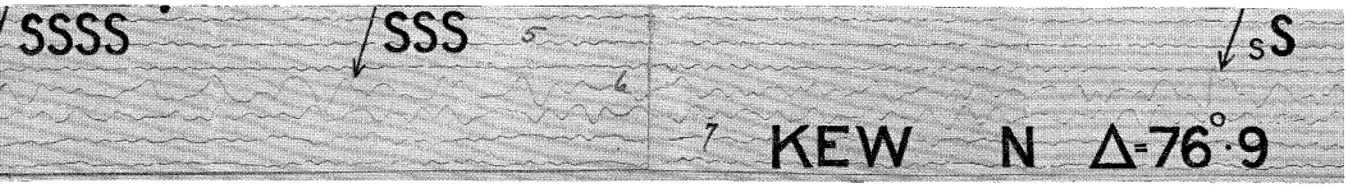
Scrase.







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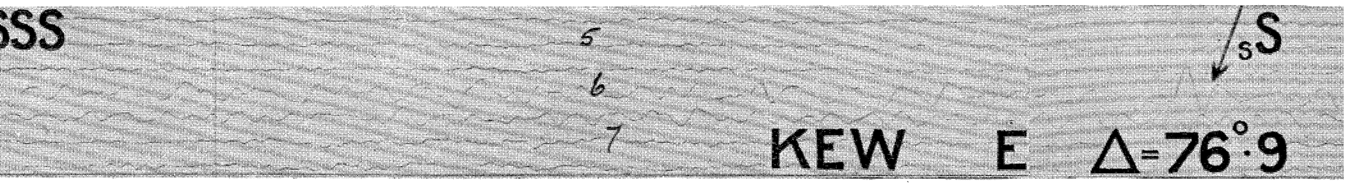
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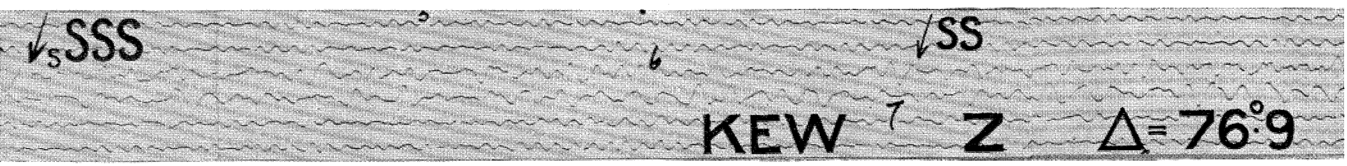
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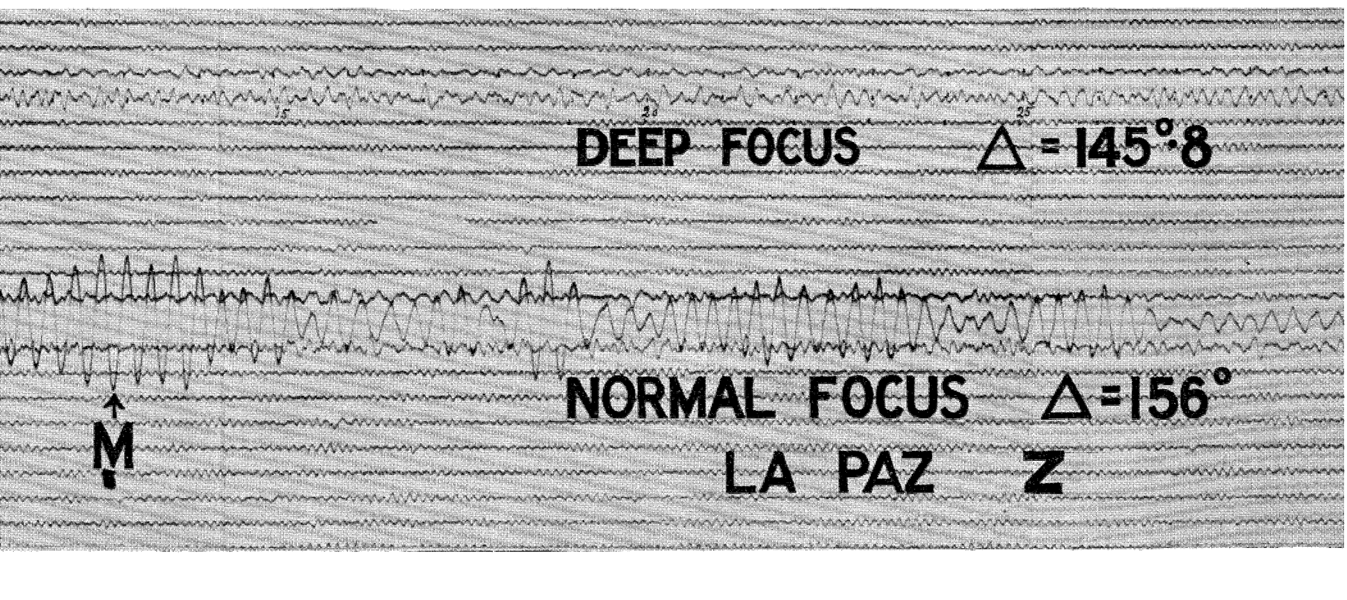
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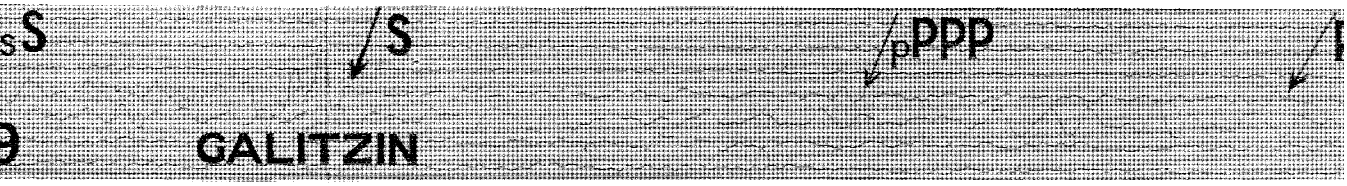
NORMAL FOCUS Δ=156°
LA PAZ Z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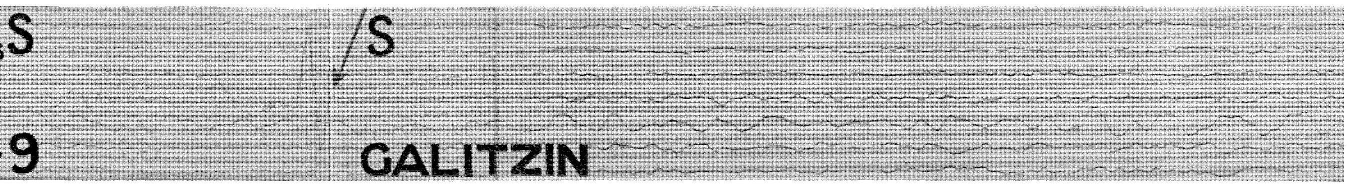
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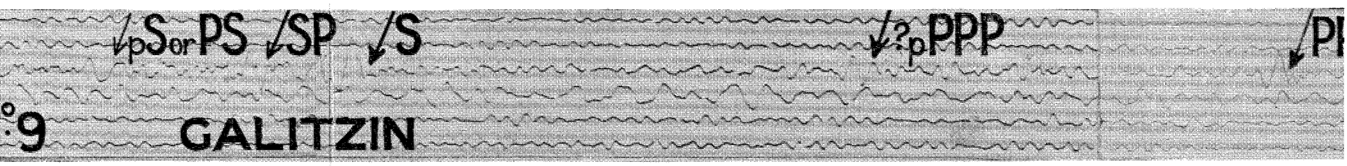
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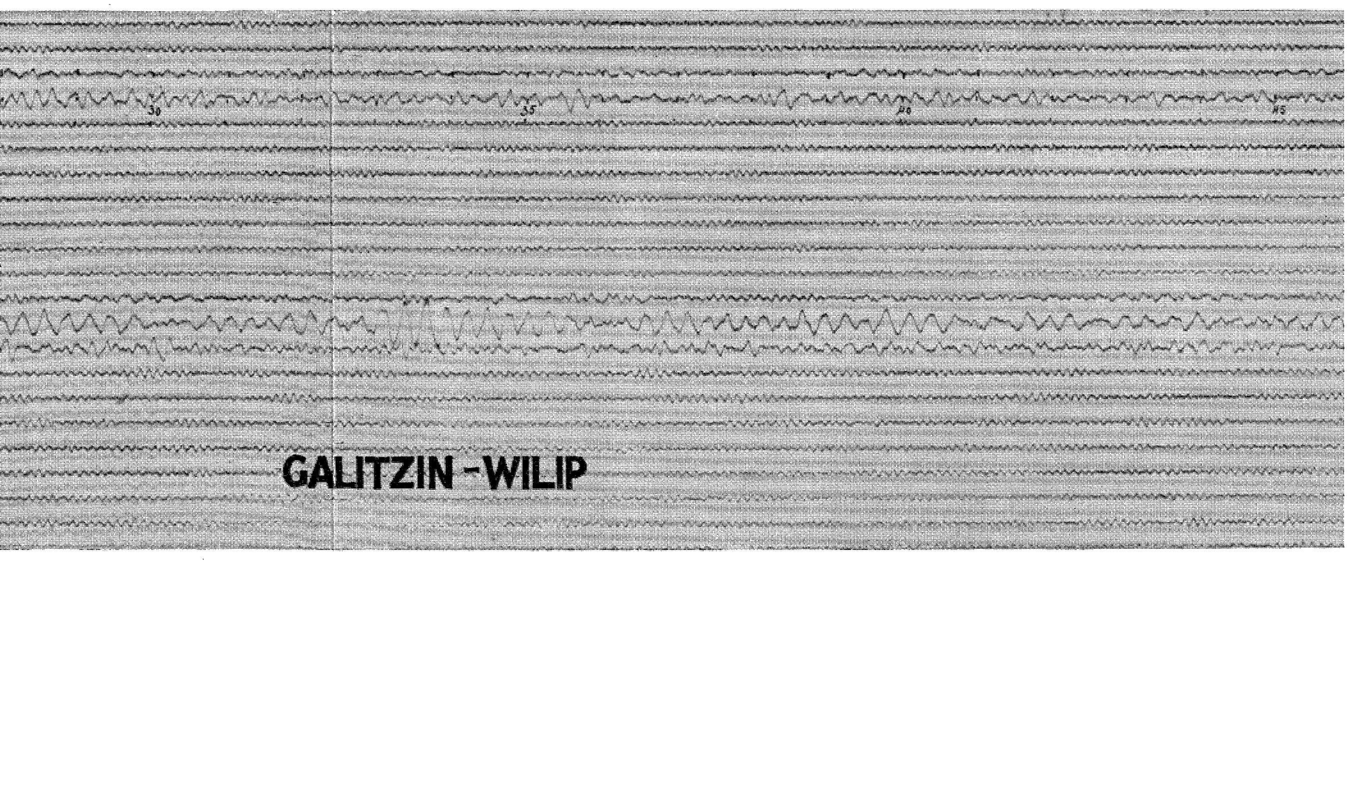
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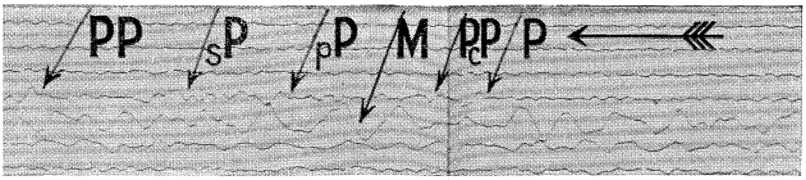
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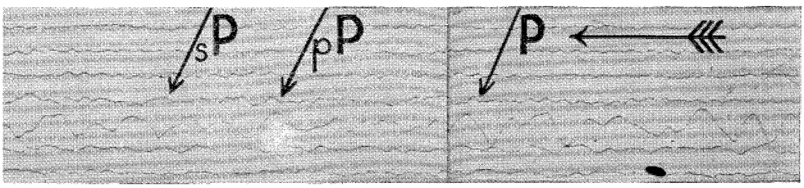
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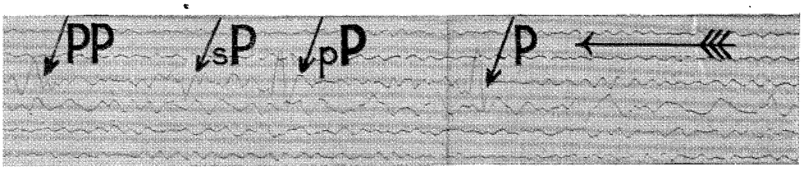
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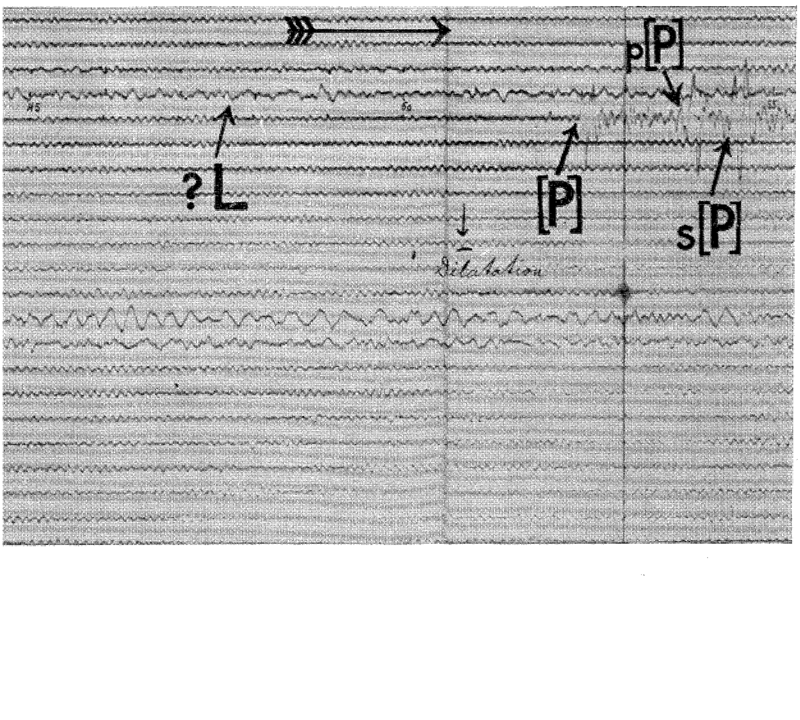
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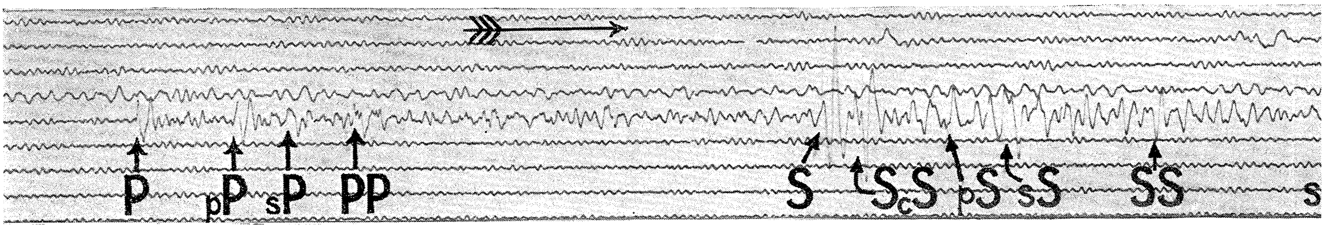
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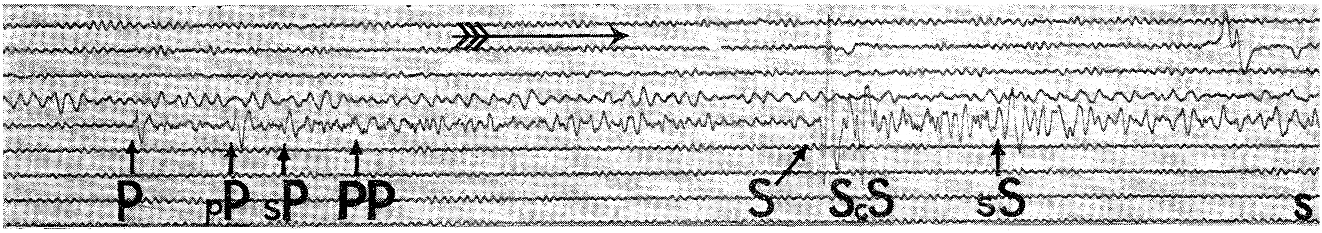
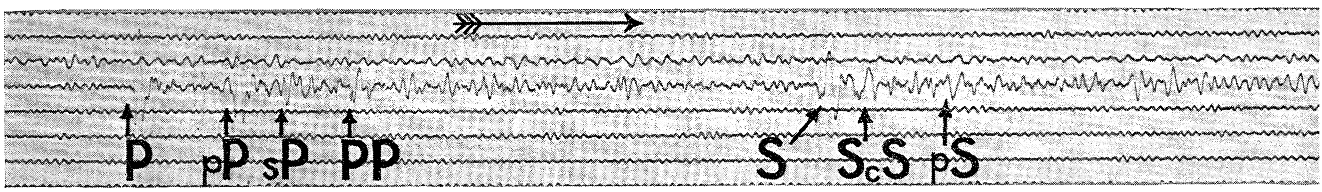
SS
s


P
pP
sP
PP
S
ScS
sS
S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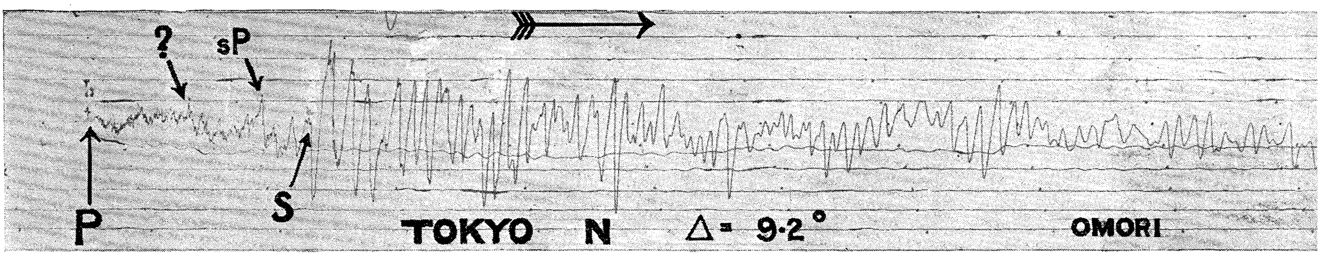
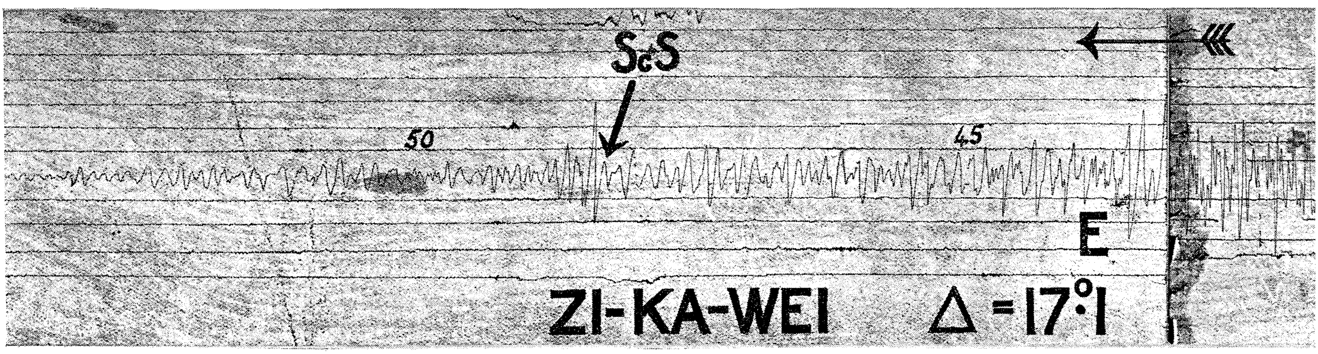
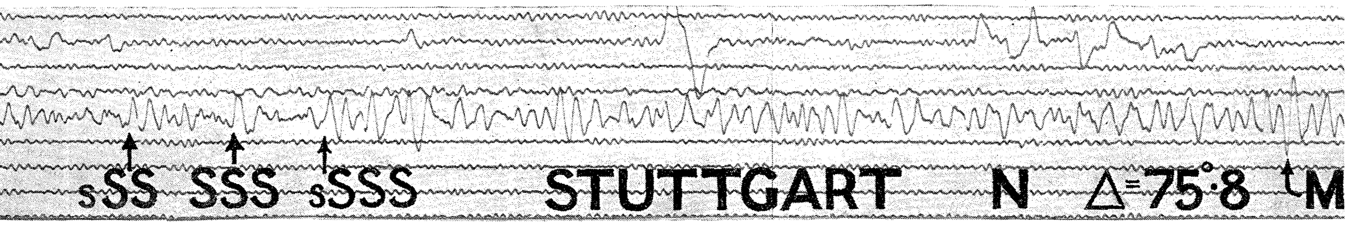
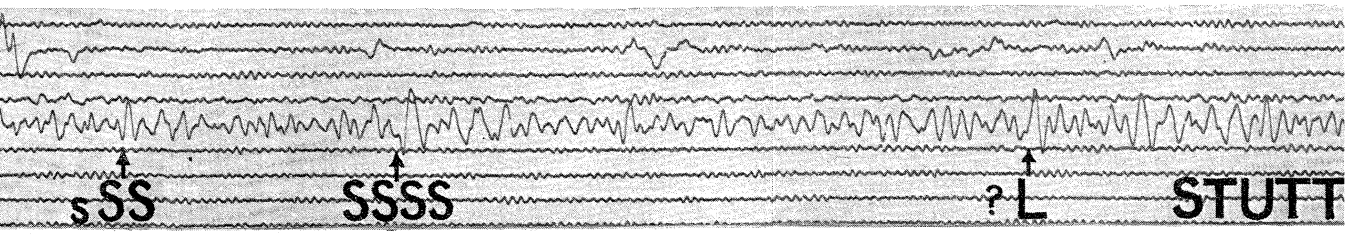
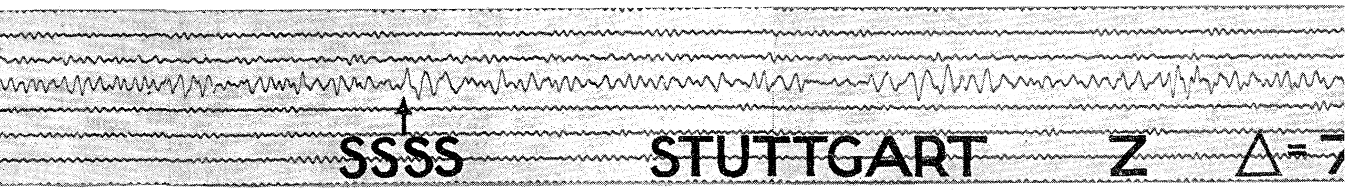
pP
sP
PP
S
ScS
pS

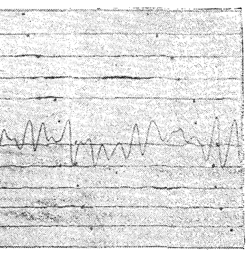

?
sP
P
S
TOKYO N Δ= 9·2°
OMORI

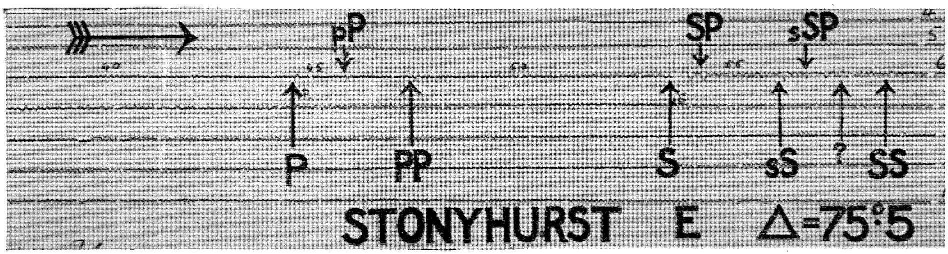

ScS
50
45
E
ZI-KA-WEI Δ=17°·1

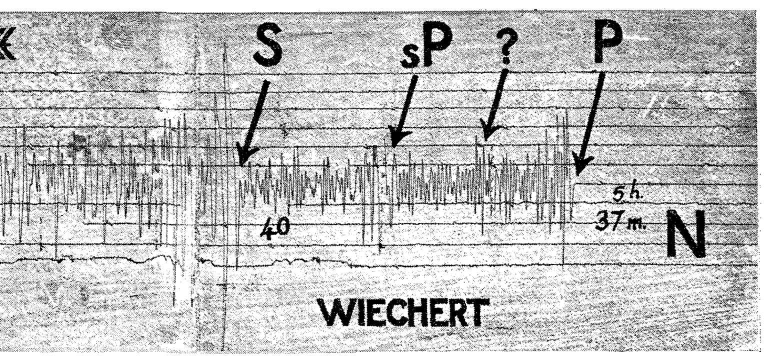

sSS
SSS
sSSS
STUTTGART N Δ=75°8
M

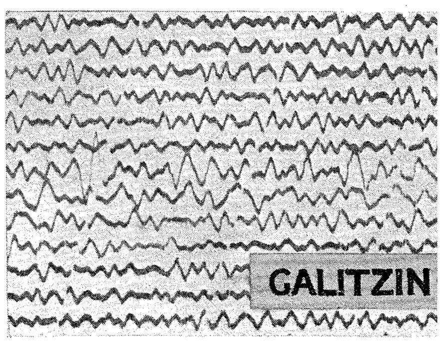

sSS
SSSS
? L
STUTT

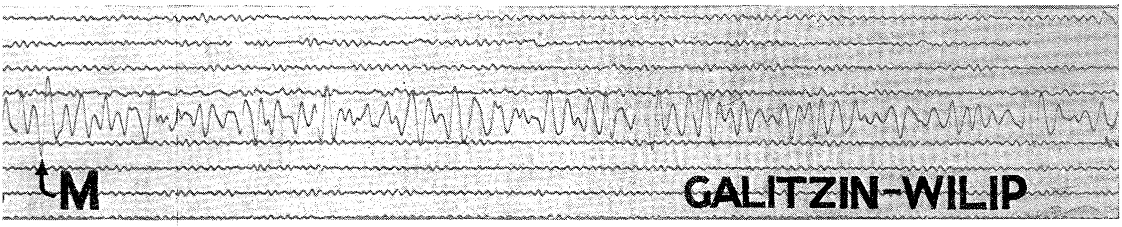

SSSS
STUTTGART Z Δ=7

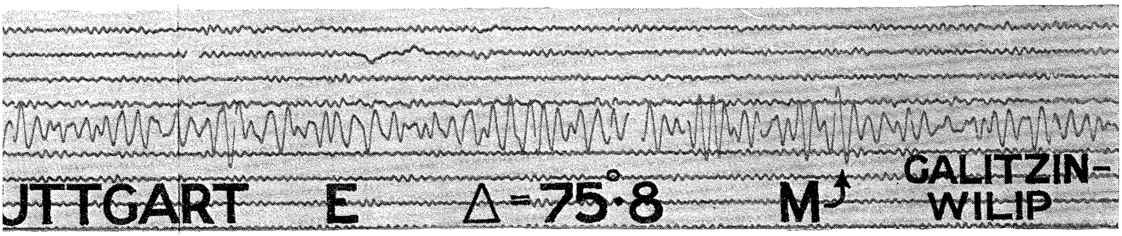


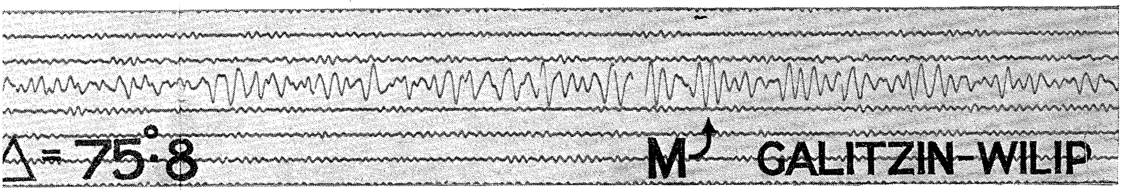

pP
SP
sSP
P
PP
S
sS
?
SS
STONYHURST E Δ=75°5

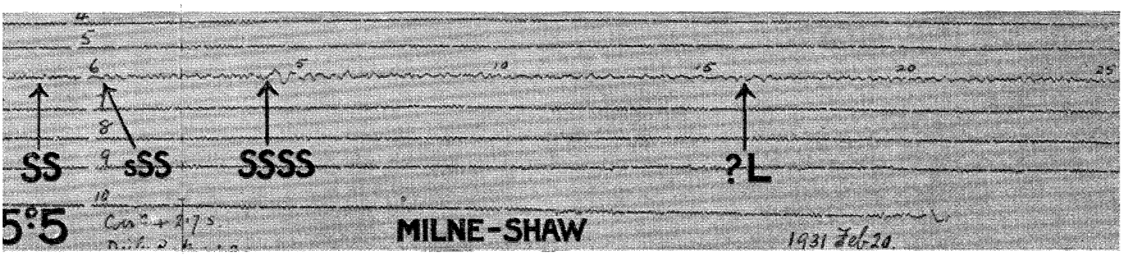

S
sP
?
P
5 h.
37 m.
40
N
WIECHERT

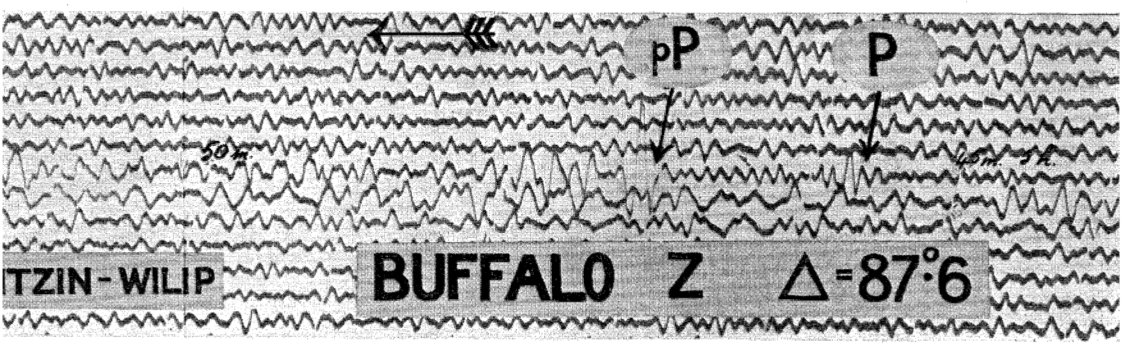

GALITZIN

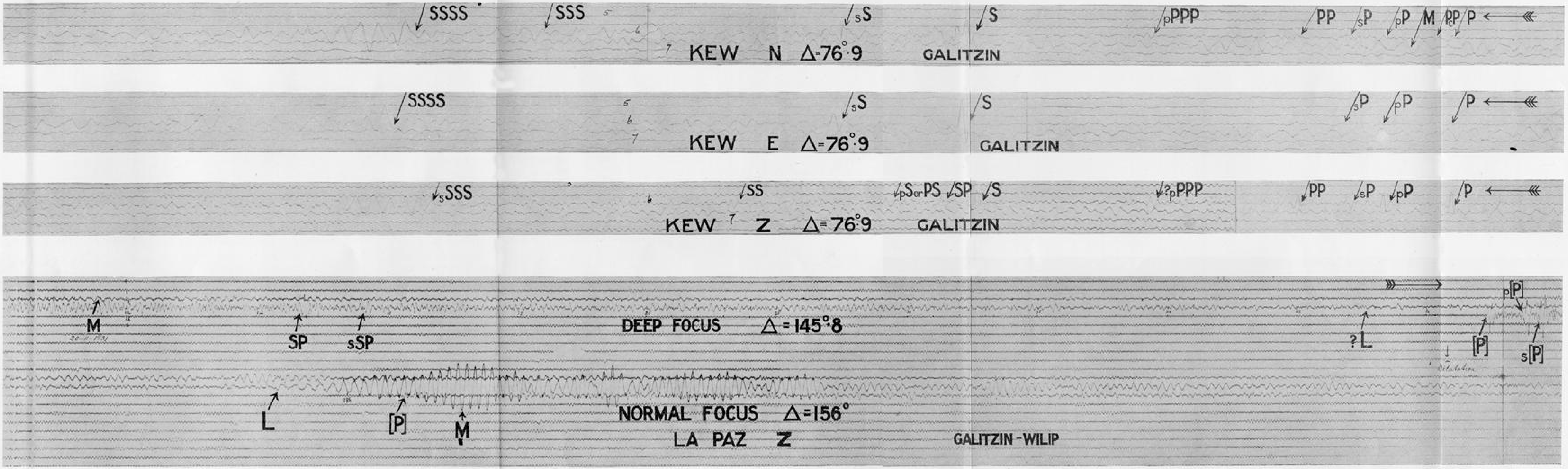

M
GALITZIN-WILIP

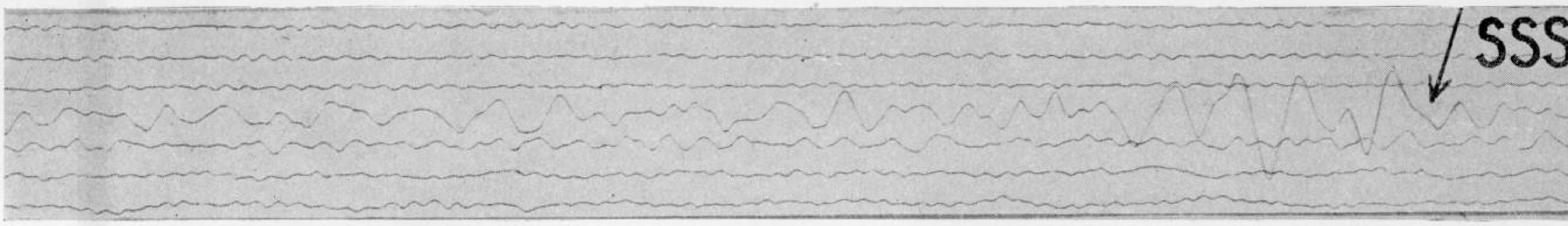

JTTGART E Δ=75°8 M
GALITZIN-
WILIP

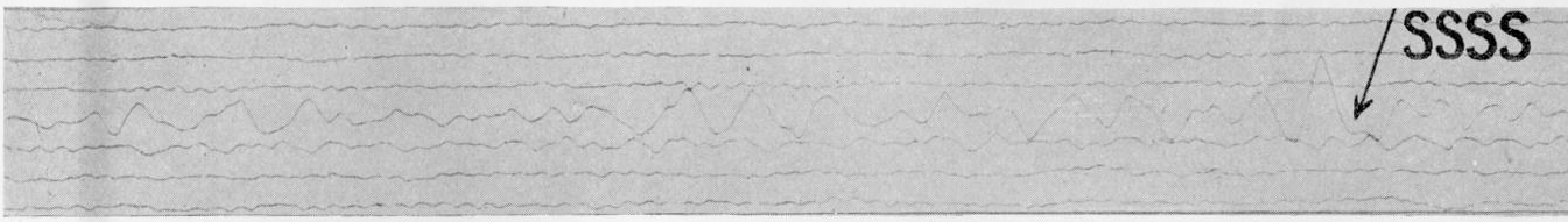

Δ=75°8
M
GALITZIN-WILIP

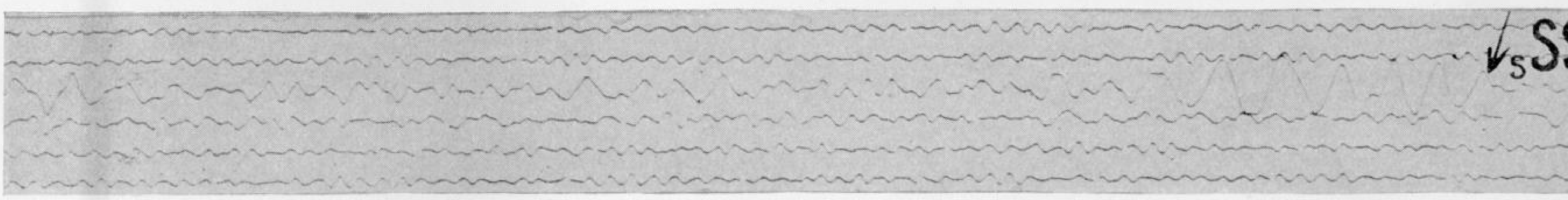

SS
sSS
SSSS
?L
5°5
MILNE-SHAW
1931 Feb 20

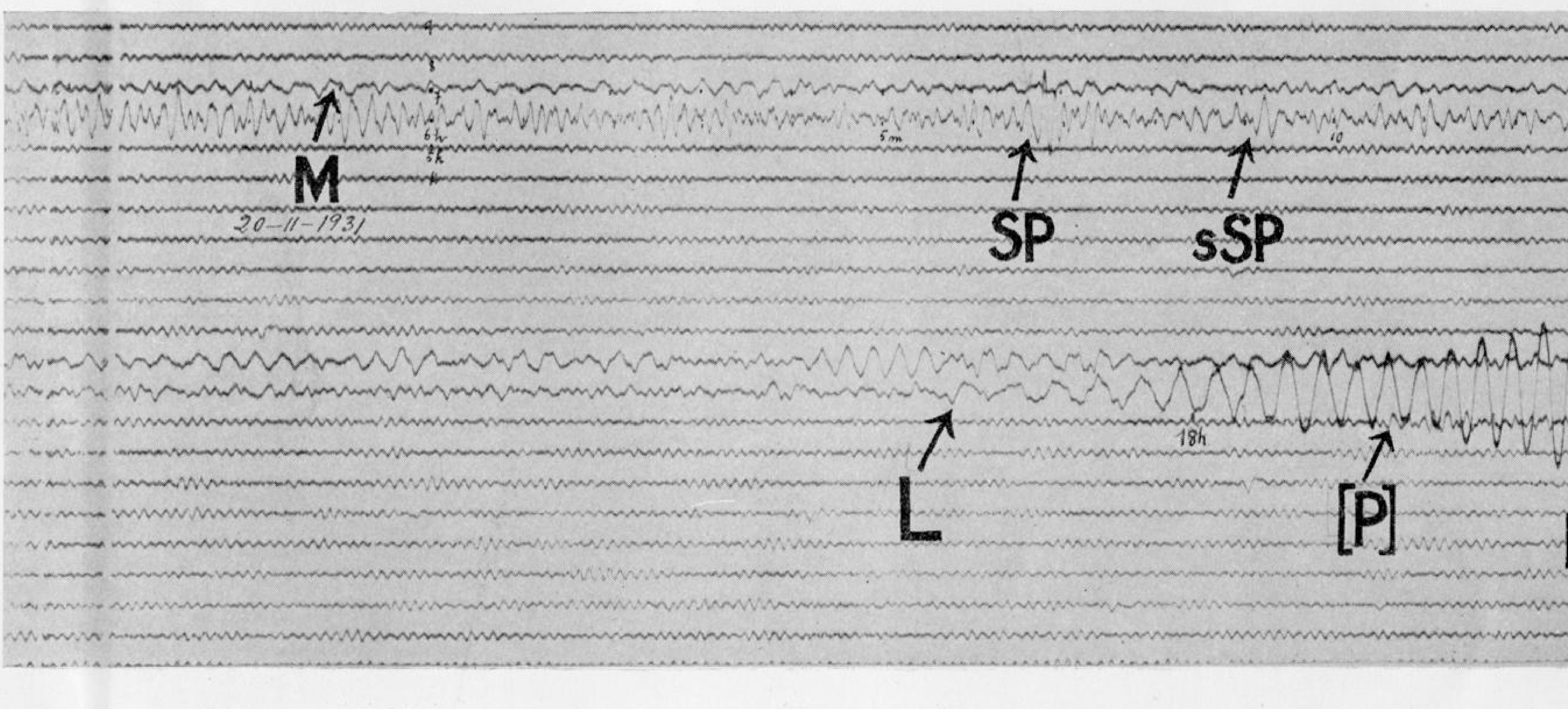

pP
P
TZIN-WILIP
BUFFALO Z Δ=87°6

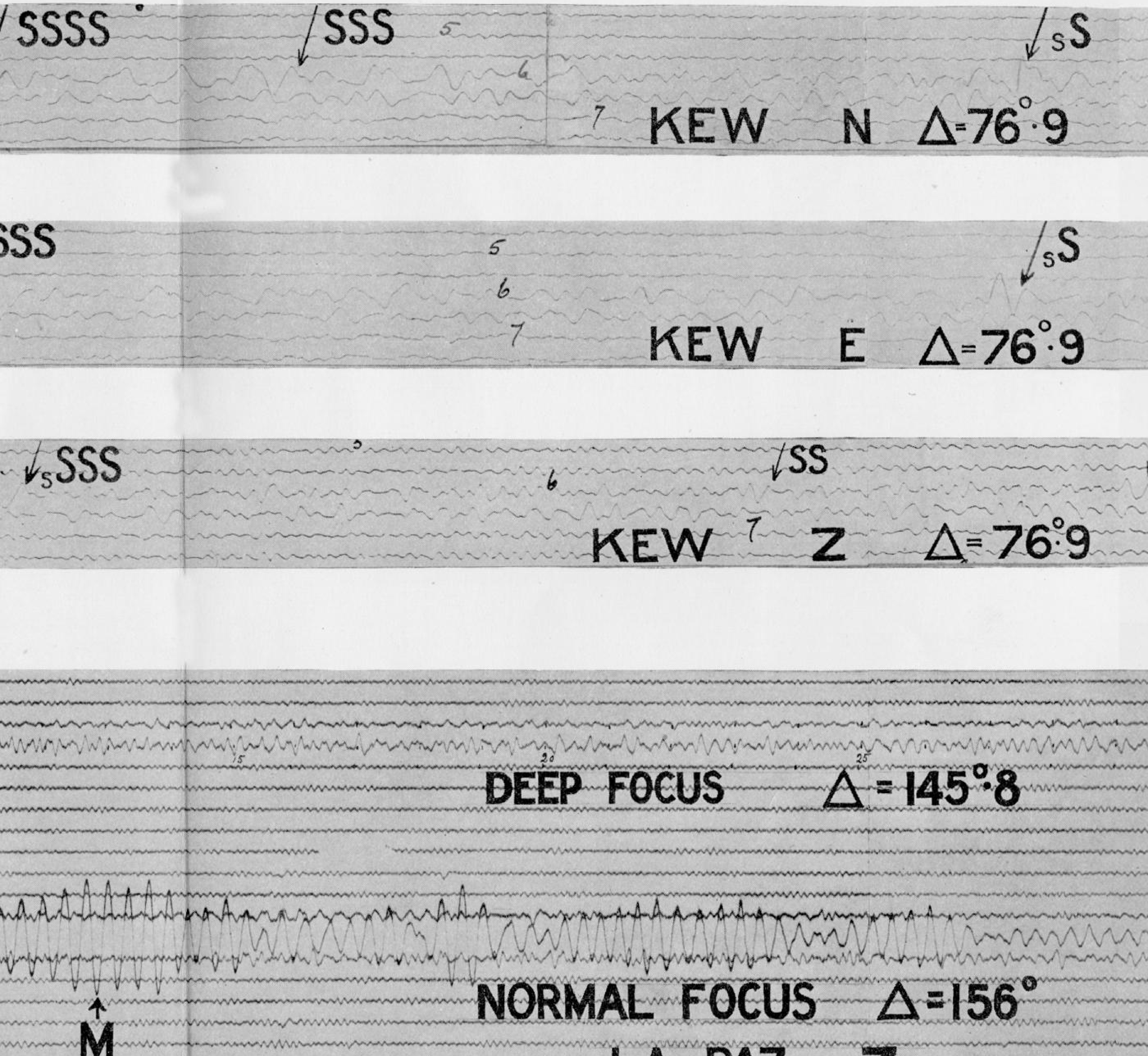

SSSS
SSS
sS
S
pPPP
PP
sP
pP
M
PP
P
KEW N Δ=76°·9
GALITZIN
SSSS
sS
S
sP
pP
P
KEW E Δ=76°·9
GALITZIN
sSSS
SS
pS or PS
SP
S
?pPPP
PP
sP
pP
P
KEW Z Δ=76°·9
GALITZIN
M
SP
sSP
DEEP FOCUS Δ=145°·8
?L
[P]
p[P]
s[P]
L
[P]
M
NORMAL FOCUS Δ=156°
LA PAZ Z
GALITZIN-WILIP

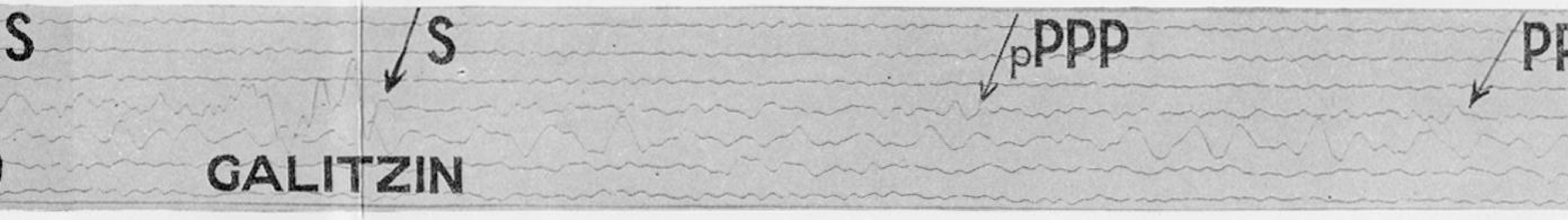

SSS

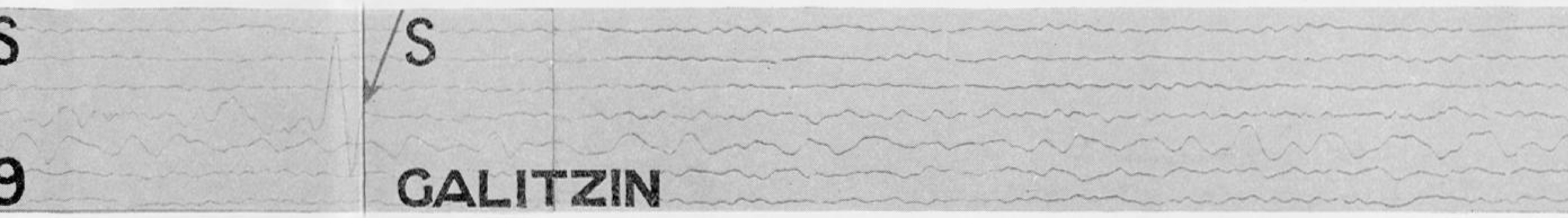

SSSS

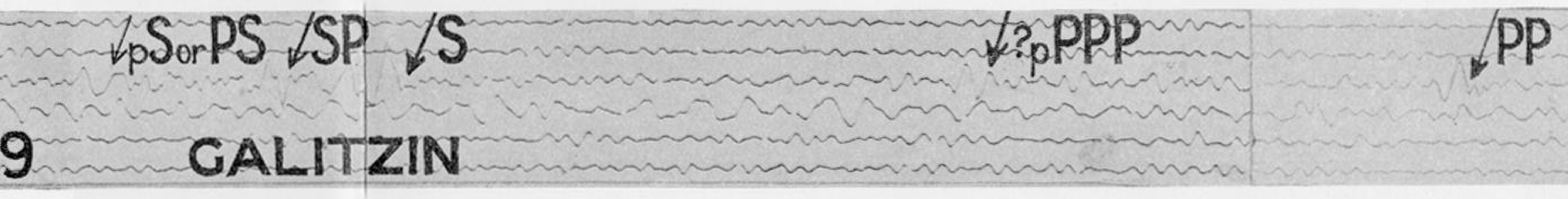

sSS

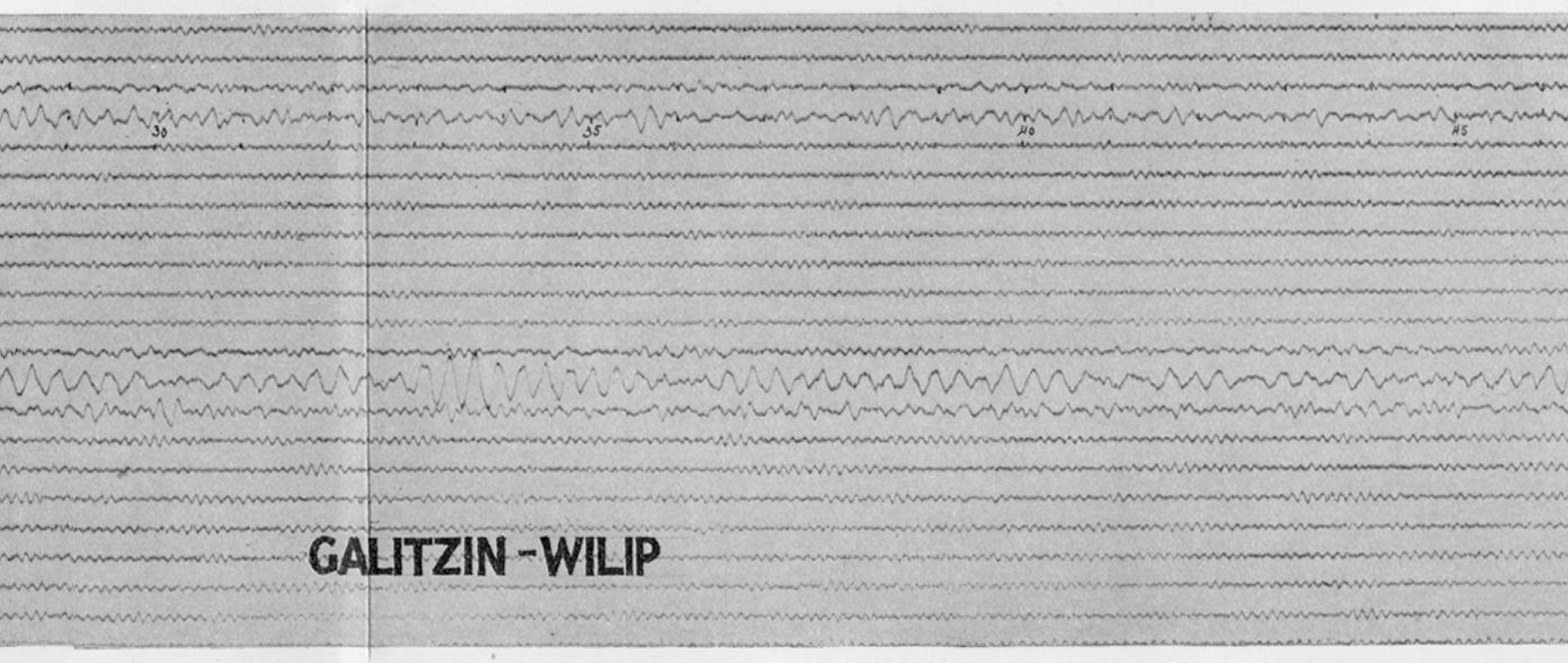

M
20-11-1931
SP
sSP
L
18h
[P]

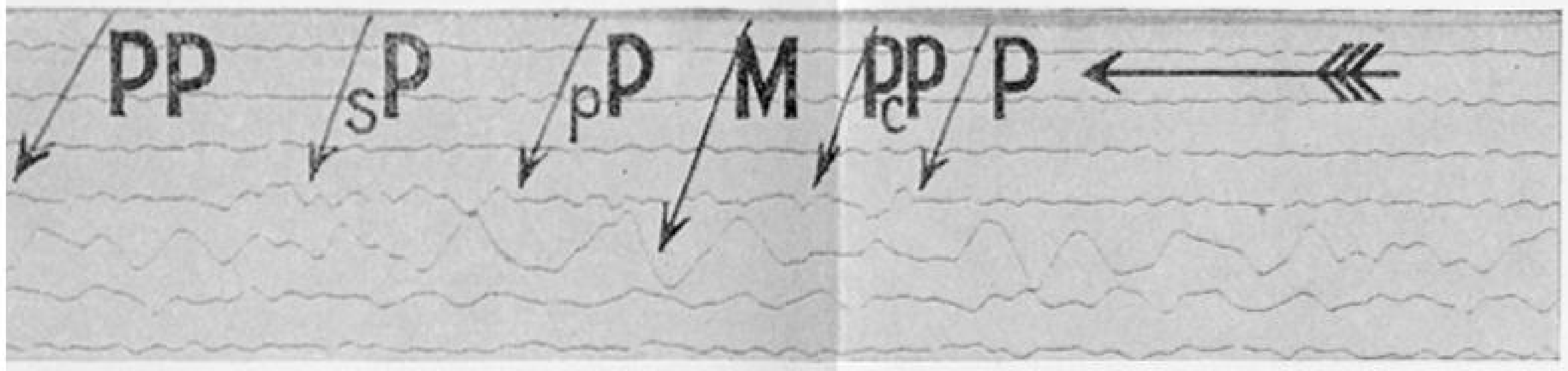

SSSS
SSS
$_{s}$S
KEW N Δ=76°·9
SSS
$_{s}$S
KEW E Δ=76°·9
$_{s}$SSS
SS
KEW Z Δ=76°·9
DEEP FOCUS Δ=145°·8
NORMAL FOCUS Δ=156°
LA PAZ Z
M

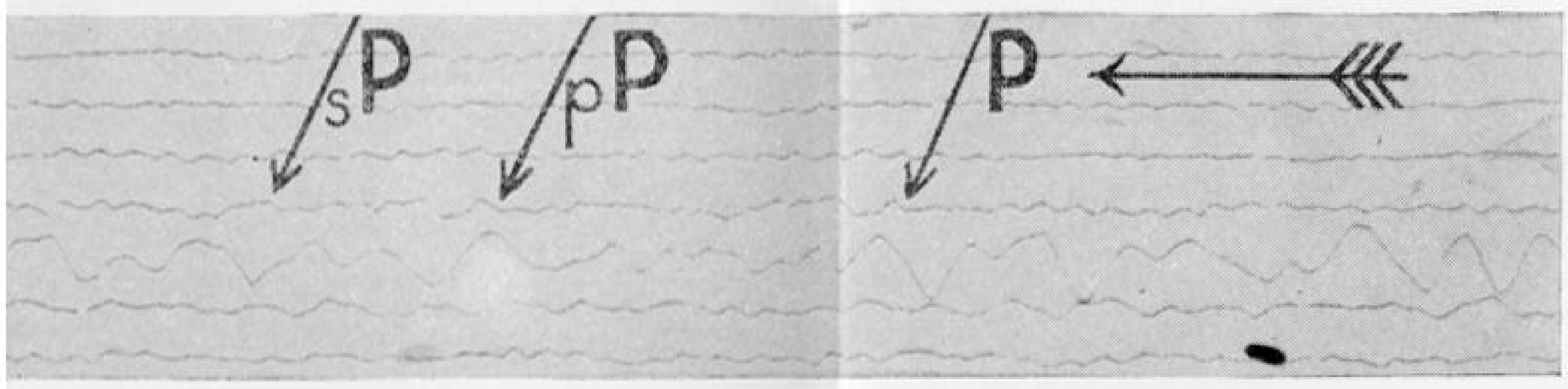

S
S
pPPP
PP
GALITZIN

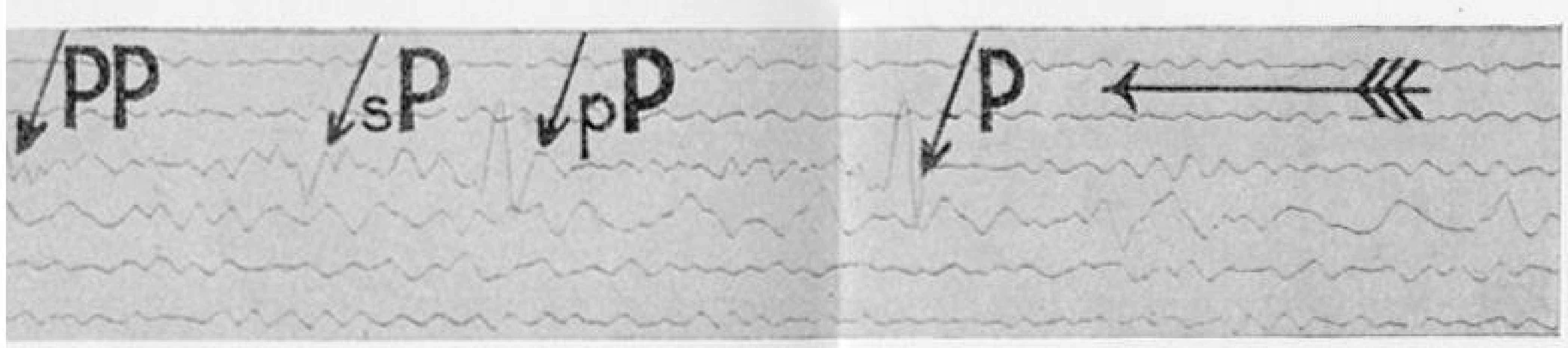

S
S
GALITZIN

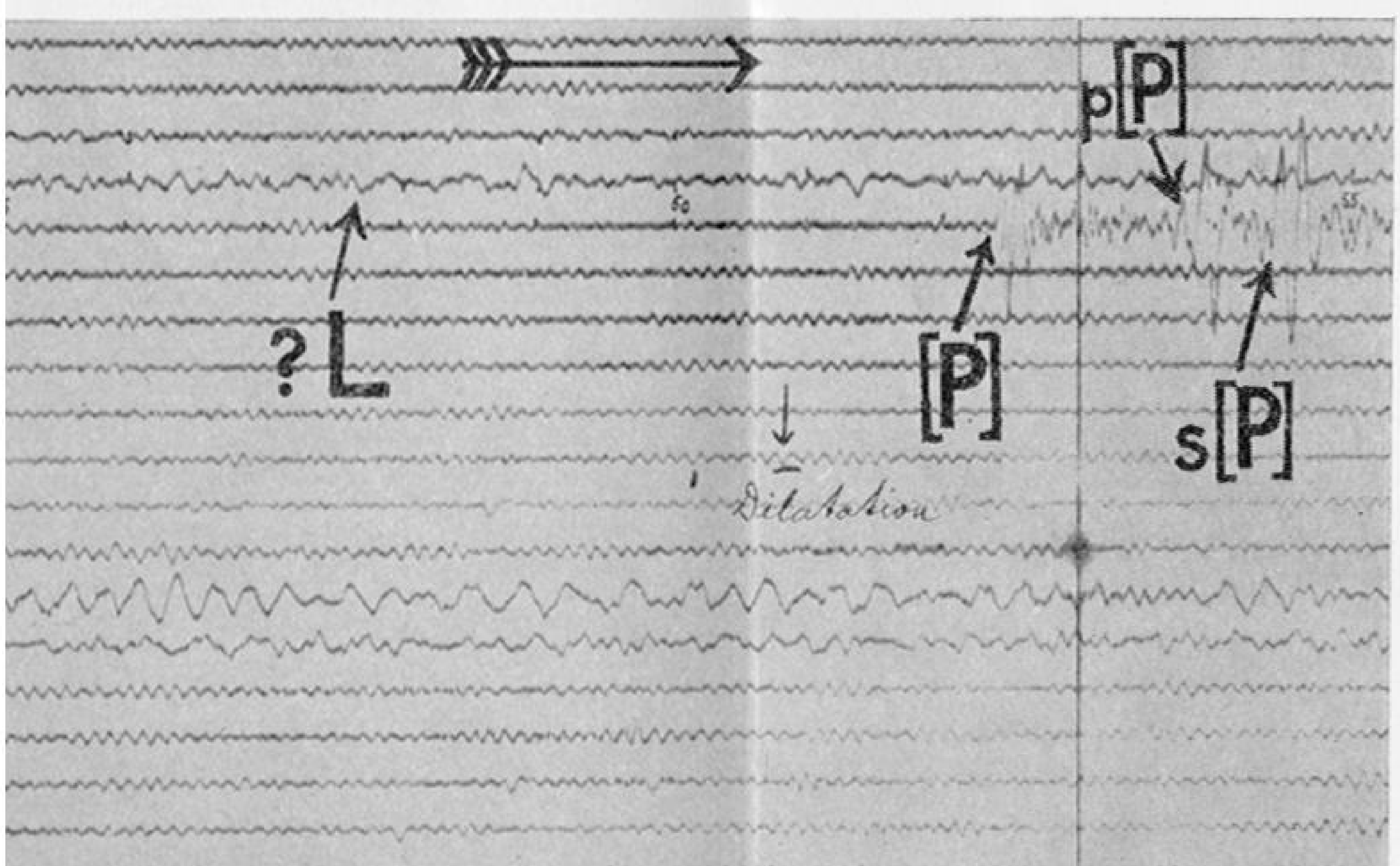

pS or PS
SP
S
?pPPP
PP
GALITZIN

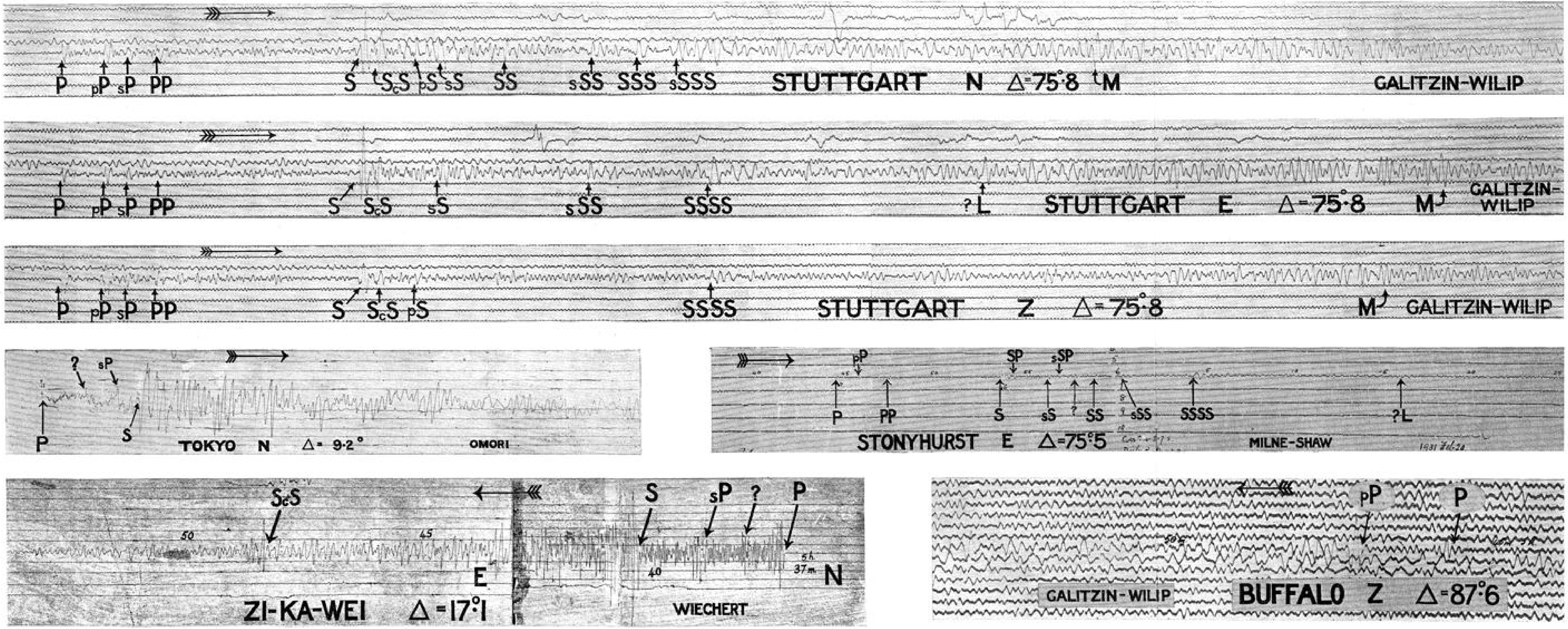

30
35
40
45
GALITZIN - WILIP

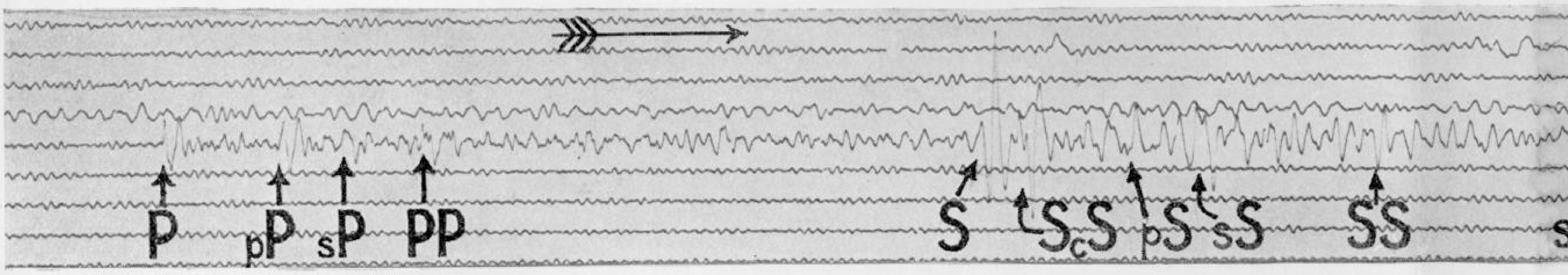

PP
sP
pP
M
PcP
P

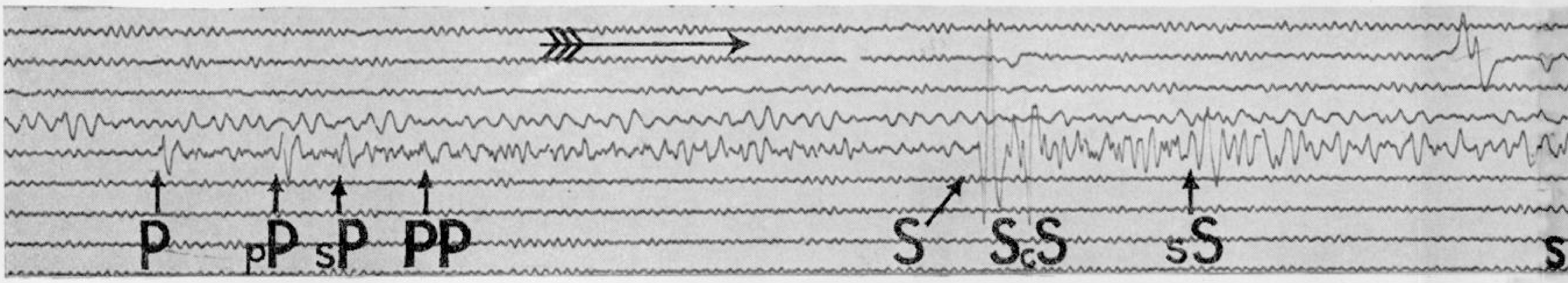

sP
pP
P


PP
sP
pP
P


p[P]
?L
[P]
s[P]
Dilatation


P pP sP PP S ScS pS sS SS sSS SSS sSSS
STUTTGART N Δ=75°8 M
GALITZIN-WILIP
P pP sP PP S ScS sS sSS SSSS ?L
STUTTGART E Δ=75°8 M
GALITZIN-WILIP
P pP sP PP S ScS pS SSSS
STUTTGART Z Δ=75°8 M
GALITZIN-WILIP
? sP P S
TOKYO N Δ= 9·2°
OMORI
pP SP sSP P PP S sS ? SS sSS SSSS ?L
STONYHURST E Δ=75°5
MILNE-SHAW
ScS 50 45 40 S sP ? P 5h. 37m. E N
ZI-KA-WEI Δ=17°1
WIECHERT
pP P
GALITZIN-WILIP
BUFFALO Z Δ=87°6


P
pP
sP
PP
S
ScS
pS
sS
SS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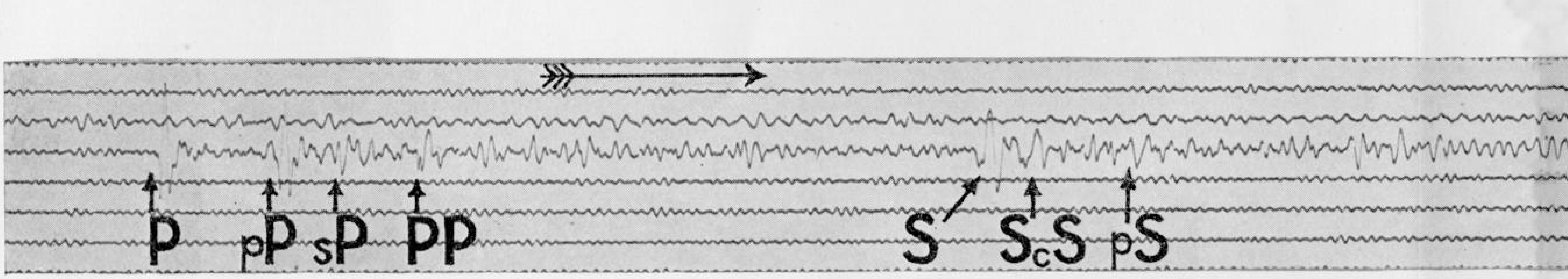
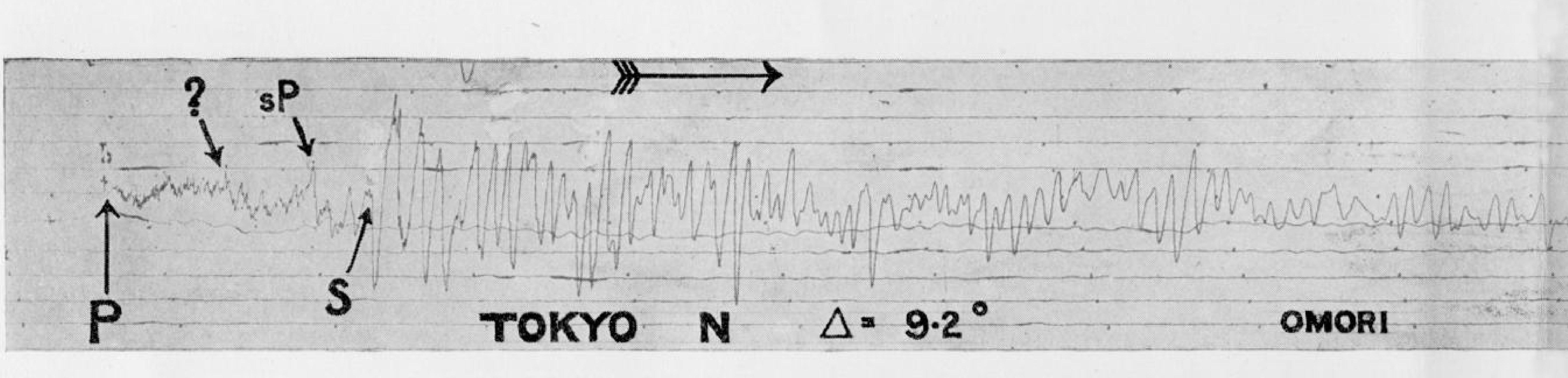
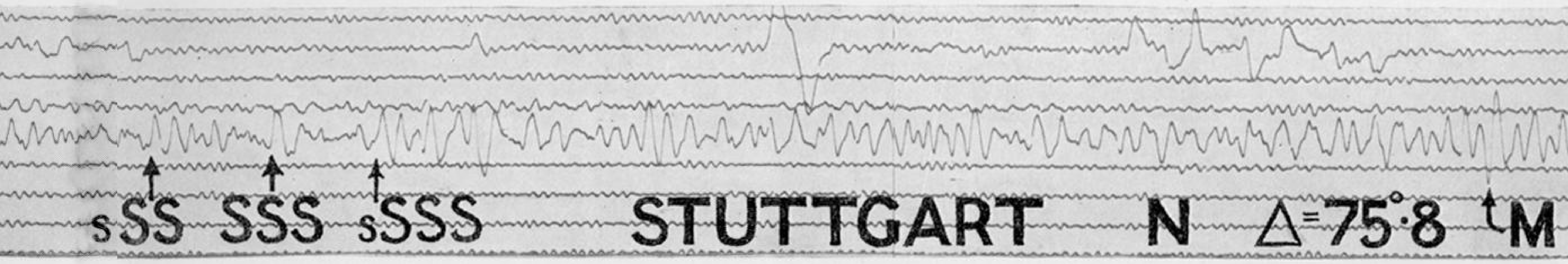
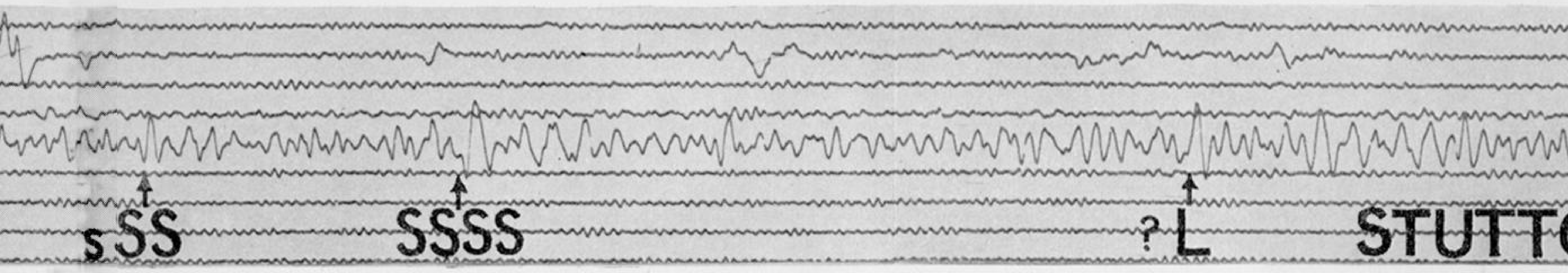
pP
sP
PP
S
ScS
sS
S

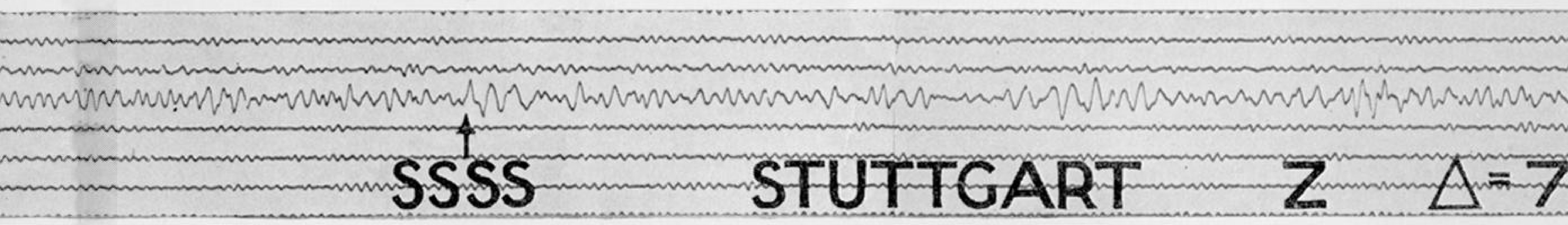

P
pP
sP
PP
S
ScS
pS

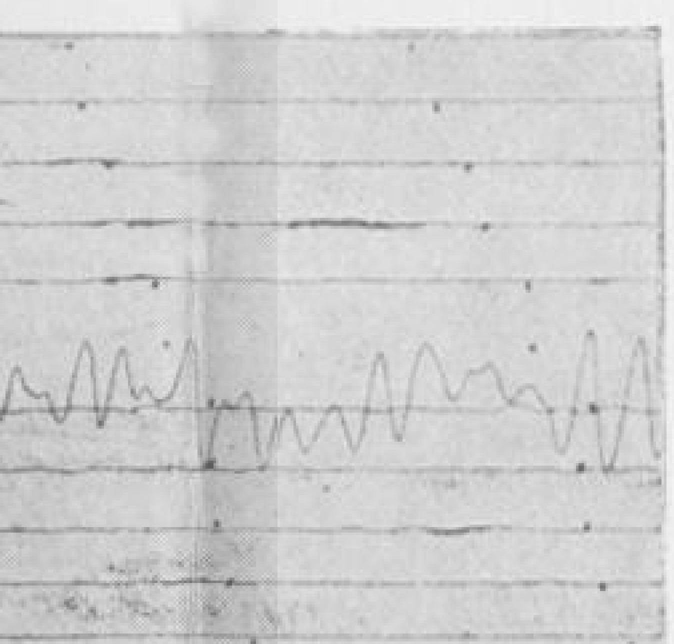

?
sP
P
S
TOKYO N Δ = 9·2°
OMORI

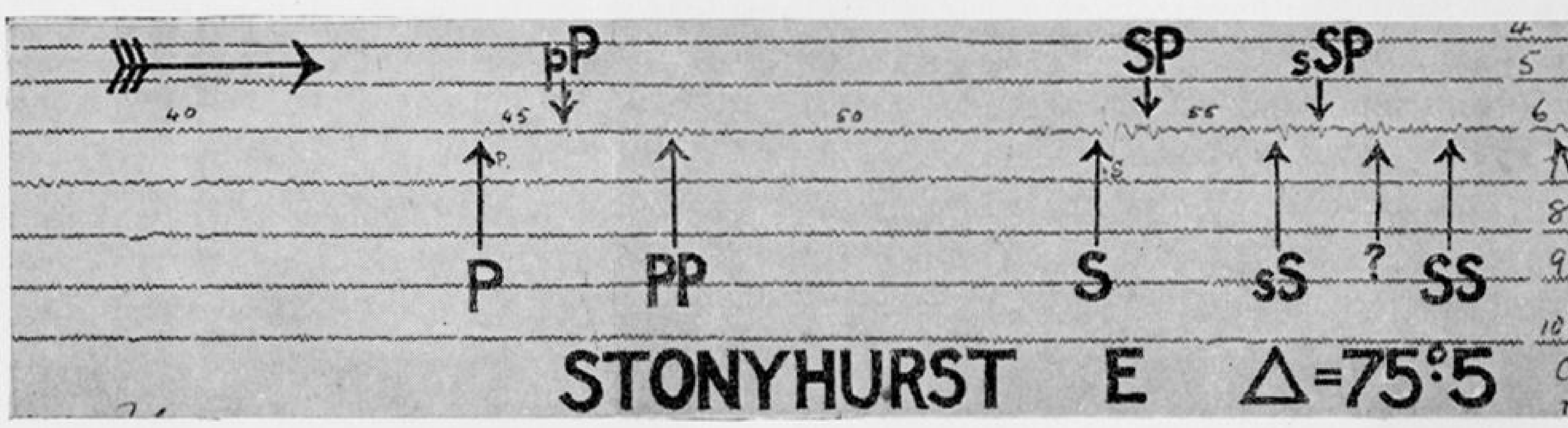

ScS
50
45
E
ZI-KA-WEI Δ = 17°·1

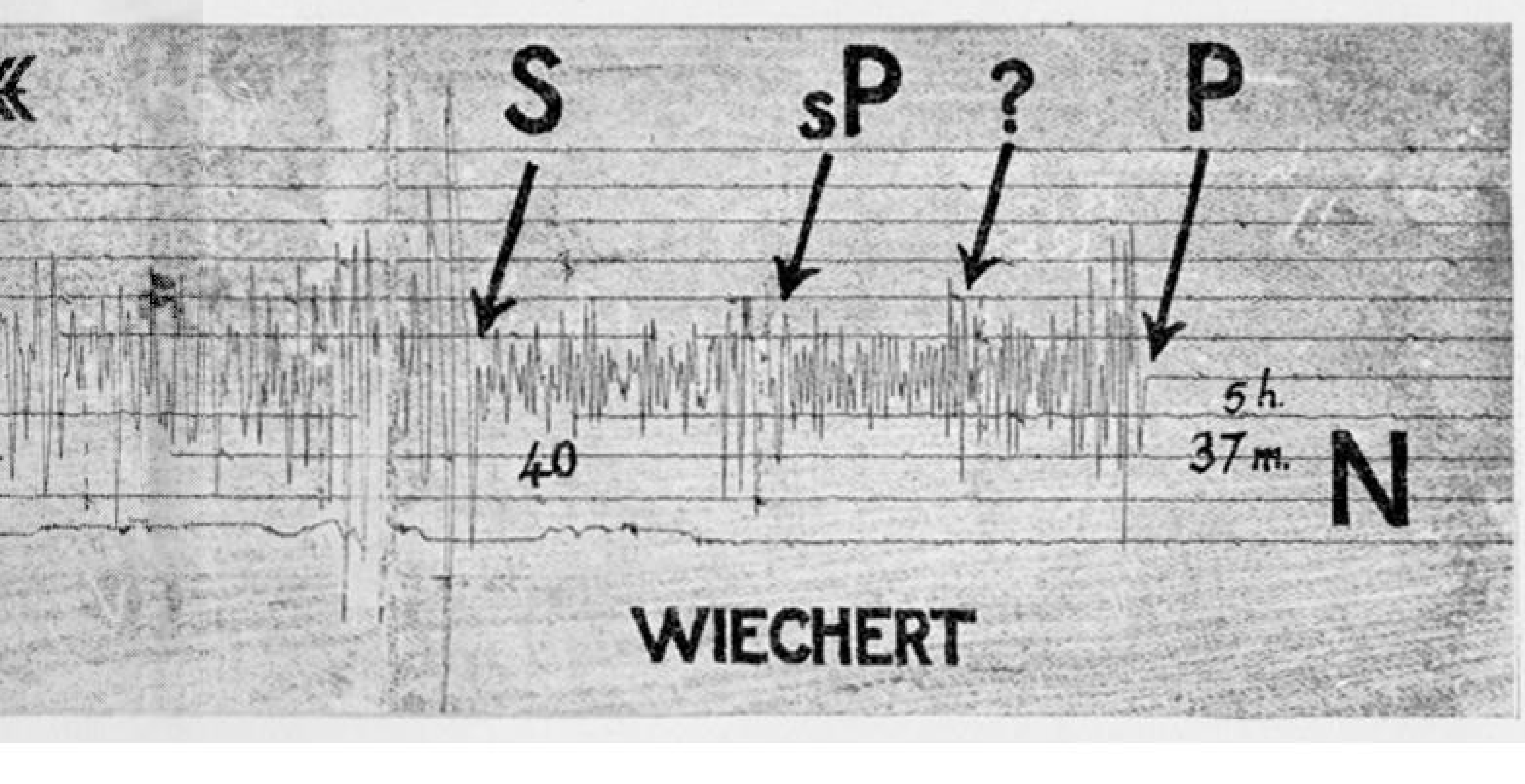

sSS SSS sSSS
STUTTGART N Δ=75°·8 tM

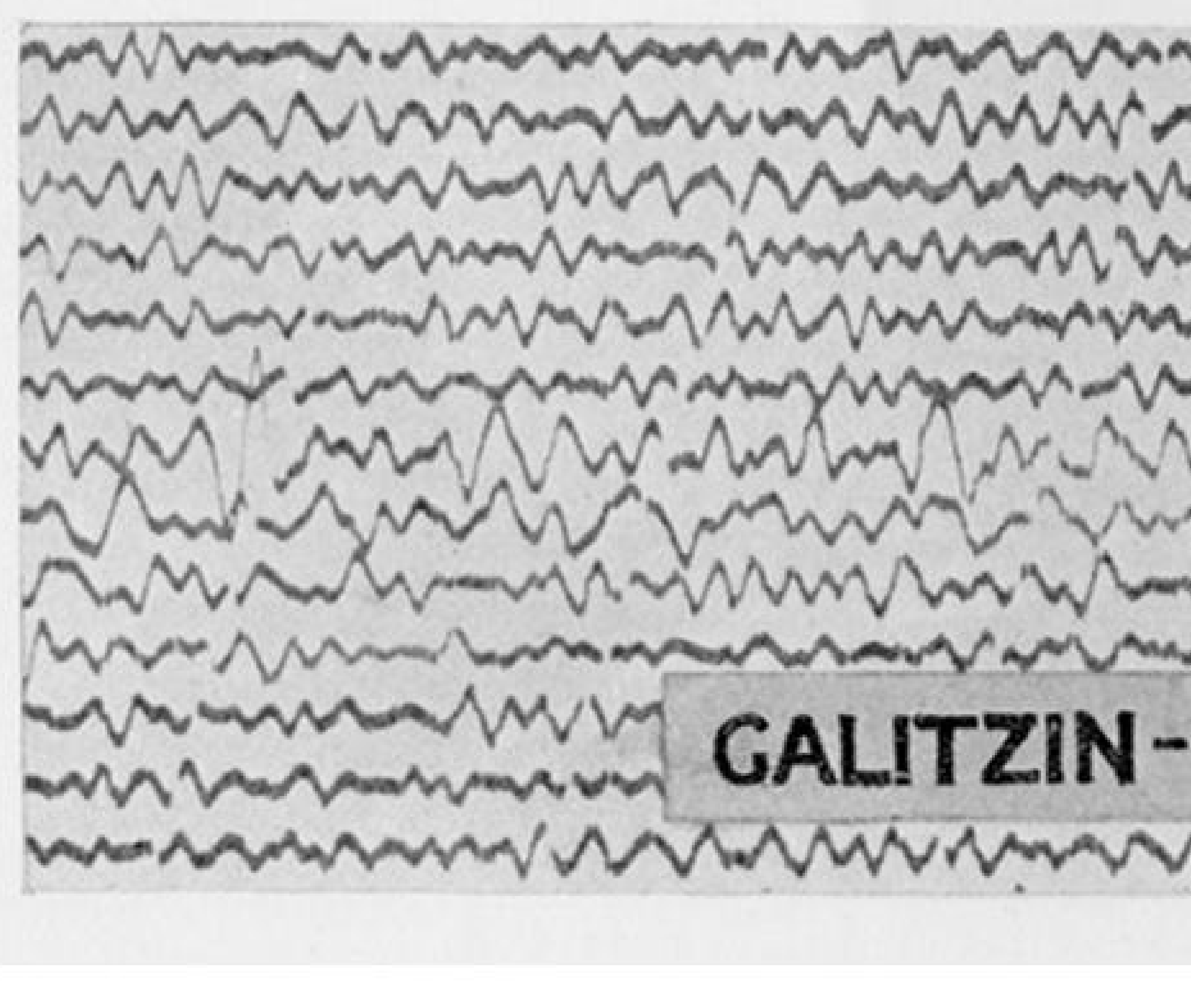

sSS
SSSS
?L
STUTT

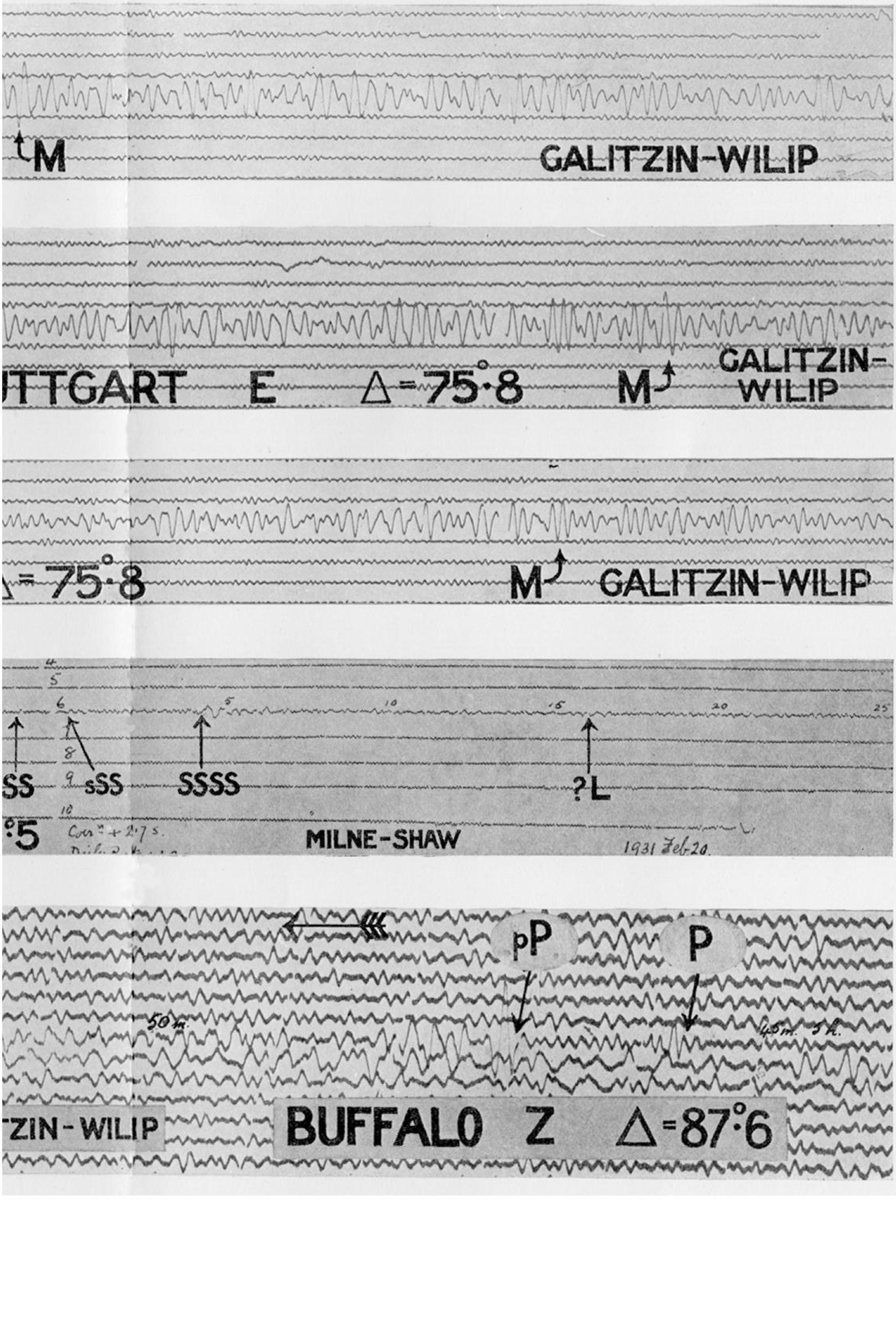

SSSS
STUTTGART Z Δ=75




pP
SP
sSP
P
PP
S
sS
?
SS
STONYHURST E Δ=75°5


S
sP
?
P
5 h.
37 m.
40
N
WIECHERT


GALITZIN -


M
GALITZIN-WILIP
UTTGART E Δ=75°8
M
GALITZIN-WILIP
Δ=75°8
M
GALITZIN-WILIP
SS
sSS
SSSS
?L
°5
MILNE-SHAW
1931 Feb 20.
pP
P
50m.
45m. 5h.
TZIN-WILIP
BUFFALO Z Δ=87°6