6. Travel Times of the Principal Earthquake Waves for Uppsala.

By

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Introduction.

The travel time tables of earthquake waves nowadays in general use (JEFFREYS and BULLEN (1), GUTENBERG and RICHTER (2)) have been determined to a high degree of accuracy. In their determination use has been made of the records at a great many different seismological stations in various parts of the world running various kinds of seismographs. The chief aim of this paper is to see what differences there may exist between these general travel times and those recorded at a single station with a single type of seismograph. The records used are those of the WIECHERT horizontal seismograph (1000 kg pendulum) at the Meteorological Institute at Uppsala (lat. 59°51′29″N, long. 17°37′37″E). Only normal or shallow earthquakes have been included in the present study.

Materials used. Method of determination.

The material given by GUTENBERG and RICHTER (3) has been used. They have made a careful revision of the values given in the International Seismological Summary, and the values in (3) may thus be considered as very reliable. The earthquakes are in (3) divided into three qualities: A (epicenter probably located within 1 degree of arc), B (within 2 degrees), and C (within 3 degrees). Only those earthquakes of qualities A and B that have been clearly recorded at Uppsala have been used. The data of the earthquakes used cannot be given here. A reference to (3) and to the »Observations séismographiques» published by Uppsala may suffice. The epicenters are indicated in Fig. 1. The number of records used was 315 in all (from 1913, 1918, and every year 1920—1943). Individual errors due to special records or personal factors are eliminated by using as many earthquakes as possible.

The distances from Uppsala to the various epicenters have been determined graphically by means of a thin celluloid-band graduated in degrees of arc placed on a globe. The band was made 3 cm wide, so that it may easily and exactly be placed with its central line along the great circle arc between any two points on the globe. The circumference of the globe used was 168 cm, which makes $1^\circ = 4.7$ mm, thus easily making a good estimate of the tenths of degrees possible. It is necessary that the globe is perfectly spherical and that its latitudes and longitudes are perfectly exact, if this method will yield good results. These requirements (especially the first-mentioned one) were not quite satisfied by my globe so that a smaller correction had to be applied to a certain area (a sector including South America). After application of this correction a comparison of graphically determined and calculated geocentric distances for a representative material (78 determinations) gave a standard deviation of $0^\circ.1$ for a single measurement. This is fully satisfactory regarding the fact that GUTENBERG's quality A (highest accuracy) is determined only within 1°. The error in the distance is thus of no importance in comparison with the uncertainty in the location of the epicenters. The graphical method is furthermore about three times as quick as the calculation method. The distances determined are the geocentric distances, which are preferable to the geographic ones (GUTENBERG and RICHTER (4) and JEFFREYS (5)).

The time-differences, constituting the travel times, have been calculated by means of a calculating machine. The calculations may easily be made with the times given in minutes and seconds without transformation of seconds to tenths and hundreds of minutes. If t_1 and t_2 are two times to be subtracted ($t_1 - t_2$) the simple and obvious rule is to subtract 40 from the result in case the number of seconds in t_2 is greater than that in t_1. For addition ($t_1 + t_2$) the corresponding rule is to add 40 to the result, if the sum of the seconds in t_1 and t_2 is greater than 60.

The travel times have been determined graphically by plotting the points in diagrams with travel time and distance as axes. The scales used have generally been 1 minute = 20 mm and $1^\circ = 5$ mm except for L and M, where 1 minute = 10 mm. All observations have been treated as if they were of equal weight. The weight depends obviously not only on the quality A or B, but also on the exactness of the determination from the records. As the application of different weights is rather arbitrary, I have not considered it worth while doing it; it merely increases the work without improving the results. Some single and very discordant values have been excluded as surely depending on false readings from the records.

The task is now to get the closest possible fit to the observations. In order to effect this, curves have been drawn not only for P–O (O = origin time), S–O, but also for S–P. A difference between S–P calculated from the first two graphs and that determined graphically from the third de-

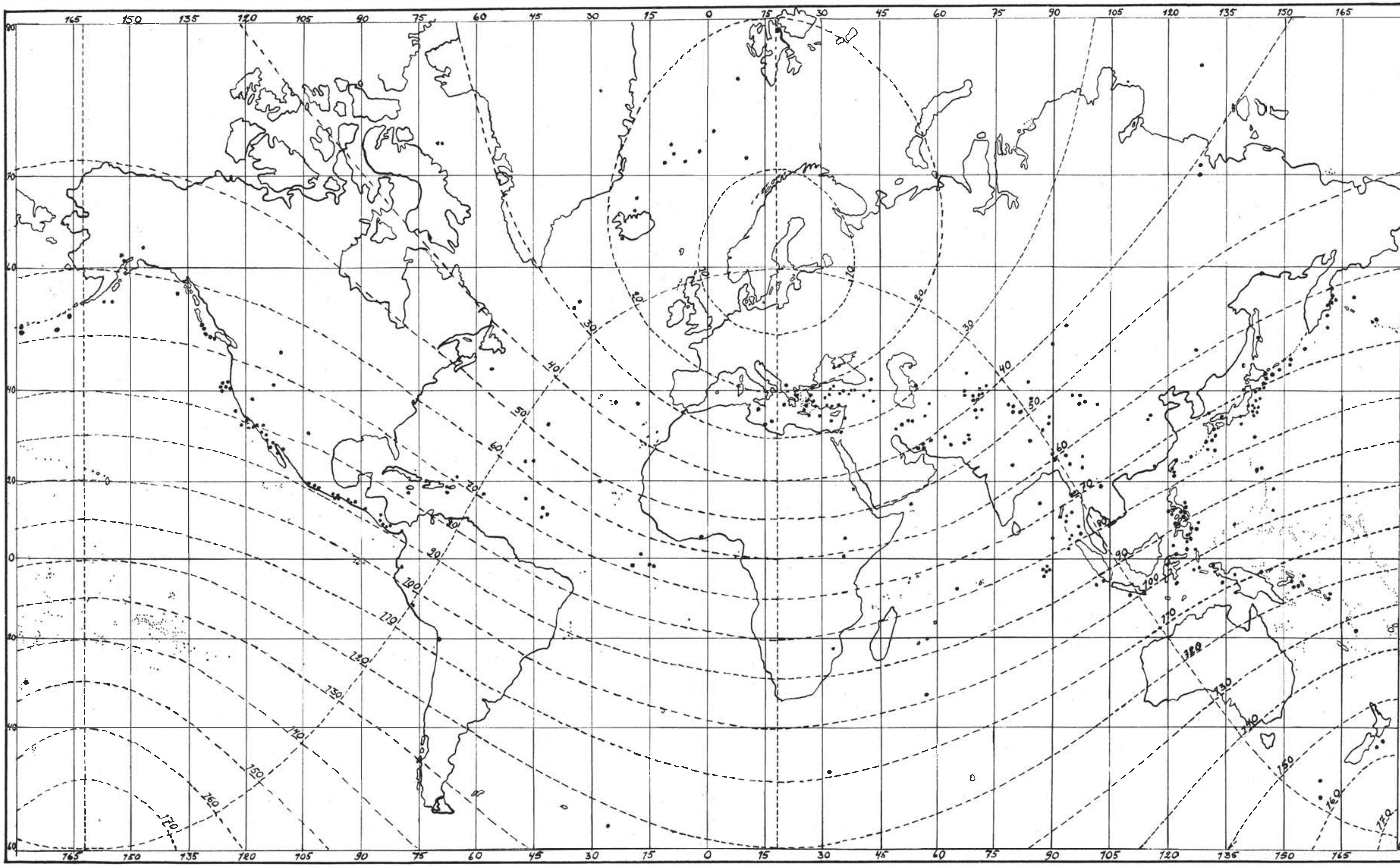

Fig. 1.

pends obviously only on different drawing of the curves. If any greater discrepancies existed the different curves were inspected and correction made where it seemed necessary. After that the mean of *S–P* from the two different determinations was calculated. Starting from the values of *P–O* which were best determined, *S–O* were deduced by adding the adopted values of *S–P* to *P–O*. The same procedure was made for *P–O*, *PP–O*, and *PP–P*, for *S–O*, *SS–O*, and *SS–S*, and for *S–O*, *L–O*, and *L–S*. After that the individual deviations (ΔT) from the mean curve were plotted against distance with a ΔT-scale 6 times as extended as the original *T*-scale. These graphs made further improvements possible, partly only by inspection (as for *P–O* and *S–O*), partly as a result of the calculation of the deviations from the mean curve (for *PP–O* and *SS–O*). The values of *S–P*, *PP–P*, *SS–S* thus corrected were compared with the graphs of these differences. The resulting values have been smoothed. For a complete smoothing it had, however, been necessary to give the times to tenths of a second.

It is obvious that for a given epicentral distance the travel time of a phase depends both on the depth of the focus and the ellipticity of the earth. If travel times for a spherical earth and for a certain normal depth are wanted, corrections ought to be applied to every individual earthquake-reading. The ellipticity is easily corrected for (see (5)). But a correction to some standard depth or to a surface focus requires an accurate knowledge of the individual depths of focus. These are, however, not known, and such a correction cannot be made. A simple calculation now shows that the time-correction due to ellipticity in general does not amount to more than $^1/_5$ of the time-correction due to focal depth (for *P* and *S*). Taking account also of other sources of error, it is not worth while to make any corrections for ellipticity in the present paper.

Resulting travel times.

The resulting travel times are given in Table 1 (p. 121–p. 125). The times have been determined only for *P*, *S*, *PP*, *SS*, *L*, and *M*, as there are not sufficient observations of other phases to get reliable travel times. The times given may be regarded as the closest possible fit to the observations. The differences *S–P*, *PP–P*, *SS–S*, *L–S*, and *M–P*, which are of use in the calculation of distance, are also given in Table 1. It ought perhaps to be emphasized that the values in Table 1 are strictly applicable only to Uppsala and its seismograph. When multiple phases (see below) have been observed for the principal phases, only the first phase has been used.

For *L* the observations show such a considerable scatter that it is almost impossible to place a straight line fitting the observations with any degree of accuracy. In this case I have tried to see which of the already existing travel times for L best fits the Uppsala observations. The result was that STONELEY's (6) LR-curve (adopted by JEFFREYS in (1)) is the best, whereas STONELEY's LQ, GUTENBERG's (2) G (which corresponds to LQ) and MACELWANE's (9) curve (which has hitherto been used in the routine analysis at Uppsala) fit the observations decidedly worse. The values for L given in Table 1 closely correspond to STONELEY's LR-curve. In fact it is not possible to obtain the closest possible fit to the observations by a straight line for all distances. The values given correspond to the observations fairly well up to $\Delta = 90^\circ$, but for greater distances the observations are much earlier than the straight line requires (see below).

The remarks for L are in the main applicable also to M. M is generally meant to be the beginning of the maximum movement. As this is often very difficult to determine exactly and as it is generally not given in the bulletins, I have used M to denote the first maximum. Comparison has been made with MACELWANE's (9) values for M. As it is to be expected my values are somewhat later. As for L the fit is fairly good up to $\Delta = 90^\circ$, but for greater distances M comes earlier than according to the straight line. This may be due to false readings, as in some cases M may be taken among the long waves. It is seen from Table 1 that in several cases $M-L$ is not equal to $(M-O)-(L-O)$. This is only due to the fact that in calculating $M-L$ two decimals were used for $M-O$ and $L-O$, which was necessary to get $M-L$ smoothed out. In Table 1 $M-O$ and $L-O$ have afterwards been reduced correctly to one decimal.

Comparison with other determinations.

Comparison has been made with JEFFREYS' and BULLEN's (1) and GUTENBERG's and RICHTER's ((2) and (12)) travel times (Table 2), which are reckoned from the same zero time (O) as I have used. Index U = Uppsala times, index J = JEFFREYS' and BULLEN's times, and index G = GUTENBERG's and RICHTER's times. GI refers to the times given in (2), GII to those in (12). The GII times are valid only for a surface focus. JEFFREYS' and BULLEN's times have been used both for a surface focus (I) and for a focus at the base of the granitic layer (II; depth = 33 km). GUTENBERG and RICHTER (2) give multiple phases. Comparisons have been made with that or those of the multiple phases which best correspond to my times. The numbers of the multiple phases according to GUTENBERG and RICHTER are given in parenthesis in Table 2.

It is apparent from Table 2 (especially for P_U-P_J and S_U-S_J) that the differences are to a great extent due to the depth of the focus. The differences must be = 0 in most of the cases for some depth between the

Table 2.

Δ	P_U-P_J		S_U-S_J		PP_U-PP_J		SS_U-SS_J		P_U-P_{GI}	PP_U-PP_{GI}	S_U-S_{GI}		SS_U-SS_{GI}		P_U-P_{GII}	S_U-S_{GII}
	I	II	I	II	I	II	I	II								
	s	s	s	s	s	s	s	s	s	s	s		s		s	s
10°	−5	−1	+20	+25					−4						−6	—
15	−2	+2	+11	+17			−7*	−1*	−3		+3(2)				−5	+10
20	−4	±0	±0	+6			−3	+3	−2		+2				−6	+1
25	−3	+2	−1	+7	−7	−3	±0	+6	−3	−7(1)	−1				−5	−2
30	−2	+3	±0	+8	−7	−3	−2	+4	±0	—	±0				−2	±0
35	−3	+2	−3	+5	−11	−7	−6	±0	−2	−8	−3				−4	−2
40	−5	±0	−7	+2	−12	−8	−9	−3	−5	−8	−5			−1(1)	−8	−5
45	−3	+2	−6	+2	−6	−1	−1	+7	−4	−8	−2			—	−7	−4
50	−1	+4	−2	+7	−4	+1	+10	+18	±0	—	+4			+14	−3	+1
55	−3	+2	−1	+7	−5	±0	+16	+24	−1	—	+1			+16	−4	−1
60	−5	±0	−5	+4	−4	+1	+17	+25	−4	—	−5			+18	−7	−4
65	−3	+2	−6	+3	−2	+3	+11	+19	−3	−1	−5			+13	−6	−5
70	−2	+3	−6	+3	±0	+5	+4	+12	−2	+2	−5(2)			+5	−5	−1
75	±0	+5	−5	+4	+1	+6	−1	+7	+2	+5	+8(1)	−8(2)		±0	−1	+3
80	±0	+5	−5	+4	+2	+7	−4	+4	+1	+4	+5	−9		−1	−2	+2
85	−2	+4	−6	+2	+1	+6	−5	+3	±0	±0	−2	−12		+1(1)	−3	−2
90	−3	+3	−6	+3	−1	+4	−6	+2	−2	±0	−5	−14	+10(1)	−3(2)	−5	−5
95	−4	+2	−4	+5	−2	+3	−6	+2	−2	±0	−2	−13	+11	−5	−5	−6
100	−5	±0	−3	+5	−4	+1	−6	+2	−4	±0	−1	−17	+14	−7	−7	−6
105	−6	±0	−3	+6	−5	±0	−4	+4	−4	−1	−1	−18	+19	−4		−5
110					−6	−1	−1	+7	−6	−1			—	+1		
115					−8	−3	+2	+10		−2				+4		
120					−8	−3	+5	+13		−2				—		
125					−9	−4	+6	+14		−3				—		
130					−9	−4	+8	+16		−2				—		
135					−10	−5	+8	+17		−2				+6		
140					−9	−4	+8	+17		+1				+7		
145					−8	−3	+7	+16		+3				+5		
150					−7	−2	+6	+15		+6				+2		
155					−5	±0	+5	+14		+10				—		
160					−2	+3	+2	+11						—		

* for $\Delta = 16°$.

surface and the depth of 33 km, i. e. just the region within which the foci of the normal earthquakes are situated. It is obvious that if travel times are directly deduced from a single or a few earthquakes the times are affected by the special depths of these earthquakes, whereas in this paper a reduction to some normal depth has been made by using a great number of earthquakes. The weighted mean depth of focus calculated from $P_U - P_J$ is 17 km; that from $S_U - S_J$ (excluding the observations for 10° and 15°) is 16 km, assuming a ratio of 1.17 between the velocities of both P and S in the intermediate layer (thickness 18 km) and the upper layer (thickness 15 km). The depth naturally varies with distance. That the depth of the focus is not the only explanation is evident from the fact that corresponding $P_U - P_J$ and $S_U - S_J$ do not give the same depth. The height of the station above the geoid is also of a slight importance. This height is 14 m for Uppsala, and Uppsala may thus be taken as lying on the geoid. Uppsala is situated at a distance of 6 362 km from the center of the earth, thus 9 km below the surface of the mean sphere of radius 6 371 km. The seismograph is in contact with the granitic layer.

Great differences in $S(S_U - S_J)$ occur for $\Delta \leq 15^\circ$. These differences are well established and are real (see Table 4, p. 126—129). The differences $S_U - S_G$ are smaller, which is evident from the following more detailed table:

Δ	$S_U - S_G$
12°	+ 4 sec
13	+ 5
14	+ 4
15	+ 3
16	+ 3
17	+ 2
18	+ 3
19	+ 3
20	+ 2

The values of S_G are here taken from (14). The big differences $S_U - S_J$ are surely due to the difficulties in determining S at short distances (see below).

The differences for PP and particularly for SS are naturally greater. The great positive values of both $SS_U - SS_J$ and $SS_U - SS_{GI}$ for $\Delta = 50^\circ$—70° are well established by the observations and seem to be real. Several deviations are certainly due to the way in which the WIECHERT seismograph responds to the earth movement (phase-lag etc.).

In Table 3 I have given for various distances Δ the values of $2 \cdot P_{\frac{\Delta}{2}} - PP_\Delta$ and $2 \cdot S_{\frac{\Delta}{2}} - SS_\Delta$, calculated from the Uppsala times. For a focus at some depth (not at the surface) it is easily shown that $2 \cdot P_{\frac{\Delta}{2}} - PP_\Delta < 0$

Table 3.

$\varDelta$	$2\,P_{\frac{\varDelta}{2}}-PP_{\varDelta}$	$2\,S_{\frac{\varDelta}{2}}-SS_{\varDelta}$
	s	s
20°	—	+40
30	+ 3	+24
40	+ 4	+ 9
50	− 2	−12
60	+ 1	−17
70	− 6	−20
80	−12	− 9
90	− 5	− 6
100	+ 2	+ 3
110	− 1	− 1
120	− 1	−14
130	+ 3	−19
140	+ 4	−19
150	+ 7	−15
160	+ 3	−11

and $2 \cdot S_{\frac{\varDelta}{2}}-SS_{\varDelta} < 0$. This may explain the dominating negative values, especially for $2 \cdot S_{\frac{\varDelta}{2}}-SS_{\varDelta}$. Another interesting result from Table 3 is that the great positive value of $2 \cdot S_{\frac{\varDelta}{2}}-SS_{\varDelta}$ for $\varDelta = 20^\circ$ may be explained even to its numerical magnitude from the corresponding difference S_U-S_{γ}, mentioned above. This indicates that S_U is observed too late for $\varDelta \leqq 20^\circ$ to an amount approx. $= S_U-S_{\gamma}$. The positive values of the differences in Table 3 for $\varDelta \leqq 40^\circ$ may possibly to some degree be due to reflexion at the base of the granitic layer instead of at the free surface (see JEFFREYS (11)).

Accuracy of the Uppsala travel times and comparison between different quadrants.

To give an exact measure of the accuracy of the deduced times is very difficult, as it depends not only on the accuracy of the readings but also on the accuracy of epicenter and origin time. The total error $d\,T$ in the travel time T is clearly composed of a time-error $d\,T_0$ and a distance-error $\left(\frac{d\,T}{d\,\varDelta}\right) \cdot d\,\varDelta_0$:

$$d\,T = d\,T_0 + \left(\frac{d\,T}{d\,\varDelta}\right) \cdot d\,\varDelta_0.$$

In this paper I have only considered the time-deviations of the points from the mean-curve, and what is given below is strictly not the accuracy of the values but only the scatter of the observations.

In Table 4 (p. 126—p. 129) I have given the details of the various curves. The material has been divided into the four quadrants from Uppsala and into certain intervals of Δ. The division of the world thus effected is apparent from Fig. 1, which gives on Mercator's projection the N—S and E—W great circles through Uppsala and the distances for every ten degrees (dashed lines). ΔT in Table 4 is the correction to be applied to the individual values in order to bring them into coincidence with the adopted curves. »ΔT-range» gives the range in ΔT for each case, n is the number of observations, $\overline{\Delta T}$ the arithmetical mean of ΔT. The table has been made as detailed as possible to give a more complete picture of the material used and to facilitate comparison with similar investigations for other stations.

S–P as well as the other differences (PP–P; SS–S) have been treated separately, as it is not given that

$$|\Delta T_{S-P}| = |\Delta T_{S-O}| + |\Delta T_{P-O}|.$$

This depends on the fact that in determining S–P only those earthquakes can be used where both P and S are clearly recorded. It may be mentioned that in many individual cases P–O and S–O show correction of the same sign and about the same magnitude, indicating an error in the origin time O or a clock-error, which, however, is unlikely, whereas S–P, which is independent of O and clock-error comes out all right.

The observations are distributed about the mean curves according to a normal error-curve. This has been ascertained by drawing frequency curves for ΔT for the various phases and phase-differences. The standard deviation σ of a single observation has thus been calculated according to the formula

$$\sigma = \sqrt{\frac{\Sigma(\Delta T)^2}{n}},$$

where n is the total number of observations for each phase. $\frac{\sigma}{\sqrt{n}}$ is the standard error of the mean. The results are:

Phase	σ	$\frac{\sigma}{\sqrt{n}}$
P –O	± 5.0 sec	± 0.3 sec
S –O	8.4 »	0.5 »
S –P	6.5 »	0.4 »
PP–O	9.8 »	1.0 »
PF–P	8.5 »	0.9 »
SS–O	15.4 »	1.5 »
SS–S	10.7 »	1.2 »
L –O	2.1 min	0.1 min
M –O	(3.3 »)	(0.2 »)

For $L-O$ and $M-O$ the calculations are made only for $\Delta \leqq 90^\circ$, as great discrepancies from the normal distribution occur for greater distances (see Table 4). The frequency-curve for $M-O$ differed from all the others in showing a secundary maximum for $\Delta T = +6$ min. This is certainly due to cases in which M has been read among the long waves, thus 6 min too early in the mean. It may perhaps be objected that the number of observations for $PP-O$ and $SS-O$ is too small to get reliable values. The addition of 20 further observations for $PP-O$ and 17 for $SS-O$ (taken from (3) p. 20, which had not been used before, as the origin times are given only to tenths of a min) conformed to the previous observations, which may thus be taken as representative.

The division into quadrants was made in order to see if any differences in travel times existed for different directions. In this case we are independent of my travel times, as it is only a question of the differences between the quadrants, and we could clearly have used any normal for reference. The differences for $P-O$ and $S-O$ seem to be consistent with each other, which they also ought to be if there existed any differences in the elastic constants or the density in different azimuths. The differences between the travel times for the different quadrants seem to be greater for S than for P. This is, however, contradicted by theory. Starting from the mathematical expressions of the velocities of P and S, it is easily shown that

$$\frac{d\,c_s}{d\,c_p} = \frac{1}{\sqrt{1+\alpha}} < 1, \quad \text{where} \quad \alpha = \frac{\lambda}{\mu}$$

in the usual notation (c_p and c_s = the velocities of P and S resp. and α assumed constant), which means that the change in velocity is less for S than for P for any change in the elastic constants or the density. Thus the differences in travel times ought to be less for S than for P. The differences may not be regarded as any indication of different properties as they are furthermore contradicted by the corresponding differences for $PP-O$ and $SS-O$ (compare GUTENBERG (8)). It ought to be mentioned that JEFFREYS and BULLEN (10, p. 33) have found a similar difference between the times of P for Japanese (NE) and American (NW) earthquakes for $\Delta > 54^\circ$ as is evident from Table 4 both for P and S. Any definite conclusions may not be drawn from this. There is, however, a very striking similarity in the general run of ΔT for $P-O$ and $S-O$ for the different quadrants.

It may be noted that the two observations of $S-O$ for 10°—20° from the SE-quadrant conform very well with JEFFREYS' values (compare Table 2), whereas the 10 observations from the NW-quadrant show a different feature. A special investigation of the S-phase directly from the records was made for the 10 earthquakes from the NW-quadrant for 10°—20°. The results showed no sensible difference from the older determinations, when the most obvious and clearest phase was taken for S. There was, however, in most of these records a very slight change in the character of the trace preceding S by an amount approx. $= S_U - S_J$ (Table 2). This first phase is probably the correct S. It is not possible to prove this conclusively by a determination of the change of direction of the movement, as the amplitudes in the 10 records are too small to get the necessary reliability. The times given for $S-O$ for 10°—20° correspond to the most obvious phase, and they are practically useful, though they are perhaps not theoretically justified. A thorough treatment of this matter is given by LEE (13).

For $L-O$, however, the matter is different, as it shows a decided difference in travel time between the quadrants. We are here considering only distances $\Delta \leq 90^\circ$. As the velocity of L depends on the surface properties of the earth, it is also in this case that differences might be expected. The differences in Table 4 indicate the smallest velocity in the NE- and SE-quadrants and greater velocity for the SW- and NW-quadrants. The NE- and SE-quadrants up to 90° consist mainly of the Euro-Asiatic continent, whereas the NW- and SW-quadrants to a greater or lesser extent are covered by oceans. The result is thus in accordance with what has been expected elsewhere (see for example GUTENBERG (7)). The positive values of ΔT in the NE-quadrant for $\Delta > 90^\circ$ may possibly be due to the fact that these waves have to some extent passed the Pacific Ocean. This deduction is however fairly uncertain. It is obvious that for a certain distance the difference in travel time (ΔT) corresponds to a difference in mean velocity (Δc) determined by the relation

$$\frac{\Delta c}{c} = -\frac{\Delta T}{T}.$$

The values of $\frac{\Delta c}{c}$ are given in Table 5. The weighted mean value of $\Delta c/c$ indicates a difference of 5 % in c between the NW- and NE-quadrants

Table 5.

Δ	ΔT NW—NE min.	$\frac{\Delta c}{c}$ NW—NE	ΔT NW—SE min.	$\frac{\Delta c}{c}$ NW—SE
25°	+0.5	−0.04	+1.3	−0.11
35	+2.3	−0.14	+1.2	−0.07
45	+3.1	−0.15	+2.4	−0.11
55	+1.6	−0.06	+0.8	−0.03
65	+1.1	−0.04	+3.7	−0.12
75	+1.3	−0 04	+4.5	−0.13
85	+2.0	−0.05	+1.6	−0.04
Mean		−0.05		−0.09

and 9 % between the NW- and SE-quadrants. The mean velocities of surface waves in the different quadrants are thus:

$$\begin{aligned} &\text{NW}: \; c \\ &\text{SW}: \; c \\ &\text{NE}: \; 0.95 \cdot c \\ &\text{SE}: \; 0.91 \cdot c. \end{aligned}$$

As the mean velocity for our L–O-curve is 4.023 km/sec, we can approximately calculate c by taking account of the number of observations in the different quadrants:

$$63 \times c + 18 \times c + 80 \times 0.95 \times c + 65 \times 0.91 \times c = 226 \times 4.023$$

giving $c = 4.21$ km/sec. The mean velocities are thus:

NW: 4.21 km/sec
SW: 4.21 »
NE : 4.00 »
SE : 3.83 »

STONELEY's velocity of 3.972 km/sec for L gives:

NW: 4.15 km/sec
SW: 4.15 »
NE : 3.95 »
SE : 3.78 » .

This is of course a very approximate determination.

The values given are mean values for each quadrant for $\Delta = 10^\circ$—90°. The velocity depends on the period, of course, so that the values given here may be regarded as mean values even with respect to the period of L. The velocity of L varies from point to point. A method suggests itself here to determine this variation by a method of addition. If R = the earth's radius, we have clearly

$$R \cdot d\Delta = c \cdot dt$$

or

$$dt = \frac{R \cdot d\Delta}{c}.$$

Integrated this gives the travel time of L

$$T = \int_0^T dt = R \int_0^\Delta \frac{d\Delta}{c} = R \sum_1^n \frac{\delta \Delta_n}{c_n},$$

where $\delta \Delta_n$ is a finite difference in Δ, within which $c = c_n$. Only a quadrant or smaller sector is considered. By first taking the nearest earthquakes (within $\delta\Delta_1$) we can calculate a mean value c_1 of c in $\delta\Delta_1$. By then passing to earthquakes within $\delta\Delta_2$ we already know the first term in the sum above and are able to calculate c_2, and so on step by step, taking due account of the period of L. It may then be valuable to compare the results with other stations. The difficulty is of course to get reliable readings of L, and it may be necessary to use a great number of earthquakes. It is outside the scope of this paper to carry out this idea.

Accuracy in the determination of distance.

If T = the time difference between two phases and H = the depth of the focus we have in the general case

$$T = T(\Delta, H),$$

which on differentiation and solving for $d\Delta$ gives

$$d\Delta = \frac{1}{\frac{\partial T}{\partial \Delta}} \cdot dT - \frac{\frac{\partial T}{\partial H}}{\frac{\partial T}{\partial \Delta}} \cdot dH.$$

For normal earthquakes H is assumed constant and the equation may be written

$$d\Delta = \left(\frac{d\Delta}{dT}\right) \cdot dT.$$

This relation expresses the evident facts that the error in the distance ($d\Delta$) is due partly to an error in travel-time difference (dT) and partly to the slope of the corresponding travel-time difference curve $\left(\frac{d\Delta}{dT}\right)$. In Table 6 the results are given for $S-P$, $PP-P$, $SS-S$, $L-S$, and $M-P$. dT has been put equal to σ. No σ has been calculated for $L-S$ and $M-P$, but

Table 6.

Δ	$S-P$		$PP-P$		$SS-S$		$L-S$		$M-P$	
	$d\Delta/dT$ o/s	$d\Delta$	$d\Delta/dT$ o/s	$d\Delta$	$d\Delta/dT$ o/s	$d\Delta$	$d\Delta/dT$ o/m	$d\Delta$	$d\Delta/dT$ o/m	$d\Delta$
20°	0.118	±0°.8			0.154	±1°.6	8.0	±17°.6	2.5	±8°.5
30	0.143	0 .9	0.250	±2°.1	0.143	1 .5	5.0	11 .0	2.4	8 .2
40	0.154	1 .0	0.286	2 .4	0.143	1 .5	4.4	9 .7	2.2	7 .5
50	0.154	1 .0	0.500	4 .3	0.222	2 .4	5.0	11 .0	2.2	7 .5
60	0.200	1 .3	0.400	3 .4	0.333	3 .6	4.0	8 .8	2.1	7 .1
70	0.182	1 .2	0.400	3 .4	0.400	4 .3	4.0	8 .8	2.2	7 .5
80	0.182	1 .2	0.333	2 .8	0.250	2 .7	3.6	7 .9	2.1	7 .1
90	0.200	1 .3	0.286	2 .4	0.200	2 .1	3.3	7 .3	2.0	6 .8
100	0.250	1 .6	0.333	2 .8	0.167	1 .8	3.1	6 .8	2.0	6 .8

as in these cases almost the whole error depends on errors in $L-O$ and $M-O$, dT has been taken as the sum of σ for $L-O$ and $S-O$, $M-O$ and $P-O$ respectively. We see from Table 6 that $S-P$ yields the most accurate determinations ($d\Delta \simeq \pm 1°$). On comparing $PP-P$ with $SS-S$ we find (except for $\Delta \simeq 60°—80°$) that $SS-S$ is more accurate than $PP-P$ in spite of a smaller time error in $PP-P$. This just depends on the greater slope $\left(\text{smaller } \frac{d\Delta}{dT}\right)$ of the $SS-S$-curve. The difference in accuracy is, however, fairly unimportant. A similar difference exists between $L-S$ and $M-P$. The errors in the distances calculated from $L-S$ and $M-P$ are very large, and they can be used only as a first orientation.

The depth of the focus of normal earthquakes is not always or everywhere the same. Travel times valid for some normal depth are thus liable to give wrong Δ-values, because the depth in individual cases may deviate from the adopted mean. An evaluation of the second term in the general formula for $d\Delta$ for $S-P$ for normal earthquakes using JEFFREYS' values in calculating $\frac{\partial T}{\partial H}$, gives the result that a deviation in H of 10 km gives a mean error of 0°.2 (0°.17) in Δ, 20 km gives 0°.3 (0°.34) and 30 km gives 0°.5 (0° 51) and so on. In most cases the second term is thus almost negligible in comparison with the first.

Multiple phases.

In Table 7 are summarized the cases with multiple P- and S-phases among the whole material used in this paper, δP being the time-difference

Table 7.

Epicenter	Δ	δP s	δS s	Epicenter	Δ	δP s	δS s
44½°N, 34½°E	18°.5	10		34½°N, 115 °E	64°.2	9	
38 N, 26¼ E	22 .6	14	12	53 N, 165½ W	67 .5	8	4
40 N, 35½ E	22 .8	7	14	45½ N, 151 E	68 .2		5
40 N, 37½ E	23 .3		5	18 N, 96½ E	69 .0	4	
40 N, 38 E	23 .5	8		12¾ N, 92¾ E	71 .6	7	
35½ N, 25½ E	24 .9	6	8	40½ N, 125¼ W	75 .2		9
35 N, 29½ E	26 .0	15		27½ N, 129½ E	76 .7		10
40½ N, 53½ E	29 .6		7	1½ S, 89½ E	82 .5	4	
52 N, 34½ W	29 .7		8	29 N, 113 W	82 .8	5	
32 N, 49½ E	34 .9		12	22¾ S, 32½ E	83 .7	4	
35¼ N, 58¼ E	36 .0	6	13	13½ N, 121 E	84 .9	6	
29 N, 56½ E	40 .7	7		14 N, 123 E	85 .4		15
49 N, 90 E	41 .3	4		9¾ N, 84½ W	87 .5		4
18 N, 37½ E	44 .4		11	16¾ N, 98½ W	87 .9	5	
36 N, 84 E	47 .9		10	12½ N, 125½ E	88 .0	4	
28½ N, 83½ E	53 .9		4	9 N, 122½ E	89 .6		6
64¾ N, 146½ W	56 .1		8	¾ S, 81½ W	95 .4	5	
56 N, 162½ E	61 .1	11		1 S, 120 E	96 .9	10	
55¼ N, 168 E	62 .8		9	10½ S, 77 W	101 .4		14

for P and δS for S. The only way in which multiple phases may be inferred is in individual records. There was nothing like multiplicity in the travel time graphs, but only the normal scatter of points about the mean curve. As the cases in Table 7 are few, numbering 22 for P and 21 for S, no far-reaching conclusions may be drawn. The mean time-difference is 7.2 sec for P and 9.0 sec for S. Table 7 shows that multiplicity occurs for all distances for which P and S are recorded, and may be encountered for any earthquake locality. There seems to be some variation of the time-difference with distance. This is most clearly pronounced for P, which shows a clear decrease of time-difference as distance increases. For S the variation is not so simple. But there seems to be no other regularity in the geographical distribution of the time-differences. For further particulars see GUTENBERG and RICHTER (2).

The period of the maximum phase.

Though it is really outside the scope of this paper, a determination of the variation with distance of the period in the maximum phase was made in connection with the present work. It is a well-known fact that this period varies with distance, and the aim was to see what this variation looks like. The period used is the period of the first maximum (M above). The result is given in Fig. 2, where the straight lines connect points representing the mean period for every five degrees and the dashed line is a mean curve. 296 observations were used in all. The curve is fairly certain up to 90°. The slight decrease up to about 45° may perhaps be replaced by a horizontal line. The striking feature in the variation of the period is the approximate constancy up to 45° ($T = 13$—14 sec), the rapid increase between 45° and 65° (from 13 sec to 20 sec) and the less rapid

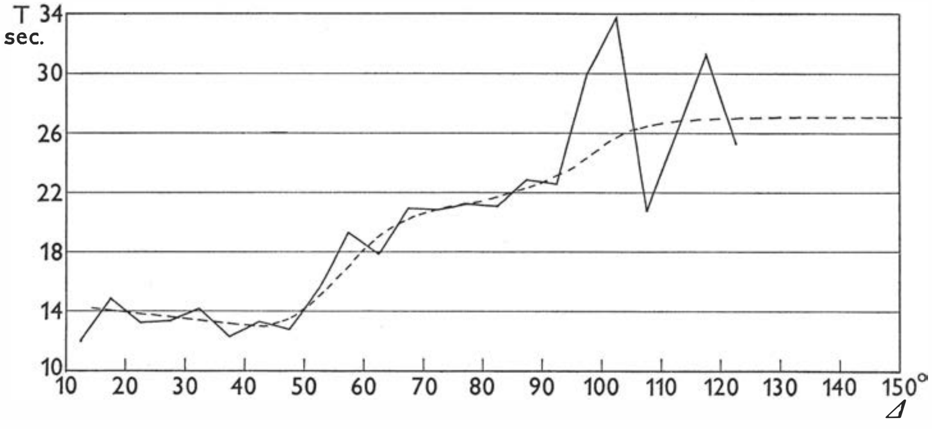

Fig. 2.

increase between 65° and 90° (from 20 sec to 23 sec). Above 90° the observations are comparatively few, and the curve is not so reliable.

It is a well-known fact among seismologists that the period varies during the maximum phase and is generally decreasing. Out of 276 cases, where several maxima were given, 60.5 % showed a decrease, 24.3 % an increase, and the rest 15.2 % an unchanged period in the course of the maximum phase. The increase is observed almost exclusively for the shortest periods.

Summary.

1. Travel times of P, S, PP, SS, L, and M have been deduced from the records of the WIECHERT horizontal seismograph at Uppsala.

2. Comparison has been made between the Uppsala times and those of JEFFREYS-BULLEN and GUTENBERG-RICHTER, showing that the discrepancies may in many cases be explained as an effect of the depth of the focus. The mean depth calculated from this is 17 km.

3. Standard deviations of single observations as well as standard errors of the various curves have been calculated.

4. A comparison of the travel times of the four quadrants from Uppsala showed no reliable difference for the bodily waves but a striking difference for $L-O$, indicating greatest velocity in the NW- and SW-quadrants and smallest velocity in the NE- and SE-quadrants. The mean velocities of L up to 90° are approximately calculated.

5. A method is suggested for a more detailed study of the velocity of surface waves.

6 The accuracy in the determination of distance from $S-P$, $PP-P$, $SS-S$, $L-S$, and $M-P$ is calculated.

7. Multiple P- and S-phases are briefly summarized and some properties deduced.

8. The variation with distance of the period of the first maximum is constructed.

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Table 1.

Δ	P–O		S–O		PP–O		SS–O		S–P		PP–P		SS–S		L–O	M–O	L–S	M–P	M–L
	m	s	m	s	m	s	m	s	m	s	m	s	m	s	m	m	m	m	m
10°	2	23	4	42					2	19					5.2	6.2	0.5	3.8	1.0
11	2	38	5	05					2	27					5.7	6.8	0.6	4.2	1.1
12	2	52	5	28					2	36					6.1	7.4	0.6	4.5	1.2
13	3	06	5	51					2	45					6.6	7.9	0.7	4.8	1.4
14	3	20	6	13					2	53					7.0	8.5	0.8	5.2	1.5
15	3	33	6	34					3	01					7.5	9.1	0.9	5.5	1.6
16	3	46	6	55			6	58	3	09			0	03	8.0	9.7	1.0	5.9	1.7
17	3	59	7	16			7	24	3	17			0	08	8.4	10.2	1.1	6.2	1.8
18	4	11	7	37			7	50	3	26			0	13	8.9	10.8	1.3	6.6	1.9
19	4	22	7	57			8	16	3	35			0	19	9.3	11.4	1.4	7.0	2.1
20	4	33	8	17			8	42	3	44			0	25	9.8	12.0	1.5	7.4	2.2
21	4	44	8	36			9	08	3	52			0	32	10.3	12.5	1.6	7.8	2.3
22	4	54	8	54			9	33	4	00			0	39	10.7	13.1	1.8	8.2	2.4
23	5	04	9	12			9	58	4	08			0	46	11.2	13.7	2.0	8.6	2.5
24	5	14	9	30	5	44	10	22	4	16	0	30	0	52	11.6	14.3	2.1	9.0	2.6
25	5	24	9	48	5	57	10	47	4	24	0	33	0	59	12.1	14.8	2.3	9.4	2.7
26	5	33	10	05	6	10	11	11	4	32	0	37	1	06	12.6	15.4	2.5	9.9	2.9
27	5	43	10	22	6	23	11	35	4	39	0	40	1	13	13.0	16.0	2.6	10.3	3.0
28	5	53	10	38	6	37	11	58	4	45	0	44	1	20	13.5	16.6	2.8	10.7	3.1
29	6	02	10	54	6	50	12	21	4	52	0	48	1	27	13.9	17.1	3.0	11.1	3.2
30	6	11	11	10	7	03	12	44	4	59	0	52	1	34	14.4	17.7	3.2	11.5	3.3
31	6	19	11	25	7	15	13	06	5	06	0	56	1	41	14.9	18.3	3.4	12.0	3.4
32	6	28	11	40	7	27	13	29	5	12	0	59	1	49	15.3	18.9	3.6	12.4	3.5
33	6	37	11	55	7	39	13	52	5	18	1	02	1	57	15.8	19.4	3.8	12.8	3.7
34	6	45	12	10	7	51	14	14	5	25	1	06	2	04	16.2	20.0	4.1	13.3	3.8
35	6	53	12	25	8	03	14	36	5	32	1	10	2	11	16.7	20.6	4.3	13.7	3.9
36	7	01	12	40	8	15	14	58	5	39	1	14	2	18	17.2	21.2	4.5	14.1	4.0
37	7	09	12	54	8	27	15	19	5	45	1	18	2	25	17.6	21.7	4.7	14.6	4.1
38	7	17	13	08	8	38	15	41	5	51	1	21	2	33	18.1	22.3	4.9	15.0	4.2
39	7	25	13	23	8	50	16	03	5	58	1	25	2	40	18.5	22.9	5.1	15.5	4.4
40	7	33	13	38	9	02	16	25	6	05	1	29	2	47	19.0	23.5	5.4	15.9	4.5

Table 1 (cont.).

Δ	P—O m	P—O s	S—O m	S—O s	PP—O m	PP—O s	SS—O m	SS—O s	S—P m	S—P s	PP—P m	PP—P s	SS—S m	SS—S s	L—O m	M—O m	L—S m	M—P m	M—L m
41°	7	41	13	52	9	13	16	46	6	11	1	32	2	54	19.5	24.0	5.6	16.3	4.6
42	7	50	14	07	9	25	17	07	6	17	1	35	3	00	19.9	24.6	5.8	16.8	4.7
43	7	58	14	22	9	36	17	28	6	24	1	38	3	06	20.4	25.2	6.0	17.2	4.8
44	8	07	14	37	9	48	17	49	6	30	1	41	3	12	20.8	25.8	6.2	17.6	4.9
45	8	16	14	52	9	59	18	10	6	36	1	43	3	18	21.3	26.3	6.4	18.1	5.0
46	8	24	15	07	10	09	18	30	6	43	1	45	3	23	21.8	26.9	6.6	18.5	5.1
47	8	33	15	22	10	20	18	50	6	49	1	47	3	28	22.2	27.5	6.9	18.9	5.3
48	8	41	15	37	10	30	19	10	6	56	1	49	3	33	22.7	28.1	7.1	19.4	5.4
49	8	49	15	52	10	40	19	29	7	03	1	51	3	37	23.1	28.6	7.3	19.8	5.5
50	8	57	16	07	10	50	19	48	7	10	1	53	3	41	23.6	29.2	7.5	20.3	5.6
51	9	05	16	21	11	00	20	07	7	16	1	55	3	46	24.1	29.8	7.7	20.7	5.7
52	9	12	16	35	11	09	20	25	7	23	1	57	3	50	24.5	30.4	7.9	21.2	5.8
53	9	19	16	49	11	18	20	43	7	30	1	59	3	54	25.0	30.9	8.2	21.6	5.9
54	9	26	17	03	11	27	21	00	7	37	2	01	3	57	25.4	31.5	8.4	22.1	6.1
55	9	32	17	16	11	35	21	16	7	44	2	03	4	00	25.9	32.1	8.6	22.6	6.2
56	9	39	17	29	11	44	21	33	7	50	2	05	4	04	26.4	32.7	8.9	23.0	6.3
57	9	46	17	42	11	53	21	50	7	56	2	07	4	08	26.8	33.2	9.1	23.5	6.4
58	9	53	17	54	12	02	22	06	8	01	2	09	4	12	27.3	33.8	9.4	23.9	6.5
59	9	59	18	06	12	11	22	22	8	07	2	12	4	16	27.8	34.4	9.7	24.4	6.6
60	10	06	18	18	12	21	22	37	8	12	2	15	4	19	28.2	35.0	9.9	24.9	6.7
61	10	13	18	30	12	30	22	52	8	17	2	17	4	22	28.7	35.5	10.2	25.3	6.9
62	10	20	18	42	12	39	23	08	8	22	2	19	4	26	29.1	36.1	10.4	25.8	7.0
63	10	27	18	55	12	48	23	23	8	28	2	21	4	28	29.6	36.7	10.7	26.2	7.1
64	10	34	19	08	12	57	23	37	8	34	2	23	4	29	30.1	37.3	10.9	26.7	7.2
65	10	41	19	20	13	07	23	50	8	39	2	26	4	30	30.5	37.8	11.2	27.1	7.3
66	10	47	19	32	13	16	24	04	8	45	2	29	4	32	31.0	38.4	11.5	27.6	7.4
67	10	54	19	44	13	25	24	18	8	50	2	31	4	34	31.4	39.0	11.7	28.1	7.5
68	11	00	19	56	13	34	24	32	8	56	2	34	4	36	31.9	39.6	12.0	28.6	7.7
69	11	07	20	08	13	43	24	46	9	01	2	36	4	38	32.4	40.1	12.2	29.0	7.8
70	11	13	20	20	13	52	25	00	9	07	2	39	4	40	32.8	40.7	12.5	29.5	7.9
71	11	20	20	32	14	01	25	15	9	12	2	41	4	43	33.3	41.3	12.8	30.0	8.0
72	11	27	20	44	14	10	25	29	9	17	2	43	4	45	33.7	41.9	13.0	30.4	8.1
73	11	33	20	56	14	18	25	44	9	23	2	45	4	48	34.2	42.4	13.3	30.9	8.2
74	11	39	21	07	14	27	25	58	9	28	2	48	4	51	34.7	43.0	13.5	31.4	8.3
75	11	45	21	18	14	36	26	12	9	33	2	51	4	54	35.1	43.6	13.8	31.8	8.5

76	11 51	21 29	14 45	26 26	9 38	2 54	4 57	35.6	44.2	14.1	32.3	8.6
77	11 57	21 40	14 53	26 41	9 43	2 56	5 01	36.1	44.7	14.4	32.8	8.7
78	12 02	21 51	15 01	26 56	9 49	2 59	5 05	36.5	45.3	14.7	33.3	8.8
79	12 08	22 02	15 10	27 11	9 54	3 02	5 09	37.0	45.9	15.0	33.8	8.9
80	12 13	22 12	15 18	27 25	9 59	3 05	5 13	37.4	46.5	15.2	34.2	9.0
81	12 18	22 23	15 26	27 40	10 05	3 08	5 17	37.9	47.0	15.5	34.7	9.1
82	12 23	22 33	15 34	27 55	10 10	3 11	5 22	38.4	47.6	15.8	35.2	9.3
83	12 28	22 43	15 42	28 10	10 14	3 14	5 27	38.8	48.2	16.1	35.7	9.4
84	12 33	22 52	15 50	28 24	10 19	3 17	5 32	39.3	48.8	16.4	36.2	9.5
85	12 37	23 01	15 58	28 38	10 24	3 21	5 37	39.7	49.3	16.7	36.7	9.6
86	12 42	23 11	16 06	28 53	10 29	3 24	5 42	40.2	49.9	17.0	37.2	9.7
87	12 47	23 21	16 14	29 08	10 34	3 27	5 47	40.7	50.5	17.3	37.7	9.8
88	12 51	23 30	16 21	29 22	10 39	3 30	5 52	41.1	51.1	17.6	38.2	9.9
89	12 56	23 40	16 29	29 36	10 44	3 33	5 56	41.6	51.6	17.9	38.7	10.0
90	13 00	23 49	16 37	29 50	10 49	3 37	6 01	42.0	52.2	18.2	39.2	10.2
91	13 04	23 58	16 44	30 04	10 54	3 40	6 06	42.5	52.8	18.5	39.7	10.3
92	13 09	24 07	16 52	30 18	10 58	3 43	6 11	43.0	53.4	18.8	40.2	10.4
93	13 13	24 16	17 00	30 32	11 03	3 47	6 16	43.4	53.9	19.1	40.7	10.5
94	13 18	24 25	17 08	30 47	11 07	3 50	6 22	43.9	54.5	19.5	41.2	10.6
95	13 22	24 34	17 15	31 01	11 12	3 53	6 27	44.4	55.1	19.8	41.7	10.7
96	13 27	24 43	17 23	31 15	11 16	3 56	6 32	44.8	55.7	20.1	42.2	10.8
97	13 31	24 52	17 31	31 29	11 21	4 00	6 37	45.3	56.2	20.4	42.7	11.0
98	13 35	25 00	17 38	31 43	11 25	4 03	6 43	45.7	56.8	20.7	43.2	11.1
99	13 39	25 09	17 45	31 57	11 30	4 06	6 48	46.2	57.4	21.0	43.7	11.2
100	13 43	25 17	17 52	32 11	11 34	4 09	6 54	46.7	58.0	21.4	44.2	11.3
101	13 48	25 26	18 00	32 26	11 38	4 12	7 00	47.1	58.5	21.7	44.7	11.4
102	13 52	25 34	18 07	32 40	11 42	4 15	7 06	47.6	59.1	22.0	45.2	11.6
103	13 57	25 43	18 15	32 54	11 46	4 18	7 11	48.0	59.7	22.3	45.7	11.7
104	14 01	25 51	18 22	33 08	11 50	4 21	7 17	48.5	60.3	22.6	46.2	11.8
105	14 05	25 59	18 29	33 22	11 54	4 24	7 23	48.9	60.8	23.0	46.7	11.9
106	14 09		18 37	33 37		4 28		49.4	61.4		47.2	12.0
107	14 13		18 44	33 51		4 31		49.9	62.0		47.8	12.1
108	14 17		18 51	34 05		4 34		50.3	62.6		48.3	12.2
109	14 21		18 58	34 19		4 37		50.8	63.1		48.8	12.3
110	14 25		19 05	34 33		4 40		51.2	63.7		49.3	12.5
111			19 12	34 47				51.7	64.3			12.6
112			19 19	35 01				52.2	64.9			12.7
113			19 26	35 15				52.6	65.4			12.8
114			19 33	35 29				53.1	66.0			12.9
115			19 39	35 42				53.6	66.6			13.0

Table 1 (cont.).

Δ	$P-O$	$S-O$	$PP-O$	$SS-O$	$S-P$	$PP-P$	$SS-S$	$L-O$	$M-O$	$L-S$	$M-P$	$M-L$
	m s	m s	m s	m s	m s	m s	m s	m	m	m	m	m
116°			19 46	35 56				54.0	67.2			13.1
117			19 53	36 10				54.5	67.7			13.3
118			19 59	36 23				54.9	68.3			13.4
119			20 06	36 37				55.4	68.9			13.5
120			20 13	36 50				55.9	69.5			13.6
121			20 20	37 03				56.3	70.0			13.7
122			20 26	37 16				56.8	70.6			13.8
123			20 33	37 29				57.2	71.2			14.0
124			20 40	37 42				57.7	71.8			14.1
125			20 46	37 55				58.2	72.3			14.2
126			20 53	38 08				58.6	72.9			14.3
127			21 00	38 21				59.1	73.5			14.4
128			21 06	38 34				59.5	74.1			14.5
129			21 13	38 47				60.0	74.6			14.6
130			21 19	38 59				60.5	75.2			14.7
131			21 26	39 12				60.9	75.8			14.9
132			21 32	39 24				61.4	76.4			15.0
133			21 38	39 36				61.8	76.9			15.1
134			21 44	39 48				62.3	77.5			15.2
135			21 50	40 00				62.8	78.1			15.3
136			21 56	40 12				63.2	78.7			15.4
137			22 03	40 24				63.7	79.2			15.5
138			22 09	40 36				64.2	79.8			15.7
139			22 16	40 48				64.6	80.4			15.8
140			22 22	40 59				65.1	81.0			15.9
141			22 28	41 10				65.5	81.5			16.0
142			22 34	41 22				66.0	82.1			16.1
143			22 40	41 33				66.5	82.7			16.2
144			22 46	41 45				66.9	83.3			16.3
145			22 53	41 56				67.4	83.8			16.4
146			22 59	42 07				67.8	84.4			16.6
147			23 05	42 18				68.3	85.0			16.7
148			23 11	42 29				68.8	85.6			16.8
149			23 17	42 40				69.2	86.1			16.9
150			23 23	42 51				69.7	86.7			17.0

151			23 29	43 02				70.1	87.3			17.1
152			23 35	43 13				70.6	87.9			17.3
153			23 41	43 24				71.1	88.4			17.4
154			23 47	43 35				71.5	89.0			17.5
155			23 53	43 45				72.0	89.6			17.6
156			23 59	43 55				72.5	90.2			17.7
157			24 05	44 05				72.9	90.7			17.8
158			24 11	44 15				73.4	91.3			17.9
159			24 17	44 25				73.8	91.9			18.1
160			24 23	44 35				74.3	92.5			18.2
161								74.8	93.0			18.3
162								75.2	93.6			18.4
163								75.7	94.2			18.5
164								76.1	94.8			18.6
165								76.6	95.3			18.8
166								77.0	95.9			18.9
167								77.5	96.5			19.0
168								78.0	97.1			19.1
169								78.4	97.6			19.2
170								78.9	98.2			19.3
171								79.3	98.8			19.5
172								79.8	99.4			19.6
173								80.3	99.9			19.7
174								80.7	100.5			19.8
175								81.2	101.1			19.9
176								81.6	101.7			20.0
177								82.1	102.2			20.1
178								82.6	102.8			20.3
179								83.0	103.4			20.4
180								83.5	104.0			20.5

Table 4.

Δ	NE			SE			SW			NW			n	$\overline{\Delta T}$
	n	ΔT-range	$\overline{\Delta T}$	n	ΔT-range	$\overline{\Delta T}$	n	ΔT-range	$\overline{\Delta T}$	n	ΔT-range	$\overline{\Delta T}$		
		s	s		s	s		s	s		s	s		s
P—O														
10°.0— 20°.0	0			3	− 3 to + 9	+4	0			13	− 8 to + 5	−1	16	±0
20 .1— 30 .0	1		±0	29	−10 +12	−1	2	−2 to +2	−2	3	−10 + 7	−3	35	±0
30 .1— 40 .0	1		+4	15	− 3 +11	+1	2	+1 +2	+2	2	− 2 + 6	+2	20	+1
40 .1— 50 .0	7	− 5 to + 4	−1	16	−10 +12	+1	1		−1	1		+4	25	±0
50 .1— 60 .0	8	− 4 + 6	+2	6	− 8 + 8	±0	4	−5 +5	±0	3	− 2 +10	+5	21	+1
60 .1— 70 .0	28	−10 + 9	+1	4	− 3 +10	+3	9	−4 +8	±0	10	− 8 + 8	−2	51	±0
70 .1— 80 .0	28	− 9 +13	+2	9	− 6 + 7	+2	1		−4	13	−11 + 7	−1	51	+1
80 .1— 90 .0	9	− 9 + 9	±0	8	− 1 +13	+5	0			21	−10 + 8	±0	38	+1
90 .1—100 .0	12	−10 +11	+1	3	0 + 4	+2	0			1		−1	16	+1
100 .1—110 .0	2	− 6 + 6	±0	0			2	−4 −1	−2	0			4	−1
n	96		+1	93		+1	21		±0	67		−1	277	(+0.5)
S—O														
10°.0— 20°.0	0			2	+24 to +26	+25	0			10	−14 to + 5	− 4	12	+1
20 .1— 30 .0	0			29	−18 +21	− 4	2	−1 to +1	±0	3	−20 +21	− 1	34	−3
30 .1— 40 .0	1		+ 7	15	− 7 +23	+ 4	2	+8 +9	+9	2	+ 2 + 6	+ 4	20	+5
40 .1— 50 .0	7	− 3 to + 6	± 0	14	−13 + 8	± 0	1		−4	1		+13	23	±0
50 .1— 60 .0	10	− 5 +17	+ 4	6	− 5 +19	+ 3	4	−5 +2	−2	2	+ 3 +13	+ 8	22	+3
60 .1— 70 .0	26	−20 +13	± 0	4	− 8 +17	+ 3	9	−9 +4	−2	10	−12 +11	− 3	49	−1
70 .1— 80 .0	29	− 9 +11	+ 2	10	− 6 +14	+ 4	1		−5	15	−17 + 4	− 5	55	±0
80 .1— 90 .0	11	− 8 +21	+ 5	7	− 7 + 9	± 0	0			22	−21 +15	− 4	40	−1
90 .1—100 .0	7	−14 +16	+ 1	2	+ 6 +12	+ 9	0			0			9	+2
100 .1—110 .0	0			0			1		−2	0			1	−2
n	91		+ 2	89		+ 1	20		−1	65		− 3	265	±0

S–P														
10°.0– 20°.0	0			2	+15 to +19	+17	0			11	−17 to +5	−3	13	±0
20 .1– 30 .0	0			29	−17 +15	−3	2	+1 to +3	+2	3	−10 +14	+1	34	−2
30 .1– 40 .0	1		+3	13	−15 +14	+1	2	+7 +7	+7	2	±0 +4	+2	18	+2
40 .1– 50 .0	7	−4 to +6	+1	14	−12 +8	±0	1		−3	1		+8	23	±0
50 .1– 60 .0	9	−4 +7	+1	5	−5 +10	+4	4	−5 +4	−1	3	−1 +6	+3	21	+1
60 .1– 70 .0	25	−21 +7	−1	4	−5 +7	±0	9	−7 +3	−2	9	−6 +12	−1	47	−1
70 .1– 80 .0	27	−9 +11	±0	9	−6 +7	+1	1		−1	14	−16 +11	−2	51	±0
80 .1– 90 .0	9	−4 +12	+4	7	−11 +9	−3	0			21	−15 +15	−1	37	±0
90 .1–100 .0	7	−13 +8	−1	2	+2 +2	+2	0			0			9	±0
100 .1–110 .0	0			0			1		+2	0			1	+2
n	85		±0	85		±0	20		±0	64		−1	254	±0
PP–O														
10°.0– 30°.0	0			3	−3 to +8	+1	0			0			3	+1
30 .1– 50 .0	4	−10 to −2	−5	19	−12 +16	−1	1		+6	2	+4 to +25	+15	26	±0
50 .1– 70 .0	8	−19 +7	−5	3	−10 +30	+10	0			0			11	−1
70 .1– 90 .0	13	−16 +16	+2	3	−11 +5	−4	2	−10 to +10	±0	16	−22 +30	+1	34	+1
90 .1–110 .0	13	−22 +22	−2	4	−3 +19	+5	2	−6 +8	+1	0			19	±0
110 .1–130 .0	5	−10 +6	±0	0			1		+2	0			6	±0
130 .1–150 .0	2	−1 +1	±0	0			0			0			2	±0
150 .1–170 .0	2	±0 +5	+3	0			0			0			2	+3
n	47		−1	32		+1	6		+2	18		+3	103	±0
PP–P														
10°.0– 30°.0	0			3	−6 to +12	+1	0			0			3	+1
30 .1– 50 .0	4	−6 to −1	−3	19	−11 +11	−2	1		+5	2	+6 to +19	+13	26	−1
50 .1– 70 .0	8	−18 +6	−5	3	−11 +28	+6	0			0			11	−2
70 .1– 90 .0	13	−21 +11	−1	3	−10 +1	−5	1		−6	16	−16 +29	+3	33	±0
90 .1–110 .0	10	−7 +20	+2	3	−1 +9	+4	2	−2 to +9	+4	0			15	+3
n	35		−1	31		−1	4		+2	18		+4	88	±0

Table 4 (cont.).

Δ	NE			SE			SW			NW			n	$\overline{\Delta T}$
	n	ΔT-range	$\overline{\Delta T}$	n	ΔT-range	$\overline{\Delta T}$	n	ΔT-range	$\overline{\Delta T}$	n	ΔT-range	$\overline{\Delta T}$		
		s	s		s	s		s	s		s	s		s
SS—O														
10°.0— 30°.0	0			3	− 6 to + 4	± 0	0			0			3	±0
30 .1— 50 .0	2	+ 6 to + 6	+ 6	12	−33 +23	− 1	1		+30	0			15	+2
50 .1— 70 .0	17	−35 +20	−10	4	+ 6 +24	+17	2	+19 to +24	+22	5	− 5 to +12	+5	28	−1
70 .1— 90 .0	17	−33 +29	± 0	6	−16 + 9	− 2	1		+ 3	19	−26 +35	−4	43	−2
90 .1—110 .0	9	−40 +52	− 2	2	− 6 +13	+ 3	2	−12 +28	+ 8	0			13	±0
110 .1—130 .0	5	− 7 +19	+ 2	0			1		− 4	0			6	+1
130 .1—150 .0	1		+ 6	0			0			0			1	+6
150 .1—170 .0	1		− 2	0			0			0			1	−2
n	52		− 3	27		+ 2	7		(+13)	24		−2	110	(−0.6)
SS—S														
10°.0— 30°.0	0			3	± 0 to + 8	+ 2	0			0			3	+2
30 .1— 50 .0	2	± 0 to + 5	+ 3	11	−11 + 8	− 2	1		+21	1		+4	15	+1
50 .1— 70 .0	15	−23 +14	− 8	4	+ 4 +28	+14	2	+18 to +24	+21	5	− 8 to + 7	−1	26	−1
70 .1— 90 .0	15	−15 +21	+ 2	6	− 6 +11	− 1	1		+ 8	13	−18 +14	−3	35	±0
90 .1—110 .0	0			0			0			0			0	
n	32		− 3	24		+ 1	4		(+18)	19		−2	79	±0

Table 4 (cont.).

Δ	NE			SE			SW			NW			n	$\overline{\Delta T}$
	n	ΔT-range	$\overline{\Delta T}$	n	ΔT-range	$\overline{\Delta T}$	n	ΔT-range	$\overline{\Delta T}$	n	ΔT-range	$\overline{\Delta T}$		
		m	m		m	m		m	m		m	m		m
L—O														
10°.0—20°.0	0			2	−0.1 to +0.9	+0.4	0			9	−0.7 to +0.6	−0.2	11	−0.1
20 .1—30 .0	1		−0.2	18	−3.1 +0.8	−1.0	2	−0.9 to −0.2	−0.6	2	−0.1 +0.7	+0.3	23	−0.8
30 .1—40 .0	1		−2.2	11	−4.2 +2.6	−1.1	2	+0.6 +0.7	+0.7	2	−0.4 +0.7	+0.1	16	−0.9
40 .1—50 .0	4	−2.6 to +0.1	−1.4	8	−1.7 +2.6	−0.7	0			1		+1.7	13	−0.7
50 .1—60 .0	8	−3.4 +0.4	−1.2	6	−1.8 +1.5	−0.4	4	−0.5 +2.7	+0.5	3	−1.2 +2.4	+0.4	21	−0.4
60 .1—70 .0	27	−3.5 +2.8	−0.2	4	−5.4 −0.3	−2.8	9	−3.0 +3.5	+1.4	9	−2.8 +4.2	+0.9	49	+0.1
70 .1—80 .0	28	−4.2 +2.6	−0.1	10	−5.8 +1.6	−3.3	1		−0.5	13	−3.1 +4.9	+1.2	52	−0.4
80 .1—90 .0	11	−6.2 +2.7	−1.0	6	−2.4 +1.8	−0.6	0			24	−4.4 +5.6	+1.0	41	+0.2
90 .1—100 .0	13	+0.1 +6.4	+2.5	5	−1.3 +4.1	+1.1	0			1		+0.8	19	
100 .1—110 .0	7	−1.3 +7.8	+4.2	0			1		+4.2	0			8	
110 .1—120 .0	4	+1.8 +5.1	+3.2	0			0			0			4	
120 .1—130 .0	2	+3.0 +3.3	+3.2	0			1		+4.1	0			3	
130 .1—140 .0	1		+1.1	0			0			0			1	
140 .1—150 .0	1		+5.4	0			0			0			1	
150 .1—160 .0	2	+4.6 +9.6	+7.1	0			0			0			2	
n (10°—90°)	80		−0.5	65		−1.3	18		+0.8	63		+0.8	226	−0.3
n (total)	110			70			20			64			264	