

## THE TIMES OF P AND S IN NORTHEASTERN AMERICA

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For a study of Lg, the wave discovered by Press and Ewing (1952), the records of some North American earthquakes were used. In the course of this study it became clear that it was essential for the understanding of the nature of the Lg waves to know at what depth the earthquakes in which they were recorded originated, especially whether their foci were above or below the Mohorovicic discontinuity.

One of the shocks was the Helena shock of October 31, 1935 which is considered to be shallow. But the opinions vary as to one of the others, the strong Timiskaming earthquake of November 1, 1935. It was, therefore, attempted to redetermine the epicentre and depth of this earthquake. The tables of Jeffreys and Bullen, (J.-B.) (1940) were used, but it was soon found that there was a systematic deviation from them. For distances up to about  $13^\circ$ , where all the stations except one were contained within a sector of  $120^\circ$ , the slope of the *P* time-curve was smaller than that of any J.-B. curve that would conform to the observations at great distances.

This as a matter of fact could not cause surprise, for in later years velocities of *P* waves greater than those corresponding to the J.-B. tables have repeatedly been found for the layer immediately below the Mohorovicic discontinuity. Well observed blasts and rockbursts have furnished data that are much more accurate than those obtainable from earthquakes.

For Europe the observations of the Burton on Trent explosion of 1944 indicated that the times of Pn at small distances were about 4 sec. smaller than those of the J.-B. tables (Jeffreys 1947), and those of an explosion in Danish waters gave a similar result (Lehmann 1948). Consequently the *P* velocity below the Mohorovicic discontinuity would be greater than that found by Jeffreys and Bullen which is 7.75 km./sec. The Heligoland explosion of 1947, so well timed and recorded by numerous stations, field stations as well as permanent ones, out to a distance of 998 km., yielded the velocity 8.18 km./sec. (Willmore 1949). [8.18 is the reciprocal of the slope of the time curve.

Some of the other velocities quoted were determined in the same way, whereas others were obtained by multiplication of the reciprocal of the slope by the ratio of the radii to the Mohorovicic discontinuity and the surface of the Earth. It makes a difference of 0.04]. Schulze and Förtsch (1950) who also studied the observations came to a similar result. Also the Haslach explosions in Southern Germany were very well recorded; many field stations were set up. A careful study of the observations was made by Rothé and Peterschmitt (1950) who for the Pn velocity found 8.15 km./sec. There were, however, only 5 observations of this wave, the most distant one at 210.20 km. Reich, Schulze and Förtsch (1948) found the velocity 8.2 km./sec. from the same observations.

In South Africa the velocity 8.27 km./sec. was found for Pn at distances up to 500 km. from seismograms of numerous earth tremors in the Witwatersrand gold-mining area (Willmore et Al. 1952). From rockbursts in Canada the velocity 8.17 km./sec. was found (Hodgson 1953). In Southern California some atomic and other explosions were recorded. B. Gutenberg sums up the results obtained for the velocities (1952). For Pn 8.2 km./sec. is found. Extensive work on these lines was done by Tatel, Adams and Tuve, Carnegie Institution of Washington (1953). They find a velocity of 8.1 km./sec. or slightly less at the top of the mantle. For a summary of explosion results see Reinhardt, 1954, pp. 28-38.

Various values had been found for the velocity of Pn from earthquake investigations, some of them smaller others greater than those derived from explosion records (See e.g. Leet, 1941, p. 326 and p. 334). For Southern California Gutenberg found 8.06 km./sec. (Gutenberg 1943, 1944), but for the layers above the Mohorovicic discontinuity velocities had been found that disagreed more seriously with those obtained from explosions. Gutenberg, therefore, undertook a revision of his results for earthquakes and was able to interpret his data so as to obtain agreement with explosion results (Gutenberg 1951). The Pn velocity was corrected to 8.15 km./sec. For small distances the slope of the J.-B. Pn curve is 14.28 sec./degree corresponding to the velocity 7.75 km./sec. below the Mohorovicic discontinuity (Jeffreys 1939). The disagreement with explosion results caused Jeffreys to revise his findings (Jeffreys 1952). He arrived at the result that for European earthquakes the slope of the *P* curve needed a correction up to 8° and, in order to make it join on to the subsequent part of the curve, also a change of height. There was no strong indication

of the need for further corrections. When the corrections were applied it was found that up to  $15^\circ$  the Pn curve could be taken to be a straight line having the equation  $t(\text{Pn})=10^{\text{s}}.4 + \Delta^\circ \times 13.70$  sec./degree. The corresponding velocity is 8.07 km./sec. The constant term of the equation is not the actual time of intercept of the Pn curve, but has been so determined as to make the straight line join on to the J.-B. curve for greater distances without altering the height of this curve. Jeffreys finds that for Japanese earthquakes the tables need no alteration up to  $20^\circ$ , but the need for a reduction of about 2 sec. between  $20^\circ$  and  $40^\circ$  is indicated. For North America the evidence is conflicting. The earthquakes used for North America are all from the western part, having their epicentres off California, Oregon, Mexico and in Nevada. There are not many observations at the shortest distances. As we have seen, explosion records yield higher velocities for Pn also in these regions.

As to eastern North America there are not many earthquakes strong enough and sufficiently well recorded to be useful for the determination of the velocity of Pn. In the index catalogues of the epicentres contained in the International Seismological Summary I find 32 earthquakes from the years 1925 to 1942, and of these only 8 have enough *P* observations to come into consideration. Several of them are under the suspicion of having had their foci below normal because the macroseismic areas are large relative to the intensity in the epicentral region. For the I.S.S. all except one have been taken to be normal.

Two strong earthquakes, the Grand Banks earthquake of 1929 and the Texas earthquake of 1931, were left unconsidered because they had few observations at small distances; they are at the outskirts of, or may even be said to be outside the region in question. Two of the earthquakes originally selected were quite small and they yielded results differing markedly from those derived from the others; they were therefore neglected. The earthquakes retained are those listed on the following page.

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The *P* trial times used were: For distances up to  $12^\circ$  the times determined by the linear expression  $7^{\text{s}}.37 + \Delta^\circ \times 13.58$  sec./degree found by Willmore for the Heligoland explosion, and for greater distances the J.-B. times for a surface focus with a correction applied to its height so as to make it join on to the straight line.

No.	Date	Epicentre	Depth (km.)	Source
1	1925 Mar. 1	48.2N 70.8W	65	I.S.S.
2	1935 Nov. 1	46.8N 79.1W	60	G. and R.
3	1937 Mar. 9	40.4N 84.2W		I.S.S.
4	1939 Oct. 19	47.8N 70.0W	40	G. and R.
5a	1940 Dec. 20	43.8N 71.3W		I.S.S.
5b	» » 24	» »		»

[G. and R. stands for Gutenberg and Richter: Seismicity of the Earth (1949)].

First the observations for distances smaller than  $12^\circ$  were compared with the lower section of the trial time curve, the straight line, and corrections to the slope were found for each earthquake separately by the method of least squares. The results obtained were:

Number	Correction	Mean error
1	0.15	$\pm 0.12$
2	-0.10	$\pm 0.06$
3	-0.03	$\pm 0.27$
4	-0.11	$\pm 0.30$
5	0.08	$\pm 0.17$

Some of the slopes are not too well determined; no significant change is indicated.

To the above results the following remarks apply.

1. The observations of 1925 are not very accurate, and 4 abnormally large residuals were omitted, leaving only 6 for the determination of the slope. They were consistent and were all used; the sector comprising the stations was  $126^\circ$  wide.

2. Here the observations had much greater precision and 13 could be used. Of the 16 observations in the I.S.S. 2 were left out because their residuals were large. One, that of Ann Arbor, which was deviating but not abnormal, was left out because it was known to me that the time correction had been known to 0.1 min. only. Toronto has given 2 *P* readings, one from each component record, differing by 4 seconds. The earlier one is deviating. I have read the records, and as far as I can see the earlier reading is not correct. The recording speed of the component in question is quite irregular and

it is a « jump » that has caused the mistake. There was no dependance on azimuth of the remaining residuals and they were all combined. The sector containing the stations was  $139^\circ$  wide.

3. 8 stations in northeastern to eastern azimuth recorded the earthquake and only one of them had an abnormal residual. The above correction was determined from the remaining 7 residuals. There were also some stations to the west, but their observations were less consistent, and they were not considered.

4. The epicentre here taken is  $0^\circ.5$  to the west of that of the I.S.S. It fits the observations definitely better, but there may still be some uncertainty. 7 stations at distances ranging from  $2^\circ.1$  to  $7^\circ.5$  were used for the determination of the slope of the time-curve. They were in azimuths ranging from  $125^\circ$  to  $243^\circ$ , but the residuals showed no marked dependance on azimuth.

5. The two earthquakes of 20 and 24 Dec. 1940 were from the same epicentre. 5 of the observations agreed exactly or differed by 1 sec. only. 5 stations had somewhat more diverging observations; those of the first shock were more consistent than those of the second and they were taken. 3 observations of the second shock were used because the stations did not record the first shock. 6 of the stations are in a westerly azimuth; the azimuth of the others vary from north through east to south. The residuals show no marked dependance on azimuth, and they were all combined for the determination of the slope.

The result here found for the slope of the time-curve disagrees with that obtained by Leet and Linehan (1942). They find for  $P_n$  up to 800 km: 7 sec. +  $\Delta$  km/8.44 km./sec. or the slope 13.10 sec./degree, and state that the maximum deviation from the line is 0.<sup>s</sup>5 and that the standard deviation is  $0^\circ.04$ . They studied the original records and their readings evidently differed from those published in the I.S.S.

The 2 earthquakes picked out originally and later left unconsidered were those of 30 Sept. 1937 and 15 July 1938. There were 6 useful observations in the first one and 4 in the second. In both cases slopes much smaller than those otherwise found were indicated.

The fact that the slope of the  $P$  curve for small distances is very nearly the same as that found from explosion records indicates that the earthquakes are not deep. Their foci are not likely to be much below the Mohorovicic discontinuity, for, with increasing depth below this discontinuity, the slope of the  $P$  curve decreases markedly. From  $2^\circ$  to  $12^\circ$  the mean slope of the J.-B. curve for a surface focus is 14.0 sec./degree, but for a focus at depth  $h = 0.01$  the mean slope is 13.6

sec./degree, (this latter slope being the one now known to result from a surface focus). For  $h = 0.00$  the slope is the same as for a surface focus. Therefore the slopes found are compatible with any depth above the Mohorovicic discontinuity as well as with small depths below.

We shall consider also the observations of  $P$  for distances greater than  $12^\circ$  and compare them with our trial time-curve which is the J.-B. time-curve for a surface focus. In so doing we shall look for indications of focal depth. We take the J.-B. curve corresponding to a surface focus, but in fitting it on to our observations we do not use its height (or we correct its height) and since the difference between the J.-B. curves for a surface focus and for  $h = 0.00$  is chiefly one of height we shall not be able to distinguish between depths of focus down to  $h = 0.00$  and slightly below. But with depth increasing below  $0.00$  the shape of the time-curve changes, the change being most marked for distances smaller than  $24^\circ$ . At  $12^\circ$  the difference between the curves for  $h = 0.00$  and  $h = 0.01$  is 2.7 seconds and at  $24^\circ$  it is 6.0 seconds, whereas for greater distances the curves are very nearly parallel. Thus if we have good observations at distances not much greater than  $12^\circ$  and again close to or beyond  $24^\circ$  we shall be able to see which of the two time-curves gives the closest fit, and to conclude whether or not the depth is normal.

Deep focus reflections are the best indications of depth, but when the depth is small they are not easily separated and identified because they follow so closely upon the phases marking the direct waves. In the Timiskaming earthquake Helwan at a distance of  $81^\circ$  reads pP 12 seconds after  $P$ , but no other station has read a phase which has been — or could be — identified as this phase. The identification therefore is doubtful.

We shall use also the observations of  $S$  and see if they give any indication of focal depth. Corresponding to our straight  $P$  line for distances up to  $12^\circ$  we take an  $S$  line  $T(S) = a \text{ sec.} + 24.04 \text{ sec./degree} \times \Delta^\circ$ , ( $24.04 = 13.58 \times 1.77$ ) and find that it gives a good fit up to about  $14^\circ$ . From that distance onwards we take the J.-B. curve for a surface focus. At  $14^\circ$  the straight line that fits the observations for small distances is about 13 secs. below the J.-B. curve. Nevertheless the observations for greater distances are found to fit on to this curve at its original height so that actually there is a discontinuity in the  $S$  curve at about  $14^\circ$  epicentral distance.

It is not so for *P*. The curve for a surface focus has to be lowered about 3 seconds, varying a little from one earthquake to another, in order to fit the observations and it then joins on to the straight line when this is continued up to about 14°.

In tables 1 to 4 the observations of *P* and *S* were compared with our trial tables. The earthquake of 1925 (No. 1) was omitted because the observations were not very accurate and many of them were « abnormal ».

The second earthquake, the Timiskaming earthquake of Nov. 1, 1935, was much better observed. It is the earthquake which has given rise to the present investigation. It was studied by E. A. Hodgson who at first determined the epicentre 46° 47' N 79° 4' W and the depth 200 km. (Hodgson 1936), but later corrected it to 46° 35' N 79° 4' W and now regarded the depth as normal (Hodgson 1937). The I.S.S. has the epicentre 46°.8 N 79°.2 W and normal depth. The epicentre here adopted is that of Gutenberg and Richter (1949) which is quite close to Hodgson's first epicentre. They take the depth to be 60 km.

In Table 1 the observations of *P* and *S* and their residuals are tabulated. 6:3:35 has been taken for  $T_0$  instead of 6:3:40 used in the I.S.S. and elsewhere. A few « abnormal » observations were left out. The observations at Hamburg and Copenhagen had rather large residuals and they were also left out. There is a disturbing microseismic movement at Copenhagen and the same is probably the case at Hamburg. To save space small groups of stations have been represented by one of the stations of the group and the number in parenthesis next to the observation is the number of stations in the group. The observation quoted is not always the observation of this station but it has been so chosen as to give the mean residual of the group. For distances up to that of Columbia (12°.9) the *P* travel times are seen to be in very close agreement with our straight line. There is unfortunately a gap up to 22°; there are 2 stations in this gap, but they have « abnormal » observations. Bozeman at 22°.0 has a large residual, but from Ivigtut (22°.9) onwards the *P* residuals are consistent. They are taken against the J.-B. curve lowered by 3<sup>s</sup>. This curve does not join on to the straight line at 12°. The line has to be continued to 16° in order to meet the curve, but lack of observations makes it impossible to say how exactly the two parts of the time-curve join together.

TABLE 1

1935, Nov. 1, 6:3:35		46°.8N 79.°1W				
Station	$\Delta$ °	Az °	P m s	O-C s	S m s	O-C s
Ottawa . . . . .	2.7	120	45	1	1 18	4
Toronto . . . . .	3.1	183	51	2	26	2
Vermont . . . . .	4.8	116	1 13	0	2 1	-3
Ithaca . . . . .	4.8	155	1 13	0	5	1
Pennsylvania . . . . .	6.1	171	30	0	36	0
Oak Ridge . . . . .	6.9	125	41	0		
Weston . . . . .	7.1	125	44	0		
Philadelphia . . . . .	7.4	155	49	1	3 7	0
Chicago Loyola . . . . .	7.9	234			3 14	-5
Chicago Univ. . . . .	7.9	234	1 56	1	16	-3
Charlottesville . . . . .	8.8	176	2 8	1	27	-4
Halifax . . . . .	11.1	95	38	0	4 35	-1
Florissant . . . . .	11.5	229	44	0	44	-1
Saint Louis . . . . .	11.6	229	45	0	50	2
Columbia . . . . .	12.9	187	3 1	-1	5 20	1
Bozeman . . . . .	22.0	280	5 0	5	9 1	5
Ivigut . . . . .	22.9	41	3	0	11	-2
Tucson . . . . .	28.2	251	51	-2	10 45	4
San Juan . . . . .	30.3	154	6 13	1	11 10	-5
Pasadena . . . . .	32.0	261	(6) 6 29	2		
Berkeley . . . . .	32.8	271	6 38	4	11 41	-1
Sitka . . . . .	35.2	309	6 55	0	12 31	0
Stonyhurst . . . . .	47.2	52	(2) 8 35	2	(2)15 33	4
Uccle . . . . .	52.3	53	(3) 9 13	1	(3)16 44	4
Toledo . . . . .	53.1	69	(3) 9 19	1	16 53	2
Stuttgart . . . . .	56.1	53	(7) 9 38	-2	17 33	1
Huancayo . . . . .	58.7	176	9 58	-1	57	-9
Pulkovo . . . . .	59.3	34	10 2	-1	18 1	-13
Trieste . . . . .	60.4	54	(2)10 8	-2	(2)18 27	-1
Sucre . . . . .	66.7	166	(2)10 55	3	(2)19 42	-4
Yalta . . . . .	71.7	44	(6)11 24	1		
Ksara . . . . .	80.7	50	12 15	2	22 28	4
Chiufeng . . . . .	92.5	348	13 12	1	24 21	4

The *S* residuals are less satisfactory than those of *P*. I read the records of all the stations up to the distance of 35° (Sitka) and found that except in the records of short-period instruments *S* was a well-marked phase. The onset, however, was not always well defined and some of my readings differed from those in the I.S.S. It is my readings that appear in the table. My corrections to those of the I.S.S. are + 5<sup>s</sup>, - 8<sup>s</sup>, - 4<sup>s</sup> and - 15<sup>s</sup> for Chicago Univ., Charlottesville, Florissant and Columbia respectively. At Charlottesville I have an additional reading 8<sup>s</sup> later which agrees with that of the station. The *S* I have

read for Philadelphia is very clear, but the station itself has read *S* where *L* begins. Up to the distance of Columbia,  $12^{\circ}.9$ , the curve of reference is the straight line with the constant  $a = 9$  sec. This constant, however, is not very well determined, its uncertainty being about  $\pm 1$  sec. There is no sign of a downward curvature of the actual travel time curve; on the contrary, an upward bend may be said to be indicated, but this is likely to be accidental. From  $22^{\circ}$  onwards the observations have been compared with the J.-B. curve for a surface focus at its original height. They are in fair agreement with it, no systematic departure being indicated. Since the corresponding *P* curve is 3 sec. below the *P* curve for a surface focus, *S-P* is about 3 sec. greater than the J.-B. *S-P*. For distances smaller than  $13^{\circ}$  the *S-P* of the earthquake are distinctly smaller than those of the J.-B. tables, the difference increasing with increasing distance. There is a discontinuity in the *S* curve which, however, is more clearly brought out by some of the other earthquakes where there are observations in the gap here left open.

The Ohio earthquake of March 9, 1937, has series of *P* and *S* observations in fair agreement with our trial time lines (see Table 2). For the *S* line 11 sec. has been taken as the time of intercept, but this

TABLE 2

Station	1937, March 9, 5:44:35		40°.4N 84°.2W			
	$\Delta$ °	Az °	P m s	O-C s	S m s	O-C s
Cincinnati . . . . .	1.3	190	25	0	43	1
Chicago Univ. . . . .	3.0	300	57	9	1 21	-2
Madison . . . . .	4.7	307	1 13	2	2 9	5
Toronto . . . . .	4.8	46			10	4
Buffalo . . . . .	5.0	56	1 14	-1	5	-6
Florissant . . . . .	5.0	254	16	1	17	6
Saint Louis . . . . .	5.0	252	13	-2	2 11	0
Philadelphia . . . . .	6.9	68	44	3		
Des Moines . . . . .	7.2	283			3 6	2
Ottawa . . . . .	8.0	48	1 55	-1	21	-2
Little Rock . . . . .	8.6	232	2 9	5	39	1
Williamstown . . . . .	8.6	71	4	0	32	-6
Vermont . . . . .	9.1	61			3 47	-3
Oak Ridge . . . . .	9.7	74	19	0	4 4	0
Weston . . . . .	9.9	74	22	0		
Shawinigan Falls . . . . .	10.3	50	27	0	4 19	0
Seven Falls . . . . .	11.8	51	2 42	-6	4 51	-4
East Machias . . . . .	13.2	65			5 28	0

constant has no great certainty although the residuals are almost symmetrically distributed. Their trend indicates a smaller slope of the line than that assumed. There is only one  $P$  observation at greater distances.

In the Saint Lawrence earthquake of Oct. 19, 1939,  $P$  and  $S$  were small. I have read many of the records and my readings often differed by 1<sup>s</sup>, 2<sup>s</sup> or even 3<sup>s</sup> from those of the I.S.S. I have, however, taken the I.S.S. readings except for  $S$  at Halifax where my reading was 10<sup>s</sup> later than that of the station. The observations of Weston, Georgetown and Cincinnati are not in the I.S.S. and for these stations my readings were taken. The Cleveland  $P$  and the Fordham  $S$  seemed to me uncertain, hence the parentheses. At Halifax a small movement of indefinite onset preceded the  $P$  onset read, which, therefore, may not correspond to the other  $P$  readings. Many of the readings of the I.S.S. are marked  $i$ . This, however, does not always mean that the corresponding phases are so well defined as to have their onsets exactly where they were read, but it indicates that the pulse selected had a sharp onset. Actually most of the movement recorded in this earthquake, in the forerunners as also in the surface waves, had unusually short period as if a shaking had taken place and not just a single shock.

In Table 3 most of the  $P$  and  $S$  readings available are tabulated; a few « abnormal » observations were left out. With  $T_0 = 11:53:56$  the  $P$ 's at small distances agree well with those derived from our linear expression. The  $P$ 's for greater distances were compared with the J.-B. times for a surface focus with 4<sup>s</sup> subtracted from them. The fit is seen to be good.  $S$  for distances up to 13<sup>o</sup>.6 were compared with  $t(S) = 11^s + \Delta^o \times 24.04$  sec./degree and for 7 of the observations the agreement is good; the 4 others have large residuals. At 13<sup>o</sup>.8 the residual against the time derived from the above expression is 16<sup>s</sup>, but the residual against the J.-B. time for a surface focus is only 5<sup>s</sup>, in agreement with most of the residuals for greater distances. Thus the discontinuity in the  $S$  curve is clearly indicated and here occurs at a distance of about 13<sup>o</sup>.8. For greater distances  $S - P$  exceed those of the J.-B. surface tables by about 9<sup>s</sup>. For the smaller distances  $S - P$  are smaller than those of the tables, but they are about 2 sec. greater than those of the Timiskaming earthquake.

The  $P$ 's of the New Hampshire earthquakes of Dec. 20 and 24, 1940, are in fair agreement with our trial times up to 12<sup>o</sup>. At greater distances most of the travel times exceed those of our trial tables

TABLE 3

1939, Oct. 19, 11:53:56		47.°8N 70.°0W				
Station	$\Delta$ °	Az °	P m s	O-C s	S m s	O-C s
Seven Falls . . . . .	0.9	217	27		39	
Shawinigan Falls . . . . .	2.1	241	38	2	1 8	7
East Machias . . . . .	3.5	153	54	-1	33	-2
Ottawa . . . . .	4.6	243	1 10	0	2 4	2
Harvard . . . . .	5.4	196	20	-1	22	1
Weston . . . . .	5.5	190	21	-1	13	-10
Halifax . . . . .	5.5	125	(26)	(4)	24	1
Williamstown . . . . .	5.6	208	24	1	34	8
Fordham . . . . .	7.5	205	50	1	3(21)	(10)
Georgetown . . . . .	10.3	213			4 17	-2
Cleveland . . . . .	10.4	236	2(36)	(6)	19	-2
Cincinnati . . . . .	13.6	236			5 38	0
Chicago Loyola . . . . .	13.8	252	3 18	3	5 59	5
Florissant . . . . .	17.3	248	(2)3 59	0	(2)7 22	6
Cape Girardeau . . . . .	17.8	243	4 2	-5	31	3
Lincoln . . . . .	20.2	261	34	-1	8 11	-10
Saskatoon . . . . .	23.8	296			9 34	6
Salt Lake City . . . . .	30.5	265			11 24	6
Tucson . . . . .	34.5	260	6 49	1	12 25	5
Haiwee . . . . .	37.0	271	(2)7 9	0		
Pasadena . . . . .	38.2	268	(5)7 18	-1		
Toledo . . . . .	46.9	75	8 30	0		
La Paz . . . . .	64.0	178	10 32	-2		
Sverdlovsk . . . . .	67.9	27	58	0	19 56	-5
Ksara . . . . .	75.2	58	11 43	1		

(J.-B. surface times - 5 sec.) by 3<sup>s</sup> or 4<sup>s</sup>, but at 15° Florissant and Saint Louis have smaller travel times. *S* travel times for small distances were compared with our trial times for  $a = 11^s$  and the fit is satisfactory. For greater distances the residuals were determined against the J.-B. times for a surface focus. The residuals are not large except at Cape Girardeau ( $\Delta = 15^\circ.3$ ), where the residual against the time derived from our linear expression is much smaller,  $-5^s$ . It is clearly seen that there is a discontinuity in the *S* curve also of these earthquakes.

The earthquakes so far considered were all in the I.S.S. There may have been other well recorded earthquakes in Northeastern America in later years but I know of only one, the Oklahoma earthquake of April 9, 1952. It was recorded by numerous stations at distances up to 23° and could, therefore, be expected to yield data of interest for the present investigation. The U.S. Coast and Geodetic Survey determined the epicentre 35°.4N 97°.8W and found  $H = 16:29:29.5$ ,  $h = 125$

TABLE 4

		1940, Dec. 20, 7:27:26		1940, Dec. 24, 13:43:46		43.°8N 71.°3W	
Station	$\Delta$ °	Az °	P m s	O-C s	S m s	O-C s	
Harvard . . . . .	1.3	189	25	0	43	1	
Weston . . . . .	1.4	181	26	0			
Williamstown . . . . .	1.8	232	32	0	53	-1	
Shawinigan Falls . . . . .	2.9	339	45	-2	1 26	5	
East Machias . . . . .	3.0	71	49	1			
Seven Falls . . . . .	3.3	4	50	-2	30	0	
Fordham . . . . .	3.5	214	53	-2	32	-3	
Ottawa . . . . .	3.5	298	54	-1	32	-3	
Philadelphia . . . . .	4.8	218	1 12	-1	2 8	2	
Buffalo . . . . .	5.6	263	26	2	2 26	0	
Pennsylvania . . . . .	5.7	242	28	3			
Pittsburgh . . . . .	7.2	246	1 46	1	3 10	6	
Chicago Loyola . . . . .	12.1	268	2 51	-1	4 57	-5	
Florissant . . . . .	15.1	258	3 30	-1	6 22	-3	
Saint Louis . . . . .	15.2	256	3 31	-2	25	-3	
Cape Girardeau . . . . .	15.3	253	3 38	4	14	-16	
Lincoln . . . . .	18.9	270	4 23	4	7 58	5	
Tucson . . . . .	32.9	263	6 36	3	11 56	0	
Pasadena . . . . .	37.2	271	(5)7 13	3			

km. I have taken the  $P$  and  $S$  arrival times published in the bulletin of the International Central Bureau at Strasbourg and in addition those of some western stations kindly sent me from the U.S. Coast and Geodetic Survey. Taking the time of occurrence 16:29:27 I determined the transmission times as tabulated in table 5 and determined their residuals against our trial tables. For  $P$  the straight line was taken up to  $14^\circ$  and here joined on to the J.-B. curve for a surface focus lowered by 5 sec. For  $S$  the straight line was taken up to  $14^\circ.1$ .

Evidently the epicentre could not be determined with great precision since there are not many near stations and the distribution in azimuth is unsatisfactory. Actually about half of all the stations listed are in a westerly or northwesterly azimuth whereas the others are northeast to east of the epicentre. The residuals of these two sets of stations have been placed in separate columns and obviously the trend of neither set will be much affected by a small shift of the epicentre. The easterly observations are in good agreement with our trial times. The westerly stations have negative residuals at the smaller distances and positive residuals for  $\Delta > 14^\circ$ . However, neither set of residuals indicate focal depth greater than normal. The depth was

assumed to be 125 km which is close to the J.-B. 0.015. At  $14^\circ$  the  $P$  time for this depth is  $8^s.2$  smaller than that for a surface focus, but at  $23^\circ$  the difference is  $13^s.2$ . Thus the 0.015 curve bends much more strongly than that for a surface focus for the distances here represented and the Oklahoma transmission times could not be adapted to it.  $S$  for distances up to  $14^\circ.1$  are in approximate agreement with our straight line when  $a$  is taken  $= 10^\circ$ . The U.S. Coast and Geodetic Survey has kindly sent me copies of some of their records and I was, therefore,

TABLE 5

1952, April 9, 16:29:27				35.94N 97.98W			
Station	$\Delta$	Az	P	O-C	O-C	S	O-C
	o	o	m s	s	s	m s	s
Fayetteville . . . . .	3.0	53	48	0		1 21	- 1
Lubbock . . . . .	3.8	116	59	0			
Saint Louis . . . . .	6.7	62	1 41	3		2 57	6
Rapid City . . . . .	9.6	336	2 17		-1	4 1	0
Chicago . . . . .	10.3	48	24	-3		4 12	- 6
Cincinnati . . . . .	11.2	67	40	1		4 40	1
Tucson . . . . .	11.3	256	2 39		-2	(5 46)	
Columbia . . . . .	13.9	94	3 16	0		5 44	0
Boulder City . . . . .	13.9	280	16		0	5 39	- 5
Cleveland . . . . .	14.1	60	16	-2		5 49	0
Palomar . . . . .	15.9	266	43		1	(7 0)	
China Lake . . . . .	16.1	278	46		2		
Riverside . . . . .	16.2	266	47		1		
Buffalo . . . . .	16.5	49	49	0			
State College . . . . .	16.6	48	48	-3			
Tinemaha . . . . .	16.6	282	54		3		
Pasadena . . . . .	16.8	266	3 53		0		
Hungry Horse . . . . .	17.6	316	4 4		1		
Fresno . . . . .	17.8	281	9		3		
Reno . . . . .	17.9	290	12		5		
Kirkland Lake . . . . .	18.3	40	10	-2		(7 21)	
Philadelphia . . . . .	18.5	68	16	2		8 2	18
Lick . . . . .	19.3	283	26		2		
Mineral . . . . .	19.4	292	27		1		
New York . . . . .	19.5	66	27	1		7 51	-15
Palisades . . . . .	19.6	66	27	0		8 13	5
Fordham . . . . .	19.6	66	27	0		7 55	-13
Berkeley . . . . .	19.8	285	31		1	(7 31)	
Harvard . . . . .	21.6	62	49	1		8 43	- 6
Weston . . . . .	21.7	63	51	2		8 46	- 5
Shawinigan Falls . . . . .	21.9	51	53	1		8 57	3
Seattle . . . . .	22.0	312	4 59		6		
Victoria . . . . .	23.0	313	5 3		1		
College . . . . .	41.8	331	7 49		1		
Kiruna . . . . .	67.2	21	10 54	1			
Uppsala . . . . .	71.3	29	11 23	3			

able to correct an error of 1 min. in the Chicago S. Tucson seems to have read *L* for *S* which does not appear in its records. *S* at greater distances was disappointing. It was often missing or another phase was read for it. There are only four *S* readings that fit the tables approximately, in spite of the many observing stations at the required distances. This earthquake, therefore, could not give much additional information about *S* close to and beyond the discontinuity of the time curve.

We may summarize the results arrived at as follows. For the northeastern American earthquakes considered the *P* curve is a continuous curve the lower section of which — up to a distance of about  $14^\circ$  — may be taken to be a straight line, while the rest of the curve is a J.-B. curve for a surface focus so displaced as to join on to the line. The slope of the straight line has been taken to be 13.6 sec./degree, corresponding to the velocity of 8.2 km./sec. below the Mohorovicic discontinuity.  $7^s.37$  has been taken for time of intercept and the times of occurrence of the earthquakes have been determined accordingly. We have no means of determining the actual values of  $T_0$ .

In the earthquake of 1952, April 9, there are enough observations in the critical range  $12^\circ - 24^\circ$  to show definitely that the *P* curve of this earthquake does not bend more strongly than the J.-B. curve for a surface focus. There are fewer observations in this range of the other earthquakes, but their observations for greater distances are not earlier, on the average they are slightly later than those of the 1952 earthquake (see  $\Delta P_2$  below) and thus they do not indicate focal depth.

The *S* curve of the earthquakes is not continuous. The lower section is a straight line corresponding to the *P* line and having the slope  $24^s.0$  while the rest of the curve is a J.-B. curve for a surface focus at its proper height. At about  $14^\circ$  where the transition from the one curve to the other takes place, the J.-B. curve is about  $13^s$  above the straight line. The differences of height of the various sections of the curves are not exactly the same in all the earthquakes. They are given in the table below where  $\Delta T_0$  stands for our correction to the I.S.S.  $T_0$ ,  $a(S_1)$  is the time of intercept of the *S* line,  $\Delta P_2$  and  $\Delta S_2$  the corrections to the height of the J.-B. *P* and *S* curves for a surface focus and  $\Delta(S_2 - P_2)$  the difference of these corrections or the amount by which the *S* - *P* of the earthquakes from about  $14^\circ$  onwards exceed the J.-B. *S* - *P* for a surface focus.

Most of these corrections are not very accurately determined, but

$\Delta P_2$  is unmistakably negative and  $\Delta S_2$  is 0 or positive. Thus for the greater distances  $S-P$  is always greater than the  $S-P$  of the J.-B. tables. This is contrary to what would be expected if the foci were deep.  $\Delta S_2$  and  $\Delta(S_2-P_2)$  of the earthquake of Oct. 19, 1939 are exceptionally great. This earthquake is not very strong and  $P$  and  $S$  are small everywhere as mentioned previously. It seems possible that a small first wave was lost at the greater distances.

	$\Delta \frac{P}{S}$	$\Delta(S_1)$ s	$\Delta P_2$ s	$\Delta S_2$ s	$\Delta(S_2-P_2)$ s
1935, Nov. 1 . . . . .	-5	9	-3	0	3
1937, March 9 . . . . .	+4	11			
1939, Oct. 19 . . . . .	+7	11	-4	5	9
1940, Dec. 20, 21 . . . . .	+2	11	-2	0	2
1952, April 9 . . . . .	-2.5	10	-5	0	5

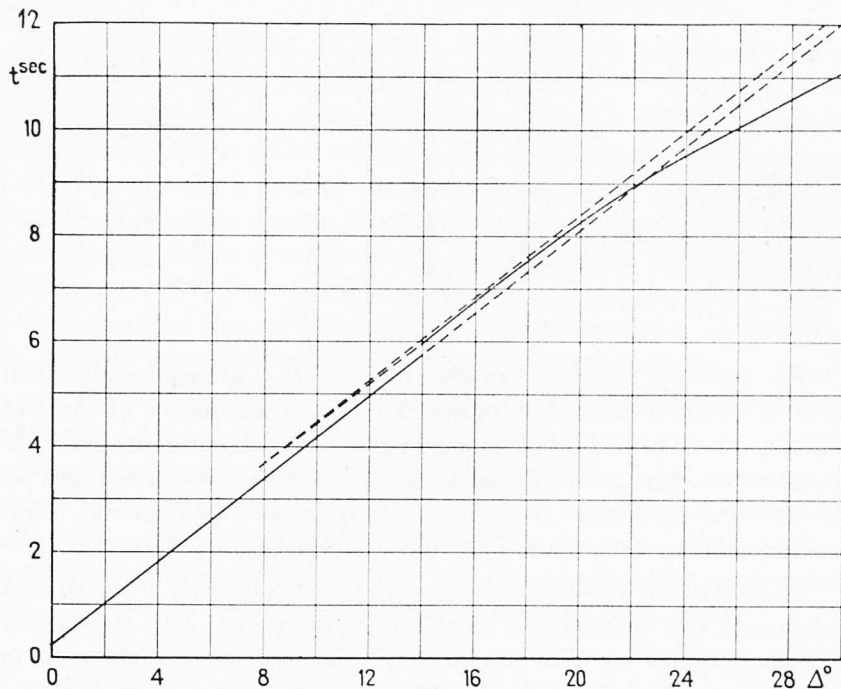
For distances smaller than about  $14^\circ$ ,  $S-P$  is always smaller than the  $S-P$  of the J.-B. surface tables. This is a consequence of the fact that the velocities of both  $P$  and  $S$  are greater below the Mohorovicic discontinuity than assumed when the tables were constructed and is, therefore, no indication of depth of focus greater than normal. Thus there is nothing to indicate that the earthquakes are deep.

In most of the records of these earthquakes, obtained at the shorter distances,  $S$  is a distinct and clearly recorded phase. This is contrary to what is found for Europe, where  $S$  at distances from about  $5^\circ$  to about  $13^\circ$  usually is quite weak or even absent, with the result that a later phase often is read for  $S$ . This behaviour of  $S$  was tentatively explained on the assumption of the presence of a « soft » layer at some depth below the Mohorovicic discontinuity (Lehmann 1953). Since it was known that  $S$  was well recorded in Northeastern America at the distances where it was weak in Europe, it was believed that in Northeastern America the « soft » layer was absent. However, the discontinuity in the  $S$  curve now found to subsist indicates strongly the presence of a « soft » layer also in Northeastern America, but this layer will be placed considerably deeper in accordance with the fact that the  $S$  curve breaks off at a much greater epicentral distance.

The layer responsible for this break was characterized as « soft », because  $S$  is very much delayed in it while  $P$  is not. It has, however,

been found in later studies to be reported on elsewhere, that the word « soft » was not very well chosen.

Our observations indicate a break in the  $S$  curve. This may be due either to a sudden or a gradual decrease in the  $S$  velocity. A gradual decrease followed by a later increase could produce a loop as the one shown in the figure with the first branch beyond  $14^\circ$  car-



rying so little energy that the corresponding waves could not be observed. For  $\Delta < 14^\circ$  later waves corresponding to the upper branches may be recorded, but they are not easily distinguished in the movement following the first phase.

The fact that the  $S$  phase is differently recorded in Europe and in Northeastern America and that the travel times differ so markedly, shows that differences of structure extend to depths below the Mohorovicic discontinuity.

Mention has been made of the fact that macroseismic evidence in the case of many earthquakes in Northeastern America seemingly indicate depth greater than « normal ». The macroseismic areas are often

extremely extended, while the intensity in the epicentral region is not correspondingly high.

Various formulae have been developed for the determination of depth of focus when the intensity in the epicentral region and the radius of perceptibility are known. A well known formula is Gassmann's formula (1925), based on the observations of Swiss earthquakes. Among others who have considered the question are Blake (1937) and Neuberger (1938). Gutenberg and Richter (1942) have developed formulae from Californian observations, and have applied them to shocks in other regions calculating the « apparent depth »  $h'$ . On p. 182 of the paper quoted they say: « It is likely that this quantity in many cases differs from the true depth,  $h$ , as it must be much affected by differences in local structure and ground. It should be taken merely as a measure of the perceptibly disturbed area, relative to the epicentral intensity ». They find that there are regions in Northeastern America in which the apparent depth usually is rather great, and the earthquakes here considered are all from these regions. For the 1935 Timiskaming earthquake they find  $h' = 67$  km., (p. 183), and on p. 186 they mention that the earthquakes of Feb. 28 (March 1) 1925 and Dec. 20, 1940, also had large radii of perceptibility relative to their epicentral intensity. According to Devlin et Al. (1942), the macroseismic area of the latter was about 500,000 sq. miles ( $r = \text{ca. } 640$  km.). On the isoseismal map no intensity beyond V is indicated, but the description of the damage done in the epicentral region shows that it has, at least, been close to VI. When this value is taken the depth as calculated from the formula of Gutenberg and Richter is about 90 km. On the interpretation of microseismic data Leet and Linehan (1942) found a much smaller depth.

The radius of the macroseismic area of the St. Lawrence earthquake of 1939 was 700-900 km. (see I.S.S.) and the damage done was slight. The Oklahoma earthquake of 1952 was also very widely felt, and did not cause much damage.

It is well known that the radius of perceptibility depends on the structure of the region as said by Gutenberg and Richter. We may mention as an example the South German (Oberschwaben) earthquake of June 27, 1935. According to Hiller (1936) it was felt to a distance of more than 500 km. to the east and northeast of the epicentre, and to the north to a distance of ca. 380 km., but in the Alps it was not felt more than 250 km. away. The formula of Gutenberg and Richter

gives the depth as directly proportional to the radius of perceptibility. It is thus seen that there may be an uncertainty of at least 100% in the determination of the depth when a formula developed for one region is applied to one of widely different structure.

The result is that we are unable to determine the depths of the earthquakes here considered from macroseismic data. We can say that they are not surface shocks, but they are not necessarily deeper than « normal ». Microseismic evidence suggests that they are not deep.

#### ACKNOWLEDGMENT

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#### RIASSUNTO

*Vengono esaminati i tempi di tragitto delle onde P ed S per terremoti dell'America nord-orientale. Si trova che per distanze epicentrali dell'ordine di 14° circa le curve dei tempi di tragitto possono essere rappresentate da rette con pendenza di 13,6 sec./grado e 24,0 sec./grado rispettivamente. Per maggiori distanze i tempi delle P si adattano alle dromocrone Jeffreys-Bullen per ipocentro superficiale abbassato di quel tanto che porti la curva a congiungersi con la linea retta. I tempi delle S concordano con la dromocrona Jeffreys-Bullen per ipocentro superficiale, considerato alla sua quota originale. La curva non si raccorda con la linea retta rappresentante i tempi di tragitto per distanze minori. La curva S presenta pertanto una discontinuità a circa 14°.*

*Fu indicata la profondità ipocentrale maggiore della normale, quando i tempi di tragitto di alcuni terremoti dall'America nord-orientale vennero confrontati con le tavole correnti; ma quando furono confrontati con le tavole sperimentali qui descritte, non ci fu indicazione di profondità.*

*Le aree interessate percettibilmente da questi terremoti sono grandi*

*a paragone dell'intensità all'epicentro. Sono esposti i motivi che non autorizzano a ritenere profondi detti terremoti.*

#### SUMMARY

*P and S travel times for earthquakes in Northeastern America were investigated. It was found that up to about 14° epicentral distance the time-curves could be taken to be straight lines of slopes 13.6 sec./degree and 24.0 sec./degree respectively. From there onwards the P times fitted the Jeffreys-Bullen time-curve for a surface focus lowered so as to join on to the straight line. The S times fitted the Jeffreys-Bullen time-curve for a surface focus retained at its original height. The curve did not join on to the straight line representing the travel times for smaller distances. Thus the S curve was discontinuous with a break at about 14°.*

*Depth of focus greater than normal was indicated when the travel times of some earthquakes from Northeastern America were compared with current tables, but when they were compared with the trial time-tables described, there was no indication of depth.*

*The perceptibly affected areas of these earthquakes are large relative to the epicentral intensity. Reasons are given why this does not warrant the conclusion that they are deep.*

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## CONTENUTO DI URANIO E TORIO NELLE METEORITI

M. CURATOLO - D. PALUMBO - M. SANTANGELO

Molti ricercatori in questi ultimi anni si sono interessati al problema della composizione delle meteoriti; dai risultati sperimentali si è cercato trarre elementi circa la genesi di questi materiali, questione ancora aperta, ed avere informazioni sui processi chimici e termodinamici cui le meteoriti furono soggette prima della loro caduta sulla terra.

Uno degli aspetti del problema è quello dell'abbondanza percentuale degli elementi chimici e della loro composizione isotopica nella materia meteorica dei diversi tipi: ciò perché esso è connesso con quello più generale dell'origine e distribuzione degli elementi nel cosmo e nella terra, nonché con quello dell'età delle meteoriti (<sup>1</sup>).

In un recente lavoro Urey e collaboratori (<sup>2</sup>), esaminando un gran numero di analisi chimiche effettuate su questi materiali, sono pervenuti alla formulazione di alcuni criteri di classificazione in base alla percentuale dei componenti più abbondanti ed alla presenza o meno di disomogeneità strutturali nella massa fondamentale. Fra gli elementi meno abbondanti presentano particolare interesse quelli delle due famiglie radioattive naturali Torio e Uranio; le loro concentrazioni sono state determinate per alcune meteoriti siliciche (stony meteorites) e per qualcuna ferrica (iron meteorites) (<sup>3</sup>).

Purtroppo però i valori trovati, con metodi diversi, scartano tra loro, anche per lo stesso tipo di campione, comunque se pure è azzardato fare estrapolazioni e dedurre conclusioni da dati ancora così incerti, sono questi per il momento i pochi che si possono sfruttare per un tentativo di interpretare le possibili relazioni di costituzione e origine tra meteoriti e materiali terrestri.

I punti più delicati per la determinazione del contenuto di elementi radioattivi naturali nelle meteoriti, sono i seguenti:

- 1) basso contenuto di Uranio e Torio ( $10^{-7} \div 10^{-9}$ );
- 2) alta probabilità di contaminazione dei campioni;
- 3) inadeguatezza di alcuni metodi di misura.

Poiché nel nostro laboratorio, in questi ultimi tempi è stata im-