PKIKP and Pseudo-*PKIKP* Phases at distances of less than 140°*

B. Gutenberg†

(Received 1959 December 14)

Summary

In several attempts to establish from observations the travel-time curve for *PKIKP* (called *P′* or *P″* by some authors) the beginning of this curve has been drawn with a relatively strong curvature corresponding to a decrease of $dt/d\theta$ from roughly 4 s/deg at $\theta = 110°$ to about 2 s/deg at 130°. Apparently, travel times of different wave types had been combined. Actually, the observed travel-time curve of *PKIKP* is nearly a straight line in agreement with calculations. Near an epicentral distance of 115° the amplitudes of *PKIKP* increase by a factor of roughly 5. This probably indicates the transition from the diffracted to the direct *PKIKP*.

The portions of the travel-time curves with a slope corresponding to $dt/d\theta$ near 4 s/deg which erroneously had been attributed to *PKIKP* belong to several wave types which seem to follow *P*, *pP* and *sP* or precede *PP*, each at roughly constant time intervals. Among causes for such multiplicity of phases are effects of irregularities in the Earth, of discontinuities and of diffraction.

1. The problems

Extensive travel times of *PKIKP* at distances of between about 110° and 140° seem to have been collected first by Rudolph and Szirtes (1914) who stated in a preliminary note based on observations of 74 earthquakes 1906–1913 that at an epicentral distance of about 112° a travel-time curve branches from that of *PP*, and that this curve can be followed to the anticentre where these waves arrive about 1½ min later than at 112°. However, the reported travel times of 11 min at 112° and 12½ min at 180° seem to contain a systematic error of about 8 min; most reported times and interpretations of phases by Rudolph and Szirtes are incorrect. Apparently, the war and Rudolph's death prevented a detailed publication of their results.

The first detailed observed travel-time curve of *PKIKP* at distances of less than 140° has been published by Angenheister (1921); he designated the longitudinal waves through the core by *P′*. Later, the symbol *P″* has been used occasionally for *PKIKP* at distances of less than 143°. This procedure is followed

* Contribution No. 959 from the Division of the Geological Sciences, California Institute of Technology.

† Died 1960 January 25.

here in some of the illustrations. Most travel-time curves and tables for *PKIKP* at distances of less than 140° which had been published between 1922 and 1933 are based mainly on Angenheister's data (condensed in Table 1). In addition to various investigations based on specific shocks, in which some data for the times of *PKIKP* have been given, specific investigations of the travel times of *PKIKP* have been published by Gutenberg & Richter (1934, p. 90) and by Jeffreys (1938, 1939a, 1939b).

Table 1

Travel times t of PKIKP in min: s according to various authors: h = focal depth in km, θ = distance in degrees

Author	h	$\theta = 105$	110	115	120	125	130	135
(a) Observed								
Angenheister (1921)	30	18 : 05	18 : 29	18 : 50	19 : 07	19 : 22	19 : 34	19 : 45
Gutenberg–Richter (1934) No. 2	30	—	18 : 00	18 : 20	18 : 37	18 : 53	19 : 04	19 : 12
Gutenberg–Richter (1934) No. 3	30	18 : 00	18 : 15	18 : 31	18 : 47	18 : 59	19 : 10	19 : 17
Denson (1950)	30	—	18 : 15	18 : 39	18 : 54	19 : 05	19 : 14	19 : 22
Bolt (1959)*	0	—	18 : 35	18 : 44	18 : 54	19 : 04	19 : 13	19 : 23
Gutenberg (1959)	600	17 : 17	17 : 27	17 : 38	17 : 49	17 : 59	18 : 09	18 : 18
(b) Calculated from assumed velocity as function of depth								
Jeffreys–Bullen (1940)	0	—	18 : 33	18 : 43	18 : 53	19 : 02	19 : 12	19 : 21
Gutenberg (1958)†	0	—	(18 : 36)	18 : 46	18 : 56	19 : 06	19 : 15	19 : 24
Jeffreys–Bullen (1940)‡	600	—	17 : 26	17 : 36	17 : 46	17 : 55	18 : 05	18 : 14
Gutenberg (1958)†‡	600	—	(17 : 29)	17 : 39	17 : 49	17 : 59	18 : 08	18 : 17

* $t = 19{:}\,03{\cdot}7 + 1{\cdot}92\,(\theta - 125°)$s.
† Based on Table 4 in Gutenberg (1958, p. 309) for times in the core.
‡ Assumed correction for depth −1 : 07.

Originally it had been believed that *PKIKP* waves arriving at distances of between 110° and about 142° are the result of longitudinal waves diffracted through the core. The main progress resulted from the suggestion by Lehmann (1936) that these waves are a consequence of a sudden or rapid increase in the velocity inside the core. Subsequently, Gutenberg & Richter (1938) have given a specific solution with a gradual transition from the outer to the inner core which later has been improved by Gutenberg (1958a; 1959, pp. 105–109). Jeffreys (1939b), on the other hand, has supposed that the transition is sudden. However, to fit the data, he had to assume that approaching the inner core there is a decrease in velocity which is not indicated otherwise (see, e.g. Gutenberg, 1959, pp. 110–113).

Jeffreys (1939a) has pointed out that on the basis of Airy's theory the waves diffracted at the caustic of *PKP* could not be observable at a distance of much beyond 10° preceding the caustic. This has been confirmed by observations (Gutenberg 1958b). In addition to the problem of the type of transition from the outer to the inner core which is not discussed here, there are the questions, at what minimum epicentral distance do *PKIKP* waves arrive through the inner core, and what form the observed travel-time curve has of diffracted *PKIKP* waves, arriving at shorter distances.

2. The beginning of *PKIKP*

Travel-time curves based on observed *PKIKP* waves and constructed without reference to theoretical curves begin at epicentral distances slightly over 100° where small waves are found preceding *PP*. As soon as theoretical curves of *PKIKP* were based on the conception of an inner core it appeared that *PKIKP* waves could not arrive at distances of less than somewhere between about 110° and 120°. The complicated travel-time curves including a loop with several branches differing by small time intervals (see, e.g. Jeffreys 1939a, p. 358) make accurate determinations very difficult. This can be seen also in Figure 1, which

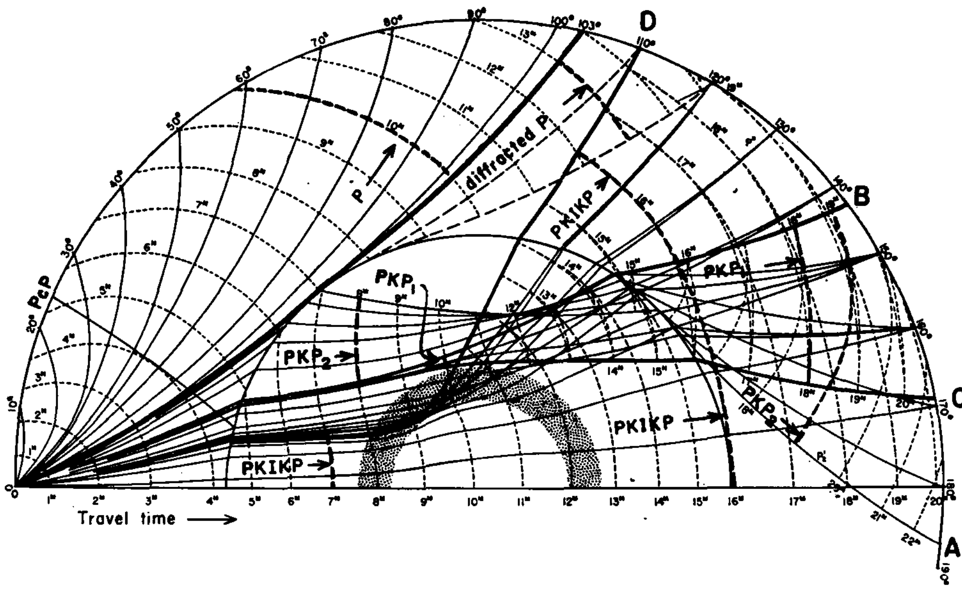

Fig. 1.—Wave paths and wave fronts (travel times) of longitudinal waves in the Earth. Based on Gutenberg & Richter (1939, p. 123).

shows in addition that *PKIKP* waves arriving at distances of less than roughly 140° have nearly the same angle of incidence, corresponding to their nearly straight line travel-time curve. The amplitudes of these waves should be rather small since relatively little energy leaves the source between the rays arriving at the rather wide range of distances between about 110° and 140° (*D* and *B* in Figure 1). Nevertheless, it may be expected that a noticeable increase in amplitudes is observable at the distance corresponding to *D* in Figure 1.

Denson (1952, p. 130) studied the amplitudes of *PKIKP* as function of the epicentral distances. From his results, it appears that a/T (a = ground amplitude in microns, T = period in s) decreases noticeably at distances θ between 110° and 120°. In shocks of magnitude 7·0, a/T begins to exceed 1 μm/s in the vertical component of short-period *PKIKP* at about $\theta = 116°$. The corresponding long-period waves show slightly smaller values of a/T. Since records of the earthquake of 1957 April 16, at 4:04:04, adopted source at $4\frac{1}{2}$° S $107\frac{1}{2}$° E at a depth of 600 km, magnitude m = 7·2 have been very useful in the investigation of several problems, values of a/T have been calculated from the records of vertical components of *PKIKP* at stations for which instrumental constants have been available. The results show that at distances of less than 110° (Relizane, 106°·4; Rathfarnham, 107°·7; Toledo, 109°·3) a/T is $\frac{1}{4}$ to $\frac{1}{2}$ μm/s, while at distances of between 110° and 129° (Malaga, 110°·3; Alberni, 117°·3; Horseshoe Bay, 118°·1; Victoria, 118°·5; Banff, 121°·3; Santa Clara, 124°·3; Pasadena, 128°·4) its value is between $1\frac{1}{2}$ and 3 μm/s. However, we must consider that in a 600 km deep shock the distances at which *PKIKP* waves arrive with a given angle of incidence are one to two degrees shorter than in shallow shocks. Combining the new results with those of Denson it seems that in shallow shocks of $m = 7{\cdot}0$ *PKIKP* begins to have values of a/T near 1 μm/s at a distance of roughly 115° and that at this distance possibly the actual *PKIKP* waves begin. However, there is no well-defined caustic anywhere near this distance; compare Figure 2. The

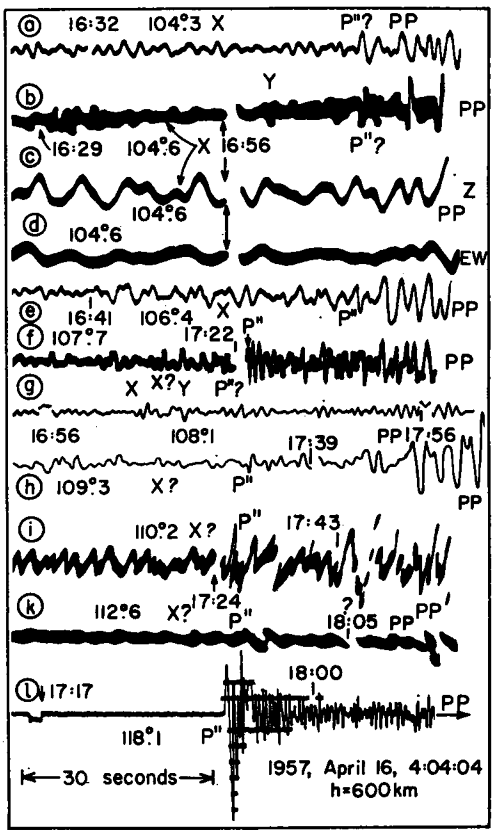

FIG. 2.—Portions of seismograms showing *PKIKP* (≡ *P″*) at epicentral distances between 104° and 119° on records of shock of 1957 April 16, 4:04:04, focal depth 600 km, all on the same time scale. (d) is an East–West component; the others are vertical components. The recording stations are (a) Alger, (b) to (d) Kew, (e) Relizane, (f) Rathfarnham, (g) Sitka, (h) Toledo, (i) Malaga, (k) Coimbra, (l) Horseshoe Bay

reason is probably the relatively small energy going into these *PKIKP* waves near the source (Figure 1).

3. The diffracted *PKIKP* waves

All early travel-time curves for the observed *PKIKP* waves start at a distance of about 105° with a slope nearly parallel to that of *P* or of *PP*. At distances between about 115° and 125° the apparent velocity corresponding to these curves gradually increases and at distances beyond 130° this slope corresponds to about that to be expected from calculations on the basis of velocity–depth curves. Tables 1 and 2 illustrate these facts. The travel-time curve for a focal depth of 600 km, given by Gutenberg & Richter (1936, p. 350), had been based on the observed travel-time curve for shallow shocks (Gutenberg & Richter 1934) and therefore gives a decrease in $dt/d\theta$ from about 3·4 s/deg. at θ = 107°·5 to 1·8 at 127°·5. Very recent travel-time curves do not contain observations of waves giving $dt/d\theta$ noticeably in excess of 2 s/deg.

Table 2

Values of $dt/d\theta$ in s/deg., based on Table 1. Symbols as in Table 1

Author	*h*	θ = 107½	112½	117½	122½	127½	132½
(a) From observed curves							
Angenheister (1921)	30	4·8	4·2	3·4	3·0	2·4	2·2
Gutenberg–Richter (1934) No. 2	30	—	4·0	3·4	3·2	2·2	1·6
Gutenberg–Richter (1934) No. 3	30	3·0	3·2	3·2	2·4	2·2	1·4
Denson (1950)	30	—	4·8	3·0	2·2	1·8	1·6
Bolt (1959)	0	1·92	1·92	1·92	1·92	1·92	1·92
Gutenberg (1959)	600	2·0	2·2	2·2	2·0	2·0	1·8
(b) from calculated curves							
Jeffreys–Bullen (1940)	0	—	2·0	2·0	1·8	2·0	1·8
Gutenberg (1958)	0	—	(2·0)	2·0	2·0	1·8	1·8

The change in $dt/d\theta$ with distance in the older observed travel-time curves for *PKIKP* (Table 2) has puzzled many seismologists. This change cannot be explained theoretically. In several instances (e.g. Jeffreys 1938, p. 299) observations of *PKIKP* at distances of less than about 120° have been disregarded. "Even between 120° and 142°·5 the readings are scattered and may not at all refer to the same phenomenon" (Jeffreys 1938, p. 299).

Records of the shock of 1957 April 16, 4:04:04 offer an opportunity to investigate which observed travel times of phases near *PKIKP* belong to one and the same curve on the basis of the form, periods and amplitudes of the respective waves. Figure 2 shows examples of records, Figure 3 gives travel times which are based on readings by the author. Apparently, several wave types, two of them marked by *X* and *Y* respectively, follow the *P* group (*P*, *pP*, *sP*). Others precede *PP*, as it has been discussed by Gutenberg (1960). At distances where *P*, *pP* and *sP* become small, the related later waves also decrease and finally disappear. On the other hand, at the distances where *PKIKP* and *PKP* become large, they are followed by more and more "unexplained" phases (cf. Figure 3). Figure 4 gives examples of such seismograms. The additional phases are better developed on records of short-period instruments than on those of long-period. Figure 4a shows an example of similar unexplained phases following *P*. In many instances such waves are so large and clear that they may lead to misinterpretation of records. Frequently their travel-time curves seem to follow well-defined travel-time curves (cf. Figure 3), but good judgment is needed to discriminate between probable and accidental alignment along reasonable curves. Apparently, in several

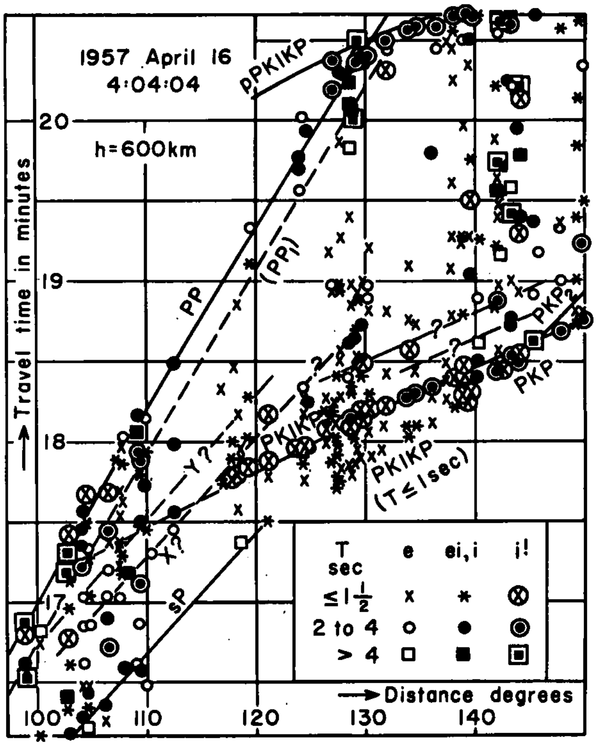

FIG. 3.—Observed travel times and travel-time curves for shock of 1957 April 16, 4: 04: 04, focal depth 600 km.

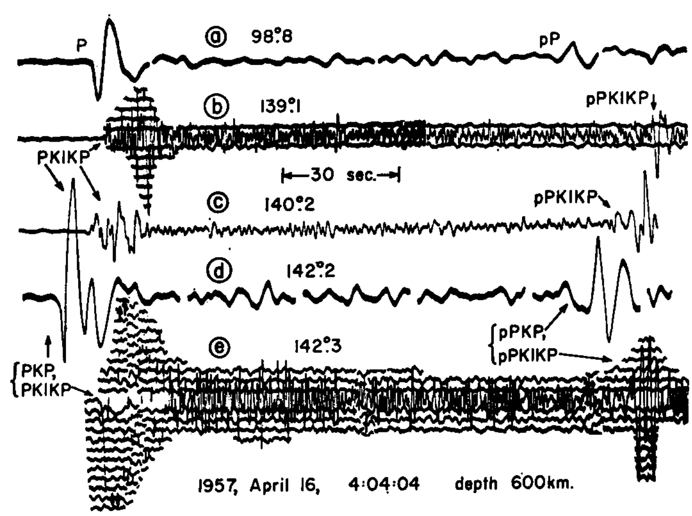

FIG. 4.—Portions of vertical components recorded from the same shock as those in Figure 2. The records, showing multiplicity and unexplained phases, are on the same time scale; (a) shows portion between *P* and *pP* recorded at Stuttgart; (b) to (e) portions between *PKIKP* and *pPKIKP*. The recording stations are (b) Montreal, (c) Lubbock, (d) Florissant, (e) Weston; in (e) the maxima of *PKIKP* and *PKP*, which coincide, are cut off on both sides.

of the travel-time curves for observed *PKIKP* waves (Table 1), the beginning of the curve for *X* (Figures 2 and 3) had been connected with the curve for *PKIKP* at somewhat greater distances. The new observed curve for *PKIKP* corresponds closely to the calculated curve for a focal depth *h* of 600 km.

4. Reasons for unexplained travel-time curves and for motion between established phases

The problem of "multiplicity" of phases on records has been studied already by A. Mohorovičić (1914). Later, Gutenberg & Richter (1934, p. 129) expressed "considerable doubt as to whether the hypothesis of dispersion is adequate to account for the observations". Benioff (oral communication) has found examples of records of near-by shocks from the same source, in which practically every detail of each wave is duplicated. Consequently, for shocks with a simple displacement at the source the whole complicated motion recorded at a given distant station must depend on processes along the path of the waves.

Irregularities in the structure of the Earth which are of the magnitude of the wave lengths involved play a role in the creation of scattered waves following the main phases. Tatel (1954) has pointed out that centres of scattering at a surface may cause conversion from Rayleigh waves to longitudinal waves. "The complex nature of a seismogram can be attributed in part to the interaction of seismic waves with surface irregularities." Moreover, there are various types of diffracted waves which are not found on the basis of the usual wave theory in which terms of second and higher order are neglected. Waves reflected at discontinuities in and near the crust, especially at the Mohorovičić discontinuity, are an additional source of "unexplained" phases (Gutenberg 1960). Another source of multiplicity which has been mentioned already by A. Mohorovičić (1914, p. 157) is provided by the fact that at each discontinuity, especially those in and near the crust, reflected and refracted transverse waves originate, if a longitudinal wave is incident, and vice versa.

As A. Mohorovičić (1914, p. 157) has already pointed out, the establishing of travel-time curves requires the use of original records or good copies so that the individual phases can be studied and compared. Reported arrival times may lead to incorrect conclusions concerning the travel-time curve of a given phase as in the case of the "observed" travel-time curves of *PKIKP*.

Seismological Laboratory,
California Institute of Technology,
Pasadena, California:
1959 *December.*

References

Angenheister, G., 1921. Beobachtungen an pazifischen Beben, *Nachr. Ges. Wiss. Göttingen, Math-Phys. Kl.*, 113–146.

Bolt, B. A., 1959. Travel times of *PKP* up to 145°. *Geophys. J.*, **2**, 190–198.

Denson, M. E., 1952. Longitudinal waves through the Earth's core. *Bull. Seismol. Soc. Amer.*, **42**, 119–134.

Gutenberg, B., 1958a. Wave velocities in the Earth's core. *Bull. Seismol. Soc. Amer.*, **48**, 301–314.

Gutenberg, B., 1958b. Caustics produced by waves through the Earth's core. *Geophys. J.*, **1**, 238–248.

Gutenberg, B., 1959. *Physics of the Earth's Interior* (Academic Press, New York and London).

Gutenberg, B., 1960. Waves reflected at the "surface" of the Earth; *P'P'P'P'*. *Bull. Seismol. Soc. Amer.*, **50**, 71–79.

Gutenberg, B. & Richter, C. F., 1934. On seismic waves, I. *Beitr. Geophys.*, **43**, 56–133.

Gutenberg, B. & Richter, C. F., 1936. Materials for the study of deep-focus earthquakes. *Bull. Seismol. Soc. Amer.*, **26**, 341–390.

Gutenberg, B. & Richter, C. F., 1938. *P'* and the Earth's core. *Mon. Not. R. Astr. Soc. Geophys. Suppl.*, **4**, 363–372.

Gutenberg, B. & Richter, C. F., 1939. On seismic waves, IV. *Beitr. Geophys.*, **54**, 94–136.

Jeffreys, H., 1938. Southern earthquakes and the core waves. *Mon. Not. R. Astr. Soc. Geophys. Suppl.*, **4**, 281–308.

Jeffreys, H., 1939a. The times of the core waves. *Mon. Not. R. Astr. Soc. Geophys. Suppl.*, **4**, 548–561.

Jeffreys, H., 1939b. The times of the core waves (second paper). *Mon. Not. R. Astr. Soc. Geophys. Suppl.*, **4**, 594–615.

Jeffreys, H. & Bullen, K. E., 1940. *Seismological Tables* (Brit. Assoc. Adv. Sci.), 48 pp.

Lehmann, I., 1936. *P'*. *Publ. Bureau Centr. Seismol. Internat., Trav. Sci.*, **14**, 87–115.

Mohorovičić, A., 1914. Hodograph der ersten longitudinalen Wellen eines Bebens. *Jugoslav. Akad. Zagreb, Bull. Trav. Cl. Sci. Math et Naturelles*, **2**, 139–157.

Rudolph, E. & Szirtes, S., 1914. Ueber eine neue Laufzeitkurve (Vorl Mitt.). *Phys. Zeitschr.*, **15**, 737–739.

Tatel, H. E., 1954. Notes on the nature of a seismograph II, *J. Geophys. Res.*, **59**, 289–294.