Reports

Seismic Waves within Earth's Outer Core: Multiple Reflection

Abstract. *Seismic waves reflected as many as four times within Earth's outer core are routinely recorded from large earthquakes. Observations of these waves are confined to rays near grazing incidence on the core-mantle boundary, in agreement with theoretical expectation. Minor adjustments to outer-core velocities may be necessary to account for certain of these arrivals that are not predicted by present core models. A change of 10 kilometers or more in the currently accepted core radius, 3473 kilometers, is not corroborated by the new data.*

An unexpected result of recent study of Earth's core (*1*) was the discovery that, for large earthquakes, phases of the type *PKKP*, *PKKKKP*, and *PKKKKKP* (*2*) are regularly observed at high-magnification stations throughout the world. These data were previously believed to be associated with unlocated aftershocks or other events. I now examine the characteristics and important consequences of these new observations.

The data were drawn from original seismograms and routine station reports for three large events that were well recorded, with strong onsets, by nearly all seismograph stations. These events were relocated, from observations of *P*, *pP*, and *PKP*, by use of a modified version of an earlier computer program (*3*). Table 1 summarizes the adopted hypocenter parameters.

The new observations were first identified from plots of uncorrected arrivals with travel-time curves for the better-known core phases. The methods described by Engdahl *et al.* (*4*) were then used for computation of travel times for the new phases, and the data were corrected for elevation and ellipticity. Ellipticity corrections are calculated by determination of the points of reflection and refraction at the core boundary and by application of materials developed by Bullen (*5*). Corrected data for multiple reflections of the type *PKKP*, *PKKKP*, *PKKKKP*, and *PKKKKKP* are plotted in Fig. 1. Approximately half the data shown were routinely reported as *P* arrivals by observatories throughout the world. When one considers the state of the art it is remarkable that such consistent data have not been previously identified or suggested. Parameters related to the points *A* and *B* (Fig. 1) are listed in Table 2. Figure 2 is an example of a *PKKKKP* arrival, clearly recorded by the Large-Aperture Seismic Array (LASA), from the Novaya Zemlya event.

Examination of Fig. 1 reveals that most of the data are not associated with the cusp *B* as might be expected (*7*), but fall along a line of slope about 4.4 sec/deg that extends to considerable distances beyond the cutoff point *A*. The same slope was determined from the *PKKKKP* phase, recorded by LASA (see Fig. 2), by correlation of wave peaks and troughs between subarray elements.

For aid in interpretation of this phenomenon, reflection coefficients for a *P* wave incident at the core-mantle boundary from within the core were computed for the Bullen B model of Earth. Figure 3 makes it readily apparent that after several core transits little energy is reflected back into the core, with the exception of rays near the critical angle ($i = 36.4$ deg, corresponding to $dT/d\Delta = 4.45$ sec/deg). This result agrees well with the observed data (Fig. 1).

The data occurring beyond the cutoff point *A* remain to be explained. Phinney (*8*) recently presented theoretical considerations suggesting leakage

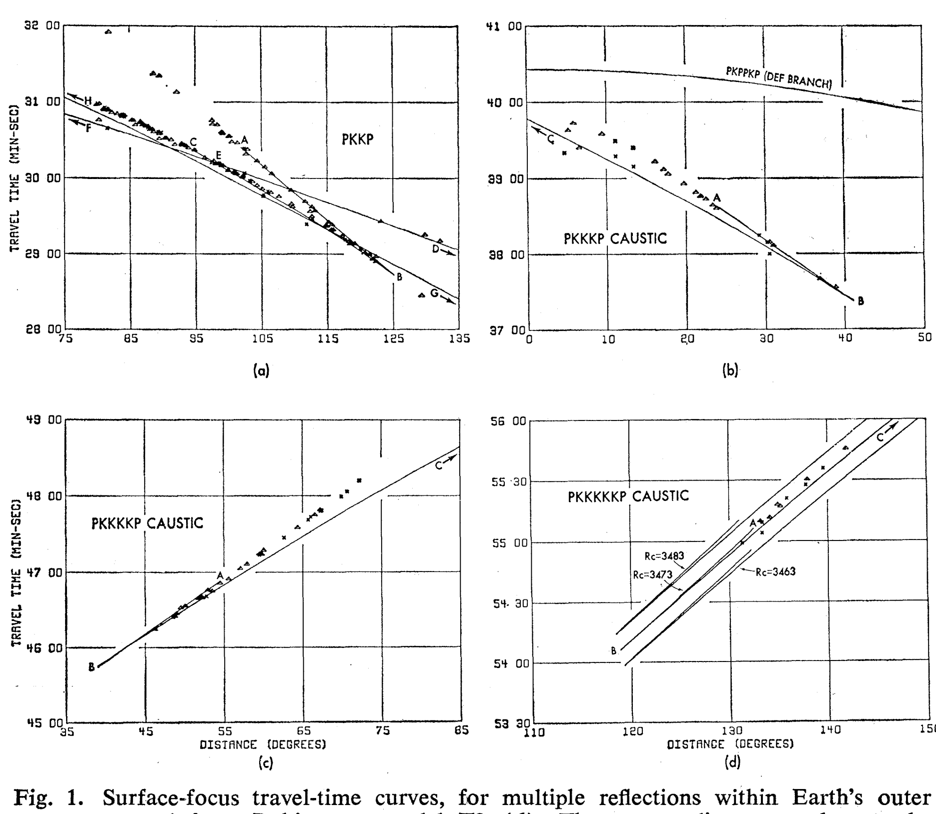
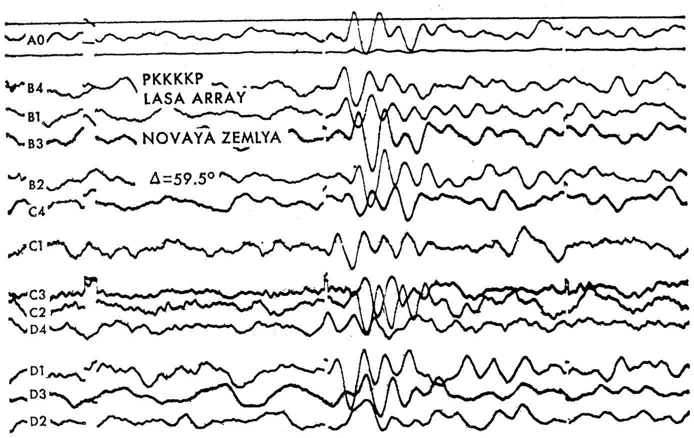


Fig. 1. Surface-focus travel-time curves, for multiple reflections within Earth's outer core, computed from Bolt's core model T2 (*6*). The core radius was taken to be 3473 km unless otherwise indicated. Cusps and other points are identified according to common usage. Data obtained from original seismograms are plotted as triangles. Crosses represent observations derived from other sources. All data have been corrected for elevation and ellipticity, and adjusted to a surface focus.



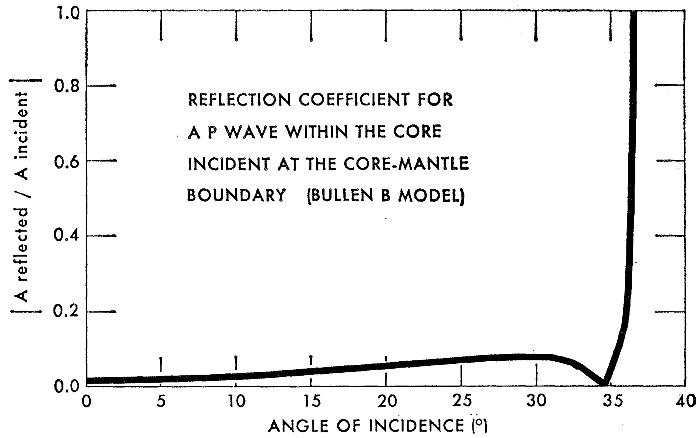


Fig. 2 (left). Recordings by LASA of *PKKKKP* from the Novaya Zemlya event. The marked intervals correspond to 10 seconds; *A0*, *B4*, *B1*, and so on identify subarray elements. Fig. 3 (right). Reflection coefficient as a function of angle of incidence in the core as measured from the vertical.

Table 1. Hypocenter parameters for events used in this study. Depths are based on $pP - P$ differences; magnitudes are after Pasadena (California Institute of Technology). G.M.T., Greenwich Mean Time.

Region	Date	Origin G.M.T. (hr min sec)	Geographic coordinates	Depth (km)	Magnitude
Peru-Brazil border	3 Nov. 1965	013903.3	9.05S,71.34W	590 ± 11	6.75
Fiji Islands	17 Mar. 1966	155033.0	21.12S,179.24W	639 ± 12	6.75
Novaya Zemlya	27 Oct. 1966	055757	73.40N,54.87E	0	6.5

of core-mantle diffracted energy into the core. If such a mechanism were operative within Earth, it could explain these arrivals by diffraction alone. An alternative explanation was sought in terms of changes in the velocity model of the lower mantle or the outer core so as to refract the grazing ray at *A* to greater distances. Trial modifications of the velocities near the core-mantle boundary indicate that either extremely large changes in the lower mantle or only small changes in the outer core could account for many of these arrivals by refraction alone (*9*). Observations of *PKKP*, which were strongly recorded for these events (*10*), tentatively support a combination of these effects. Near *A*, the later arrivals are continuously recorded down to at least 97 deg; at shorter distances the observations are sporadic but consistent in slope.

These new observations have important consequences with respect to the radius of Earth's core. Recent investigators (*11*) have suggested a change of 10 to 30 km in the radius. This change should be observable as a systematic decrease or increase from theoretical travel times, for successive core transits, that is independent of changes that may be needed in the *P* portion of the path. The effect of a variation of ± 10 km in the core radius on travel times of *PKKKKKP* is demonstrated in Fig. 1d. Clearly, for currently accepted velocities of the outer core, these data do not support the suggested changes in core radius.

The degree of scatter in observed data is a measure of the variation in core radius along the core boundary. For the three events studied, points of reflection within the core were widely separated. Thus one may conclude from Fig. 1 that for these data only small variations in core radius are allowable.

These newly identified multiple reflections must now be analyzed in more detail; of particular interest are determinations of new outer-core velocities, a precise value for the radius of the core, and the nature of the core-mantle boundary. Determination of Q in the outer core from observed amplitudes also must be considered. Careful examination of seismograms may reveal even higher multiples of these waves (*12*).

Table 2. Parameters (surface focus) of the cutoff point *A* (grazing incidence at the core-mantle boundary) and the cusp *B* for multiple reflections within the core.

Phase parameters	Travel time T (min sec)	Distance Δ (deg)	$dT/d\Delta$ (sec/deg)
PKKP A	3024.5	101.9	4.45
PKKP B	2842.9	125.1	4.02
PKKKP A	3838.4	23.7	4.45
PKKKP B	3721.6	41.2	4.33
PKKKKP A	4652.3	54.4	4.45
PKKKKP B	4544.5	39.0	4.34
PKKKKKP A	5506.2	132.5	4.45
PKKKKKP B	5406.3	118.9	4.36

ERIC R. ENGDAHL
Environmental Science Services Administration, Coast and Geodetic Survey, Rockville, Maryland 20852

References and Notes

1. E. R. Engdahl, "Core phases and the earth's core," dissertation, Saint Louis University (1968).
2. Symbols *P* and *K* indicate longitudinal waves that have made one passage through Earth's mantle and core, respectively; for possible paths from source to station, they are combined in the order in which respective portions of the ray follow each other.
3. E. R. Engdahl, *Bull. Seismol. Soc. Amer.* **56**, 325 (1966).
4. ——— *et al.*, *ibid.*, in press.
5. K. E. Bullen, *Monthly Notices Roy. Astron. Soc. Geophys. Suppl.* **4**, 317 (1938).
6. B. A. Bolt, *Bull. Seismol. Soc. Amer.* **54**, 191 (1964).
7. K. E. Bullen, *Geophys. J.* **3**, 354 (1960).
8. R. A. Phinney, "Diffraction theory for *PKP*," paper presented at the 49th annual meeting of the American Geophysical Union (1968).
9. A small change in outer-core velocities has a cumulative effect after repeated core transits: for example, a displacement of the point *A* by only 2.5 deg for *PKP* implies a corresponding shift in *A* by 12.5 deg for *PKKKKKP*.
10. A more extensive analysis of the *PKKP* data shown in Fig. 1a has been published (*1*).
11. D. S. Carder, *Bull. Seismol. Soc. Amer.* **54**, 2271 (1964); J. Dorman *et al.*, *Proc. Nat. Acad. Sci. U.S.* **54**, 364 (1965); K. E. Bullen and R. A. W. Haddon, *ibid.* **58**, 846 (1967); F. Press, "Earth structure by Monte Carlo inversion of geophysical data," before the 49th annual meeting of the American Geophysical Union, 1968.
12. Several weak observations corresponding to predicted arrival times of *PKKKKKKP* were also recorded from these events.
13. I thank A. F. Espinosa for critical review of the manuscript and for helpful suggestions; and C. Kisslinger, O. W. Nuttli, and W. V. Stauder for guidance.

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