GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 18, PAGES 3557-3560, SEPTEMBER 15, 2001

Strong seismic scatterers near the core-mantle boundary west of Mexico

Fenglin Niu

Department of Terrestrial Magnetism, Carnegie Institution of Washington, USA

Lianxing Wen

Department of Geosciences, State University of New York at Stony Brook, USA

Abstract. PKP phases observed in Japan show strong precursors with clear onsets for earthquakes that occurred in south America. The onset times of the PKP precursors can all be explained by existence of seismic scatterers in the lowermost 100 km of the mantle west of Mexico, within an area of 200 km × 300 km. Forward modeling of PKP precursor amplitudes indicates that a P-wave velocity variation of at least 6% is required to explain the large amplitudes of the observed PKP precursors, suggesting that the core-mantle boundary region beneath west of Mexico is a highly anomalous region characterized by strong seismic scatterers.

Introduction

PKP precursors are caused by the seismic scattering in the lowermost mantle (Fig. 1) [*Cleary and Haddon*, 1972; *Doornbos and Husebye*, 1972; *Haddon and Cleary*, 1974; *Husebye et al.*, 1976]. These scatterers could be heterogeneities of seismic velocities and density, core-mantle boundary (CMB) topography, or both. PKP precursors provide an ideal dataset to identify seismic scatterers in the lowermost mantle and constrain their detailed seismic structures. Arrival times of PKP precursors are directly related to the location of seismic scatterers, and the amplitudes of the PKP precursors are associated with the geometry and magnitude of the seismic heterogeneities. Analyses of PKP precursors provide us a unique opportunity to map seismic "scatterers" in the lowermost mantle, and have yielded many insights into the seismic structure of the lowermost mantle [*Hedlin et al.*, 1997; *Vidale and Hedlin*, 1998; *Wen and Helmberger*, 1998b]. However, it is impossible to distinguish between the source-side scattering and receiver-side scattering from a single seismogram, as PKP precursors can be caused by seismic scattering beneath both the source or/and the receiver [*Cleary and Haddon*, 1972; *Doornbos and Husebye*, 1972; *Haddon and Cleary*, 1974; *Husebye et al.*, 1976; *Hedlin et al.*, 1997; *Vidale and Hedlin*, 1998; *Wen and Helmberger*, 1998b] (Fig. 1). Same is also true for the great-circle scattering and the off great circle scattering. Nevertheless, one can potentially determine the location of seismic scatterers in a good certainty using seismic observations recorded in dense seismic arrays. For example, Wen (2000) develops a migration technique to determine the seismic scatterers using the arrival times of PKP precursors. He shows that the precursor onsets, observed in a dense seismic array in Tanzania, can be best explained by an isolated seismic scatterer beneath the Comoros hotspot.

In this study, we report strong PKP precursors observed in the dense seismic array in Japan for earthquakes occurred in the South America (Fig. 2). We adopt the migration technique suggested by Wen (2000) to determine the location of the seismic scatterers in the lowermost mantle. We then apply forward modeling of precursor amplitudes to place bounds on the magnitude of the seismic anomalies.

PKP Precursors Observed at the J-array

There are more than 400 short-period seismic stations deployed over the Japanese islands. This dense seismic network (known as the J-array [*J-Array Group*, 1993]) records PKP precursors at the epicentral distance range of 120°∼ 145° from the intermediate and deep earthquakes occurred in the South America (Fig. 2). We searched the South American events occurred from 1990 to 1999, and chose 4 high-quality events for analysis (Table 1). The data selection is based on the signal-to-noise ratio of a seismogram, and only those seismograms with low noise are used.

The PKP precursors observed at the J-array show large amplitudes compared to the global average [*Wen and Helmberger*, 1998c; *Hedlin and Shearer*, 2000] and exhibit clear onsets. In Fig. 3, we show an example of PKP seismograms recorded by the J-array for event 07/13/92. We hand-pick the onsets of both the PKP precursors and the PKPdf phase. The precursor onsets are usually several seconds late compared to the earliest predicted arrivals based on the random scatterer models [*Haddon and Cleary*, 1974; *Husebye et al.*, 1976] (Fig. 3). Seismic scatterers are therefore not homogeneously distributed beneath the sources and receivers.

Mapping Seismic Scatterers from PKP Precursors

We adopt the technique developed in Wen (2000) to determine the location of the seismic scatterers from the travel time of PKP precursors and perform forward modeling of precursor amplitude to constrain the magnitude of the seismic scatterers.

Here we briefly review the method used in Wen (2000) to locate seismic scatterers based on the PKP precursor onsets. For an assumed depth of seismic scattering, PKP precursor energy arriving at a certain time can be attributed to scatterers located along the two "isotime scatterer arcs" (blue arcs, Fig. 4a) in both the source- and the receiver-side of

Paper number 2001GL013270.
0094-8276/01/2001GL013270$05.00

Table 1. Event list

Date *(y m dy)*	Time *(h min s)*	Lat. *deg.*	Lon. *deg.*	Depth *km*	Mag. *Mw*
1991 04 09	06 02 25.3	-9.83	-74.78	135.0	5.8
1992 07 13	18 11 34.0	-3.92	-76.63	100.0	6.3
1997 03 25	16 44 32.6	-9.06	-71.29	603.0	6.0
1999 04 26	18 17 25.0	-1.70	-77.70	174.0	5.9

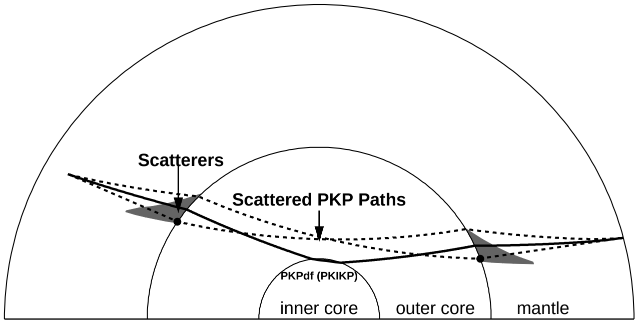

Figure 1. Ray paths of PKP precursors and PKIKP phase at a distance of 135° for a 500 km deep source. P waves can be deflected to the outer core by seismic scatterers in the lower mantle beneath source or/and the receiver, and precede the PKIKP phase. The shaded regions indicate seismic scatterers in the great-circle plane, which would produce seismic waves arriving earlier than the PKPdf phase.

the mantle. A precursor closer to the PKP arrival in time corresponds to "isotime scatterer arcs" closer to the source and the receiver in geographic location. As we mentioned before, for a single PKP observation, it is impossible to distinguish between the scattering from source-side mantle and that from receiver-side mantle; same is also true for scattering from the great-circle path and that from the off-great circle path. However, using dense seismic observations, one can potentially locate the seismic scatterers. If the precursors observed at an array of seismic stations are caused by the same seismic scatterers in the lower mantle, these "isotime scatterer arcs" will overlay at the location(s), where the seismic scattering energy originates.

We discretize sampling regions into grids and test different depths of seismic scattering. For one assumed depth of scattering, we calculate "scatterer probability" and "hit counts" for every grid. The "scatterer probability" is calculated following these procedures: 1) a unit value is assigned to a grid if the grid is situated in the "isotime scatterer arc" of the precursor energy. Zero value is given otherwise; 2) while all seismic observations are considered together and their sampling patches overlay, grid values are averaged. "Probability" at one grid can be interpreted as the ratio of the number of seismic observations whose PKP precursor energy sample the grid over the total number of seismic observations used in the study. The "hit count" at one grid is simply the total number of PKP precursors sampling the grid. The grid(s) with the highest "scatterer probability" and a large "hit count" is (are) considered to be the most probable location(s) where the PKP precursor onset energy originates.

Results and Discussion

The two possible regions which could cause the strong PKP precursors from the source-receiver geometry are the lowermost mantle beneath west of Mexico and the Kuril islands region. We divide these two region by 2° x 2° blocks after taking into account of the uncertainties due to a possible time pick error. In general, PKPdf phases recorded by the J-array can be hand picked in a good certainty with an accuracy less than 1 second (Fig. 3), as we selected the data only for intermediate and deep earthquakes. A 1 second error of time pick will result in uncertainties in geographic location at the CMB of about 36 km for a receiver at 131° and about 180 km for a receiver at 140°.

Only the onsets of the PKP precursors are used to locate the seismic scatterers for following reasons: 1) all observations show clear onsets; 2) the late arrivals following the precursor onsets could be resulted from scattering of the first arrival by shallow seismic heterogeneities; 3) in order to effectively utilize the energy following the onsets, a complete knowledge of source time function is required. The source effects are, however, difficult to remove at high frequencies. The advantage of this approach is that we can identify seismic scatterers in a good confidence. The trade-off is that we could potentially miss some scatterers by discarding the energy following the onsets.

The "scatterer probability" and "hit counts" are calculated at assumed depths of 0, 30, 50, 100, 500 kilometers above the CMB. We present results of "scatterer probability" and "hit counts" for two assumed depths of seismic scattering: the CMB (Fig. 4b-e) and 100 km above the

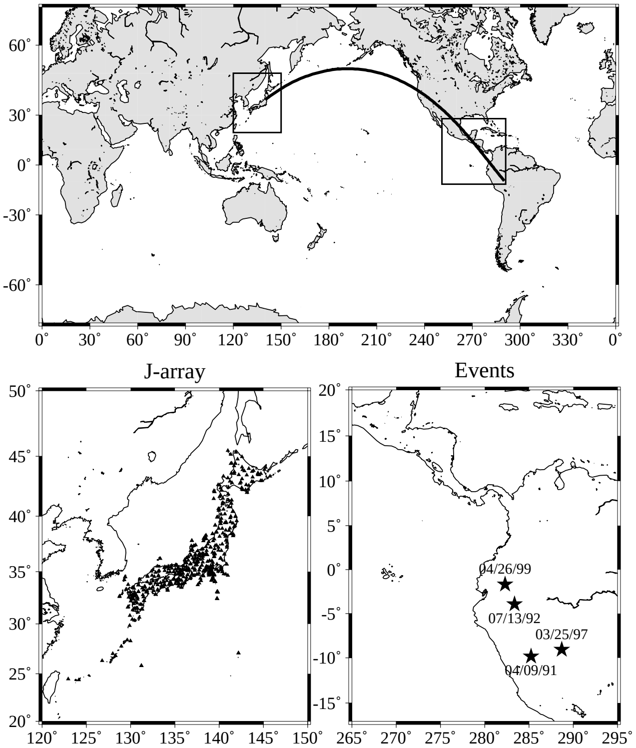

Figure 2. (*top*) Geographic relationship between the J-array and the events used in this study. Great-circle path is shown by a solid line; (*bottom*) Geographic distribution of the J-array stations and four events are shown in the left and the right, respectively.

CMB (Fig. 4f-i). The observed precursor onsets can be best explained by the seismic scattering near the core-mantle boundary west coast of Mexico (blue cluster in the center of the Fig. 4b), as this region has large values of both "scatterer probability" and "hit counts". The "scatterer probability" decreases as the assuming depth of scattering decreases from the CMB and becomes insignificant at assumed scattering depths $\geq$100 km above the CMB (Fig. 4f), suggesting that the scatterer is confined within the lowermost 100 km of the mantle. The highest "scatterer probability" for $2° \times 2°$ grids is about 0.8 (Fig. 4b). However, if we expand the region to the adjacent block, the "scatterer probability" reaches 1. In another word, all the observed precursor onsets can be explained if the seismic scatterers are distributed in the region outlined in white in Fig. 4b, with a dimension of 300 km × 200 km. On the other hand, the "scatterer probability" is low for all depths of scattering in the the receiver-side mantle (Fig. 4c, 4g), suggesting that the observed precursors are not likely caused by seismic scattering in the receiver-side mantle.

To place bounds on the magnitude of seismic heterogeneity, we search seismic structures with various wavelengths (5-120 km) and geometries (random distribution, ridge-shaped, sinusoid-shaped, Gaussian-shaped, triangle-shaped) for the maximum scattering to match the largest observed precursor. We use the hybrid method developed by Wen and Helmberger (1998a) for synthetic calculations. Synthetic calculations suggest that a P-wave velocity variation of at least 6% is required to produce the largest amplitude of PKP precursors observed at the J-array. Our calculations also suggest that the observed large precursors are less likely caused by the topography of the CMB alone, as a very large (4 km) topography is required.

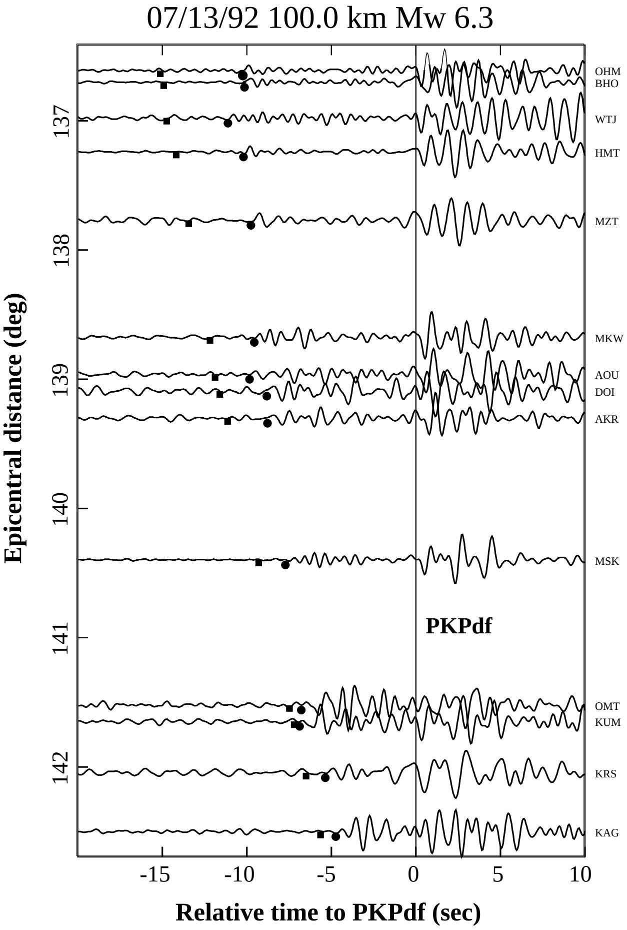

Figure 3. An example of part of PKP precursors and PKP phases observed in the J-array for event 07/13/92. Each trace is aligned along with the hand-picked PKIKP phase (t=0). The hand-picked precursor onsets and the first arrivals predicted by random scattering model are indicated by circles and squares, respectively.

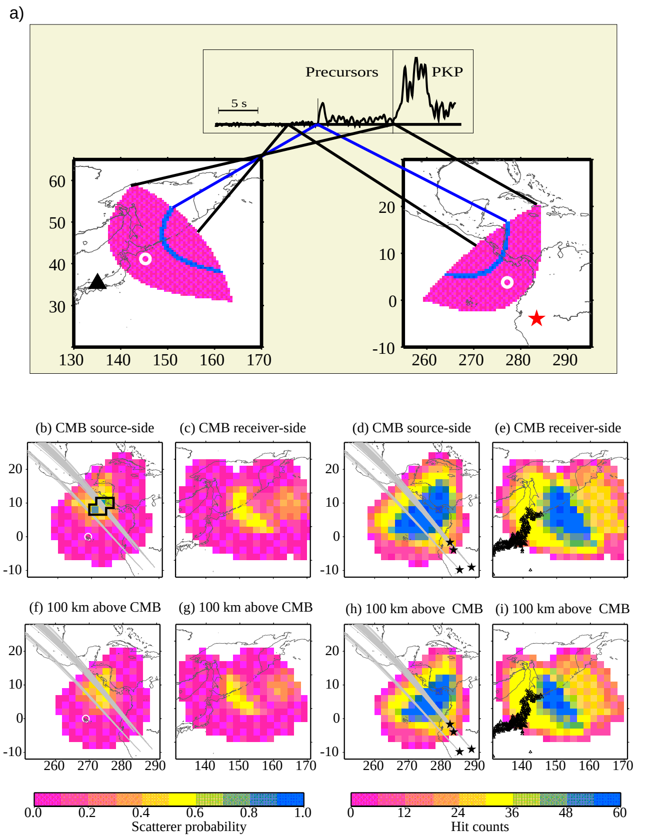

Figure 4. (*a*)Migration technique using arrival times of PKP precursors to locate seismic scatterers in the lower mantle. The energy envelope of an observed vertical component of seismogram is shown in the middle of the figure. For an assumed depth of seismic scattering (the CMB in this example), the perspective scatterers producing the precursor onset energy are located in two blue arcs in the mantle beneath the source and the receiver. The precursor energy and the geographic locations of its associated perspective scatterers are connected by lines. Star and triangle represent event and station, respectively. White circles indicate hit points of the PKPdf ray at the CMB. Maps of "scatterer probability" (*b, c, f, g*) and "hit counts" (*d, e, h, i*) (see text for explanation). Two depths of seismic scattering are assumed: the CMB (top row) and 100 km above the CMB (bottom row). The region outlined in black indicates recognized seismic scatterers. The Galapagos hotspot is indicated by a white circle. The stars and triangles represent events and stations, respectively. The grey dashed lines are great-circle paths. Iasp91 [*Kennett and Engdahl*, 1991] is used as the reference model.

The seismic scatterers might be related to the low-velocity layer observed in the same region by Revenaugh and Meyer (1997), who suggest partial melt may be present. The intensity of seismic scattering observed here is also comparable to those observed in the CMB region north of Tonga [*Vi-*

dale and Hedlin, 1998; *Wen and Helmberger*, 1998b]. However, we should emphasize that our observed short period PKP precursors could also be equally well explained by the scattering of a high-velocity anomaly.

Conclusion

We observe strong PKP precursors with clear onsets in the J-array for earthquakes occurred in south America. We use the travel time of the PKP precursor onsets to determine the location of seismic scatterer and perform forward modeling of precursor amplitude to constrain the magnitude of the seismic scatterers. The travel time analysis indicates that the PKP precursor onset times can all be explained by existence of seismic scatterers in the lowermost 100 km of the mantle west of Mexico, within an area of 200 km × 300 km. Forward modeling of PKP precursor amplitudes indicates that a P-wave velocity variation of at least 6% is required to explain the large amplitudes of the observed PKP precursors, suggesting that the core-mantle boundary region beneath west of Mexico is a highly anomalous region, characterized with strong seismic scatterers.

Acknowledgments. We thank the J-array Data Center for providing the data, M. Hedlin and another anonymous reviewer for constructive reviews. This work is supported by a fellowship of Carnegie Institution of Washington and an NSF grant EAR0001232.

References

Cleary, J. R., and R. A. Haddon, Seismic wave scattering near the core-mantle boundary: a new interpretation of precursors to PKP, *Nature, 240*, 549-551, 1972.

Doornbos, D. J., and E. S. Husebye, Array analysis of pkp phases and their precursors, *Phys. Earth Planet. Inter., 5*, 387-399, 1972.

Haddon, R. A., and J. R. Cleary, Evidence for scattering of seismic PKP waves near the core-mantle boundary, *Phys. Earth Planet. Inter., 8*, 211-234, 1974.

Hedlin, M. A. H., P. M. Shearer, and P. S. Earle, Seismic evidence for small-scale heterogeneity throughout the Earth's mantle, *Nature, 387*, 145-150, 1997.

Hedlin, M. A. H., P. M. Shearer, An analysis of large scale variations in small-scale mantle heterogeneity using GSN recordings of precursors to PKP, *J. Geophys. Res., 105*, 13,655-13,673, 2000

Husebye, E. S., D. W. King, and R. A. Haddon, Precursors to PKIKP and seismic wave scattering near the mantl-core boundary, *J. Geophys. Res., 81*, 1870-1882, 1976.

J-Array Group, The J-Array program: system and present status, *J. Geomag. Geoelectr., 45*, 1,265-1,274, 1993.

Kennett, B. L. N., and E. R. Engdahl, Travel times for global earthquake location and phase identification, *Geophys. J. Int., 105*, 429-465, 1991.

Revenaugh, J., and R. Meyer, Seismic Evidence of the Partial Melt Within a Possibly Ubiquitous Low-Velocity Layer at the Base of the Mantle, *Science, 277*, 670-673, 1997.

Vidale, J. E., and M. A. H. Hedlin, Evidence for partial melt at the core-mantle boundary north of Tonga from strong scattering of seismic waves, *Nature, 391*, 682-684, 1998.

Wen, L., and D. V. Helmberger, A 2-D P-SV hybrid method and its application to modeling localized structures near the core-mantle boundary, *J. Geophys. Res., 103*, 17,901-17,918, 1998a.

Wen, L., and D. V. Helmberger, Ultra low velocity zones near the core-mantle boundary from broadband PKP precursors, *Science, 279*, 1,701-1,703, 1998b.

Wen, L., and D. V. Helmberger, The core-mantle boundary revealed from PKP precursors, *EOS, 79*, S71, 1998c.

Wen, L., Intense seismic scattering near the core-mantle boundary beneath the Comoros hotspot, *Geophys. Res. Lett., 27*, 3627-3630, 2000.

Fenglin Niu, Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road, N.W., Washington, DC 20015, USA (email: niu@dtm.ciw.edu)

Lianxing Wen, Department of Geosciences, State University of New York at Stony Brook, Stony Brook, NY 11794, USA (email: Lianxing.Wen@sunysb.edu)

(Received April 2, 2001; revised June 20, 2001;
accepted July 5, 2001.)