Intense seismic scattering near the Earth's core-mantle boundary beneath the Comoros hotspot

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Abstract. I report strong seismic PKP precursors recorded in the seismic stations in Tanzania for earthquakes occurred in the Fiji subduction zone. The observed PKP precursors show clear onsets and rapid variations of amplitude for different events and stations. I develop a technique to use the precursor onset times to determine the location of seismic scatterers and apply forward modeling of precursor amplitudes to place constraints on the magnitude of seismic anomalies. The travel time analysis indicates that these recorded PKP precursors are caused by the seismic scattering in the lowermost 360 km of the mantle beneath the Comoros hotspot. The amplitudes of the observed PKP precursors suggest a rather complex seismic structure with a P velocity variation of at least 8%, likely associated with partial melt.

PKP Precursor

At epicentral distances between 120^0-144^0, the first arrival is the seismic PKP wave (PKIKP or PKPdf), which turns into the Earth's inner-core (Fig. 1). For a radially symmetric Earth model, there is no geometric arrival possible from the outer-core because of the shadow zone resulting from the P wave velocity decrease from the mantle to the core. However, if seismic waves are scattered by three-dimensional seismic heterogeneities in the lower mantle, some of this scattered energy could propagate through the outer-core and precede the seismic phase PKP (Fig. 1). These PKP precursors can be used to constrain small-scale seismic heterogeneities in the mantle [*Cleary and Haddon*, 1972; *Doornbos and Husebye*, 1972; *Haddon and Cleary*, 1974; *Husebye et al.*, 1976; *Bataille and Flatte*, 1988; *Cormier*, 1995; *Hedlin et al.*, 1997; *Vidale and Hedlin*, 1998; *Wen and Helmberger*, 1998b]. The arrival time of the precursor depends on radial and lateral locations of the scatterer and the amplitude of the precursor is controlled by magnitude and distribution of the seismic heterogeneity.

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Seismic Data

I collect all available PKP data recorded in a Tanzania regional seismic network deployed between 1994-1995 and in a permanent seismic station KMBO of the Global Seismic Network since its deployment in 1996 for earthquakes occurred in the Fiji subduction zone (Table 1). In this study, only the PKP phases recorded at the distance range of 131^0-141^0 and at the frequency band of 0.8 - 2 Hz are used. PKP precursors at closer distances are insensitive to seismic scattering in the deep mantle and those recorded at larger distances would be affected by the energy from the PKP caustics. All observed PKP phases show strong precursors with clear onsets. One example of the observed PKP displacements is shown in Fig. 2. The relative amplitudes of PKP precursors with respect to the PKP phases are highly varying from station to station and from event to event (Fig. 2). The amplitudes of the PKP precursors here, especially those for event 950117, are similar to those observed in the NORSAR array in Norway [*Vidale and Hedlin*, 1998] and at stations TAB and UME of the Global Seismic Network [*Wen and Helmberger*, 1998b] for earthquakes in the Fiji subduction zone. These observations are distinct from the stacks of global PKP precursors, which show a gradual onset and a small amplitude of the precursor energy [*Hedlin et al.*, 1997] (c.f., for example, the observation at KIBE from
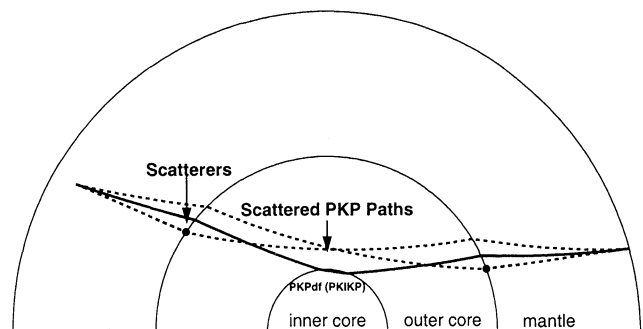

Figure 1. Raypaths of PKPdf (PKIKP) and its precursors at a distance of 135^0. PKPdf is the P wave propagating through the inner core. Seismic P wave could be deflected by the seismic scatterers in the lower mantle beneath the source or/and the receiver. The shaded regions indicate the scatterers in the great-circle path, which will produce seismic arrivals before the PKPdf phase. The reference model is PREM [*Dziewonski and Anderson*, 1981] and the source depth is 500 km.

Table 1. Event List

No.	origin	lat	lon	depth(km)
941218	94/12/18 20:38	-17.86	-178.69	551
941219	94/12/19 17:41	-17.83	-178.66	578
941227	94/12/27 17:32	-32.00	179.87	228
950117	95/01/17 16:54	-20.87	-179.23	637
960805	96/08/05 22:38	-20.69	-178.31	550
970904	97/09/04 04:26	-26.57	178.34	625
970920	97/09/20 16:11	-26.68	177.62	30
980414	98/04/14 03:41	-23.82	-179.87	499
981227	98/12/27 00:38	-21.63	-176.38	144
990306	99/03/06 20:28	-21.73	-179.47	603
990413	99/04/13 10:38	-21.42	-176.46	164

event 950117, Fig. 2). Global surveys also observe weak PKP precursors in most regions of the Earth [*Wen and Helmberger*, 1998c; *Hedlin and Shearer*, 2000].

Seismic Techniques

I develop a technique to determine the location of the seismic scatterers from the travel time of PKP precursors and adopt forward modeling of precursor amplitude to constrain the magnitude of the seismic scatterers. It
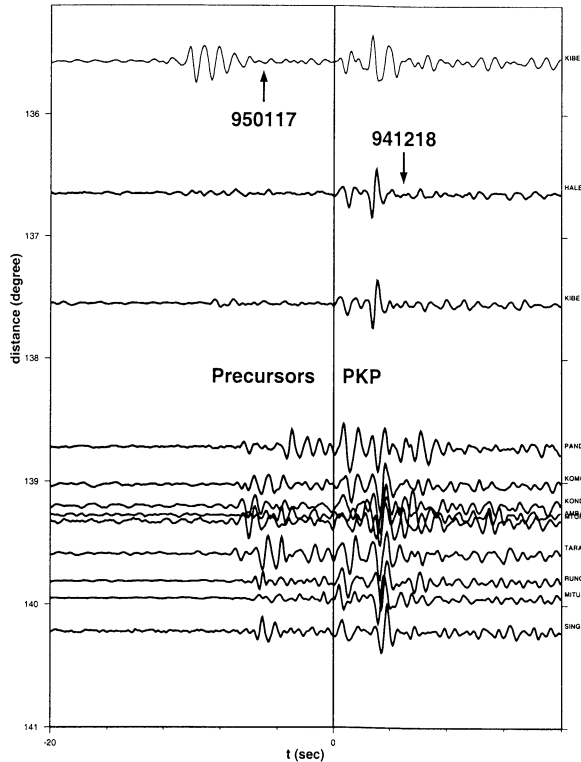

Figure 2. An example of vertical displacements of PKP precursors and PKP phases observed in the Tanzania seismic array. All observations recorded for event 941218 (heavy traces) are shown and the recording at KIBE station for event 951017 (light trace) is also presented to contrast with its observation for event 941218. Each trace is aligned along with the hand-picked PKIKP phase (t=0). All traces are filtered with the band-pass from 0.8 to 2 Hz.

is clear that PKP precursors can be caused by seismic scattering in the mantle beneath both the source and the receiver (Fig. 1). For PKP precursor energy arriving at a certain time, assuming a certain depth of scattering, the perspective seismic scatterers for producing the precursor energy are located along two arcs (for example, blue arcs, Fig. 3a) in both the source- and the receiver-side of the mantle. I term these arcs "isotime scatterer arcs". The energy closer to the PKP arrival in time corresponds with the "isotime scatterer arcs" closer to the source and the receiver in geographic location (Fig. 3a). For a single PKP observation, it is
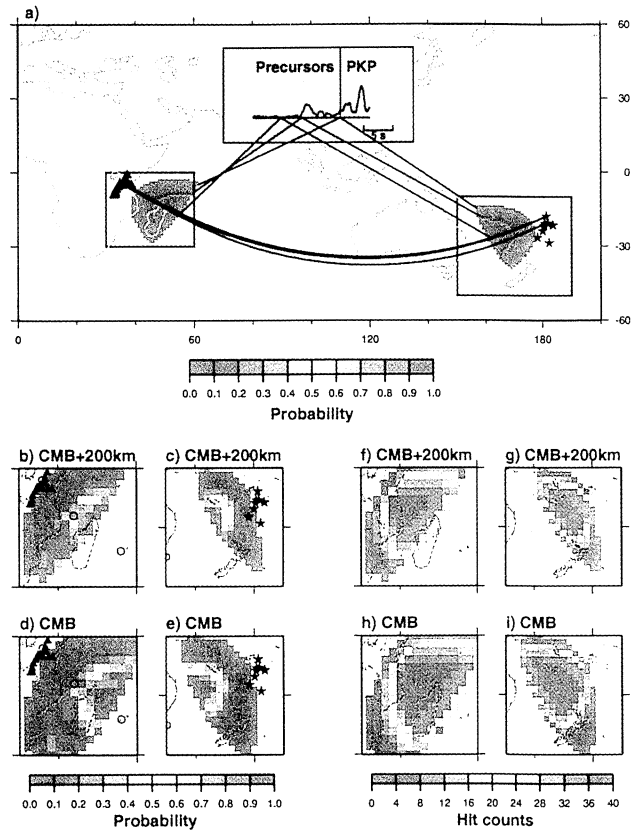

Figure 3. a) Technique using arrival times of PKP precursors to locate seismic scatterers in the lower mantle. The energy envelop of an observed vertical seismogram is shown in the middle of the figure. The great-circle path of this example PKP phase is also shown in the figure. The perspective scatterers producing the precursor onset energy are located in two "isotime scatterer arcs" (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. The core-mantle boundary scattering is assumed in this example. Stars and triangles represent events and stations used in this study. Two boxes indicate two sampling regions, with detailed results shown in Figs. 3b-3i; b-e) probability of existence of seismic scatterers in the lowermost mantle; and, f-i) number of seismograms sampling the region. Two depths of seismic scattering are assumed: the core-mantle boundary (d-e,h-i) and 200 km above the core-mantle boundary (b-c,f-g). Open-circles are locations of hotspots. Note that the "isotime scatterer arcs" overlay at the location near (d) or just beneath (b) the Comoros hotspot.

impossible to distinguish between the scattering from source-side mantle and that from receive-side mantle; same is also true for scattering from the great-circle path and that from the off-great circle path. However, using a dense seismic array, one can potentially locate 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.

Only the onsets of the PKP precursors are used to locate the seismic scatterers for following reasons: 1) all observations show clear onsets and most observations have little energy following the first arrival; 2) the energy following the precursor onset could be the result of scattering of the first arrival in the shallow mantle rather than that of the seismic P waves in the deep mantle; 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 quantify and remove at high frequency. The advantage of this approach is that we can identify seismic scatterers in a complete certainty. The trade-off is that we could potentially miss some scatterers by discarding the energy following the onsets. For this particular dataset, the advantage overwhelms the trade-off, as the energy following the first arrival is usually small for most of the observations.

Seismic Results

The sampling regions are located in the lowermost mantle east of Australia and east of southern Africa (Fig. 3). For a PKP recording, there are two sampling patches, with each in one of these two regions. I discretize these two regions into grids and test different depths of seismic scattering. For one assumed depth of scattering, I calculate "probability" and "hit count" for every grid. The "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 onset. 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 onsets sample the grid over the total number of seismic observations used in the study. For example, a "probability" value 1 at one grid means all observed precursor onsets sample this grid. The "hit count" at one grid is simply the total number of PKP precursors sampling the grid. The grid(s) with the highest "probability" and a large "hit count" are considered to be the most probable location(s) where the PKP precursor onsets originate. Grid scheme is chosen according to the uncertainties in determining the timing between the precursor onsets and the PKP arrivals. The estimated uncertainty in time

picks of PKP phase and PKP precursor onset is 0.5-1 second. The uncertainty of geographic location associated with this travel time uncertainty depends on the epicentral distance of the receiver and the depth of seismic scattering. A 0.5 second error of time pick in the recording will result in uncertainties in geographic location at the core-mantle boundary of about 18 km for a receiver at 131^0 and about 100 km for a receiver at 141^0. A grid scheme of $2^0 \times 2^0$ is used in consideration of these uncertainties. I present results for two assumed depths of seismic scattering: the core-mantle boundary (Figs. 3d-3e, 3h-3i) and 200 km above the core-mantle boundary (Figs. 3b-3c, 3f-3g). The most probable geographic location of the scatterer varies from 120 km east of the Comoros hotspot for scattering at the core-mantle boundary (Fig. 3d) to just beneath the Comoros hotspot for scattering at 200 km above the core-mantle boundary (Fig. 3b). The regions around the Comoros hotspot are well sampled by the PKP observations for both depths of seismic scattering (Figs. 3f,3h). In order to explain all the precursor onsets of the observations, the seismic scatterers must lie within the bottom 360 km of the lowermost mantle and within a distance of 120 km around the Comoros hotspot for all depths of seismic scattering.

While the onsets of the precursors can be accurately tracked back to the location of the Comoros hotspot in the lowermost mantle, it becomes difficult to use the precursor amplitudes to constrain the magnitude of seismic heterogeneities. These highly varying amplitudes suggest that seismic waves encounter a rather complex seismic structure in the lowermost mantle beneath the Comoros hotspot. Because the PKIKP phase could be affected by possible seismic scattering or attenuation inside the inner-core [Cormier et al., 1999; Vidale and Earle, 2000], PKiKP phase is used as the reference phase. The amplitude of PKP precursors is affected by many characteristics of seismic scatterers: magnitude, wavelength, and geometry. Seismic scatterers with a large velocity perturbation may still produce weak precursors, if seismic precursors sample the seismic structures in a less optimal geometry. To place bounds on the magnitude of the seismic heterogeneity, I use the largest observed precursor (top trace, Fig. 2) and search seismic structures with various wavelengths (5-120 km) and geometries (random distribution, dome-shaped, sinusoid-shaped, Gaussian-shaped, triangle-shaped) for the maximum reflections. Forward calculations are performed by applying the hybrid method [Wen and Helmberger, 1998a]. The possibility of scattering due to the topography of the core-mantle boundary is also tested [Doornbos, 1978]. A 5 km topography of the core-mantle boundary is required to produce the observed PKP precursor energy. This magnitude of the core-mantle boundary topography does unlikely exist alone without the presence of anomalous seismic structure above. Numerical calculations indicate that a P velocity variation of at least

8% is required to produce scattering energy observed at station KIBE from event 950117. This magnitude of P wave velocity variation is likely involved with partial melt [*Williams and Garnero*, 1996].

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