

Observation of near-podal P'P' precursors: Evidence for back scattering from the 150–220 km zone in the Earth's upper mantle

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[1] P'P' (PKPPKP) are P waves that travel from a hypocenter through the Earth's core, reflect from the free surface and travel back through the core to a recording station on the surface. Here we report the observations of hitherto unobserved near-podal P'P' waves (at epicentral distance $<10^\circ$) and very prominent precursors preceding the main energy by as much as 60 s. We interpret these precursors as a back-scattered energy from horizontally connected small-scale heterogeneity in the upper mantle beneath the oceans in a zone between 150 and 220 km depth beneath the Earth's surface. From these observations, we identify a frequency dependence of attenuation quality factor Q in the lithosphere through forward modeling of the observed amplitude spectra of the main and back-scattered P'P' waves. **Citation:** Tkalčić, H., M. P. Flanagan, and V. F. Cormier (2006), Observation of near-podal P'P' precursors: Evidence for back scattering from the 150–220 km zone in the Earth's upper mantle, *Geophys. Res. Lett.*, 33, L03305, doi:10.1029/2005GL024626.

1. Introduction

[2] Precursors to P'P' at epicentral distances of about 50° – 70° were observed and reported first in the 1960's as small-amplitude arrivals on seismograms [Gutenberg, 1960]. Most prominent of P'P' precursors were explained by waves generated by earthquakes or explosions that did not reach the Earth's surface but were reflected from the underside of first order velocity discontinuities at 410 and 660 km in the upper mantle [Adams, 1968; Engdahl and Flinn, 1969; Whitcomb and Anderson, 1970; Richards, 1972]. Since the time of these pioneering studies, numerous examples of precursors to P'P' have been reported [e.g., Davis *et al.*, 1989], indicating that structure of the upper mantle was not uniformly smooth.

[3] A scattering hypothesis [e.g., Cleary and Haddon, 1972; Haddon *et al.*, 1977; Cleary, 1981] for the origin of the P'P' precursors, however, soon cast considerable doubt on the hypothesis of underside reflection from radial discontinuities. Forward scattering from small-scale (10–100 km) heterogeneities in the lowermost and uppermost mantle could explain the combined behavior of the frequency content, angle of approach, and complexity of the P'P' precursors, accounting for a majority of the observed P'P'

and PKP precursor observations. P'P' precursors whose arrival times corresponded to possible reflections from radial discontinuities at shallower depths in the mantle (<220 km) were hence dismissed as the effects of either scattering in the lowermost mantle or distributed heterogeneity in the uppermost mantle [Haddon *et al.*, 1977].

2. Observation of Near-Podal P'P' Precursors

[4] A common characteristic of early observations of P'P' and their precursors was that they were mostly assembled at epicentral distances of about 50° – 70° , which can be explained by the fact that a maximum amplitude of PKP waves due to a triplication occurs between 145° and 155° . Unlike the majority of these earlier observations of P'P' precursors, we report unprecedented observations at near-podal epicentral distances ($<10^\circ$) of highly energetic P'P' precursor arrivals (Figures 1a, 1b). This is a result of a systematic and thorough search for podal P'P' arrivals from waveforms available through the IRIS data center, for both individual and array stations [Tkalčić and Flanagan, 2004].

[5] An example of P'P' precursor observations at the short-period ILAR array in Alaska is illustrated in Figure 2. Vertical components for two band-pass filters: a) 0.2–0.7 Hz and b) 1.0–1.5 Hz are shown. The event was located in the southern Alaska, about 7 degrees away from ILAR array (Figure 1c). At 0.2–0.7 Hz, the main P'P' and the precursor arrivals of energy are visible at all ILAR stations. The main P'P' phase arrives within ± 1 second as predicted by ak135 model [Kennett *et al.*, 1995] and even with up to 2 second error due to possible event mislocation, there are no other seismic phases arriving within this time window that could cause misinterpretation. At 1.0–1.5 Hz, the energy of the main phase is below noise level, but energetic signals of the precursors persist. The precursor energy is visible up to 3Hz, which motivates us to take a closer look at properties such as scattering and attenuation along a P'P' ray-path.

3. Interpretation of Near-Podal P'P' Precursors

[6] Scattering of P'P' waves can occur anywhere along the ray path beneath the receiver, core-mantle boundary, inner-core boundary, or antipodal bounce point area. If P'P' waves were forward-scattered, simple travel time calculations reveal that all forward scattering would arrive as energy following P'P' rather than as a precursor. This is a distinguishing property of near-podal geometry and is true regardless of the location or distribution of scatterers in the mantle. For some strong velocity anomalies concentrated near the receiver, it is possible to create some P'P' precursors, but they would arrive with very different slowness

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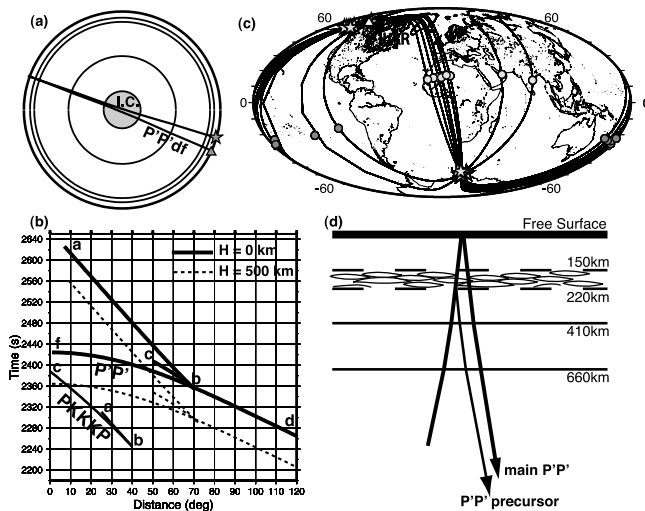


Figure 1. (a) Ray-path of podal P'P'df waves connecting the source (star) with the receiver (triangle). (b) Theoretical travel time curves of P'P' from sources at 0 and 500 km depth using ak135 [Kennett et al., 1995] are shown by solid and dashed lines, respectively. The P'P'df branch corresponds to the waves bottoming in the inner core. PKKKP waves could be observed in the same epicentral distance range preceding P'P'df waves with significantly different slowness. (c) Surface projections of ray-paths for the events in Alaska (stars) for which we observe P'P' precursors on ILAR array (triangle). Stars in the Southern Hemisphere are bounce points near the antipode; circles are surface projections of the corresponding bottoming points in the inner core (one at source and another at receiver side). (d) Schematic representation of the reflection of P'P' waves in the antipodal mantle. Back scattering originates in a zone between 150 and 220 km in the upper mantle.

than the main P'P' phase (additional information in auxiliary material¹).

[7] It is highly unlikely for our observations that a specific near-source geometry-related effect, such as a dipping slab, in which case a high-velocity lithospheric slab would propagate P energy faster in the direction of the slab, could cause multi-pathing. First, mechanisms with a P-wave energy radiation pattern favorable to produce a podal P'P' phase are thrust-faulting source mechanisms, where one lobe with maximum P-wave energy extends vertically downward from the source region. The seismic energy that is released in the direction of the slab is thus much smaller than the main P'P' energy (unless the slab itself is not vertical). Even if this were the case for observations at ILAR, which were recorded in Alaska above the subducting Pacific plate, it is impossible to acquire as much as 55–60 seconds of advance time. Furthermore we also observe similar P'P' precursors on another, independent set of broadband recordings, for an Afghanistan-Tajikistan border earthquake (1999/11/08 16:45:44.3; 36.475°, 71.230°), recorded at the Tien Shan Continental Dynamics (GHENGIS) and Kyrgyz Seismic Telemetry (KNET) regional seismic networks. These precursors had advance

times similar to that observed at ILAR, also inconsistent with forward scattering from any dipping structure associated with the intermediate depth earthquakes in this region. Further evidence against forward scattering or multipathing near the receiver is given by an azimuth slowness analysis of data from ILAR array (K. Koper, Generic Array Processing Code, 2005, available at <http://www.eas.slu.edu/People/KKoper/Free/index.html>), which found strikingly similar slowness and back-azimuth for both the precursor and main P'P' phase, that agree well with the location of the earthquake. Despite the fact that ILAR is a small aperture array and cannot provide high-resolution determination of slowness in an absolute sense, our results demonstrate that the relative directions of the incoming energy for both phases are similar and hence more consistent with back scattering. Moreover, a P'P' ray-path at near-podal epicentral distances could be thought of in terms of two antipodal PKP legs. If forward scattering were responsible for the precursors, they would also be observed for antipodal PKP ray-paths. Although there are many antipodally-observed PKP waveforms with a high quality of signal-to-noise available, precursors to antipodal PKP waves have never been reported.

[8] Results of our azimuth slowness analyses are also inconsistent with precursor origin from scattering near the core-mantle boundary. It has been suggested that various scattered phases of PKP as well as PK(KKP) or PKK(KP) (where parentheses indicated scattered part of the signal) might account for precursors of PKKKP (double reflection from the inner side of the core mantle boundary) and P'P' waves. These could be an alternate explanation to underside reflections from 410- and 660-km discontinuities at epicentral distances equal and longer than 30° [Cleary, 1981; Vinnik, 1974; Muirhead, 1985]. Even if these calculations were extrapolated to shorter distances, forward-scattered PKP branches would arrive with very different slowness and PKKKP waves would arrive earlier than our observed precursors. PKKKP-BC phase could be recorded on seismograms at about the same time when the precursors to P'P' are

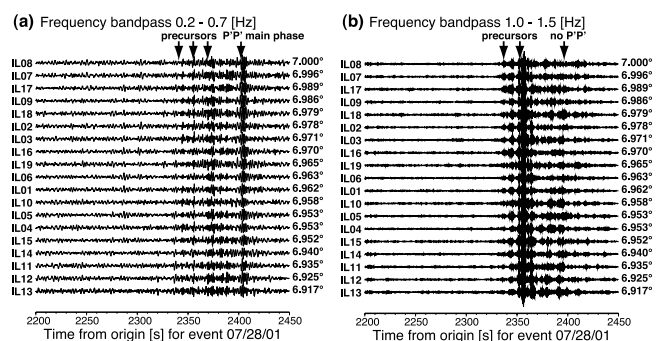


Figure 2. Vertical component records from ILAR array are shown for two bandpass filters: (a) 0.2–0.7 Hz and (b) 1.0–1.5 Hz. This earthquake (1999/07/28 07:32:44.6 lat = 59.005°, lon = -155.099°) was located in the southern Alaska, about 7° southwest of ILAR array. Both the main P'P' phase and precursors are visible at lower frequencies. Precursors to P'P' are characterized by several distinct arrivals between approximately 57 and 30 s preceding P'P'. At higher frequencies, the main P'P' phase is below the noise level and not visible.

¹Auxiliary material is available at <ftp://ftp.agu.org/apend/gl/2005GL024626>.

observed (see Figure 1b), but the BC branch of PKKKP has a very different slowness than the DF branch of P'P' at near-podal epicentral distances, and based on our observations of near-zero slowness at GHENGIS and KNET networks, we can also eliminate this possibility.

[9] Therefore, we suggest that the observed P'P' precursors are back-scattered energy from reflectors in the upper mantle (see Figure 1d). Back-scattered energy at near-podal epicentral distance would have a higher frequency content than the main phase and virtually the same slowness consistent with our analysis. Travel time calculations show that the earliest individual packet of energy at about 57 s preceding P'P' corresponds to an underside reflection from about 220 km depth, and the latest packet at about 30 seconds preceding P'P' corresponds to a reflection from a depth of 150 km. A 220-km discontinuity is not yet confirmed as a global property of Earth, however there are numerous sporadic observations beneath both continents and oceans worldwide [e.g., *Gu et al.*, 2001]. There is also evidence for a reflector at 200 km depth beneath the northwest Pacific from precursors to PP waves [*Rost and Weber*, 2001]. The reflection points of the observed P'P' for all Alaskan earthquakes are in the Antarctic plate, north of Antarctica and far from mid-ocean ridges (Figure 1c), where precursors to P'P' at longer epicentral distances were reported by *Adams* [1971].

[10] Because PKP waves have maximum amplitudes near 150° , it is not surprising that most observations of P'P' and their precursors associated with 410- and 660-km discontinuities are made near epicentral distances of 60° . An interesting factor to consider is the observability of reflections from upper mantle discontinuities having topography [e.g., *Flanagan and Shearer*, 1998]. Since 410- and 660-km discontinuities have opposite Clapeyron slopes, they move in opposite directions when their positions are perturbed by lateral temperature variations. For example, a cold environment perturbs the 660-km discontinuity downwards, so a convex region of 660-km discontinuity acts like defocusing lens. We examined cross sections of shear velocity tomograms [*Ritsema et al.*, 1999] in this region and found that indeed the 150–220 km depth zone is confined within a large cold domain in the upper mantle extending below 660 km. This, along with the fact that the corresponding PKP waves are far from their maximum amplitude at near-podal distance, might explain why there are no prominent observations of underside reflections from the 660-km discontinuity for near-podal P'P'.

[11] The higher frequency content of the precursors to P'P' may be explained by a combination of the effects of higher attenuation in the uppermost mantle and the frequency dependence of backscattered energy from small-scale heterogeneities. The effects of upper mantle attenuation are relatively simple to model. Modeling the effects of the back-scattered radiation pattern of small-scale heterogeneities is necessarily more speculative. The largest effect on frequency content, however, will most likely be that of the exponential attenuation of amplitude with frequency due to intrinsic attenuation rather than the simple first and second order power law increase in amplitude with frequency due to scattering by heterogeneities of varying scale length and shape. Hence, we first consider the effects of mantle attenuation on the backscattered energy.

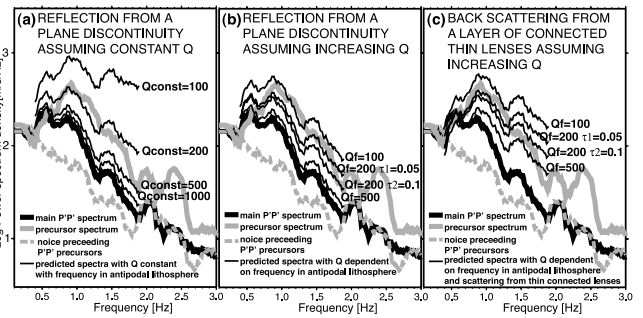


Figure 3. Amplitude spectra for the observed main P'P' phase (thick black line), P'P' precursor (thick gray line) and noise preceding the precursors (dashed gray line). The spectrum of the main phase was used to calculate predictions of precursor spectrum (thin black lines). (a) Only the frequency effect of Q without the frequency dependence of scattering was taken into account. Q is assumed to be constant in the antipodal lithosphere. The used values for Q are shown above the theoretical curves. (b) Same as Figure 3a, but Q is constant for frequencies below and increases with the first power of frequency above a given corner frequency. For Q = 200, frequency corners of 0.05/0.1 (τ_1) and 0.05 Hz (τ_2) were used. (c) Q varies with frequency in the same way as in Figure 3b, but with frequency dependence proportional to the first power of frequency in order to account for integrated effect of connected thin lenses of partial melt.

[12] The difference in the attenuation experienced by P'P' relative to the back-scattered precursors is simply given by the effect of the travel time accumulated by the additional two legs of the main P'P' phase ray-path in the attenuating uppermost 150–220 km of the mantle. In Figure 3 we plot predictions of precursor spectra based on the spectra of the main phase assuming that Q is constant with frequency in the lithosphere (Figure 3a) according to $A_{\text{precursor}} = A_{\text{main}} * e^{-\frac{\pi * f * \Delta t}{Q_{\text{const}}}}$, where Δt is the two way travel time through the antipodal lithosphere. The high-energy content of the precursor compared to the main arrivals can be explained by the difference in attenuation experienced by additional two legs that the main P'P' phase spends in the antipodal lithosphere with a frequency-dependent Q in the upper mantle. In Figure 3b we assume frequency dependent Q model, having a flat relaxation spectra below 0.1 Hz with increasing Q as the first power of frequency above 0.1 Hz according to *Choy and Cormier* [1986]. Q_{const} from the above formula now becomes Q(f). Our preferred Q model for the antipodal bounce point region from ILAR (oceanic upper mantle in the surrounding Antarctica) has a constant relaxation spectrum below 0.1 Hz, and Q increasing with first power of frequency above 0.1 Hz. The frequency dependence agrees with that first proposed by *Gutenberg* [1958], who suggested a Q proportional to frequency to predict the observed amplitudes of high frequency P'P'.

[13] To achieve a better fit to the lower frequency band of precursor energy, we investigated the effects of possible frequency dependent scattering. For Rayleigh scattering (scatterer scale lengths much smaller than wavelength), the radiation patterns of scattered particle velocity will

contain a factor proportional to the square of frequency [Sato and Fehler, 1998]. For either thin lenses of heterogeneity, oriented perpendicular to an incident wavefront or for the integrated effect of connected small scale heterogeneity, we might expect this frequency dependence to be proportional to the first power of frequency. Combined effect of back scattering for bottom and top boundary of partial melt lenses is $-R*v(t) + R*v(t + \Delta t)$, where v is velocity, R is reflection coefficient (negative for liquid over solid and positive for solid over liquid) and Δt is the two way travel time through thin liquid layer. We assumed the velocity in the solid to be equal to 10 km/s and velocity in the liquid to be equal to 4 km/s. We neglected transmission coefficients through the bottom of the thin layer. As the thin layer goes to zero, the above expression can be approximated with $-R*\Delta t*dv/dt$, and if we assume plane wave incidence, dv/dt equals to $i*\omega*v$, where ω is frequency. Assuming back-scattered radiation patterns proportional to the first power of frequency together with the effect of a frequency dependent Q model, we now achieve better fits to predicted precursor energy in the lower end (0.2 to 0.5 Hz) of the band in which signal to noise ratios are high for the main P'P' phase (Figure 3c).

4. Discussion

[14] We interpret our best fit to the frequency content and slowness of near-podal P'P' precursor energy as back-scattering from horizontally connected small-scale heterogeneity concentrated in the uppermost 150–220 km of the mantle. Possible candidate scatterers include compositional blobs of variable size and elastic impedance or lenses of partial melt. Compositional heterogeneities may be eclogitic slab fragments [e.g., Allegre and Turcotte, 1986; D. L. Anderson, Speculations on the nature and cause of mantle heterogeneity, submitted to *Physics of the Earth and Planetary Interiors*, 2005]. The impedance contrasts of the heterogeneities may also be associated with a rheologic change from dislocation creep to diffusion creep, which has been proposed as a mechanism to account for a transition from an anisotropic uppermost mantle to an isotropic lower mantle [Karato, 1992]. Partial melt lenses are more effective than either compositional or solid-solid phase changes in accounting for the large impedance contrasts needed to account for the amplitude of the observed P'P' precursors at ILAR. Our best observations of P'P' precursors back-scattered from this depth range at ILAR occur beneath oceanic regions, far from mid-ocean ridges. Little or no partial melt, however, has ever been postulated in the upper mantle as deep as 150–220 km, far from mid-ocean ridges. Compared to P'P' precursors observed at ILAR, precursors observed from P'P' in the Afghanistan-Tajikistan Border region have relatively lower frequency content, perhaps related to an antipodal bounce point near the Pacific mid-ocean ridge. Important future observations include an assessment of regional variations in the frequency content of P'P' precursors, especially whether similar back-scattering is observed beneath continental regions. Perhaps the mechanism producing the backscattering from a diffuse 150–220 km deep zone, a possible plate decoupling zone beneath oceanic regions is identical to the mechanism producing occasional observations of a Lehmann discontinuity near 220 km depth beneath continental regions.

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