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Evidence for back scattering of near-podal seismic P’P’ waves from the 150-220 km zone in Earth’s upper mantle

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The deepest and most inaccessible parts of Earth’s interior – the core and core-mantle boundary regions can be studied from compressional waves that turn in the core and are routinely observed following large earthquakes at epicentral distances between 145° and 180° (also called P’, PKIKP or PKP waves)[1-4]. 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. P’P’ waves are sometimes accompanied by precursors, which were reported first in the 1960s as small-amplitude arrivals on seismograms[5] at epicentral distances of about 50º-70º. Most prominent of these observed precursors were explained by P’P’ 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[6-9]. Here we report the discovery of hitherto unobserved near-podal P’P’ waves (at epicentral distance less than 10º) and very prominent precursors preceding the main energy by as much as 55 seconds. We interpret these precursors as a back scattered energy from undocumented structure in the upper mantle, in a zone between 150 and 220 km depth beneath Earth’s surface. From these observations, we identify a frequency dependence of Q (attenuation quality factor) in the lithosphere that can be modeled by a flat relaxation spectrum below about 0.05-0.1 Hz and increasing with as the first power of frequency above this value, confirming pioneering work by B. Gutenberg[10].

Our understanding of Earth’s composition and dynamics has evolved dramatically in the last several decades, especially with the expansion of modern broadband seismic networks and development of seismological methods such as tomographic imaging. Many details about Earth’s deep interior, however, remain elusive or completely unknown. Faster progress toward understanding of Earth’s lowermost mantle and core regions has been hindered by the difficulty of observing and analyzing core-sensitive seismic phases. For example, core-mantle and inner-outer core boundaries can be studied from P waves that reflect from these boundaries (PcP and PKiKP waves, respectively). These phases, however, are not widely observed on seismograms, particularly at very short epicentral distances[12?]. Moreover, with the current configuration of stations and the world’s seismicity, the existing collection of PKP waves does not sample equally well all parts of the inner core. For this reason seismic phases with more complex geometry, like PnKP (where n is a number of multiple reflections from the inner side of the core mantle boundary) and P’P’ (Fig. 1a, 1b) are employed as a necessary supplement to PKP measurements when using seismic travel times to study core structure.

Since the time of pioneering observations in the 60’s and early 70’s, numerous examples of precursors to P’P’ have been reported[13-16], indicating that structure of the upper mantle was not uniformly smooth. As the amount of waveform observations was growing, 410- and 660-km discontinuities were gradually accepted as global features of Earth's interior[17-19]. Early evidence of these radial discontinuties was taken not only from observations of complex P and S waveforms at ranges corresponding to rays grazing the discontinuities, but also from long range observations of precursors to the P’P’ phase that were interpreted to be underside reflections from the discontinuities.

An alternative scattering hypotheses[20-25] for the origin of the P’P’ precursors, however, soon cast considerable doubt on the hypothesis of underside reflection from radial discontinuties. 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 discontinuties 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.[26?]

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°. This characteristic, considered with the geometry of two separate single legs of PKP, can be explained by the fact that a maximum amplitude of PKP waves due to triplication (simultaneous arrivals and interference of 3 branches of PKP waves) is observed between 145° and 155°. Thus, $360°-2\Delta=\{70°,50°\}$ for PKP epicentral distance $\Delta=\{145°,155°\}$. Unlike the majority of these earlier observations of P’P’ precursors, we report unprecedented observations at near-podal epicentral distances (less then 10°) of very clear and energetic P’P’ precursor arrivals (Fig. 2). 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[27]. Our search found that the arrivals associated with P’P’ energy are indeed extremely difficult to observe at near-podal epicentral distances, unless filtering and array stacking enhanced their amplitudes.

An example of P’P’ precursor observations at the short-period ILAR array network in Alaska is illustrated in Fig. 2 (see Fig. 1c for the location and geometry of P’P’ ray-paths). 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 the ILAR network (Fig. 1c). At 0.2-0.7 Hz, the main P’P’ and the precursor arrivals of energy are visible at all ILAR stations, which were sorted by epicentral distance. At 1.0-1.5 Hz, the energy of the main phase is below noise level, but sharp onsets of the precursors persist. The precursor energy is visible even at 3Hz, which motivates us to take a closer look at properties such as scattering and attenuation along a P’P’ ray-path.

Scattering of P'P' waves could take place 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 such short epicentral distance geometry and corresponding seismic wave arrivals and is true regardless of the location or distribution of scatterers in the mantle. For some strong velocity anomalies conncentrated near the receiver, it is possible to create some P'P' precursors but they would arrive with very different slowness or apparent angle of incidence than the main P'P' phase.

It is feasible that a specific near-source geometry-related effect, such as a dipping slab, could cause multi-pathing, in which case a denser lithospheric slab would propagate compressional energy faster in the direction of the slab. It is highly unlikely, however, that this is the case in our observations. First, mechanisms with a compressional energy radiation pattern favorable to produce a podal P'P' phase are thrust faulting source mechanisms, where one lobe with maximum compressional energy extends vertically downward from the source region. The seismic energy that is released in the direction of the slab and travels through it is thus much smaller than the main P'P' energy (unless the slab itself is not vertical). Even if this were the case in our observations at ILAR, which were recorded in Alaska above the subducting Pacific plate, it would be difficult to acquire as much as 55 seconds of advance time. We also observed similar P'P' precursors on another, independent set of broadband recordings, for an Afghanistan-Tajikistan border earthquake, recorded at the Kazakhstan regional seismic network. The precursor in the recordings from the Afganistan-Tajikistan border earthquake 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 a slowness analysis from beams formed at the ILAR array, which found strikingly similar slowness and back-azimuth for both the precursor and main P'P' phase that agree well with those predicted for from the location of the earthquake[28]. Despite the fact that the ILAR network has a small aperture 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 consistent and hence inconsistent forward scattering near the receiver. Furthermore, the P'P' ray-path at near-podal epicentral distances could be thought of in terms of two antipodal PKP legs, each corresponding to the epicentral distance of 175-180°. If forward scattering were responsible for the precursors, they would also be observable for very 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 in published literature.

Results of our 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, and could be an alternative explanation to underside reflections from 410- and 660-km discontinuities at epicentral

distances equal and longer than 30°[23,29,30]. 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.
We are also aware of a possibility that PKKKP-BC phase could be recorded on seismograms at about the same time when the precursors to P'P' are observed (see travel time diagram in Fig. 1b). The BC branch of PKKKP has a very different slowness than the DF branch of P'P' at near-podal epicentral distances, and hence we can also eliminate this possibility from results of our slowness analyses.

Therefore, we suggest that the observed P'P' precursors are back-scattered energy from reflectors in the upper mantle (see illustration in Fig. 1d). Back-scattered energy at near-podal epicentral distance would have a higher frequency content than the main phase and virtually the same slowness. Travel time calculations show that the earliest individual packet of energy at about 55 seconds 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 the 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[26?]. There is also an evidence for a reflector at 200 km depth beneath the northwest Pacific from precursors to PP waves[31]. 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 (Fig. 1c), where precursors to P'P' at longer epicentral distances were reported in 1971[13].

One curiosity is that we do not observe any 410- or 660-km related precursors to P'P'. Because PKP waves have maximum amplitudes near 150º, it is not surprising that most observations of P'P' and their precursors are made near epicentral distances of 60º (see previous comments and a note on relationship between geometry of P'P' and PKP). An interesting factor to consider is the observability of reflections off upper mantle discontinuities having topography[18]. 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 through shear velocity tomograms[32] in this region and found that indeed 150-220 zone is confined within a large cold domain in the upper mantle. 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'.

The observation of different frequency content between the main P'P' phase and the precursors as well as high amplitudes of the observed precursors persisting at higher frequencies motivated us to investigate this phenomenon more closely. The higher frequency content of the precursors to P'P' could 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. The modeling of the effects of the back-scattered radiation pattern of small-scale heterogeneities is necessarily more speculative. The largest effect on frequency content, however, will undoubtedly be the effect of the exponential attenuation of amplitude with frequency due to intrinsic attenuation rather than the simple first and second 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 attenuation.

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 that the main P'P' phase spends in the attenuating uppermost 150-220 km of the mantle. In Fig. 3a we plot predictions of precursor spectra based on the spectra of the main phase assuming that Q is constant with frequency in the lithosphere according to

$$A_{precursor} = A_{main} * e^{\frac{\pi * f * \Delta t}{Q_{const}}}$$

while in Fig. 3b we assume frequency dependent Q model, having a flat relaxation spectra below 0.1 Hz (this was the modeled frequency corner) with increasing Q as the first power of frequency above 0.1 Hz[33]. Our precursor modeling formula now becomes:

$$A_{precursor} = A_{main} * e^{\frac{\pi * f * \Delta t}{Q(f)}}$$

Fig. 3b demonstrates that 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 PKPPKP phase spends in the antipodal lithosphere with a frequency-dependent Q in the upper mantle. Our preferred Q model from the antipodal bounce point from ILAR (oceanic upper mantle in the surrounding Antarctica) has a constant relaxation spectrum between 0.05 to 0.1 Hz, Q increasing with first power of frequency above 0.1 Hz. The frequency dependence agrees with that first proposed by Gutenberg[10], who suggested a Q proportional to frequency to predict observed amplitudes of the amplitudes of high frequency P'P' observations.

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 (heterogeneity scale lengths much smaller than wavelength), the radiation patterns of scattered particle velocity will contain a factor proportional to the square of frequency[34]. 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. Including these possible frequency dependencies together with the effect of a frequency dependent Q model, we achieved the best fits to predicted precursor energy by assuming back-scattered radiation patterns proportional to the first power of frequency 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 (Fig 3c).

In conclusion, we interpret our best fit to the frequency content and slowness of near-podal P'P' precursor as backscattering 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. The impedance contrasts of the heterogeneities may also be associated with a rheologic change from dislocation creep to diffusion creep, which Karato[35] has proposed as a mechanism to account for a transition from an isotropic uppermost mantle to an isotropic lower mantle. Partial melt lenses will be 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 ridge. 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, however, precursors observed from P'P' in the Afganistan-Tajikistan Border region have relatively lower frequency content, perhaps related to an antipodal bounce point near a mid-ocean ridge. Important future observations include an assessment in 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 depth 150 km zone beneath oceanic regions is identical to the mechanism producing occasional observations of a Lehmann discontinuity near 220 km depth beneath continental regions.

Figure Captions:

Figure 1 **a**, A schematic representation of Earth. The vertical cross-section shows main subdivisions and discontinuities as well as podal P'P'df ray-paths connecting the source with the receiver. A podal P'P'-DF ray-path consists of two antipodal PKIKP ray-paths with bottoming points in the inner core very close to Earth's center. **b**, Theoretical travel time curves of P'P' and PKKKP seismic phases from a source at 0 km depth, shown by thick and thin lines, respectively. The P'P'-DF branch corresponds to the waves bottoming in the inner core. The BC branch corresponds to the waves bottoming in the lower, while the AB branch corresponds to the waves bottoming in the middle parts of the outer core. PKKKP waves could be observed in the same epicentral distance range preceding the arrivals of P'P' waves, although with significantly different slowness. Also shown (by dashed line) is a theoretical P'P' travel time curve from a 500 km deep source. Reference model ak135[11] was used. **c**, Map of Earth with surface projections of P'P' ray-paths for the observed podal P'P' precursors. Locations of 9 earthquakes as well as the location of ILAR short period network in Alaska are shown by stars and a triangle, respectively. Also shown (by stars in the southern hemisphere) are reflection points near the antipode. Circles are surface projections of the corresponding bottoming points in the inner core (one on the source, and one on the receiver side). **d**, Schematic representation of the reflection of P'P' waves in the antipodal mantle (indicated by a rectangle in part a). Thin lines show geometry of back-scattered P'P' responsible for the observed precursor energy. Back scattering originates in a zone between 150 and 220 km in the upper mantle. P’P’ waves continue their way through the lithosphere to the surface, reflect from it and travel to the receiver with similar slowness to P’P’ precursors. They are attenuated, however, significantly with respect to the precursors, owing to two additional leg paths through the antipodal lithosphere.

Figure 2 P’P’ observations at podal epicentral distance. Vertical component records at the short-period ILAR array are shown for two bandpass filters: **a**, 0.2-0.7 Hz and **b**, 1.0-1.5 Hz. This earthquake was located in the southern Alaska, about 7 degrees southwest of the ILAR seismic network. Both the main P’P’ phase and precursors are visible at lower frequencies. Precursors to P’P’ are characterized by several distinct arrivals in 55-30 second interval before P’P’. Note a difference in frequency content between the precursor and the main P’P’ energy. At higher frequencies, the main P’P’ phase is below the noise level and not visible.

Figure 3 Amplitude spectra for the observed main P’P’ phase (thick black line), P’P’ precursor (thick gray line) and noise preceeding the precursors (dashed gray line). The spectrum of the main phase was used to calculate predictions of precursor spectra (thin black lines). Only frequency effect of Q (quality factor) without frequency dependence on scattering was taken into account. **a**, Q was assumed to be constant in the antipodal lithosphere, with values used shown above the theoretical curves. **b**, Q has a flat relaxation spectrum for frequencies below 0.1 Hz and increases with as the first power of frequency above a given corner frequency. For Q=200, frequency corners of 0.1 (Qf_1) and 0.05 Hz (Qf_2) were used. **c.** Q varies with frequency in the same way as in **b**, but with frequency dependence proportional to the first power of frequency in order to account for integrated effect of connected small-scale heterogeneity or lenses of partial melt.

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Some references left for the discussion part, possibly more to add?

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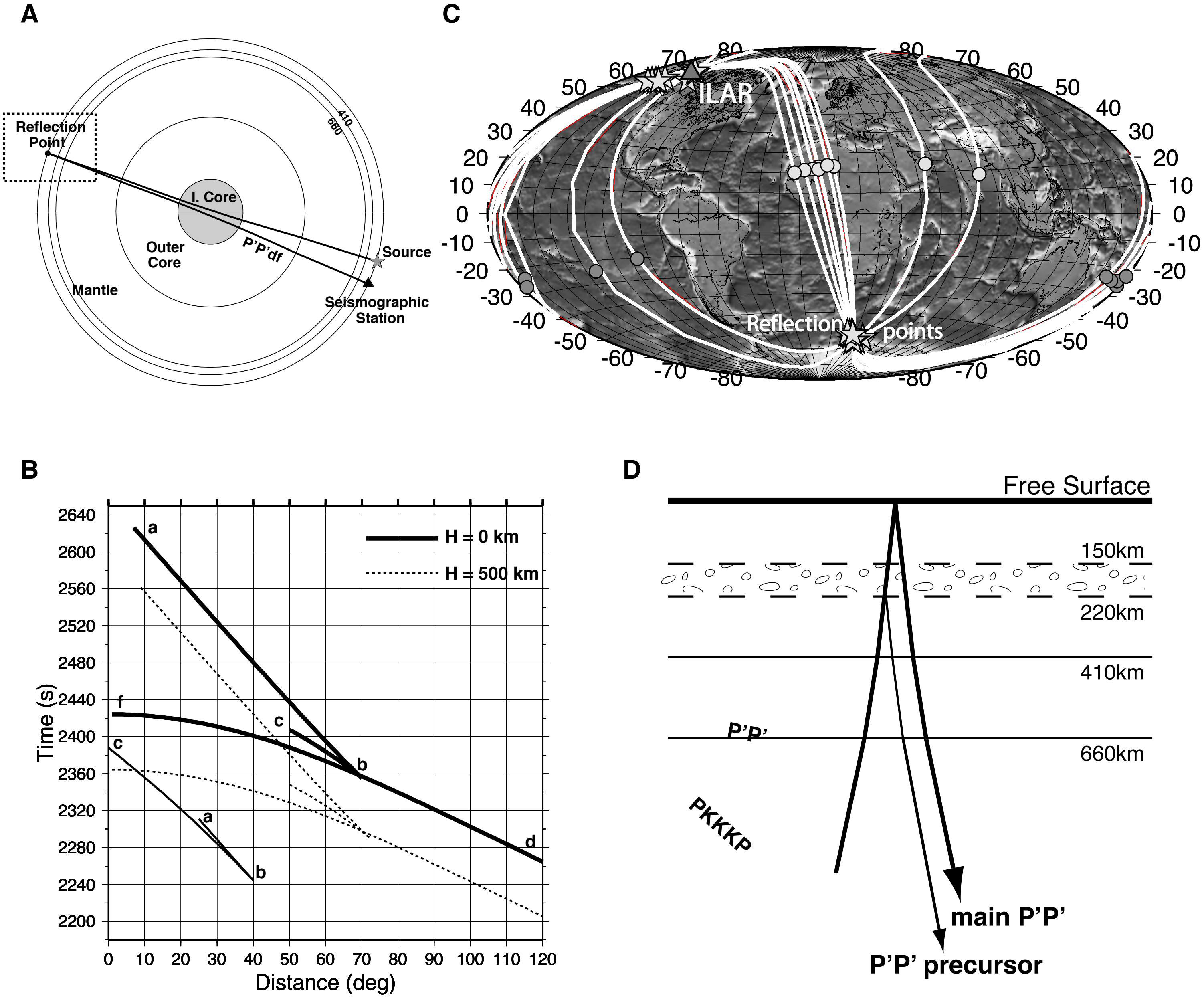
A
Reflection Point
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660
I. Core
Outer Core
Mantle
P'P'df
Source
Seismographic Station
C
ILAR
Reflection points
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
B
Time (s)
Distance (deg)
H = 0 km
H = 500 km
a
b
c
d
f
2640
2600
2560
2520
2480
2440
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2280
2240
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50
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80
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120
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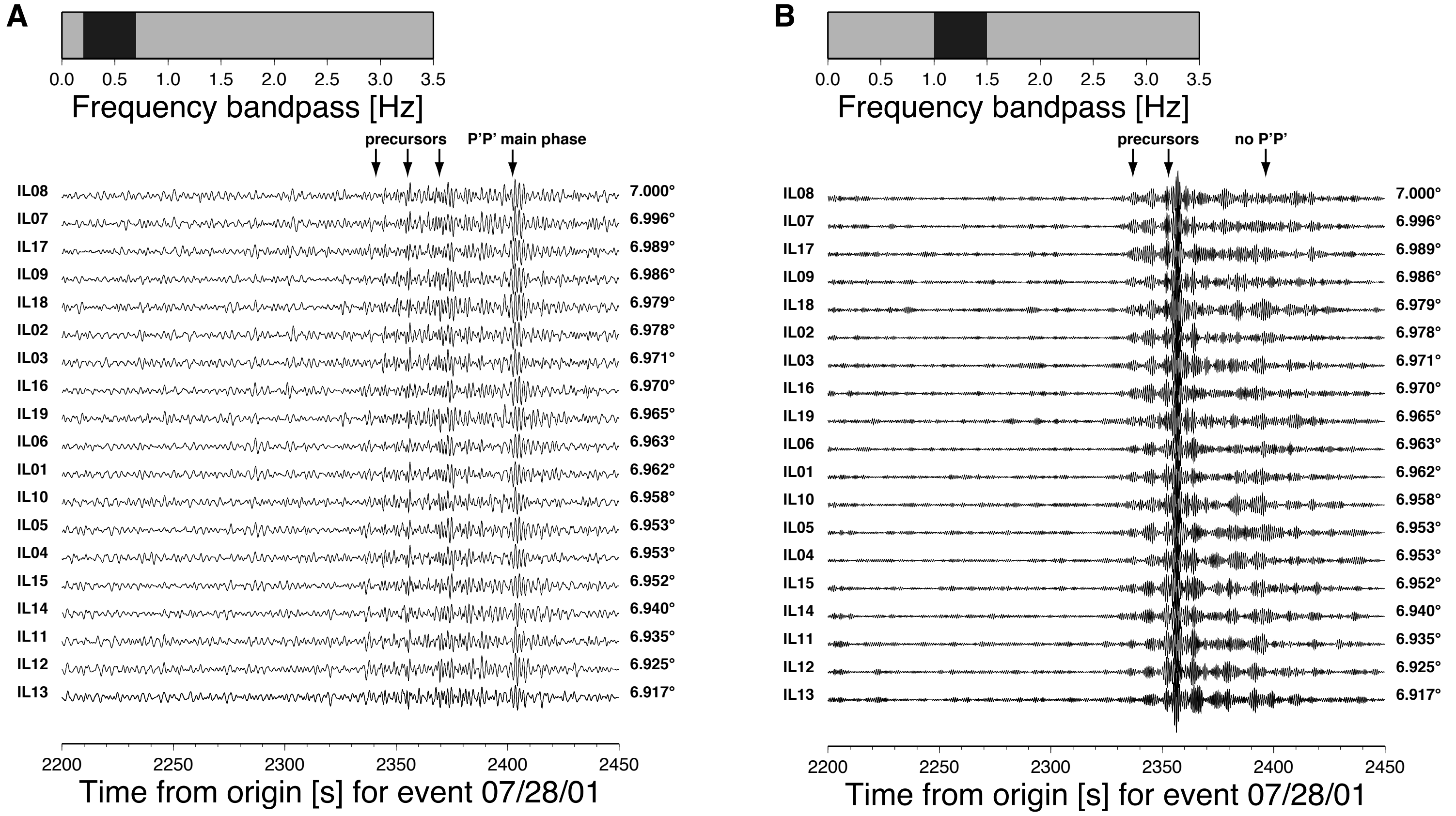
220km
410km
660km
P'P'
PKKKP
main P'P'
P'P' precursor

Figure 1


A
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0.5
1.0
1.5
2.0
2.5
3.0
3.5
Frequency bandpass [Hz]
precursors
P'P' main phase
IL08 7.000°
IL07 6.996°
IL17 6.989°
IL09 6.986°
IL18 6.979°
IL02 6.978°
IL03 6.971°
IL16 6.970°
IL19 6.965°
IL06 6.963°
IL01 6.962°
IL10 6.958°
IL05 6.953°
IL04 6.953°
IL15 6.952°
IL14 6.940°
IL11 6.935°
IL12 6.925°
IL13 6.917°
2200
2250
2300
2350
2400
2450
Time from origin [s] for event 07/28/01
B
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Frequency bandpass [Hz]
precursors
no P'P'
IL08 7.000°
IL07 6.996°
IL17 6.989°
IL09 6.986°
IL18 6.979°
IL02 6.978°
IL03 6.971°
IL16 6.970°
IL19 6.965°
IL06 6.963°
IL01 6.962°
IL10 6.958°
IL05 6.953°
IL04 6.953°
IL15 6.952°
IL14 6.940°
IL11 6.935°
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Time from origin [s] for event 07/28/01

Figure 2

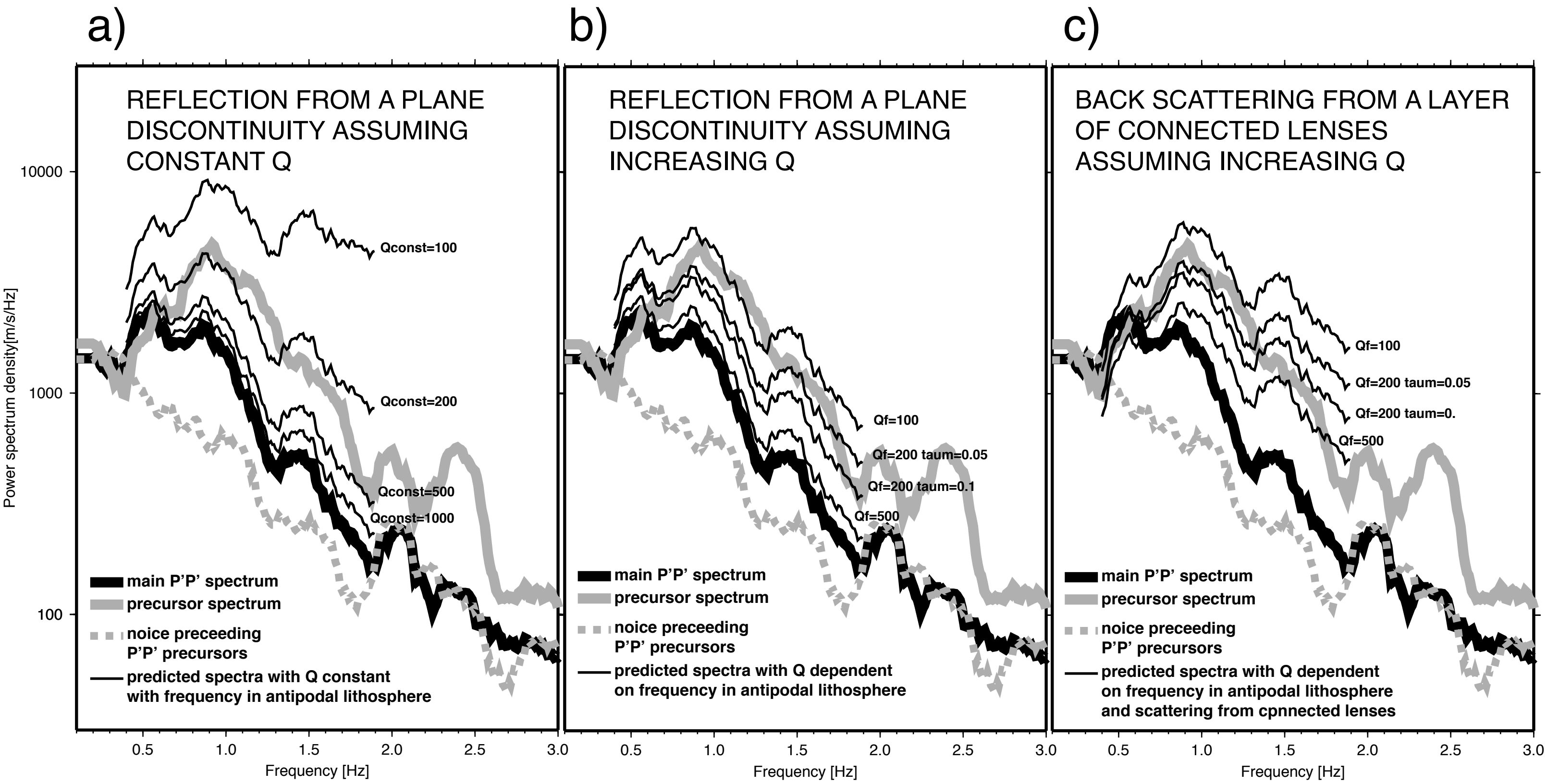
a)
REFLECTION FROM A PLANE DISCONTINUITY ASSUMING CONSTANT Q
Qconst=100
Qconst=200
Qconst=500
Qconst=1000
main P'P' spectrum
precursor spectrum
noice preceeding P'P' precursors
predicted spectra with Q constant with frequency in antipodal lithosphere
b)
REFLECTION FROM A PLANE DISCONTINUITY ASSUMING INCREASING Q
Qf=100
Qf=200 taum=0.05
Qf=200 taum=0.1
Qf=500
main P'P' spectrum
precursor spectrum
noice preceeding P'P' precursors
predicted spectra with Q dependent on frequency in antipodal lithosphere
c)
BACK SCATTERING FROM A LAYER OF CONNECTED LENSES ASSUMING INCREASING Q
Qf=100
Qf=200 taum=0.05
Qf=200 taum=0.
Qf=500
main P'P' spectrum
precursor spectrum
noice preceeding P'P' precursors
predicted spectra with Q dependent on frequency in antipodal lithosphere and scattering from cpnnected lenses
Power spectrum density[m/s/Hz]
10000
1000
100
Frequency [Hz]
0.5
1.0
1.5
2.0
2.5
3.0

Figure 3