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Body-Wave Imaging of Earth's Mantle Discontinuities from Ambient Seismic Noise

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32. The OH-NO spin states with $S = 0$ and $S = 1$ are not distinguished in our model; the 4 × 4 matrices for each spin state are therefore identical.
33. Although the quadrupole moment vanishes in the $j = 1/2$ state of NO, the quadrupole moment in the molecular frame contributes to the collisions producing NO states with $j = 3/2$ and 5/2 that yield important contributions to the measured cross sections.

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Supplementary Materials
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Supplementary Text
Figs. S1 to S3
Tables S1 and S2
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Body-Wave Imaging of Earth's Mantle Discontinuities from Ambient Seismic Noise

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Ambient seismic noise correlations are widely used for high-resolution surface-wave imaging of Earth's lithosphere. Similar observations of the seismic body waves that propagate through the interior of Earth would provide a window into the deep Earth. We report the observation of the mantle transition zone through noise correlations of *P* waves as they are reflected by the discontinuities associated with the top [410 kliometers (km)] and the bottom (660 km) of this zone. Our data demonstrate that high-resolution mapping of the mantle transition zone is possible without using earthquake sources.

Earth's upper and lower mantle are separated by the transition zone, where the mantle mineralogy changes. At the top (~410 km depth) and bottom (~660 km depth) of the transition zone, phase changes introduce a rapid increase in seismic velocities over narrow depth intervals. This transition zone has a major role in Earth dynamics, particularly as it influences the convection within the mantle, slowing the subduction of slabs and the ascent of plumes (*1*, *2*). Information from rock physics and the seismic character of the 410-km and 660-km discontinuities can constrain the mineralogy and temperatures of the mantle (*3*). However, mapping the depths and lateral variations of these discontinuities (*4*, *5*) remains difficult. Seismic studies based on the analysis of waves emitted by earthquakes are limited by the geographical distribution of the earthquakes and by the uncertainties in our knowledge of the location and the rupture processes.

Promising results from correlations of the coda of seismic waves (*6*) have led to the recent proposal that correlations of the continuous records of seismic ambient noise recorded at two distant points can provide an estimation of Earth's impulse response between these two points (*7*). This impulse response contains information on seismic wave speeds (*7*) and amplitude decays (*8*) without the need for the use of active sources or earthquakes. Because these seismic noise sources are located at Earth's surface, the noise correlations are dominated by surface waves, and the technique has become useful for seismic imaging at different scales (*9–13*). Seismic noise propagates continuously through Earth and is mainly created by oceanic swells and atmospheric disturbances (*14–19*).

Surface waves, however, are not sufficient to explore the deep structure of Earth, as they have limited depth resolution. Recent studies have detected high-frequency body waves within noise correlations at both the crustal scale (*20–22*) and at a very local scale (*23*). Here, we describe the use of seismic noise correlations to extract body-wave reflections from the 410-km and 660-km discontinuities of Earth's transition zone.

It is now known that seismic noise includes body waves that propagate through the whole planet (*19*, *24*, *25*), just as surface waves propagate through the upper layers of Earth (Fig. 1A). As for the surface-wave component of the wave field, we do not expect the noise field to be under the exact mathematical conditions for retrieval of the complete Earth impulse responses (*26*, *27*). We show in the following that conditions are nonetheless favorable enough to extract deep body-wave phases by correlating ambient seismic noise. Because the signals we track have small amplitudes, we have applied specific processing techniques that are designed to improve the signal-to-noise ratio.

We used data from the temporary POLENET/LAPNET experiments in northern Finland (*28*) (Fig. 1B), complemented with data from permanent broadband stations. We previously extracted *P* waves and *S* waves (*22*) that are reflected on the Moho (the lower limit of Earth's crust). These data showed that the ancient crust in the study area (*29*, *30*) is relatively transparent to seismic waves. Here, we used data from 42 stations that were continually operating from January to December 2008. For each of the 861 station pairs (fig. S1), we calculated the noise correlation of the vertical records in the frequency range 0.1 to 0.5 Hz, using the same processing as that implemented to extract Moho-reflected waves (*22*). We subsequently used the station pairs for which

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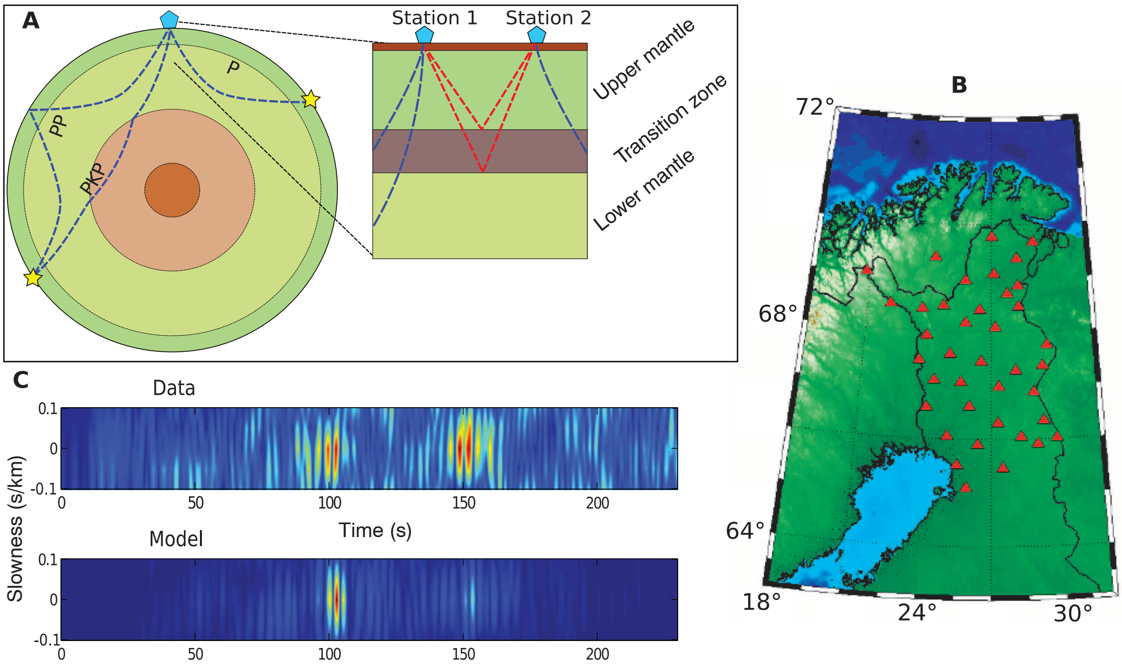

Fig. 1. Reflected body waves from the mantle transition zone discontinues beneath Finland. (**A**) Earth model in which noise is generated from oceanic sources (stars) and propagates partly as body waves (dashed blue lines) to the seismic sensors (pentagons). Correlation of the seismic noise recorded at the two sensors in theory yields the complete set of waves that would be recorded at one sensor if a seismic source had been active at the other sensor. The right panel shows the two body-wave reflections that are the focus of this report: *P* waves reflected on the 410-km and 660-km discontinuities (red dashed lines). (**B**) Map showing the stations of the seismic array (red triangles) in northern Finland. (**C**) Slowness-time stacks of the noise correlations (top) and the synthetic seismograms calculated using the AK135 standard Earth model (bottom). Note the wave arrivals at the same times as predicted by the AK135 model.

potential body waves reflected at the 410-km and 660-km interfaces did not arrive within the surface-wave train. For each of these traces, we folded the positive and negative time lags of the correlations and zeroed out the time window corresponding to the surface-wave arrivals.

To observe small-amplitude waves (fig. S2), we used stacking techniques that allow us to enhance the coherent body waves. Prior to the stacking, we aligned the traces along the predicted arrival times of the 410-km *P*-wave reflection using the AK135 standard Earth model (*31*) that was adapted to take into account the local crustal structure. Once aligned, the whole data set was stacked in the slowness-time domain.

The results of the slowness-time stack (Fig. 1C) show two peaks of energy at arrival times of approximately 100 and 150 s. Both peaks are located at zero slowness, which means that no further velocity correction is needed in addition to the initial alignment using the AK135 model, and that these are vertically propagating waves. We tentatively interpreted these two peaks as *P* waves reflected by the 410-km discontinuity (*P*410*P*) and the 660-km discontinuity (*P*660*P*).

To support this interpretation, we compared the two types of data by calculating the synthetic seismograms for each station pair and applying the same processing as that used for the field data. Prior to the stacking, we normalized the spectral amplitude of the synthetic seismograms and multiplied it by the average spectrum of the noise correlations. The comparison of the synthetics and the data stack confirms our interpretation that the observed peaks are the *P*410*P* and *P*660*P* reflections, despite slightly different waveforms

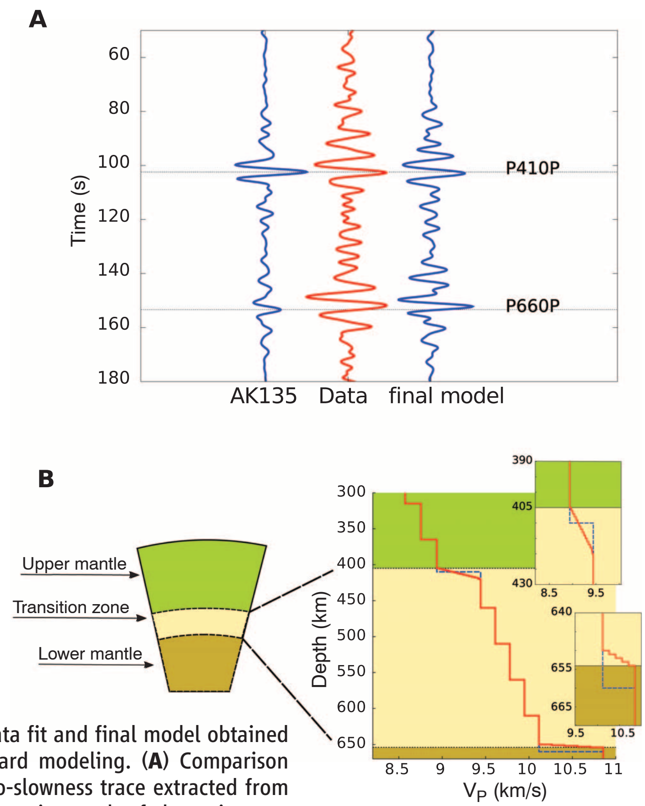

Fig. 2. Data fit and final model obtained from forward modeling. (**A**) Comparison of the zero-slowness trace extracted from the slowness-timestack of the noise correlations (red) and two zero-slowness traces of the synthetic seismogram stacks (as processed for the noise correlations): the AK135 standard Earth model (blue, left) and our final model (blue, right). The predicted vertical travel times for the *P*410*P* and *P*660*P* reflections in the AK135 model are shown (horizontal lines). The stack traces are normalized using the peak amplitude. (**B**) Final model (red line) for the mantle transition zone beneath northern Finland as compared to the AK135 model (dashed blue line). Insets show the detailed structure of the two discontinuities.

(Fig. 1C). The agreement of data and synthetic stacks is a good indication of the quality of the retrieved Green's function.

We attribute the minor differences between field data and synthetics to structural differences between the global reference model (*31*) and Earth's mantle beneath the study area. To test this hypothesis, we calculated the synthetic seismogram stacks for a series of models (table S1), and we qualitatively evaluated the fit between the stack of synthetic seismograms and the correlations (fig. S3). With the AK135 model as reference, we modified the depths of the two discontinuities and used gradients over narrow depth intervals, rather than first-order discontinuities. The stack of synthetics associated with the best model (Fig. 2A) is in good agreement with the data: The overall fit of the observations was drastically improved relative to that obtained using the AK135 model. With this refined model, the arrival times and the relative *P*410*P* and *P*660*P* amplitudes are similar.

The final model (Fig. 2B) of our study shows a "410-km discontinuity" that is 15 km thick and ranges from 405 to 420 km in depth. The "660-km discontinuity" is 4 km thick, at depths of 650 to 654 km. The depths of these two discontinuities are within the variations observed at a global scale (*4*, *5*) and are in good agreement with a receiver function study in the same area (*32*). Our additional constraints on the fine structure of the discontinuities corresponded to those predicted by the thermodynamic modeling of the phase transitions (*33*, *34*) and to constraints provided by seismological studies (*35*, *36*).

We have shown that it is possible to identify and characterize deep body waves that propagate through Earth. Our study used a dense seismic network that is located above a relatively transparent Earth crust. Using seismic noise to image mantle discontinuities has several advantages. First, the correlation technique is independent of earthquake occurrence, and therefore independent of the uncertainties that are associated with source location, origin time, and detailed slip history. Second, the amount of noise correlation scales according to N^2, where N is the number of stations, so it is relatively easy to obtain a large amount of data. Finally, the body waves that we have extracted are relatively high frequency (0.1 to 0.5 Hz) and they are sufficiently broadband to finely resolve the structure of the discontinuities.

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Supplementary Materials
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Materials and Methods
Figs. S1 to S3
Table S1
Reference (*37*)

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Flows of Research Manuscripts Among Scientific Journals Reveal Hidden Submission Patterns

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The study of science-making is a growing discipline that builds largely on online publication and citation databases, while prepublication processes remain hidden. Here, we report on results from a large-scale survey of the submission process, covering 923 scientific journals from the biological sciences in years 2006 to 2008. Manuscript flows among journals revealed a modular submission network, with high-impact journals preferentially attracting submissions. However, about 75% of published articles were submitted first to the journal that would publish them, and high-impact journals published proportionally more articles that had been resubmitted from another journal. Submission history affected post-publication impact: Resubmissions from other journals received significantly more citations than first-intent submissions, and resubmissions between different journal communities received significantly fewer citations.

With the rise of Web technologies and online databases, knowledge is increasingly available regarding the process of science-making itself (*1*). Gathering such "meta-knowledge" presents the opportunity to better understand, and optimize, the practice of research