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For example, the paleomegaflood of the Big Lost River, which occurred sometime between ~19 ka and 95 ka (29), was probably an outburst from the Pleistocene Glacial-Lake East Fork and had a peak flow of $6 \times 10^{6}$ m$^3$/s (25). Such an event would have easily surpassed the drainage divide between Box Canyon and the Wood and Lost River drainages (Fig. 1). The divides themselves also have shifted since the formation of Box Canyon because of volcanism that postdates the Box Canyon flood (Fig. 2).

Our findings suggest that Box Canyon and other amphitheater-headed canyons carved into basalt by large floods [for example, Dry Falls, Washington, USA (30), and Ásbyrgi Canyon, Iceland (31)] might be better terrestrial analogs of Martian canyons in volcanic terrains than seepage channels in sand.

References and Notes

19. U.S. Geological Survey: Box Canyon creek, gauge 13095500. This well log information can be found at http://waterdata.usgs.gov/awis.
23. Materials and methods are available as supporting material on Science Online.
30. J. H. Buntz, J. Geol. 31, 617 (1923).
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Anticorrelated Seismic Velocity Anomalies from Post-Perovskite in the Lowermost Mantle

Alexander R. Hutko,1,2 Thorne Lay,1,2 Justin Revenaugh,3 Edward J. Garnero3

Earth’s lowermost mantle has thermal, chemical, and mineralogical complexities that require precise seismological characterization. Stacking, migration, and modeling of over 10,000 P and S waves that traverse the deep mantle under the Cocos plate resolve structures above the core-mantle boundary. A small $\frac{0.07 \pm 0.15\%}{0.07 \pm 0.15\%}$ decrease of P wave velocity ($V_p$) is accompanied by a $1.5 \pm 0.5\%$ increase in S wave velocity ($V_s$) near a depth of 2570 km. Bulk-sound velocity ($V_p = (V_{s^2} + 4V_{s^2})^{1/2}$) decreases by $-1.0 \pm 0.5\%$ at this depth. Transition of the primary lower-mantle mineral, (Mg1-x-y Fe_x Al_y)(Si,Al)O3 perovskite, to denser post-perovskite is expected to have a negligible effect on the bulk modulus while increasing the shear modulus by $\sim 6\%$, resulting in local anticorrelation of $V_p$ and $V_s$ anomalies; this behavior explains the data well.

Increasing pressure ($P$) and temperature ($T$) with depth in Earth causes minerals to undergo phase transitions to new crystalline structures accompanied by abrupt changes in density ($\rho$), isentropic bulk modulus ($K_B$), and shear modulus ($G$) that result in seismic P wave velocity ($V_p = (K_B + 4/3G)\rho^{1/2}$) and S wave velocity ($V_s = (2G\rho)^{1/2}$) discontinuities. The pri-
mary mineral in the lower mantle, magnesium-
perovskite ([Mg1-xFexAl]2SiAlO6) (Pv), has recently been discovered to undergo a phase transition to a 1 to 1.5% denser polymorph called post-perovskite (pPv) in the lowermost mantle
(1—4). This phase change is unusual in that it involves a substantial increase in
G with little change in Ks. Theoretical estimates of high-
temperature elasticity for the two phases of pure
MgSiO3 suggest that Vp increases by ~2% but
Vs changes much less (~±0.5%) across the
transition (5—7). The bulk-sound velocity
\[ V_p = \left( \frac{sy}{V_p} \right) = (K_b/V_p)^{1/2} \]
for pPv is thus anomalously low, by about 1%, as compared with that for Pv. The reliable seismic calculation
of Vs structure requires precise Vp and Vs struc-
tures in the same location, which is viable in
only a few places. Here we provide a direct test
for the presence of pPv in the deep mantle by
determining the Vp and Vs structures in a region
having a strong Vp discontinuity and a positive
Vs volumetric anomaly. Confirmation of the
regional presence of pPv in the deep mantle
allows mineral-physics estimates of its proper-
ties to be applied to the interpretation of the
depth seismological observations.

We studied the lowermost mantle beneath the
Cocos Plate, which is well sampled by P and S
waves from South American earthquakes rec-
corded by seismic stations in western North
America (Fig. 1). This region is known to have
higher-than-average Vp (8—11) and slightly higher-
than-average Vp (8, 12). Investigations of deep
mantle structure below the Cocos region have
consistently yielded models with 1 to 2% Vp dis-
continuities situated 200 to 300 km above the
core-mantle boundary (CMB) (13—16), but a
large range of Vp discontinuity models involve
no detectable discontinuity (16), a small (~0.5%)
increase (17), or a large (~1 to ~3%) decrease
(18).

To resolve the Vp structure under the Cocos
region, we collected 17,550 high-quality P waves
from 243 earthquakes in South American sub-
duction zones recorded by >800 broadband and
short-period seismic stations in and near Califor-
ia. These data provide dense sampling of struc-
ture near the CMB, with ray paths spanning
epicentral distances from 60° to 80°. P wave
reflections from the CMB (PcP) sample the same
region (5° to 15°N) as S wave reflections from the
CMB (ScS) (Fig. 1) for a high-quality S
wave data set that has previously been analyzed
(11, 13, 14). This allows us to determine precise
Vp and Vs structures in the same localized region.

We imposed a demanding signal-quality
criterion on the P waves to ensure stable
going evacuation for the PcP portion of the
wavefield. At distances beyond 60°, PcP typi-
cally have amplitudes <20% of P wave (fig. S1). Combining data from many events requires the
equalization of the signal shapes, which we
achieved by deconvolving source wavelets
obtained by alignment and linear stacking of the
direct P wave arrivals for each event separately.
We then filtered the deconvolved signals for each
event in various frequency passbands and
stacked the signals on the expected travel time
for PcP; if a stable, high signal-to-noise–ratio
PcP image was not formed for a given passband,
the event was discarded. This process eliminated
many data, including numerous events used in
earlier Vp studies, having either poor down-going
radiation patterns or excessive differences in the
waveshapes of the direct P wave and PcP. The
resulting data set has relatively uniform
PC, S and PcP reflections accounted for a sys-
tematic northward increase in lowermost-mantle
Vs across the region (fig. S4), but the stacks are
similar to those found when the data are aligned
on direct P wave arrivals (fig. S5B). Subdivision
of the data bins into smaller latitude intervals of
2.5° confirms the stability of the basic features in
the bins (fig. S5, C and D). The low amplitude
(<2% of the direct P wave) of any P wave
reflectivity at depths above the PcP arrival
directly indicates that, at most, only tiny PcP
precursors come from the lowermost mantle in
this region. In contrast, ScS precursors from the
lowermost mantle that are 25% as large as direct
S waves are observed in this region (fig. S3), as
has long been known (14).

Modeling of the P wave data stacks (19) demon-
strates that only small velocity variations are
present and bounds the depths of abrupt
changes to within ±10 km. We therefore con-
strained the depth of any associated Vp features to

![Fig. 1. (A) Earth cross section with representative ray paths for direct (P) and CMB reflected (PcP/ScS) phases and any reflections from deep mantle discontinuities (dashed line). The D" region structure in the lowermost mantle is the focus of this study. (B) Map indicating the study configuration, involving 75 earthquake epicenters (green stars), seismic stations (red triangles), and surface projections of PcP/CMB reflection points (blue dots). The dotted line shows the surface trace of a cross section made through the migration image volume in the lower mantle (Fig. 3). (C) The inset map shows both PcP and ScS CMB reflection points and two data bins where these overlap, used in waveform stacking analysis.]
match the \( V_p \) structures in modeling the \( S \) wave stacks, slightly modifying previous \( V_s \) models (20). We assumed that the largest amplitude features in the \( P \) and \( S \) wave data stacks near 300 km above the CMB represent reflectivity from colocated \( V_s \) and \( V_p \) discontinuities. This maximizes the reflection coefficient and provides upper bounds on any possible \( V_p \) discontinuity compatible with the weak \( P \) wave reflectivity near this depth.

For the 10° to 15° bin, our preferred model has a seismic velocity discontinuity 324 \((\pm 10)\) km above the CMB (2567 km deep) with changes of \( V_s (\delta V_s) \) and \( V_p (\delta V_p) \) of 2.1% and −0.1%, respectively, from which we calculated a \( V_s \) change \((\delta V_s) \) of −1.4%. A density contrast of 1.1% is assumed on the basis of associating the \( V_s \) discontinuity with the conversion from \( P \) to \( P_{PV} \); the data are insensitive to this choice, and there is no constraint on the density structure. The estimated uncertainties are +0.2% for \( \delta V_s \) and ±0.15% for \( \delta V_p \) on the basis of the suites of models found to give adequate fits to the data (fig. S6B). Any sharp \( V_p \) discontinuity near 324 km above the CMB must have a \( \delta V_p < ± 0.15% \), given the low noise levels of the stacks, which is a marked constraint on the structure. The \( V_s \) structure has some additional complexity at greater depths, especially near 191 km above the CMB.

At this depth, the \( V_p \) structure does not have a discontinuity in our average models, but a \( \delta V_p \) of −0.4% at variable depths can fit arrivals seen in smaller latitudinal bins (fig. S5, C and D). \( V_p \) decreases within the lowermost 40 km of the mantle, whereas \( V_p \) increases here.

For the 5° to 10° bin, the primary discontinuity is slightly deeper [299 km above the CMB (2592 km deep)], with \( \delta V_p = 1.1\% \), \( \delta V_p = −0.05\% \), and \( \delta V_p = −0.74\% \). The estimated \( \delta V_p \) depends on the choice of the direct \( S \) wave or \( ScS \) as a reference phase (we selected \( ScS \)) and could be 50% larger than the value given above (fig. S3), which leads to corresponding increases of the estimated \( \delta V_p \) and \( \delta V_p \). A much stronger \( \delta V_p \) at this depth was proposed by Kito et al. (18).

The strongest feature in the \( P \) wave stacks for the 5° to 10° subregion is near 189 km above the CMB, where a change in velocity gradient with depth \((dV_p/dz)\) and a 0.2 to 0.4% \( \delta V_p \) discontinuity are well resolved. The data sampling this subregion are at large distances where the sensitivity to this structure is high. The main effect comes from the change in \( dV_p/dz \), as even smoothly varying models like Preliminary Reference Earth Model and International Association for Seismology and Physics of Earth’s Interior model 1991 (IASP91) produce a general feature like that in the stacks (Fig. 3), but to match the stack amplitude, an additional small velocity jump is needed. This jump is sharp and must occur across ~20 km in depth to fit data stacks at higher frequencies (fig. S6A). This feature was previously detected in (17). As noted above, \( V_p \) increased near this depth in the 10° to 15° subregion, but there is no clear structure in the 5° to 10° region. This structure is within the interval where \( P_{PV} \) is likely to be present (Fig. 2). A pronounced \( V_p \) reduction occurs 51 km above the CMB with a small increase in \( V_p \).

The velocity discontinuities near 300 km above the CMB in these models are sharp for simplicity; the \( V_s \) discontinuities have been shown to occur across no more than 30 km in depth (20). For both subregions, spreading the corresponding \( V_p \) discontinuity across 30 km in depth decreases the apparent reflectivity by no more than a factor of 2, and our uncertainty estimates allow for this. Whereas tight bounds are placed on the structure at this depth, the near-CMB structure is less well resolved.

To ensure that the waveform stacks are not contaminated by out-of-plane scattering, we apply a Kirchhoff diffraction migration method (13), which seeks coherent scattering from a large 3D grid of possible isotropic point scatterers. This provides a more general parameterization of the medium than our localized 1D data stack-
One profile through the data image volume (movie S1) is shown in Fig. 3, along with profiles through synthetic images. The migration images (Fig. 3) show regions of positive (red) and negative P wave arrival amplitudes (blue), with PcP forming a strong red arrival along the CMB with adjacent blue sidelobes. Suppressing the PcP energy in the data by zeroing amplitudes within 3 s of the PcP arrival before the migration allows weak shallower features to show up better. With the ray paths being limited to a single corridor, there are artifacts due to limited source-receiver geometry and narrow frequency bandwidth; however, these are well accounted for in the migration images of synthetic seismograms, with a comparison of the data and IASP91 synthetic highlights featuring not explained by a smooth velocity model. Synthetic for our preferred 1D velocity models from the double-array stacking analysis clearly match the data well, particularly the structure ~300 km above the CMB (shown in blue in Fig. 3). The migrations do not show any evidence of contamination from out-of-plane scatterers, ensuring that the 1D models are reasonable for the ~300-km lateral Fresnel zones averaged by the data in the 0.25 to 0.5 Hz passband.

Globally, the lowermost 800 km of the mantle is observed to have large-scale heterogeneities in seismic velocities, and \( V_p \) and \( V_s \) are anticorrelated overall (21–23), but this is at least partly the result of large low-shear velocity provinces (LSSVPs) under the Pacific and Africa having negative \( V_p \) anomaly with weaker negative or no \( V_s \) anomaly, which is not the behavior expected for pPv. The LLSVP observations are commonly attributed to a chemical anomaly (24–26); if pPv is present in these regions (27), thermal and chemical effects must overwhelm the velocity effects of the phase change. Some regions in the lowermost 300 km of the mantle—notably beneath the circum-Pacific band of subduction zones—have positive \( V_s \) anomalies but limited resolution of \( V_p \) anomalies (8, 28). The Cocos region is unique in that it permits \( V_p \) and \( V_s \) to be well enough resolved to directly compute \( V_s \) behavior reliably.

Our determination of anticorrelation of \( V_p \) and \( V_s \) under the Cocos, arising from the presence of a strong \( V_p \) increase with a small \( V_s \) decrease, is consistent with the expectations for the Pv-to-pPv transition, supporting this interpretation of the structure. The overall velocities in our models are faster than those in global models, which indicates lower-than-average temperatures favorable to the presence of pPv, but the phase change itself appears to cause most of the \( V_p \) anomaly. For this region, then, a laboratory calibration of temperatures at the phase transition pressure indicated by the discontinuity provides a reasonable estimate of absolute mantle \( T \) of ~2500 K at the discontinuity, and properties of pPv can be considered to explain the overall seismic structure above the CMB (15, 20). This includes the reductions of \( V_s \) right above the CMB in our models and the accompanying increases in \( V_p \), which can be explained if a steep thermal gradient reverses pPv to Pv right above the CMB (15, 27, 29).

Some experiments and theories suggest that increasing the Fe content in Pv lowers the pressure at which Pv transforms to pPv (6, 30, 31); however, other high P-T experiments with pyrolic-type compositions (~10% Fe content) show very limited differences in transition pressure relative to end member MgSiO3, when different pressure standards are used (32). The presence of Al is predicted to increase the Pv-to-pPv transition pressure and to broaden the pressure range of the two-phase zone up to 13 GPa (~150 km) (33, 34), which would dramatically weaken any seismic energy reflected from the phase change. Including either Fe or Al in pPv tends to reduce the changes in seismic properties across the Pv-to-pPv transition, with the effect of Fe being about three times stronger than that of Al (34, 35). Although estimates of the precise properties of pPv differ between methods, for pyrolic-type silicates it is consistently found that the jump in \( V_p \) is strong and positive, any change in \( V_s \) is small, and the predicted change in \( V_s \) is strong and negative, consistent with our observations under the Cocos plate. Whereas complex compositional variations (such as former oceanic crust, if it has sunk to the base of the mantle) might still be needed to explain some of the secondary features in the Cocos region, the structure near 2600 km of depth in this region is well explained by the Pv-to-pPv phase change.

**Fig. 3.** Vertical cross sections through the volume imaged by scattering migration for the \( P \) wave data set with \( PcP \) as the reference phase. Horizontal axes denote lateral distance along the line in Fig. 1 going from southeast (SE) to northwest (NW). The CMB is shown by the black line. The top row is for the full waveforms, and the bottom is for waveforms with \( PcP \) masked out with a 6-s-wide symmetric taper applied around the predicted arrival time for \( PcP \) for each seismogram. The left column shows the migration stack of observed data, and the other columns show migration images of synthetic seismograms generated from a merge of synthetics for our preferred models (Fig. 2) for the two subregions (middle) and the 1D model (IASP91) (right). The synthetic merging was based on whether the \( PcP \) reflection point at the CMB was north or south of 10°N (indicated with a black tick mark in the upper middle panel). All data stacks have been weighted proportional to the number of seismograms contributing to each grid point, so lateral transitions to zero values (green) represent very small data sampling, not the absence of structure.

**References and Notes**

Differential Rescue of Light- and Food-Entrainable Circadian Rhythms

Patrick M. Fuller, Jun Lu, Clifford B. Saper*

When food is plentiful, circadian rhythms of animals are powerfully entrained by the light-dark cycle. However, if animals have access to food only during their normal sleep cycle, they will shift most of their circadian rhythms to match the food availability. We studied the basis for entrainment of circadian rhythms by food and light in mice with targeted disruption of the clock gene Bmal1, which lack circadian rhythmicity. Injection of a viral vector containing the Bmal1 gene into the suprachiasmatic nucleus of the hypothalamus restored light-entrainable, but not food-entrainable, circadian rhythms. In contrast, restoration of the Bmal1 gene only in the dorsomedial hypothalamic nucleus restored the ability of animals to entrain to food but not to light. These results demonstrate that the dorsomedial hypothalamus contains a Bmal1-based oscillator that can drive food entrainment of circadian rhythms.

The circadian timing system (CTS) exerts endogenous temporal control over a wide range of physiological and neurobehavioral variables, conferring the adaptive advantage of predictive homeostatic regulation (1). When food is freely available, light signals from the retina entrain circadian rhythms to the day-night cycle (2). However, when food is available only during the normal sleep period (restricted feeding (RF)), many of these rhythms are reset so that the active phase corresponds to the period of food availability (3, 4). In light entrainment, retinal ganglion cells that contain the photopigment melanopsin provide signals to neurons in the suprachiasmatic nuclei (SCN) of the hypothalamus that generate circadian rhythms through a series of molecular transcriptional, translational, and posttranslational feedback loops (5). The SCN in turn synchronizes circadian rhythms in peripheral tissue clocks through synaptic and humoral outputs (5, 6). During RF, the SCN remains on the light cycle and SCN lesions do not prevent food entrainment, which suggests that another clock may supersede the SCN (3, 4, 7). Two recent studies have suggested that at least one food-entrainable clock may be located in the dorsomedial nucleus of the hypothalamus (DMH), but the importance of this clock for food entrainment has been disputed (3, 8–10).

The core components of the molecular clock include the activating transcription factors BMAL1 and CLOCK and the negative regulatory feedback elements encoded by the Per and Cry genes (11, 12). Bmal1 is the only circadian clock gene without a known functional paralog and hence the only one for which a single gene deletion causes a complete loss of behavioral and molecular rhythmicity (13). Because its gene product BMAL1 is a transcription factor that likely influences many downstream genes, Bmal1−/− mice also exhibit other physiological defects unrelated to the circadian defect (14), including progressive arthropathy, decreased locomotor activity levels and body mass, and a shortened life span (15–18).

In this study, we used Bmal1−/− mice, which harbor a null allele at the Bmal1 locus (19). The circadian patterns of locomotor activity (LMA) and body temperature (TTb) were monitored by telemetry (Fig. 1, A to C, and fig. S2). As previously reported, these animals showed no circadian rhythms in a 12-hour-light/12-hour-dark (LD) cycle or constant darkness (DD) when given ad libitum (AL) access to food (Fig. 1B). We also attempted to entrain Bmal1−/− mice to a 4-hour window of RF during the normal sleep period for mice, under both LD (ZT4–8 from 4 to 8 hours after light onset) and DD (CT4–8 from 4 to 8 hours after presumptive light onset) conditions. In LD and DD conditions, wild-type (WT) and heterozygous littermates showed an elevation of TTb and LMA ~2 to 3 hours before food became available (Fig. 2, A and D, and fig. S2). By contrast, Bmal1−/− mice did not show a comparable elevation in TTb or increase in LMA before the window of RF in DD; TTb and LMA were, however, markedly elevated in the Bmal1−/− mice after food presentation (Fig. 2, B and D, Fig. 3C, and fig. S2). In addition to the preprandial elevation in TTb under RF, WT and heterozygous littermates demonstrated a clear circadian TTb rhythm (Fig. 2A), whereas Bmal1−/− mice showed a persisting ultradian TTb pattern throughout the remainder of the day (Fig. 2B). In DD conditions, Bmal1−/− mice occasionally showed periods of torpor (TTb below 31°C), which were distributed randomly across the circadian day. Consequently, the Bmal1−/− mice not only failed to show elevation of TTb or LMA in anticipation of the RF but were often asleep or were in torpor through the window of RF, requiring us to arouse them by gentle handling after presentation of the food to avoid their starvation and death during RF.

After 14 days in this RF regimen, mice were killed to examine clock gene expression in the brain and were compared to mice that had been fed AL. As previously reported (8), WT animals with AL food showed peak expression of Per1 and Per2 mRNA at ZT5–6, and Bmal1 at ZT18–19 in the SCN (Fig. 3, D and E), but little or no expression at other hypothalamic sites. By contrast, WT animals under RF also showed no change in this expression pattern in the SCN (Fig. 3, D and E) but did show induction of Per1 and Per2 at ZT3–9 (preceding, during, and after the RF window) in the DMH with peak expression levels at ZT7–8 (Fig. 3F). We also saw induction of Bmal1 mRNA in the DMH, with peak expression at ZT18–21 (Fig. 3G), consistent with neurons in the DMH showing induction of rhythmic