Anticorrelated Seismic Velocity Anomalies from Post-Perovskite in the Lowermost Mantle
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(location 1, 21 ± 1 ka; location 3, 19 ± 3 ka) (17, 23). The scoured notch (location 4) yielded the same age as the boulder at location 2, 45 ± 5 ka.

Another constraint on the age of the canyon comes from an ~20-cm-thick, finely laminated bed, containing clay, silt, and sand, that is exposed in a small road cut within the talus slope [location 5 (Fig. 3 and fig. S1C)]. Two shells found within the layer yielded ages of 22.4 ± 1×102 radiocarbon years before the present (23), which is equivalent to a calibrated age of ~26 ka (27).

Together, these observations, hydraulic calculations, and dates eliminate the seepage-erosion hypothesis for the formation of Box Canyon. Here, seepage is not substantially enhancing the weathering of the headwall, and contemporary seepage flow is deficient by a factor of ~22 to evacuate sediment from the canyon. Moreover, erosion of the canyon headwall ceased ~45 ka according to the age of the scoured-bedrock notch. The observations of scoured bedrock and plunge pools point toward a flood or floods able to transport boulders (~1 m) (29). Other amphitheater-headed canyons carved into basalt by large floods [for example, Dry Falls, Washington, USA (30), and Asbyrgi Canyon, Iceland (31)] might be better terrestrial analogs of Martian canyons in volcanic terrains than seepage channels in sand.

References and Notes
23. Materials and methods are available as supporting material on Science Online.
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Supporting Online Material
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Materials and Methods
SOM Text
Figs. S1 to S6
Table S1
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We imposed a demanding signal-quality criterion on the $P$ waves to ensure stable down-going radiation for the $PcP$ portion of the wavefield. At distances beyond 60°, $PcP$ typically 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 $V_p$ 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 detections of $PcP$ and is sufficiently large and high-quality that we can identify features that have amplitudes only 10% as large as the weak $PcP$ reflections. Our screened data set includes more than 10,000 waveforms from 75 events (Fig. 1).

The $S$ wave data were equalized by deconvolving source wavelets obtained from aligning and stacking the clear $ScS$ arrivals; only records having impulsive deconvolved $ScS$ signals were retained. The total number of traces, 255, is much smaller than that for the $P$ waves, but the $S$ wave reflections from the lower mantle are far stronger than their $P$ wave counterparts. Good resolution of $V_s$ structure was obtained, as is critical for computing $V_s$.

Double-array stacking (11, 17, 19) (fig. S2) was applied to the $P$ and $S$ wave data sets to develop localized one-dimensional (1D) velocity structures for the two subregions indicated in Fig. 1 (5° to 10°N and 10° to 15°N). Stacks for the 7300 $P$ waves sampling the two subregions are shown in Fig. 2 for the passband with the highest signal quality (0.25 to 0.5 Hz); corresponding subregion stacks for the 200 $S$ waves from (20) are shown in fig. S3 for the passband ranging from 0.01 to 0.3 Hz. Alignment of the $P$ wave data on $PcP$ reflections accounted for a systematic northward increase in lowermost-mantle $V_p$ 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 (figs. S5, C and D). The low amplitude (<2% of the $PcP$ 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) demonstrates that only small velocity variations are present and bounds the depths of abrupt changes to within ±10 km. We therefore constrained the depth of any associated $V_p$ features to

![Fig. 1](https://example.com/fig1.png)

**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 collocated $V_s$ 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 (±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%, respectively, from which we calculated a $V_p$ change ($\delta V_p$) of −1.4%. A density contrast of 1.1% is assumed on the basis of associating the $V_s$ discontinuity with the conversion from $P_v$ to $pP_v$; 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 $\delta V_p <\pm0.15\%$, 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 $\delta V_s = 1.1\%$, $\delta V_p = -0.05\%$, 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 sub-region 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 $pP_v$ 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 $V_p$ 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-
ing (19). 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 image 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 features 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 300 km of the mantle is observed to have large-scale heterogeneities in seismic velocities, and Vp and Vs are anticorrelated overall (21–23), but this is at least partly the result of large low-shear velocity provinces (LLSVPs) under the Pacific and Africa having negative Vp anomaly with weaker negative or no Vs 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 Vs anomalies but limited resolution of Vp anomalies (8, 28). The Cocos region is unique in that it permits Vp and Vs to be well enough resolved to directly compute Vp behavior reliably.

Our determination of anticorrelation of Vp and Vs under the Cocos, arising from the presence of a strong Vp increase with a small Vs decrease, is consistent with the expectations for the P-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 Vs 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 Vs right above the CMB in our models and the accompanying increases in Vp, 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 pyrolitic-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 P-veto-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 pyrolitic-type silicates it is consistently found that the jump in Vp is strong and positive, any change in Vs is small, and the predicted change in Vs 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
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 nuclei 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 hypothalamic nucleus 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 (Tb) 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) and DD (ZT4–8) conditions. In LD and DD conditions, wild-type (WT) and heterozygous littermates showed an elevation of Tb 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 Tb or increase in LMA before the window of RF in DD; Tb 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 Tb under RF, WT and heterozygous littermates demonstrated a clear circadian Tb rhythm (Fig. 2A), whereas Bmal1−/− mice demonstrated a persisting ultradian Tb pattern throughout the remainder of the day (Fig. 2B). In DD conditions, Bmal1−/− mice occasionally showed periods of torpor (Tb below ~31°C), which were distributed randomly across the circadian day. Consequently, the Bmal1−/− mice not only failed to show elevation of Tb or LMA in anticipation of the RF but often slept 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