be able to refine our previous results.

29. To make this estimate, we assume that only the phase-change boundary from $\gamma$ spinel to perovskite is responsible for $S_{\text{spinell}}$. We also assume that the shallowest $\Delta S_{\text{spinell}}$ depth represents wave conversion in the ambient mantle. The temperature estimated for the coldest part of the Izu-Bonin slab is $900 \pm 100$ K (47), whereas the mantle temperature of the phase change from $\gamma$ spinel to silicate-perovskite and magnesiowüstitite near a depth of 660 km is $1900 \pm 100$ K (48).


31. Trench-advance rates over the last 5 million years increased linearly from 0 to 6 mm year$^{-1}$ near Japan and 80" near 27N. The southern Izu-Bonin trench has only advanced toward Eurasia a maximum of 150 km in the last 5 million years, and the northern part has remained nearly fixed.


43. We use International Seismological Center (ISC) hypocenters that were determined from the direct $P$ arrivals only. For some of the events the ISC catalog also contains hypocenters determined with $P$, but for the sake of consistency, we use the hypocenters determined from $P$.

44. H. Jeffreys and K. E. Bullen, Seismological Tables (Smith and Ritchie, Edinburgh, 1970).

45. We thank E. R. Engdahl for access to his set of earthquake locations; R. Gritto and L. Stixrude for their helpful discussions; and J. Vidale, P. Shearer, and M. Bukowinski, whose comments helped improve the manuscript. Supported by National Science Foundation grant EAR9004026.


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Comparisons Between Seismic Earth Structures and Mantle Flow Models Based on Radial Correlation Functions

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Three-dimensional numerical simulations were conducted of mantle convection in which flow through the transition zone is impeded by either a strong chemical change or an endothermic phase change. The temperature fields obtained from these models display a well-defined minimum in the vertical correlation functions close to or near the radius where the barrier is imposed, even when the fields were filtered to low angular and radial resolutions. However, evidence for such a feature is lacking in the shear-velocity models derived by seismic tomonography. This comparison suggests that any stratification induced by phase or chemical changes across the mid-mantle transition zone has a relatively small effect on the large-scale circulation of mantle material.

O n e goal of structural seismology is to map variations in the seismic wave speeds in sufficient detail to resolve the pattern of mantle convection. The most fundamental issue is the degree to which the large-scale flow is stratified by changes in mineralogical phase or bulk chemistry across the transition zone from depths of 400 to 700 km (1). Particular attention is being paid to the role of the 670-km discontinuity, which is dominated by the endothermic dissociation of spinel (Mg,Fe)$_2$SiO$_4$ into perovskite (Mg,Fe)$_6$SiO$_4$ plus (Mg,Fe)O. Laboratory (2) and seismic observations (3) constrain the Clapeyron slope of this phase transition to be negative and relatively steep: $-4 \pm 2$ MPa K$^{-1}$. Convection calculations that combine phase-change dynamics with two-dimensional (2D) (4, 5) and 3D (6, 7) flow geometries indicate that an endothermic transition of this magnitude acts to inhibit convection through the phase boundary.

Any restriction of the large-scale flow by this or some other mechanism (8) should be evident in the shear-wave speeds determined by seismogenic tomography. Seismic data sets have been inverted by several research groups (9-13) to obtain the shear-velocity perturbation $\delta V_{s}(r,\Omega)$ up to spherical harmonic degree 12 throughout the mantle, where $r$ is the radius ranging from the core-mantle boundary at $b = 3480$ km at the surface to $a = 6371$ km and $\Omega = (\theta,\phi)$, a point on the geographic sphere $S_1$. In regions where compositional and phase differences can be ignored, $\delta V_{s}(r,\Omega)$ is relatively small, typically less than 5% of the mean wave speed, and can be related to the aspheric temperature variations by the linear approximation

$$\delta V_{s}(r,\Omega) = (\delta V_{s}(r,\Omega) - \delta V_{s}(r,\Omega_0)) \approx \delta T(r,\Omega)$$

Progress in the calculation of 3D, solid-state convection (6, 7, 14, 15) makes it feasible to discriminate among the various stratification hypotheses by the comparison of numerical simulations of $\delta T$ with seismic estimates of $\delta V_{s}$ throughout the entire mantle.

A direct comparison of the temperature and shear-velocity fields is not the best approach, however. Convection models are still too crude to predict the details of mantle flow. Moreover, whole-mantle (WM) tomonography cannot resolve such details, and there is still considerable uncertainty in the value of $(\delta V_{s}(r,\Omega) - \delta V_{s}(r,\Omega_0))$ in the lower mantle (16). Competing convection hypotheses must therefore be tested by considering the average properties of the temperature field that can be reliably derived from low-resolution estimates of the shear-velocity and that are robust with respect to the $\delta T$-$\delta V_{s}$ scaling. In most tomographic inversions, the shear-speed variations are represented by a truncated series

$$\delta V_{s}(r,\Omega) = \sum_{l=1}^{\text{max}} \sum_{m=-l}^{l} \delta V_{s}(r,\Omega_0) Y_{lm}(r,\Omega)$$

where $b \leq r \leq a$ and $Y_{lm}$ is the surface spherical harmonic of angular degree $l$ and azimuthal order $m$. For hypotheses regarding convective stratification, the most obvious discriminants are radial functions constructed by some sort of averaging over the angular coordinates. An example is the angular squared-amplitude (power) spectrum, $S_{\delta V_{s}}(r,l) = \frac{1}{2} \delta V_{s}^{2}(r,\Omega)$. Tomographic estimates of $S_{\delta V_{s}}(r,l)$ display high amplitudes and low characteristic wave numbers in both the uppermost and lowermost mantle (9-12). These estimates have been interpreted as manifestations of thermal, and perhaps chemical, boundary layers at the top and the bottom of the mantle (9, 18). The $S_{\delta V_{s}}(r,l)$ spectrum peaks at $l = 4$ to 5 in
the upper mantle (the scale of the tectonic plates) but has a strong \( l = 2 \) signature in the lower mantle, which some researchers have attributed to convective stratification \((19, 20)\). On the other hand, a localized peak in total spectral variance expected for a stratification boundary \((5, 7, 21)\) has not been observed in the vicinity of the 670-km discontinuity.

A better diagnostic of stratification is the radial correlation function

\[
R_p(r, r') = \frac{1}{4\pi \sigma_p(r) \sigma_p(r')} \int \delta \beta(r, \Omega) \delta \beta(r', \Omega) d\Omega
\]

where

\[
\sigma_p^2(r) = \frac{1}{4\pi} \int \delta \beta(r, \Omega)^2 d\Omega
\]

This function is symmetric in the two radial coordinates and invariant with respect to any radial scaling of \( \delta \beta(r, \Omega) \). It is unchanged by the root-mean-square (rms) normalization, for example, \( R_p(r, r') = R_p(r, 0) \) for \( \delta \beta(r, \Omega) \equiv \delta \beta(r, \Omega) / \sigma_p(r) \). To the extent that \( (\partial \beta / \partial T) \) depends only on pressure, Eq. 1 implies that \( R_p(r, r') = R_T(r, r') \). Therefore, comparisons between the seismic and convection models on the basis of the radial correlation function are not sensitive to uncertainties in the temperature coefficient of shear velocity. The maximum value of the radial correlation function is unity, achieved on the diagonal \( r = r' \), and its falloff away from this median ridge is indicative of the rate at which the structures on spherical surfaces decorrelate as their depths are separated. The vertical coherence in the vicinity of a radius \( r \) can be quantified by the radial correlation length \( \rho_v(r) \), defined by the implicit equation

\[
R_p(r - \rho_v \sqrt{2}, r + \rho_v \sqrt{2}) = x
\]

According to this definition, \( \rho_v(r) \) is the half-width of the median ridge measured perpendicular to the diagonal out to some contour level \( x \). For \( 0.5 \leq x \leq 0.9 \), the diagnostic properties of \( \rho_v(r) \) are insensitive to the specific choice of \( x \); we adopt a value of 0.75. Within a stratified system, \( \rho_v(r) \) is expected to be maximized in regions where the vertical flux is high—for example, in the interior of convecting layers—and to be minimized at an internal boundary separating two layers.

For the convection simulations, we used 3D computer models \((14)\) based on the anelastic and infinite Prandtl number approximations for thermal convection in a compressible, self-gravitating, spherical fluid shell \((22)\). The models were run at total Rayleigh numbers of \(~2 \times 10^7\). In the WM simulation (Fig. 1), there were no changes in phase or chemistry with depth \((23)\). The resulting flow is representative of 3D, WM models dominated by internal heating \((15)\). The downwellings occurred primarily as narrow sheets, which broke up into cylinders as they descended, whereas the upwellings were generally weak and distributed, with a few concentrated plumes. The function \( R_T(r, r') \) is characterized by a simple, ridge-like morphology, with relatively small variations near its diagonal. Away from the boundary layers, the half-width of the 0.75 contour, \( \rho_{0.75}(r) \), ranges from a maximum of \(~400\) km in the upper mantle, where the downwellings sheets are best developed, to a minimum of \(~200\) km in the mid-mantle, where the cylindrical downwellings are most narrow (Fig. 2A, red lines). Other simulations demonstrate that the average of these two characteristic scales decreases as the Rayleigh number increases and that the ratio of the first to the second decreases as the ratio of internal heating to bottom heating is lowered \((24)\). The flow in the WM model was highly time-dependent, but the basic structure of \( R_T(r, r') \) in Fig. 1.
Stratified flows show a different structure. The phase-change (PC) run of Fig. 3 included the dynamical effects of an endothermic phase transition at the 670-km discontinuity (7, 25). In this simulation, downwellings in the upper mantle occurred in a network of interconnected sheets. Material pooled above the phase transition at the intersections of the sheets, breaking through into the lower mantle during brief episodes of high local mass flux (7). The avalanches from these flushing events formed large (~1000 km in diameter) cylindrical plumes, which sunk through the lower mantle and spread out in a thick layer at the core-mantle boundary (Fig. 3). Flow in the PC model is stratified in the sense that it has a local minimum in the normalized vertical mass flux at the phase boundary (5, 7). The stratification is also evident as a distinctive pinch in the median ridge of \( R_{h}(r, r') \) and as a corresponding minimum in the radial correlation length. The value of \( p_{0.75}(r) \) at the phase boundary was 58 km, about one order of magnitude smaller than its mid-mantle maximum, and varied by only ±10% from snapshot to snapshot during the PC run (Fig. 2B). A more broad and shallow minimum in \( p_{0.75}(r) \) occurred 700 to 800 km above the core-mantle boundary, delimiting a region in which colder material accumulates subadiabatically and diverges laterally at the base of the mantle.

The angular power spectra for the WM and PC models differ considerably (26), but in both cases the major features of the flow expressed in the radial correlation functions have low wave-number signatures. We low-pass filtered the models at angular degree and order 10 and radial order 13 to mimic the smearing that would occur if these structures were imaged by seismic tomography. Although this truncation obscured the details of the flow, including the thermal signature of all but the largest upwellings and downwellings, the morphology of \( R_{h}(r, r') \) was largely unchanged. The filtering generally reduced the correlation lengths of the WM snapshots, suppressed their upper-mantle peaks, and increased their fluctuations (Fig. 2A, black lines). The graphs of \( p_{0.75}(r) \) for the filtered PC snapshots lost some of the details associated with the surficial boundary layer, and the correlation-length minima corresponding to the phase change were increased to ~100 km and translated to slightly greater depths (Fig. 2B). However, the constriction of the median ridge at the phase change remained evident, as did the minimum defining the top of the accumulation zone in the lowermost mantle.

Radial correlation functions computed for other models of 3D convection in a spherical shell yielded similar results. Runs were done at lower Rayleigh numbers (~1.6 × 10^6) for WM models having different viscosity profiles, as well as for completely stratified models in which no mass flux was allowed across the 670-km discontinuity. The latter models approximated the stratification expected for a large, chemically induced density increase but did not include the boundary deformations expected in this situation (27, 28). In the completely stratified models, \( p_{0.75}(r) \) essentially goes to zero at the discontinuity; again, the minimum remains sharply defined when the snapshots are low-pass filtered [see (28) for correlation-function plots]. These models include simulations with a uniform viscosity profile, in which the coupling between the layers was primarily viscous, as well as runs with a 30-fold increase in viscosity in the lower mantle, where thermal coupling predominated. The addition of an exothermic olivine-spinel phase transition at a depth of 400 km to the PC model (29) reduced the characteristic time scale of material accumulation in the transition zone and so decreased the degree of stratification, but the deeper phase boundary was still marked by a well-defined minimum in \( p_{0.75}(r) \).

For comparison, we computed the radial correlation function for two WM shear-velocity structures, the Harvard model SH12/WM13 and the Scripps model SH10C, which were derived from different data sets and parameterizations (30). The two maps of \( R_{h}(r, r') \) are similar in the upper half of the mantle (Fig. 4), and the correlation lengths oscillate by only a few tens of kilometers about a mean of ~130 km (Fig. 2C). This value of \( p_{0.75} \) corresponds to...
heterogeneity with a characteristic radial wave number of \( n = 5 \), consistent with the dominant vertical scale lengths observed in the cross sections of Fig. 4 (33). The inversions have good resolving power for features of this size throughout the upper and middle mantle (34), although there are significant discrepancies between the two seismic models in the lower mantle (35). The 670-km correlation-length minimum in the PC simulation is strongly expressed in these low wave numbers (truncation at \( n_{\text{max}} = 6 \) decreases its amplitude by less than 50%). Therefore, if such a feature existed in the transition zone or upper part of the lower mantle, it would likely be recovered in inversions of the actual seismic data.

The most striking aspect of Figs. 2C and 4 is the lack of any discernible expression of the mantle transition zone. There is no evidence in either seismic model shown here, or in other published WM structures, for a decorrelation in shear-wave heterogeneity across the 670-km discontinuity (36, 37). The nearly constant value of \( \rho_0 c_s^2(n) \) throughout the upper half of the mantle suggests that stratification of the magnitude observed in the PC simulation (7) or in the two-layer models (28) is not a present-day feature of the mantle's convective regime. This interpretation does not imply that the transition-zone phase changes are not dynamically significant or that chemical gradients in the vicinity of the 670-km discontinuity do not exist. It suggests only that their combined effects on the large-scale pattern of flow are sufficiently small to escape detection in the current generation of WM tomographic models.

Three-dimensional convection simulations do not yet account for the strong temperature dependence of viscosity. The inclusion of high- viscosity descending slabs may enhance the ability of cold downwellings to become a self-sustaining thermodynamic phase change for example (27). Therefore, one can envisage a regime in which weaker, smaller scale features of flow are dynamically inhibited at the 670-km discontinuity but also in which the average vertical mass flux through the transition zone, dominated by the plate-tectonic return flow, is not much less than those in the layers above and below it. Such a model would be consistent with the seismic data indicating the penetration of cold slab material into the lower mantle beneath zones in which the subduction flux has been historically large (17, 38) and would still provide an explanation for the observations of local distortions in slab geometry (39).

REFERENCES AND NOTES
1. The controversy was launched in nearly its present form at a symposium in Hershey, PA, in 1950, 15 years before the discovery of plate tectonics.
Late Cretaceous Precessional Cycles in Double Time: A Warm-Earth Milankovitch Response

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Late Cretaceous climatic cycles are reflected in lithological and magnetic variations in carbonate sediments from South Atlantic Deep-Sea Drilling Project site 516F at a paleolatitude of roughly 30°S. Magnetic susceptibility cycles 20 to 60 centimeters in length appear to be controlled by the precession of the equinoxes. Cyclicity isparticularly robust within a 24-meter interval in the lower Campanian, where overtone spectral peaks are observed as well as secondary susceptibility maxima within individual precession cycles. One model for this behavior is that sedimentation in the narrow Cretaceous South Atlantic was controlled by equatorial climate dynamics, with the precessionally insolated signal rectified by the large land masses surrounding the ocean basin.

Quadra-periodic oscillations in the Earth's orbit about the sun cause variations in the amount and distribution of insolation received at the Earth's surface. In the last million years, the Milankovitch orbital cycles of precession, obliquity, and eccentricity are thought to have governed the Earth's climate (1). Orbital cycles exerted a strong influence on the climate of the Earth during the Cretaceous, as evidenced by cyclic vari-ations in Cretaceous deep-sea and shelf sedimentary rocks (2). Because the fluctuations associated with orbital cycles are at most 10% of the mean insolation, the Earth's climate may often have been quite sensitive to externally determined conditions. As a consequence, the geologic record of orbital cycles shows how the Earth's climate responds to modest pertur- bations and may help us to anticipate future anthropogenic climate trends.

Mesozoic sedimentary records are often marred by large variations in accumulation rate and diagenesis (3). Fourier analysis of Mesozoic climate proxy data typically offers only a rough estimate of the data's spectral properties. Data of much higher quality can be found in drill cores from Deep-Sea Drilling Project (DSDP) site 516F, on the Rio Grande Rise in the South Atlantic Ocean. In one interval of these data, the accumulation rate appears nearly constant for roughly 1 million years, so that fine details of the climate proxy spectrum can be estimated.

These details shed light on the climate dynamics of the warm Cretaceous. The Cretaceous-Paleocene part of the site 516F data consists largely of alternating carbonate and marl layers of varying color, deposited at benthic depths (500 to 1500 m) (4). In an earlier orbital-cycle analysis of this and other South Atlantic sites, optical densitometry was used to estimate an average duration of 23.5 ± 4.4 × 103 years for the Cretaceous lithologic cycles (5), close to the principal modern precessional periods of 19.0 × 103, 22.4 × 103, and 23.7 × 103 years. We have measured whole-core magnetic susceptibility from core segments spanning the Santonian (~85 Ma [million years ago]) through the earliest Danian (~64 Ma). Magnetic sus- ceptibility in carbonate sediments is influ-enced by many factors but is typically dominated by the ratio of terrigenous to biogenic components (6, 7). Chalky layers typically have lower susceptibility than marly layers. Depending on the sedimenta- tion environment, cyclic variations in suscepti- bility can be governed by terrigenous input, carbonate dissolution, or dilution by biogenic carbonate production. Distinct cyclostratigraphic patterns appear to persist for a few tens of meters within the site 516F record, corresponding to intervals of a few million years. Cores 113, 114, and 115 are part of one such stable interval, lying within the lower Campanian (8) (Fig. 1).

Short cycles are grouped into bundles of four or five, consistent with the modulation of precessional insolation variations by the Earth's orbital eccentricity. Drilling records (4) indicate that little material was lost within the core segments; core 115 is truncated, but the sum of cores 112, 113, and 114 differs by only 1 cm from nominal perfect