example, sedimentary basins, geothermal systems, island arcs, oceanic ridges, and contact aureoles). Various hydrous minerals (clays, zeolites, micas, talc, serpentine, chlorite, epidotes, and amphiboles) form under these conditions as primary or alteration minerals, and their isotopic compositions have been used to infer the sources of fluids or the temperature of mineral formation (isotope geothermometer). Many mineral water D/H fractionation factors in the literature, which were usually determined at a constant, high pressure (typically ≥100 MPa), are rather insensitive to temperature (6). However, pressure changes alone can shift mineral water D/H fractionation factors as shown for the system brucite (isotope geothermometer). Many mineral water D/H fractionation factors in the literature, which (isotope geothermometer). Many mineral water D/H fractionation factors in the literature, which

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9. Typically, 10 to 25 mg of brucite and 25 to 300 mg of water were sealed in gold capsules. Three or four gold capsules, identical except for hydrogen isotope composition, were loaded into an autoclave, cold-seal apparatus, or piston cylinder depending on the pressure-temperature conditions of interest. Temperature and pressure were controlled within ±2°C and ±1 MPa, respectively, for low-pressure (15 to 25 MPa) experiments, for which pressure was calculated from the volume of the vessel and pressure-volume properties of pure water to an error of ±0.2 to 1 MPa. In a piston cylinder experiment at 800 MPa, a pressure uncertainty is ±20 MPa. At the end of experiments, the vessels were quenched to <50°C within 5 to 30 min, and the gold capsules were weighed to check for leakage. The brucite-run products were washed with deionized water and dried. After drying in vacuum overnight at 150°C, water was extracted from brucite by heating to 90°C for an hour in a vacuum. The water extracted was converted to H2 by passing over hot uranium metal at 750°C (J. Bigeleisen, M. L. Perlman, H. C. Prosser, Anal. Chem. 24, 1356 (1952)).


A Laboratory Model for Convection in Earth’s Core Driven by a Thermally Heterogeneous Mantle

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Thermal convection experiments in a rapidly rotating hemispherical shell suggest a model in which the convection in Earth’s liquid outer core is controlled by a thermally heterogeneous mantle. Experiments show that heterogeneous boundary heating induces an eastward flow in the core, which, at a sufficiently large magnitude, develops into a large-scale spiral with a sharp front. The front separates the warm and cold regions in the core and includes a narrow jet flowing from the core-mantle boundary to the inner-core boundary. The existence of this front in the core may explain the Pacific quiet zone in the secular variation of the geomagnetic field and the longitudinally heterogeneous structure of the solid inner core.

The temperature profile in Earth’s outer core is estimated to be nearly adiabatic (I) as a consequence of its highly turbulent state. The total heat flux from the core to the mantle is estimated to be comparable to (within a factor of 2) the heat conducted down the core adiabat (1, 2). These conditions lead to an unusual thermal regime in which the turbulent convective heat transfer amounts to less than one-half of the total heat transfer from the core. The situation is further complicated by a heterogeneous heat-flow boundary condition due to the large-scale pattern of mantle convection. As a consequence, the convective part of the heat transfer in the core is likely to exhibit extremely large lateral variations, perhaps of more than an order of magnitude (3).

The importance of a thermally heterogeneous core-mantle boundary (CMB) for convection in the core has been recognized (4). Theoretical studies have investigated the flow driven by boundary heterogeneity, but mostly in the cases in which the heat-flux variation is relatively small (5). These studies have shown that, under some conditions, the convective pattern in the core can be locked to the CMB heterogeneity. In the core, we expect a generally convective state modulated by a large lateral variation in convective heat flux. In our study, we modeled this regime using laboratory experiments in a rapidly rotating spherical shell (6). Such experiments realize conditions closer to those of Earth by an order of magnitude, as compared to numerical models (7), and also include the fine-scale structures that tend to be smoothed out in numerical models.

A hemispherical shell (Fig. 1) was filled with water and rotated at 206 rotations per minute, providing an Ekman number of $E = 4.7 \times 10^{-6}$. Radial gravity was simulated by the combined effects of Earth’s gravity and centrifugal acceleration. The outer copper sphere, the model CMB, was maintained at room temperature. The inner copper sphere, the inner-core boundary (ICB), was maintained be-

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low room temperature. Thermal heterogeneity was imposed by attaching a heat-flux-regulated, thermally insulated rectangular heater at the CMB, covering a latitudinal and longitudinal rectangle of 0° to 48° and 0° to 9.7°, respectively, which is 2.3% of the CMB area (8). This patch modeled the effect of an anomalously cold region in Earth’s lower mantle, where heat flow from the core to the mantle is large. The heat-flux variation in the experiments modeled the heat-flux variation in the core in excess of that conducted down the adiabat. The total heat flux at the ICB was measured by the temperature rise of the water circulating in and out of the inner core. We recorded the temporal and spatial variations of the pattern, flow velocity, and temperature.

With a homogeneous thermal boundary condition, convection in the fully developed regime consists of nearly two-dimensional turbulence, with meandering plumes originating from the ICB and CMB (6). The mean zonal flow is westward, and the convective pattern drifts westward with this flow. We refer to this as the basic convective state.

Figure 2 shows how this basic state is modified by boundary heterogeneity for 19 < Ra/Rac < 52 (Ra is Rayleigh number, Rac is critical Rayleigh number), E = 4.7 × 10⁻⁶, and for lateral variation of heat flux at the CMB up to ~100 times its mean value. When the peak heat flux at the CMB is less than ~35 times its mean, the mean convective structure remains unaltered from the basic state (Fig. 2A). However, there is a localized eastward flow adjacent to the heterogeneity. Temperature in the fluid measured by thermistor probes indicates a higher temperature and a larger fluctuation to the east of the heterogeneity. This eastward phase shift is consistent with some of the previous theoretical studies (5). As the heat flux is increased, the anomalous flow extends toward the ICB, and temperature fluctuation changes from the predominance of spikes with negative anomaly to positive anomaly, indicating that the flow is increasingly driven by warm plumes. Because the anomalous flow is confined near the heater at the CMB, we refer to this regime as local locking.

A much different regime appears when the peak heat flux at the CMB exceeds its mean by ~35 times, featuring a large spiraling structure to the east of the heterogeneity (Fig. 2B). Dye streaks show that the flow is eastward near the heterogeneity, with a narrow radially inward flowing jet along the spiral structure (Fig. 2C). These flows are two-dimensional curtains aligned along the rotational axis, implying an essentially geostrophic balance. The spiral and the jet divide the warm region to the west from the cold region to the east, preventing mixing between them. Measurements show a trend of an eastward increase of temperature approaching the jet followed by a sharp drop in temperature across the jet. The spiral remains fixed in relation to the heterogeneity, forming a stationary front. Visual observations and temperature measurements show that the ICB (CMB) side of the front is dominated by cold (warm) plumes because the stationary front blocks the radial motion of the warm (cold) plumes. As the magnitude of heating is increased, the front extends eastward. Heat-flux measurements at the ICB show that, at Ra/Rac = 30, ~40% of the heat anomaly is advected radially across the shell, and the rest is advected laterally along the CMB. Because the basic state is replaced by a front
because of the heat-flux heterogeneity imposed by the mantle. We also expect fine-scale structures, although their spatial and temporal scales may be modified by the magnetic field. We assume that the flow is basically geostrophic, consistent with the presence of geomagnetic features that can be attributed to columnar flow (1). For simplicity, we only consider anomalous CMB heat flow from the prominent seismically fast region near CMB beneath east Asia (3). If there are two antipodal heterogeneities of the same strength, the experiments show that the eastward extent of the front is restricted. The observed absence of the westward drifting of the geothermal flux patches in the Pacific (12) is similar to the global locking regime for two reasons: (i) the front blocks the upwellings from the inner core and may inhibit the westward drifting flux patches from forming (14) and (ii) the eastward flow and the front blocks the mean westward flow. The directions of azimuthal flow in Fig. 3 agree with outer core flow models obtained from geoscientific secular variation using tangentially geostrophic approximation (15), which is consistent with the columnar nature of flows. We estimate the width and the velocity of the jet in the core as 10 km and 7 × 10^{-3} m/s, respectively, assuming a temperature difference across the front of ~10^{-4} °C (10, 16). This shows that a localized flow can exist in the core, faster than the mean azimuthal flow of ~10^{-4} m/s, inferred from the geomagnetic westward drift. Global locking is also expected to result in a hemispherical dichotomy in the growth of the inner core because of the differences in the heat flow at the ICB across the front. The model predicts a rapid inner core crystallization on the cold side of the front, leading to higher porosity and a larger growth-induced anisotropy in the inner core (17). This agrees with seismological evidence revealing slow P-wave velocity and large anisotropy in the western hemisphere of the inner core (18). The orientation of the inner core seismic structure in relation to the CMB heterogeneity agrees with the eastward phase shift we observed in the experiments.

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3. The total heat flux at the top of the convective heat flux along the adiabat $q_{\text{wav}}$ and the convective heat flux $q_{\text{conv}}$ $q_{\text{wav}} = q_{\text{conv}} + q_{\text{ad}}$. $q_{\text{wav}}$ can be assumed to be laterally uniform. In contrast, $q_{\text{conv}}$ is variable; here, we assume it has a high and a low value, $q_{\text{conv}}^{(\text{h})}$ and $q_{\text{conv}}^{(\text{l})}$, respectively. We choose a high value for convective heat flux and an adiabatic heat flux of $q_{\text{ad}}$. Then, the mean heat flow at the CMB can be The definition of lateral variation of heat flow as $q_{\text{ad}} = [q_{\text{conv}}^{(\text{h})} + q_{\text{conv}}^{(\text{l})}] / 2$ and the Nusselt number by $Nu = q_{\text{ad}} / q_{\text{conv}}^{(\text{h})}$. Then, the lateral variation of convective heat flux is given by $B = g q_{\text{conv}}^{(\text{h})} q_{\text{conv}}^{(\text{l})} = [|q_{\text{conv}}^{(\text{h})} – (|a1| - 1) (|q_{\text{conv}}^{(\text{l})} - 1) - (|a2| - 1)] / (1 - |a1|)$ (see Figs. 2A and 3). Estimates for Earth yield a 10 mm, which agree with the measurements (Fig. 2C).

7. Thermal convection in rotating systems is characterized by three dimensionless numbers: the Ekman number $E = v^2 / f L_D$, the Rayleigh number $R = \beta \Delta T L_D^3$, and the Prandtl number $Pr = \nu / \kappa$, where $v$ is kinematic viscosity, $f$ is rotation rate, $\kappa$ is thermal diffusivity, $\beta$ is compressibility, $\Delta T$ is the temperature difference, and $\nu$ is the Prandtl number. For core flow, $E = 10^{-6}$, and $Pr = 0.015$. Assuming $\Delta T = 4 \times 10^{-4}$, we obtain $Ra/R = 75 \times (Ra / 10^{11})$. This shows that $Ra$ is not large enough for nonmagnetic thermal convection. The Reynolds number is $Re = \nu V L_D / \nu = 52$ ($R = 1.8 \times 10^6$), with $Re$ and $R$ of the order of $10^6$.

8. The heater imposes a fixed total heat flux on the fluid. The perturbed temperature at the outer boundary has a Gaussian profile with a longitudinal half width of ~30°. Longitudinal temperature variation at the boundary $\Delta T_{\text{conv}}$ is defined as the temperature difference between the heater and its antipode. $Ra$ is calculated with $\Delta T$ between the heater and outer boundary at the antipode of the heater. Thermal boundary condition is constant heat flux at the heater and becomes isothermal at far field. The heat flux was increased stepwise from 4 to 10.

10. Thermally induced flow is estimated by $V_\text{th} = \rho \eta T_{\text{conv}} / (2 \rho_0)$ (20). The jet velocity $V_\text{jet}$ and $V_\text{jet}$ are estimated from the balance between vortex generation, stretching, and advection (9) as $V_\text{jet} = \rho \eta T_{\text{conv}} / (D/ \Omega )^{1/3}$ and $\delta = \rho \eta T_{\text{conv}} / (D/ \Omega )^{1/3}$, where $\delta$ is the temperature difference across the front. For Fig. 2C, $\delta = 7.1 \times 10^{11}$, and $\Delta T_{\text{convo}} = 1.5 \times 10^{11}$, which we obtain $V_\text{jet} = 2.6 \times 10^{-3}$ m/s, $V_\text{jet} = 7 \times 10^{-3}$ m/s, and $\delta = 3$ mm, which agree with the experiments.

11. In the experiments, conduction down the radial temperature gradient contributes ~10% of the total heat transfer, and its lateral variation is negligible in comparison to lateral variation of convective heat flux.

13. R. D. van der Hilst and H. Kårason, Science 283, 1885 (1999), and references therein.
15. For example, J. Bloxham, J. Geophys. Res. 97, 15665 (1992).
16. $\Delta T_{\text{front}}$ scales as ~ $q_{\text{conv}} / D/ \Omega$, where $q_{\text{conv}}$ is the convective heat flux at the heterogeneity, $\rho$ is the density, $\epsilon$ is the heat capacity. For the core, $q_{\text{conv}}$ = 50 mW/m² and $V_\text{jet} = 4 \times 10^{-4}$ m/s, we obtain $\Delta T_{\text{conv}} = 10^{11}$. A similar hemispherical temperature variation in the outer core was obtained from geoscientific secular variation, revealing a cold Pacific J. Bloxham and A. Jackson Geophys. Res. Lett. 17, 997 (1990).
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