sperm dysfunction? Ran is a nuclear GTPase involved in transporting molecules into and out of the nucleus. Its enzymatic activity is greatly stimulated by another protein, RanGAP. It is reasonable to assume that defective RanGAP encoded by the *Sd* gene somehow interferes with nuclear transport in spermatids carrying a sensitive *Rsp* gene. The precise molecular mechanism by which the abnormal RanGAP causes this selective sperm dysfunction is not known. So, the mystery of segregation distortion is not yet solved. But the identification of the *Sd* gene product opens the way to a molecular understanding of this puzzle that has kept talented scientists around the world busy for 40 years.

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PERSPECTIVES: MANTLE CONVECTION

A Thermal Balancing Act

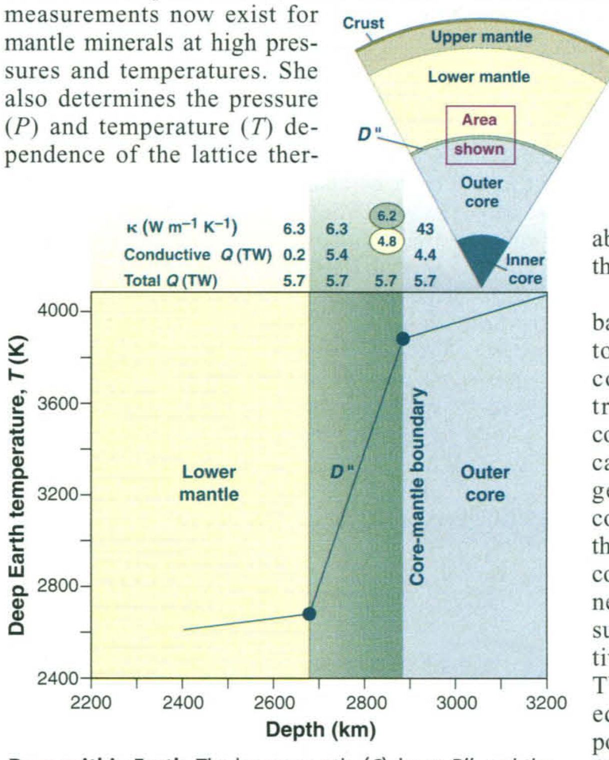
Orson L. Anderson

Earth core physicists have long faced a conundrum. The power, that is, the heat flow multiplied by the surface area, from Earth's core appears to greatly exceed the conductive capacity of Earth's mantle to carry it all away. This arises because the thermal conductivity, κ, of the core, composed mostly of iron, has been thought to be about 10 times greater than that of the rocky mantle. However, as Hofmeister shows on page 1699 (*1*), a reevaluation of the thermal conductivity of the mantle provides hope of a solution that "what the core giveth, the mantle taketh away."

To balance the power from the core, geophysicists have invoked mechanisms that either reduce the power of the core or return the excess power to the core. One mechanism requires that the core has an outside conductive layer (*2*). In another mechanism, called compositional convection, the presumed excess power drives impurities toward the center (*3*). These corrective models have complicated the description of the core's composition and thermal structure.

The problem centers on the mantle's thermal conductivity. This parameter describes how easily heat flows through the mantle. It can be separated into a radiative contribution, κ_{rad}, which is the flow of energy by radiation (as in a black body), and a lattice contribution, κ_{lat}, which is the energy flow through the minerals in the mantle.

Although well established in thermal physics (*4–6*), the contribution of radiation heat transfer at high temperature in Earth's mantle has not been effectively taken into account until now. In her research article, Hofmeister shows that κ_{rad} contributes substantially to deep Earth thermal conductivity and improves existing ideas of κ_{lat}. In equations for κ_{rad}, she includes the connection of photon and phonon lifetimes, assumed to be reflected in infrared peak widths; a few relevant measurements now exist for mantle minerals at high pressures and temperatures. She also determines the pressure (*P*) and temperature (*T*) dependence of the lattice ther-



Deep within Earth. The lower mantle (*3*), layer *D''*, and the outer core (*10*). Solid line, the temperature profile. Two values of κ are given for *D''* next to the core (circled). The lower value, 4.8, is that calculated by Hofmeister, assuming that the composition of *D''* is the same as that of the lower mantle. The upper value, 6.2, is that required to maintain a heat balance between *D''* and the outer core. *Q* is power, the heat flow multiplied by the surface area.

mal conductivity of insulators. The resulting value for κ is lower than previous estimates at low pressures and in the lithosphere (the crust and solid upper part of the mantle). A lower thermal conductivity requires a higher temperature gradient to balance the heat flow, and her results therefore necessitate a hotter lithosphere. But at the base of the mantle, Hofmeister obtains a thermal conductivity of 6.3 W m^{-1} K^{-1} (see the figure on this page), higher than the commonly accepted value for the deep mantle, 4.2 W m^{-1} K^{-1} (*7*).

How can this higher estimate be reconciled with our understanding of the heat flow between the core and the mantle? The boundary between the mantle and the core is known as the *D''* layer (*8*). I will show that including *D''* as the third component in the heat balance is the key to finding limits in the total power flowing from core to mantle and that this can be done without making special assumptions about the thermal structure of the core.

In determining the power balance, the first challenge is to estimate the power of the core and how much heat is transferred by conduction compared with convection, because this greatly affects the geodynamics. Most authors concerned with convection in the core have proposed that the convective power of the core is negligibly small (*9–11*). One suggestion is that the convective power of the core is 0.2 TW (*12*). The highest suggested value for core conductive power is 1/3 of the total power (*13*). The measured conductivity, κ, of *D''* next to the mantle and the high thermal gradient across it require a high conductive power of about 5.4 TW in *D''*. This power must be exceeded by the total power from the core. Using 30% of the core conductive power for convective power, the total power leaving the core is 5.7 TW (4.4 TW conduction plus 1.3 TW convection), as shown in the figure on this page. The preferred solution implies that there is a convective flux of 0.3 TW in the *D''* region near the mantle. In support of this interpretation, the *D''* region has been suggested as an unstable, rapidly flowing region of low viscosity at the base of the mantle. This instability spawns plumes that rise through the man-

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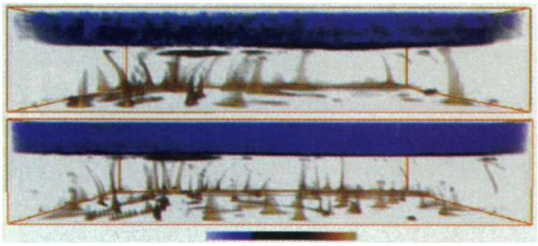
tle (*12*, *14*), carrying hot material to the surface. Thus, this convective power in D'' can be regarded as the source of power to form the plumes. Seismic evidence for partial melt in D'' under the Pacific Ocean supports this idea (*15*).

However, the theory of convection in D'' leading to the formation of plumes does not allow convection on the side of D'' next to the core. This means that convection must be shown to be present on the mantle side of D'', whereas only conduction and no convection must be demonstrated on the core side.

D'' is composed of mantle material. Hofmeister finds that κ = 4.8 W m^{-1} K^{-1} in D'' at the D''-core boundary. A mechanism must be found to increase κ of D'' near the core sufficiently to let the conduction there be equal to the total power of the core, 5.7 TW. This requires the value of κ to increase by 30% (to 6.2 W m^{-1} K^{-1}). There are three possible mechanisms by which the composition of D″ may be modified so as to increase κ: (i) D″ may consist of large chunks of mantle interspersed with small chunks of core so that the average κ is increased. (ii) The mantle rock nearest the core may be anomalously rich in the reaction products of silicate perovskite, periclase (MgO) and stishovite (SiO_2), both of which have high κ values [see figure 10 of (*1*)]. Experiments have shown (*16*) that $MgSiO_3$ perovskite breaks down to a mixture of MgO and SiO_2 at about 80 GPa, supporting this assumption, but whether $MgSiO_3$ perovskite actually breaks down at these pressures is controversial. (iii) The deepest part of D'' may be a graveyard for ancient subducted oceanic crust (*17*). The heterogeneous structure (pattern of arrival times) of seismic waves that have passed through D'' supports the concept of chemically heterogeneous structures in D'', which could be produced by any of the three mechanisms (*18*).

The mantle near the D'' boundary must now carry away the total power of 5.7 TW, and conduction is limited to about 0.2 TW. Are there sufficient mechanisms in the mantle to carry away about 5.5 TW by convection? The current wisdom is that the main mechanism by which heat is carried from the core to the base of the lithosphere is by means of plumes (see the figure on this page). Such plumes are inferred from hot spots on Earth's surface (such as Hawaii, Yellowstone, and Iceland). The rate at which topography is increased above a hot spot by thermal buoyancy can be estimated, and from this, the heat flux and power can be determined. Sleep (*19*) measured the global buoyancy flux of 37 hot spots and calculated an average heat flux of 4×10^{-3} W m^{-2}, or a mantle convective power of 2 TW. A later analysis (*20*) gave a total power of 2.3 TW. Both of these estimates fall quite short of the required power. Calculation of the buoyancy flux is limited, however, by the estimated uplift and subsidence rates near the swell. For the same hot spot, estimates of buoyancy flux may differ by as much as 40% (*19*, *21*). In addition, the estimated number of hot spots is uncertain and has varied between 20 and 117 (*22*). Considering reasonable errors that creep into buoyancy flux calculations, I suggest that the mantle convective power has been understimated by about 50%, resulting in about 4 TW accounted for.



Hot plumes. An artist's interpretation of the simulation (*23*) of convection between D'' and the lithosphere through plumes (thin, axial tubes providing conduits for hot mantle material to rise from the boundary of D'' to the lithosphere). The immature plumes moving hot mantle material convectively toward the lithosphere have not yet made contact with the lithosphere. Blue, return flow of the mantle.

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However, another 1.5 TW are still required. To get this additional power, I assume that the number of plumes associated with hot spots is substantially lower than the total number of active plumes. Some numerical models imply that immature plumes may be 50 to 75% as abundant as hot-spot plumes (see the figure on this page) (*23*). Furthermore, convective heat may be delivered in cycles to Earth's surface, at intervals producing immense eruptions far above today's level. For example, 120 million years ago, a vast amount of heated rock was transported to Earth's surface, in what has been called the "mid-Cretaceous superplume episode" (*24*). The rate at which new hot material was delivered at that time was twice that of today (*24*) and persisted for 40 million years. This episodic production of convective heat means that today there must be more power in the plumes than measured by the hot spots. From this it is reasonable to assume that the total convective heat in plumes near the base of the mantle is sufficient to balance the power budget (5.5 TW).

The above is one plausible approach to obtaining a core-D''-mantle power balance, while retaining a simple thermal structure for the core. This result was made possible by the robust κ values for D'' and the mantle reported by Hofmeister (*1*). More work is needed to narrow the limits on the value of κ for the core. This will require a physical theory of κ for the core, which is yet to be developed. The value of κ for iron should also be determined experimentally at core conditions, which will require new shock-wave measurements. A confirmation of the value of κ for mantle rocks at lower mantle conditions found by Hofmeister will also be valuable, as will a new numerical simulation study that focuses on finding the level of power in plumes close to the point at which they leave D''.

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