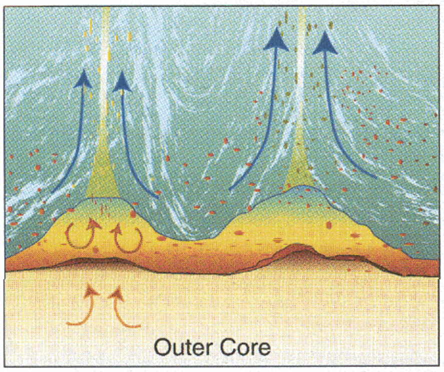
Porous Sediments at the Top of Earth's Core?

IS EARTH'S CORE LOSING MATERIAL AS WELL as heat to the overlying mantle? The idea has been explored in a number of studies over the past 20 years (*1*), and the report in *Science* by Bruce Buffett, Edward Garnero, and Raymond Jeanloz (*2*) is a welcome addition to the list. They propose that light silicate elements are being deposited at the top of the core, an idea that has some appeal. However, the authors suppose a porous, compacting mushy zone several kilometers thick, and this structure is central to their arguments related to Earth's nutation (a sideways nodding of Earth's axis along the precession path). But this assumption won't work—there cannot be a mushy zone.

The separation of nonmetallic impurities from molten iron is an age-old study. But at the high temperature and low cooling rate of the core, any such slag material must be well crystallized. The study of the accumulation and solidification of silicate, oxide, and sulfide crystals from the melt has formed a robust part of igneous petrology since 1939, when Hess (*3*) invented adcumulus growth. This is the process named by Wager and others (*4*) to describe the isothermal, isocompositional solidification of an initially porous crystalline sediment (or cumulate) from the melt, by exchange with an infinite magma reservoir. Solidification may occur through diffusion in the melt alone, or aided or impeded by compositional convection (*5*). If accumulation occurs too fast, the adcumulus growth cannot keep up, and the trapped melt presents as a residual porosity ($p_r > 0$). But if accumulation is slow enough, adcumulus growth may proceed to near-perfection ($p_r \sim 0$), so that solidification occurs at the cumulate interface, as argued here.

The growth of the inner core currently is about 0.03 centimeters per year (*2*), at least an order of magnitude slower than needed for perfect adcumulus growth by diffusion alone (*6, 7*). It is, therefore, many orders of magnitude slower than needed for perfect adcumulus growth in the presence of the strong compositional convection originally proposed by Braginsky (*5*) in respect of the light solute rejected at the inner core boundary, streaming outward to drive the dynamo.

The corresponding accumulation rate of sediment at the top of the outer core would be about 0.004 centimeters per year. [For a mushy zone several kilometers thick (*2*) formed at this rate, accumulation must have outpaced solidification for at least 100 million years.] Such an accumulation would be limited by, and equal to, the supply of impurities to the top of the core. The exchange components for solidification, therefore, reside in the flux of impurities, so that the cumulate is bathed in its own parent liquid. Here also, solidification would be powerfully aided by compositional convection of dense metallic rejected solute, which would drain away into the body of the outer core. There can be no mushy zone solidified by compaction, which cannot occur in a microscopically thin layer (*6*). The electrical conductivity coupling the core to the mantle might better be explained by core metal entrained turbulently into a basal layer of melted mantle.



Scenarios proposed for Earth's core-mantle boundary: sediments (brown) filling inverted "basins," or the core infiltrating (red) or melting (yellow) the mantle.

There is another problem with sedimentation at the top of the core. Giant magma chambers (*8*) might occur at the core-mantle boundary (CMB), caused by heat from the core melting the silicate mantle. This idea contrasts with deposition of the same silicate mineralogy from the molten core at the same place and time (*9*). The core is either melting the mantle or freezing out onto it: we cannot have it both ways.

And lastly, there are no silicate crystals below the CMB. Deposition of silicates directly from within the molten core is a thermal impossibility. The upper region of the liquid core is greatly superheated with respect to its own liquidus, which is certainly the liquidus of iron-rich metal. It is therefore far from any cotectic equilibrium with silicate material. Such a saturation can only be achieved at large degrees of undercooling, deep in the thermal boundary layer, which in fact defines the CMB (*10*).

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References and Notes

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9. That the place must be the same is guaranteed by the fact that the short-circuit of heat transfer is run by the same compositional convection engine that contains the light elements that would crystallize to form the sediment.
10. If there are cooler regions of the CMB devoid of silicate melt, they should not be regions where rejected solute is deposited from the core, but rather places where the mantle chills the core and generates downwelling cold plumes. Core material can best escape into mantle magma at the CMB.

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Response

S. A. MORSE BASES HIS ARGUMENTS ON AN analogy with magma chambers in Earth's crust. He says there can be no porous sediments undergoing viscous compaction at the top of Earth's core because other processes (for example, adcumulus growth) can consolidate the layer more rapidly. The stated rate of adcumulus growth is inferred from a few well-studied magmatic intrusions. Applying these results to the inner core, Morse predicts no mushy zone; however, more detailed and quantitative studies (*1*) support the existence of a mushy zone. Transferring results from one physical setting to another without proper analysis can lead to misconceptions, and we conclude that magma chambers are an inappropriate analogy for sediment accumulation at the top of the core.

Without reiterating the analysis, we highlight some key differences with Morse's arguments by considering the fate of calcium carbonate ($CaCO_3$) in a beaker of water. When the solid is initially immersed in water, a small amount of calcium carbonate dissolves to establish chemical equilibrium. However, as water evaporates from the beaker, the concentration of dissolved solid exceeds the solubility and calcium carbonate precipitates. In this illustration, we associate the precipitation of calcium carbonate with the formation of sediments in the core. The supersaturation of dissolved components in the core is caused by growth of the solid inner core, which preferentially removes iron from the liquid core. This means that supersaturation occurs throughout the volume of the liquid core because of the segregation of light elements and not large degrees of undercooling at the boundaries, as Morse suggests. A second key difference is that sediments can precipitate from solution at temperatures well below the melting point of the solid. Nowhere in our report (17 Nov., p. 1338) do we appeal to the existence of a silicate or oxide melt. On the contrary, we argue that sediments are a viable alternative to partial melt for explaining the ultra-low-velocity zones, although we cannot rule out the possibility of isolated regions of partial melt if large compositional variations exist in the lowermost mantle.

Solid might precipitate in the volume of the supersaturated liquid core and settle (upward or downward) under the influence of gravity until it accumulates on the surface of an existing solid. Alternatively, solid might precipitate directly onto an existing solid surface. Dendritic growth is expected in the second case because the solid surface advances into a supersaturated liquid (*2*). This means that either the settling sediments or the dendritic growth of a surface accumulates a porous solid. An interesting complication arises if the sediments are produced by chemical reactions between mineral components in the mantle and dissolved components in the liquid core. The deposition of sediments at the CMB might isolate the reactants, terminating further production of sediments. Topography on the CMB might be crucial for sustained production of sediments by allowing them to accumulate in basins while maintaining chemical contact between the mantle and core at the equivalent of mountains on the CMB. The model of sediment accumulation at the top of the core offers a plausible explanation for two vastly different data sets: seismological evidence of ultra-low-velocity zones (*3*) and astronomical evidence of anomalous dissipation at the CMB from observations of Earth's nutation (*4*). Alternative proposals such as Morse's that appeal to turbulent entrainment are physically untenable because of the large density and viscosity differences between melted mantle and liquid metal.

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