GEOPHYSICS

Earth's soft heart

A modern seismological method raises questions about the properties of Earth's inner core

By **Jessica C. E. Irving**

Earth's inner core has proven to be a challenging region for geophysicists to investigate, more than 80 years after its discovery (*1*). It grows slowly from the liquid iron alloy that constitutes the outer core, and its solidification is the result of the planet's cooling over the course of its history. The inner core provides an important part of the energy budget for the geodynamo—the mechanism that generates Earth's magnetic field—as latent heat is released and light elements are preferentially segregated into the fluid outer core. Despite the inner core's importance in the core's energy budget (*2*), its composition and material properties are difficult to ascertain. On page 329 of this issue, Tkalčić and Phạm (*3*) employ a new understanding of method that has been successfully used to study the crust and upper mantle to detect energy that has traveled as shear waves through the inner core. The shear-wave velocity (V_S) reveals a softer inner core composition than previously thought.

Inner core shear bodywaves (called *PKJKP*) provide direct evidence for its solidity, but they have been difficult to detect even after large earthquakes (*4*), making inner core V_S challenging to estimate. The inner core's solidity was therefore established using low-frequency normal mode oscillations of Earth (*5*). Tkalčić and Phạm now obviate the need for imaging *PKJKP* waves directly after a large earthquake. Instead, the authors examined global stacks of Earth's correlation wavefield, calculated from seismograms collected in the hours following large earthquakes, to detect energy that has traveled as shear waves through the inner core.

New theoretical insights (*6*) have explained the genesis of several signals in the seismic correlation wavefield, one of which is akin to *PKJKP* in that it involves interaction between a seismic phase that travels as a shear wave in the inner core with other core phases. This signal in the correlation wavefield is called a *J* phase, and its time delay and amplitude provide constraints on the inner core's V_S and attenuation. Tkalčić and Phạm find that the inner core has a slightly lower V_S than that of the long-standing Preliminary Reference Earth Model (PREM) (*7*) and is more attenuating than in PREM.

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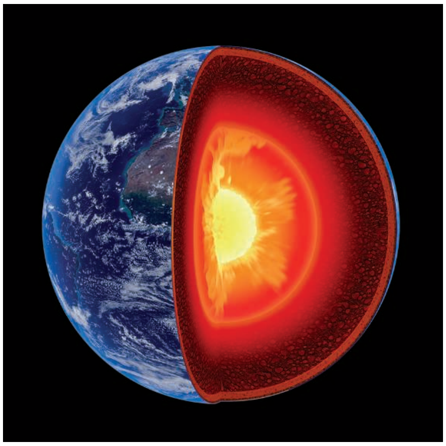
This has implications for understanding the composition of the inner core. There is already a challenge in matching the seismologically observed properties of the inner core to values estimated from mineral physics. Pure iron has a V_S that is much higher than that of PREM at inner core conditions (*8*), and many iron alloys suffer from the same velocity discrepancy. The difference between the V_S proposed by Tkalčić and Phạm and that of PREM is smaller than the effect of different alloying light elements on the V_S of iron, but it is clear that every seismic observation requires a V_S that is smaller than expected given the inner core's compressional wave velocity. Mineral physics suggests that premelting phenomena may reduce the V_S to seismological values. Recent work suggests that a ternary mixture of iron, silicon, and carbon in the inner core may reproduce the properties of PREM (*9*). It may also be possible to match the *J* phase observations with a similar composition.



The inner core, Earth's deepest region, may be softer than previously thought.

An alternative to the presence of an alloy with strong premelting effects is the presence of some fraction of melt in the inner core. Melt is often suggested as a mechanism for reducing V_S elsewhere in Earth. This melt may be fluid trapped between solid crystals as the inner core grows. Melt could also increase attenuation of the inner core (*10*), as inferred from the amplitude of the *J* phase's signal. However, Tkalčić and Phạm propose that the inner core has a reduced V_S throughout, requiring that melt pockets have not been eradicated by any form of inner core convection.

Many questions about the shear properties of the inner core remain open. PREM's V_S was strongly informed by the frequency of normal mode oscillations. A detailed assessment of the compatibility of the results of Tkalčić and Phạm with normal mode observations may lead to a better understanding of V_S and other seismic properties in the inner core. At the top of the inner core, V_S can also be inferred from waves reflected at the inner core boundary (ICB). The contrast in seismic properties across the ICB suggests that just below it, V_S is less than 3 km/s (*11*) and may be close to zero in some locations (*12*). Both Tkalčić and Phạm and normal mode studies (*13*) suggest a V_S that is closer to 3.5 km/s, likely reflecting a strong shear wave gradient at the ICB. The *J* phase is likely to be reporting the higher velocity across the bulk of the inner core. The radial and lateral variation of V_S in the inner core remain poorly understood, and there is no firm consensus on shear wave anisotropy in the inner core. The higher attenuation suggested by the amplitude of the *J* phase contrasts with the handful of observations of *PKJKP*, which may suggest that inner core shear wave attenuation is lower than that of PREM (*14*). However, because *PKJKP* detections are rare and may require focusing of seismic waves, it is not unreasonable to expect that the *J* phase results indicate an inner core that is soft, with a low V_S and considerable attenuation of shear waves.

A better understanding of the inner core's shear wave properties can help to ascertain dynamical processes including what, if any, kind of convection is taking place in the inner core and whether it is rotating relative to the mantle. The observation of *J* phases will provide an extra tool to assess the properties of Earth's "soft heart." ■

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