Investigating Earth's Dynamic Mantle and Core

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Seismologists have long sought to decipher the Earth's inaccessible and enigmatic interior through detailed interrogation of deeply penetrating seismic energy. As we approach the 100th anniversary of the discovery of Earth's core, we are rapidly moving beyond the characterization of Earth's first-order radial stratification that dominated the decades that followed detection of the core. In fact, an explosion in the availability of broadband data from a variety of agencies and organizations over the last decade has permitted both global and regional analyses of the interior at unprecedented spatial detail. Conclusions using the remote sensing tool of seismology now regularly reach well beyond solution models of Earth's internal elastic structure, and extend to the characterization of Earth's dynamic, thermal, and chemical states (Figure 1). Advancements in our understanding of the interior have been primarily and fundamentally facilitated through the efforts and successes of the IRIS mission. Data are now easily available through a variety of method, to anyone in the world.

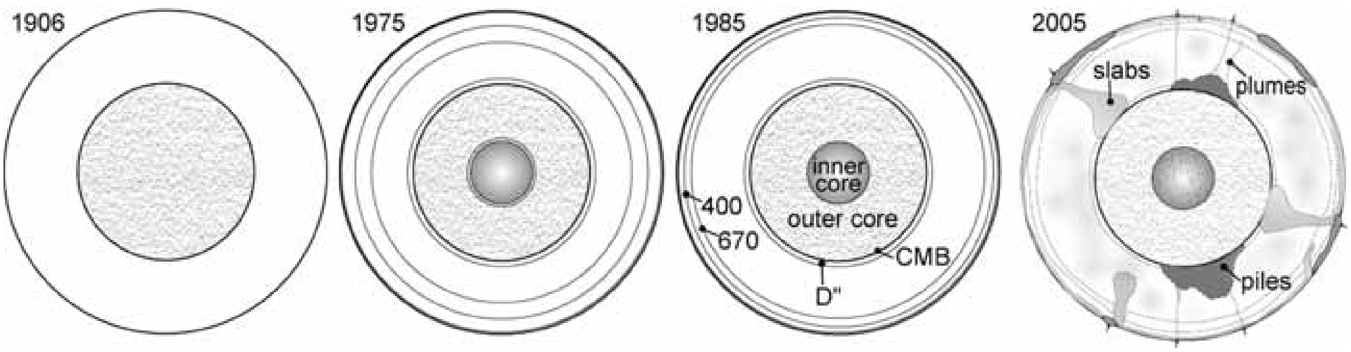

Figure 1. Seismic data provided by IRIS continues to allow for rapid changes in our models of Earth's deep interior.

Mantle Heterogeneity: The Global Picture

In convective systems, diversity in structures can occur near the boundary layers. The core-mantle boundary (CMB), in fact, contains Earth's largest absolute density contrast within the planet, and thus continues to receive significant attention in high-resolution modeling at a variety of spatial scales. The next largest density contrast is between surface rock and air or water, and while large-scale surface tectonics have been appreciated for some time, constraining the role of upper and/or lower mantle structure and the dynamic processes responsible for shaping the surface remains a challenge.

Certainly, tracing subducting slabs to their final resting place or deep plume roots upwards to hot spot volcanism have been a focus of global mantle travel-time tomography. Some recent successes in imaging the apparent connectivity of higher-than-average velocities from the crust to core beneath Mexico, presumably from the ancient Farallon slab, and possibly beneath Japan, have played into the long-standing debate about whether or not the boundary between the upper and lower mantle demarks chemical stratification. Transition zone structure and discontinuity topography may similarly provide important constraints on mantle temperature and dynamics. Several research groups can now boast 3-D global P- and S-wave mantle models, largely owing to data availability through IRIS. Attributing global heterogeneity to a solely thermal versus thermal and chemical origin is regularly pursued. Often significant holes in data coverage are still present, however, which requires future deployment and densification of instruments. EarthScope's USArray will significantly help in the study of the deep Earth that is in the hemisphere containing North America.

Mantle Heterogeneity: High-Resolution Imaging and Short-scale features

Forward-modeling waveform studies augment the global images, often revealing a variety of phenomena not yet available through the tomographic approach. These include discontinuous layering or reflectors near dominant boundary layers, such as layering some 200-300 km above the CMB (the D" layer), ultra-low velocity (10's of percent reductions from global reference structures) layering right at the CMB, and vertical boundaries between low-velocity structures and neighboring mantle which, beneath southern Africa, are mapped as extending up to 1000 km above the CMB. These features may be intimately related to ultralow velocity zone genesis from partial melt of lowermost mantle material, which can give rise to instabilities that result in the birth of whole-mantle plumes. Both forward and inverse methods now almost routinely document seismic wave speed anisotropy, anelasticity, and scattering in the mantle, particularly near the surface and CMB, where analyses utilizing reference seismic waves are most easily permitted owing to the existence of the highly reflective Earth's surface and CMB.

The Outer and Inner Core

The relatively rapidly convecting fluid iron-alloy outer core is responsible for the generation of Earth's magnetic field. Lateral heterogeneity in outer core elastic properties is generally assumed absent, based on dynamic arguments. However, the possibility for small-scale structures right at the underside of the CMB, or at the topside of the inner core boundary are possible. Certainly, high-resolution seismic studies have suggested short-scale variability (e.g., km scale) of each. Larger arrays, e.g., USArray, will help to further illuminate these possibilities in the near future.

The solid inner core is but a fraction of a percent of Earth's volume, yet continues to attract significant attention from seismologists, often in collaboration with a variety of geophysicists from other disciplines. Better constraints of the depth and lateral distribution of inner core heterogeneity, anelasticity, and anisotropy (as well as their magnitudes), and inner core super-rotation, likely hold important keys for core (and thus Earth) formation, as well as the nature of the generation of Earth's magnetic field. Global and regional arrays, PASSCAL experiments, and traditional short-period seismic arrays all have the potential to advance our knowledge in these important areas.

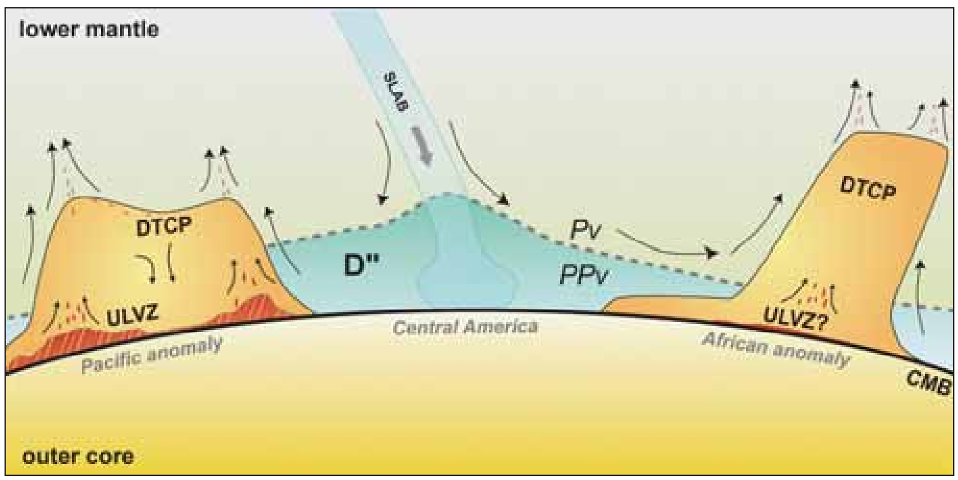

Figure 2. A current representation of the core-mantle boundary region, incorporating many of the structures that have been identified by recent seismological investigations.

Of particular relevance in imaging Earth structure at depths below the CMB is properly accounting for contaminating effects of mantle structure, especially the strong heterogeneities now widely accepted to exist at the base of the mantle. This will certainly receive ever-increasing attention as the deepest mantle comes into sharper focus and our ability to incorporate 3-D wave propagation in our imaging studies improves.

Looking to the Future: New Data, New Methods, New Disciplines

We have come a long way since the band-limited digitized recordings from analog instruments (e.g., WWSSN) of the 1960's that were pervasive in studies of the following couple decades. Significant densification of seismic station coverage has also occurred. Thus we are now afforded interrogation methods of Earth's deep interior that once were previously only enjoyed by exploration and crustal seismologists: traditional seismic array techniques, which augment waveform modeling of region studies, as well as global waveform and travel-time tomography. However, future work should more fully utilize the rich bandwidth of information in the recorded wave field. Continued availability and expansion of data made available by IRIS will enable advances on these fronts, which will specifically enhance the connection between seismic results and those from other Earth interrogation disciplines: for example, geodynamics, mineral physics, geochemistry, geomagnetism, geotectonics, and petrology. The multi-disciplinary research approach is important, as it will be a principle method in reducing uncertainty in our often large solution model spaces. More and better data permit better seismic models for this process.