Exploring the Earth’s Interior with Seismic Waves

The waves that emanate from earthquakes are capable of terrible destruction. One key goal of seismology is to understand the drivers and processes of fault rupture, the ground motion it produces, and how to mitigate its effects, for example through emerging approaches such as earthquake early warning. Earthquake waves are also a powerful tool for imaging the Earth’s interior. Another grand challenge in seismology is to map variations in seismic wave velocities and energy absorption inside the Earth, and to relate these structures to mantle convection, the motion of the tectonic plates, and their dramatic consequences including earthquakes, volcanoes and mountain-building.

Three-dimensional models of Earth structure based on seismic wave velocities clearly show cold lithosphere (which makes up the tectonic plates) subducting into the upper mantle at convergent plate boundaries. However, the fate of these descending “slabs” of lithosphere is complex, and in many cases they are deflected and contorted in the mid-mantle, before continuing on to the lower mantle where they collect at the boundary between the lower mantle and core. This behavior is fundamental to understanding how properties such as temperature, chemical composition, and viscosity vary between the slabs and the mantle layers through which they descend. Seismic models also show evidence for hot mantle rock that rises through the Earth, allowing the planet to cool. In the deepest lower mantle, zones of hot, chemically-distinct mantle exist, and two of these zones, one beneath the Pacific ocean and another beneath Africa, are thousands of kilometers wide and appear to feed hot material to the upper mantle. However, the paths of the flowing hot rock within the upper mantle are still coming into focus, with some rising nearly vertically in discrete plumes that produce trails of hotspots beneath the moving plates, some flowing to feed the mid-ocean ridges where new lithosphere is created, and some following paths that leave more cryptic patterns of volcanism at the Earth’s surface.

Another fundamental question is why the Earth’s lithosphere behaves in a “plate-like” manner in the first place. Abundant geophysical and geochemical data indicate that the lithosphere is colder and therefore stronger than the asthenosphere, the underlying layer of weaker mantle. In some regions, the properties of the boundary between the lithosphere and asthenosphere indicate that their difference in strength is enhanced by the presence of small amounts of melt in the otherwise solid asthenosphere. However, the presence of partial melt in the asthenosphere appears to be variable, and its role in enabling plate tectonics is still vigorously debated.

Seismic waves are also revealing the inner workings of plate boundaries and helping us to understand how Earth’s interior interacts with the climate system. For example, seismic studies have shed light on the interface where converging lithospheric plates meet in subduction zones, where the largest and most destructive earthquakes on the planet occur. Seismic waves can also resolve structures that mark where the subducting lithosphere releases volatiles into the overlying asthenosphere, allowing the mantle to partially melt. This melt can then rise, eventually making its way into crustal storage systems from which it periodically erupts. These processes are key for understanding volcanoes and their hazards, and also how water and carbon cycle through the Earth and are released into the atmosphere and oceans, affecting Earth’s climate. The Earth’s mantle interacts with our changing climate in other ways as well. For example, variations in mantle strength (e.g. its elasticity and viscosity which can be constrained by seismic waves) are key to the response of the surface of the Earth to melting ice sheets and glaciers, altering predictions for future sea-level rise.