The Earth’s Missing Ingredient

The discovery of a novel high-density mineral means that the earth’s mantle is a more restless place than scientists suspected— and offers new clues to the planet’s history. By Kei Hirose

The deepest hole humans have ever dug reaches 12 kilometers below the ground of Russia’s Kola Peninsula. Although we now have a spacecraft on its way to Pluto—about six billion kilometers away from the sun—we still cannot send a probe into the deep earth. For practical purposes, then, the center of the planet which lies 6,380 kilometers below us, is farther away than the edge of our solar system. In fact, Pluto was discovered in 1930, and the existence of the earth’s inner core was not established—using seismological data—until six years later.

Still, earth scientists have gained a surprising amount of insight about our planet. We know it is roughly structured like an onion, with the core, mantle, and crust forming concentric layers. The mantle constitutes about 85 percent of the earth’s volume, and its slow stirring drives the geologic cataclysms of the crust. This middle domain is mainly a mix of silicon, iron, oxygen, magnesium—each of which appears in roughly the same concentrations throughout the mantle—plus smaller amounts of other elements. But depending on the depth, these elements combine into different types of minerals. Thus, the mantle is itself divided into concentric layers, with different minerals predominating at different depths.

Although the nature and composition of most of those layers have been fairly well understood for decades, until recently the lowermost layer remained a bit of a puzzle. But in 2002 the synthesis in my laboratory of a novel, dense mineral that forms at the temperatures and pressures of the bottom 300 kilometers of the mantle solved the mystery. Since then, studies have revealed that the mineral, called postperovskite, dramatically affects the planet’s dynamics. Its apparent presence in the mantle, researchers have shown, implies that the mantle’s convection currents (in which cooler rock sinks and hotter rock upwells, taking some of the earth’s inner heat with it) are more dynamic and more efficient at carrying heat than was thought. Without postperovskite, continents would have grown slower and volcanoes would have been quieter. The formation of postperovskite may also have hastened the strengthening of the earth’s magnetic field, which made life possible on land by shielding it from cosmic rays and solar wind. In other words, postperovskite was a key missing ingredient for understanding the evolution of our planet.

Rock Bottom

Today, geophysicists map the structure of the earth by measuring seismic waves. Lacking the ability to probe the depths of the earth, early geologists who wanted to study these structures had to look for mantle rocks to be brought up to the surface by magmas of deep origin. These rocks often enclose diamonds. Because diamonds form under the pressures and temperatures that exist around 150 kilometers of depth or more, their host rocks can be presumed to originate from a similar depth; they thus provide a wealth of information about the uppermost part of the mantle. But mantle rocks or minerals derived from depths greater than 200 kilometers reach the surface only rarely.

Taking the Heat

To begin with, our discovery cast light on the amount of heat flowing from the core to the mantle. The core is mostly iron, making it twice as dense as the mantle. As a consequence, virtually no mixing occurs at the boundary between the two, and heat is exchanged predominately by a process called conduction. Conduction is the transfer of heat between substances in direct contact with one another. The core has cooled with time as heat has transferred into the mantle at the core-mantle boundary.

That flow of heat has determined how the core evolved since the earth formed. Inside the young earth, the core was entirely liquid, but at some point in the planet’s history the inner core started to crystallize so that it now, has two layers: an inner, solid core and an outer, liquid core. The faster rate of cooling suggests that the solid inner core may
be less than a billion years old, which is young compared with the earth’s age of 4.5 billion years: otherwise the inner core would be much larger than we observe at present.

The presence of a solid inner core makes the convection more regular and less chaotic, resulting in a stronger magnetic field than would exist if the core were entirely liquid. The geomagnetic field shields the earth from solar wind and cosmic rays, which can cause genetic mutations and would be especially dangerous for life on land.

**Causing a Stir**

By speeding up mantle convection, the presence of postperovskite increases the temperature of the upper mantle by hundreds of degrees. One of the consequences is that volcanoes are more active than they would otherwise be. In the early earth, when the core was hotter, the lowermost part of the mantle was also hotter and outside the range of temperatures at which postperovskite can form. As the planet slowly cooled, some perovskite started to turn into postperovskite, probably some 2.3 billion years ago, boosting the heat flow from the core and raising temperatures in the entire mantle. As a consequence, researchers have estimated, faster plate motion and increased volcanism during the past 2.3 billion years than they did during most of the previous time—although this conclusion is still being vigorously debated.

**Mantle and Core Evolution**

When the earth formed, the mantle contained no postperovskite, and the hot, iron-rich core was entirely liquid. Because the mantle was inefficient at dissipating heat, the inner earth cooled slowly (baby earth). Some 2.3 billion years ago, the formation of postperovskite at the bottom of the mantle speeded up convection. This change in dynamics may have increased volcanism, and, with it, the grown of continents (teenage earth). The consequent accelerated heat transport also cooled the core enough that, around one billion years ago, a solid inner core began to form (mature earth). Convection patterns in the liquid core layer became more regular and began to produce a strong geomagnetic field, which shields the earth’s surface from the dangers of solar wind and cosmic rays. This may have enabled life to move onto land.
To Be Continued

The earth’s lowermost mantle has long been enigmatic, but many of its characteristics are now well explained thanks to the discovery of postperovskite. In contrast, a number of questions remain about the iron-rich metallic core. The core has been much harder to study than the mantle because until recently diamond-anvil techniques were unable to re-create the pressures and temperatures that exist in the core. Very recently, however, we have produced diamond anvils that can reach the full range of pressures and temperatures that exist in the earth’s core, opening the door to addressing these unsolved mysteries about the deepest part of our planet.

It will be a bit like traveling all the way to the center of the earth, if only in our imagination.

Questions

Please answer on a separate piece of paper.

1. Why is it difficult to study deep inside the Earth?

2. The mantle constitutes about ________% of the Earth’s volume.

3. What is happening in the bottom layer of the mantle?

4. How were the depths of the Earth originally studied, and how are they studied today?

5. What is conduction?

6. Why is understanding the flow of heat important in understanding how the core of Earth evolved?

7. What did the presence of postperovskite do to convection within the mantle?

8. Why could postperovskite not form when the Earth was young?

9. Based on what you have learned in this article, propose an explanation for what will happen to this process of convection (and the Earth) in the future when the core has cooled.
A More Complex Planet

The earth is structured like an onion, with different materials appearing in each concentric layer. The discovery of a new, high-density material, called postperovskite, implies the existence of a new layer of the onion and explains puzzling behavior by seismic waves traveling through the planet.

**CRUST (UP TO 35 KILOMETERS OF DEPTH)**

The continents, which are in part submerged by the oceans, are made of diverse rock that is up to several billion years old and relatively light. Thus, they float on the denser mantle underneath. The heavy basaltic rock that forms the bulk of the oceanic crust originates from mantle magma that erupts at under-water ridges and eventually sinks back into the mantle, typically within 100 million years.

**MANTLE**

Mantle rock consists primarily of oxygen, silicon and magnesium. Despite being mostly solid, it does deform on geologic timescales. In fact, the rock slowly flows as convective currents stir the entire mantle. Heat flow dissipates the earth's inner heat and propels continental drift.

**UPPER MANTLE (35–660 KM)**

As greater depths bring higher pressures and temperatures, the mantle's elemental components arrange into different crystal structures (minerals), forming layers. These minerals—olivine, spinel and perovskite—give the layers of the upper mantle their respective names.

**LOWER MANTLE (660–2,900 KM)**

The lower mantle was for decades thought to be relatively uniform in structure. But seismological data suggested that something different was happening at the bottom.

- **Perovskite layer**
  The most prevalent mineral here (70 percent by weight) is a magnesium silicate (MgSiO3) belonging to the family of crystal structures called perovskites. In this densely packed structure, magnesium ions (yellow) are surrounded by octahedral silicon-oxygen groups (blue double-pyramid shapes). Until recently, scientists thought that no denser crystal arrangement of these elements could exist.

- **Postperovskite layer**
  At the pressures and temperatures of the bottom 300 km of the mantle, perovskite transforms into a new structure: the magnesium ions and the silicon-oxygen groups arrange themselves into separate layers. The transition releases heat and reduces volume by roughly 1.5 percent—a small difference, but one with dramatic effects on the entire planet (see illustrations on pages 82–83).

**CORE (2,900–6,400 KM)**

The deepest part of the earth consists predominantly of iron, which is liquid in the outer core and solid in the inner core. Convection stirs the outer core just as it stirs the mantle, but because the core is much denser, little mixing occurs between the mantle and the core. Core convection is thought to produce the planet's magnetic field.