Aluminous silica: A major water carrier in the lower mantle

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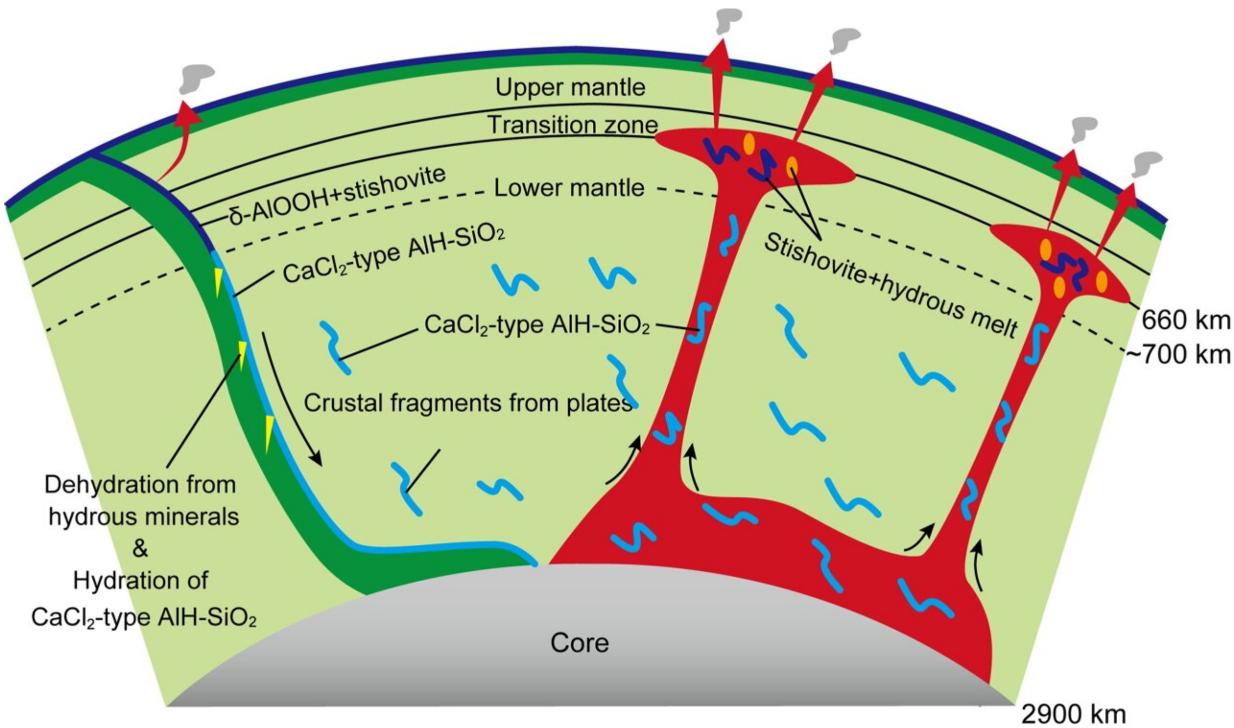

Mantle convection including water by hydrous aluminous silicas. Credit: Takayuki Ishii

Water is transported by oceanic plates into the Earth's deep interior and changes the properties of minerals and rocks, affecting the Earth's internal material cycle and environmental evolution since the formation of the Earth.

An international research group led by Dr. Takayuki Ishii and Dr. Ho-kwang Mao (Center for High Pressure Science and Technology Advanced Research, HPSTAR), Bayerisches Geoinstitut, University of Bayreuth, Germany, and Tohoku University, Japan, reveals that aluminous silicas play a major role as a water carrier in the lower mantle. They determined the alumina and water contents of silica minerals, which are important minerals in the basaltic crust of the upper part of a subducting plate.

The results show that rutile-type silica (stishovite), which is widely stable in the upper part of the lower mantle, undergoes a phase transition to a $CaCl_2$-type phase, when it contains water and alumina. The $CaCl_2$-type aluminous silica can hold more than 10 times the amount of water than other lower mantle minerals, even at very high temperatures in the lower mantle. This finding will lead to the elucidation of the origin of water in the lower mantle and the water cycle in the mantle. The results were published on October 24 in *Proceedings of the National Academy of Sciences*.

Since the birth of the Earth, water has traveled through the Earth's surface and interior, triggering earthquakes and volcanic activity and affecting the evolution of the Earth's interior environment. It is estimated that the amount of water that can be stored in the Earth's interior is several times that of the seawater on the Earth's surface.

Water (seawater) is transported to the Earth's interior by oceanic plates. To prevent water from leaking out of the plates, the minerals that make up the plates efficiently transport water by incorporating it into their crystal structures. It is thought that the minerals are transported by the plates to the lower mantle and then returned to the Earth's surface by the upwelling plume. It is still not well understood how much water is stored in the Earth's interior and how it returns to the Earth's surface. To understand these issues, it is important to know how much water mantle minerals can contain and how stably they can hold water.

It has been found that basalts found in oceanic island volcanoes such as hotspots, which are thought to have their source in the lower mantle, contain more water than other basalts. This suggests that the lower mantle plays the role of a major reservoir of water.

However, previous high-temperature and high-pressure experiments have shown that the main lower mantle minerals that make up peridotite in the lower part of the subducting plate can hold very little water. Therefore, it is highly likely that water subducted into the lower mantle is stored in the minerals in basaltic crusts, which is the upper layer of the plate.

In this study, we focused on silica minerals, which is abundant in basaltic crusts. Although this mineral has been proposed to contain large amounts of water, water solubility in aluminous silica, which more likely exists in basaltic crusts since basalt is also rich in alumina, has not been intensively investigated in lower mantle conditions.

We have synthesized aluminous silica single crystals of high quality at uppermost lower mantle conditions by high temperature and high pressure experiments, and determined their precise water content by infrared spectroscopy. As a result, we found that the amount of alumina in silica increases with temperature, and that above 1700°C, the average temperature of the mantle, rutile-type silica (stishovite), which is stable at the top of the lower mantle, undergoes a phase transition to a $CaCl_2$-type phase. The $CaCl_2$-type aluminous silica contains a larger amount (more than 1 wt.%) of water than stishovite, even above the average mantle temperature.

This is more than 10 times the water content that other lower mantle minerals can hold. Since the alumina content increases with temperature, the water content is also expected to increase in proportion to temperature. Previously reported mantle minerals release water with increasing temperature: their water content generally decreases with temperature. Since temperature increases with depth in the Earth's interior, this property implies that the water-holding capacity of minerals decreases with depth.

When water is released from minerals, it reacts with rocks to form hydrous magma, which separates from the plate and moves to the surface. Therefore, the depth at which minerals release water is considered to be the upper limit of water transport depth. It has been pointed out that in the lower mantle, which is particularly hot, minerals cannot hold water and may not be able to transport water. Contrary to this property, the minerals synthesized in this study have a water content that increases with temperature and can hold large amounts of water even under the hottest plume conditions in the mantle.

In addition, water released from other minerals is not separated from the plate, but is re-captured by aluminous silica in the basaltic layer of the plate, allowing water to be transported into the deep mantle without loss of water. Furthermore, the plume can also transport water again from the lower mantle to the upper mantle. Therefore, $CaCl_2$-type aluminous hydrous silica may be the most promising water carrier in the lower mantle. In the transition zone and upper mantle, a reverse phase transition from the $CaCl_2$-type phase to stishovite occurs, and water is thought to be released from silica as water-holding capacity in aluminous silica decreases.

The local structures of the mantle discovered so far, such as the seismic low-velocity layer just below the transition zone-lower mantle boundary, plume ponding at the boundary, and the hydrous transition zone, are thought to be explained by the presence of water, and the behavior of aluminous hydrous silica can successfully explain these phenomena.

More information: Takayuki Ishii et al, Superhydrous aluminous silica phases as major water hosts in high-temperature lower mantle, *Proceedings of the National Academy of Sciences* (2022). DOI: 10.1073/pnas.2211243119

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