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DEEP EARTH

Hydrogen dances in the deep mantle

Hydrogen ions move freely within the crystal structure of a hydrous mineral under lower mantle conditions, resulting in high electrical conductivity that may make it possible to map water in the deep mantle.

Tetsuya Komabayashi

Earth's water cycle is not limited to the clouds, rain and rivers we experience at the surface. Water also circulates through the solid Earth and this deep water cycle interacts with the surface via mantle hydration and dehydration during subduction and degassing, respectively. Processes of the deep water cycle have been discussed for relatively shallow depths but it remains unclear how deep into the mantle water persists. As water in the mantle is stored as hydrous minerals, constraining their physical properties is the key to understanding the distribution of Earth's deep water. Writing in *Nature Geoscience*, Hou and colleagues[1] demonstrate that a hydrous mineral phase, iron oxide-hydroxide, FeOOH, shows very high electrical conductivity under lower mantle conditions due to the free movement of hydrogen within the crystal structure. This high electrical conductivity could make it possible for geophysical observations to detect hydrous minerals and track the water cycle in the deep mantle.

If water in the mantle were present as a fluid, it would migrate towards the surface due to its low density. Any water in the deep mantle has therefore been transported by hydrous minerals, not as a free fluid. Since the 1960s[2], synthetic high-pressure hydrous phases, expected to carry water in subducted slabs down to the mantle transition zone at approximately 660 km (Fig. 1), have attracted attention. More recently, new synthetic hydrous phases were reported, capable of bringing water to mid-to-deep lower mantle depths greater than 1,250 km (ref. [3]). So, while water content of the mantle has been discussed down to the transition zone at 660 km (refs. [4,5]), the amount and location of water in the lower mantle remains unclear.

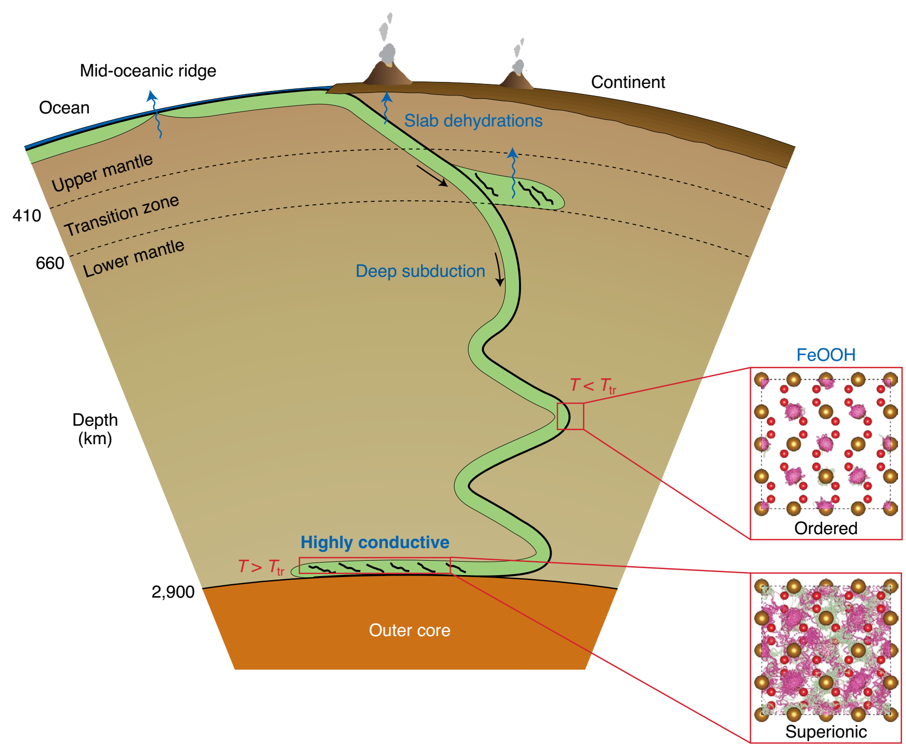

Fig. 1 | Water circulation in the mantle. The deep water cycle down to the mantle transition zone is characterized by the release of fluid water[9] (blue arrows). For water to be transported deeper, into the lowermost mantle, it relies on high-pressure hydrous phases such as FeOOH (stable in the subducted basaltic crust and sediments depicted by the thick black line). Hou and colleagues[1] show that at the core–mantle boundary, where the temperature is greater than the superionic transition temperature (T_{tr} = 1,700–2,000 K), the hydrogen ions in the FeOOH structure are moving freely through the crystal lattice and electrical conductivity is high, offering an exciting geophysical possibility for exploration of Earth's deepest water cycle. Crystal structure insets adapted with permission from ref. [1], Springer Nature Ltd.

Importantly, addition of just a little water to dry mantle rocks affects their physical properties; it reduces their melting temperatures and weakens their rheological strengths, which can trigger earthquakes. When acting as a mass transfer agent, water can also affect rock chemistry. It is therefore imperative to measure physical properties of these water-transporting minerals under extreme pressure–temperature conditions to elucidate the behaviour of water in the deep mantle, which is critically important for understanding mantle dynamics and evolution.

In ice giants, Neptune and Uranus, water is probably present and transported as ice. Under the high pressure and temperature conditions of these planetary interiors, the hydrogen ions move freely within the water ice crystal structure in a process known as superionic proton conduction[6,7]. These highly diffusive H^+ ions behave like a liquid, moving freely within a rigid oxygen sublattice. However, with the complex hydrous mineral phases found on Earth, it was unclear whether this superionic proton conduction would occur.

Hou and colleagues explore the potential for superionic proton conduction on Earth. They conducted laboratory measurements of electrical conductivity on the high-pressure hydrous phase, FeOOH, a potentially stable phase in Earth's cold subducted slabs. They find that under the pressure and temperature conditions of Earth's lowermost mantle, FeOOH is highly conductive, two to three orders of magnitude more conductive than dry mantle minerals. Their theoretical computations reveal that at 1,700–2,000 K the behaviour of H^+ ions changes from an ordered state where H^+ ions vibrate around their fixed positions to a liquid-like state within the rigid oxygen sublattice. This superionic state accounts for the high conductivity observed in the experiments, although the conductivity value is lower than that of the previously studied superionic H_2O ice because of the much smaller H^+ content in FeOOH.

FeOOH may only be a minor phase in the basaltic crust and sediments at the top of subducted slabs[8], but Hou and colleagues speculate that other high-pressure hydrous phases stable in the lower mantle could also become superionic under relevant pressure–temperature conditions. If this is the case, the effects of superionic phases on the physics and chemistry of the deep mantle would be more pronounced, so it seems of immediate interest for future research to clarify whether this superionic behaviour is unique to FeOOH or relevant more generally. In addition, it seems necessary to examine the high-temperature stability of these superionic phases; they may be stable even at ambient mantle temperatures because they should have high entropies due to the diffusive hydrogen. Finally, the high electrical conductivity of these superionic hydrous phases suggests an exciting opportunity — it could be possible to use electromagnetic data to map the distribution of water in the deep solid mantle.

Hou and colleagues offer a new approach to water in the lower mantle. While high-pressure hydrous phases are known to carry water from the surface to the deep mantle[3,9], water content is only really discussed down to the transition zone[4,5]. The high electrical conductivity due to the free movement of hydrogen in FeOOH may enable us to locate hydrogen in the deep mantle and offer better understanding of Earth's deepest water cycle. ❐

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