Mechanism for water formation on rocky exoplanets demonstrated in the lab

Experiments have revealed that the interaction between a hydrogen-rich atmosphere and a molten planet leads to high levels of water production. Through this process, planets could be enriched with water during their formation, altering their chemistry, evolution and, possibly, habitability.

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The problem

Sub-Neptunes — planets larger than Earth but smaller than Neptune — are the most common type of planet discovered in our Galaxy. They are thought to have a rocky interior, similar to that of Earth, and a thick, hydrogen-rich atmosphere that keeps their surface molten for millions of years. The interaction between the hydrogen in the atmosphere and the molten silicate interior can considerably change the properties of the planet[1]. Hydrogen can be stored in the melt and/or chemically react with it to form water. Understanding the extent of this interaction is fundamental to understanding whether water can be stored in the interior of the planet[2]. Although theory has predicted that certain reactions should occur between the atmosphere and the interior of these planets[3], it has been difficult to reproduce these interactions in the laboratory.

The solution

We used high-pressure devices called diamond anvil cells coupled with lasers to achieve high temperatures and reproduce the conditions expected at the surface and interior of an exoplanet. The samples consisted of 'tiles', measuring tens of micrometres, that had a chemical composition analogous to that of a molten planet. The samples were reacted with hydrogen at high pressure and temperature, and were then extracted and cut into tinier pieces to expose the centre. We used electron microscopy to detect and quantify each chemical element in the samples, and we used ion microscopy to do this for hydrogen-bearing species. We determined whether the hydrogen interacted with the silicate sample and measured how much water, if any, was present.

The iron in the silicate melt at the beginning of the experiment was no longer there at the end — instead, iron-rich 'pockets' had formed. We also found that hydrogen accounted for 1% of the weight of the sample after the experiment (Fig. 1). The absence of iron from the silicate and the presence of iron pockets point towards a redox reaction, with hydrogen reducing (donating electrons to) iron oxide to produce iron and water. Measurements indicate that the sample contains abundant hydrogen that can dissolve into the melt. We therefore proved that there are two ways in which hydrogen can interact with planetary magma oceans: by forming water, and by dissolving into the mantle.

The implications

Our results show that, in large rocky planets, interactions between the atmosphere and the molten interior can result in a substantial amount of hydrogen and water forming and being dissolved. Two reservoirs will form in the interior: the melt containing dissolved hydrogen, and a fluid-water phase. The presence of these reservoirs could alter the chemistry and properties of the interior and the habitability of the planet.

Because we analysed our experiments at ambient conditions, the amount of hydrogen we measured is the minimum amount that can be dissolved in the sample, not necessarily the amount dissolved at high pressures and temperatures. Hence, we know that hydrogen can dissolve in the melt to a concentration of at least 1% by weight, but we cannot say what the maximum is. In addition, because our analyses focused on the chemistry of the system, we do not have access to the structural properties (for example, volume and density) of the hydrogen-enriched melt.

Developing more-advanced protocols to determine the chemistry and properties of the melt without having to recover the sample at ambient conditions will be crucial to increasing the possibility of using experimental data in models of exoplanetary interiors.

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EXPERT OPINION

"This study shows water production and iron reduction in state-of-the-art laser-heated diamond-anvil-cell experiments. The experiments reveal the behaviour of hydrogen–silicate interactions under high-pressure and high-temperature conditions — something not explored before. Previous experiments focused on lower pressures (few GPa) and evolved melt compositions, often without iron. The paper has clear implications for the interaction of hydrogen with the rocky components of planets." (CC BY 4.0)

Caroline Dorn is at ETH Zürich, Zurich, Switzerland.

FIGURE

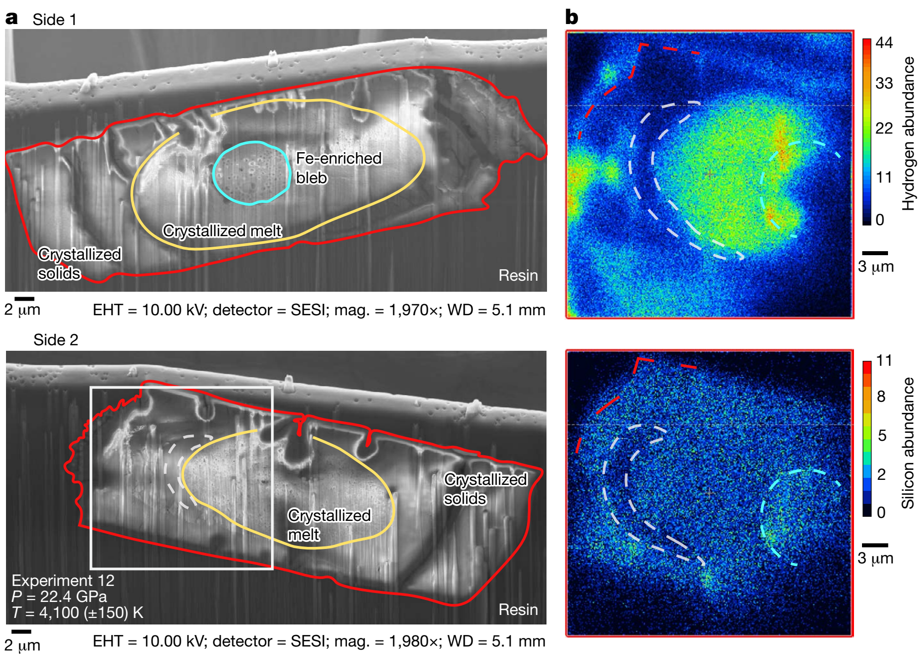

Figure 1 | High hydrogen content in silicate 'tiles' that mimic the molten interior of rocky planets. **a**, Electron images (using focused ion beam) of the sample's central slice, front (top) and back (bottom). Coloured lines delimit the sample (red), the crystallized melt (yellow) and the iron (Fe)-enriched portion, or bleb (light blue). EHT, electron high tension (accelerating voltage); mag.; magnification; *P*, pressure; SESI, secondary signal imaging; *T*, temperature; WD, working distance (the distance between the lens and the sample). **b**, 'NanoSIMS' ion maps collected on a portion of the sample. The colour scale reflects abundance: the brighter the pixel, the more abundant the element (top, hydrogen (^{16}O, ^{1}H); bottom, silicon (^{30}Si)). The intense green in the hydrogen map indicates high concentration. Dashed lines serve as a visual guide.

BEHIND THE PAPER

This project was excruciating, intense and thrilling at the same time. It took a very long time to work out a way to recover the samples after the experiments without causing them to crumble into sub-micrometre-sized pieces. We also realized that, because the standard samples were so small, we did not have a fracture-free portion of the sample big enough to collect the hydrogen data from. We had to determine a different approach to cutting the samples and mounting them. The 40×30-micrometre sample slices, attached to tiny metallic supports, underwent many transfer steps, as well as international travel, before being ready for analyses. It took so long to get the data that, when we finally got them, F.M. could not believe we had been successful. She made six back-up copies on three hard drives, because you never know what might happen.

F.M. and **A.S.**

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FROM THE EDITOR

It turns out that squeezing water out of rock isn't just for fairy tales and polemics. Under high-enough pressures and temperatures, such as those found in the early stages of planet formation, this might be exactly what is happening. The experiments by Miozzi *et al.* help to lay the foundation for our understanding of water-rich worlds such as our own.

Urmila Chadayammuri, Associate Editor, *Nature*