Constraining Planetary Melting and Differentiation with Experimentation at High Pressure and Temperature

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Studies on the origin of volatiles and water in Earth as well as of the large amount of sulfur on the surface of Mars have a connection to deep planetary interiors. To simulate these conditions, we opened a High Pressure Laboratory in 2006. It houses two non-end-loaded piston cylinder apparatuses and two multi-anvil apparatuses. The combination of these four pieces of equipment enables us to attain pressures between 0.5 and 25 GPa. This pressure range also allows us to simulate the conditions that lie deep within planetary interiors such as the center of the moon (4.5 GPa), the core mantle boundary of Mars (~22 GPa), or the upper-lower mantle boundary in Earth (25 GPa). These facilities are used to explore a variety of research topics in Earth and planetary science, including: the conditions of planetary mantle melting; the origin of volatiles (hydrogen, carbon, oxygen, sulfur); the conditions during accretion; the origin of the Earth and the moon; and, finally, simply being able to synthesize high-pressure phases that do not exist at ambient laboratory conditions.

Pressure is generated in the piston cylinder apparatus by squeezing a pressure medium (sodium chloride or barium carbonate) into a cylindrical shape, with a sample and heater enclosed. In the smaller, multi-anvil assemblies, the shape is more equi-dimensional, with six steel wedges compressing eight triangular-faceted tungsten carbide cubes that are arranged in an octahedral shape (figure 1). The sample and a heater are then placed within the ceramic octahedral pressure medium, thus allowing the sample to be studied at pressure and temperature simultaneously. We use the synchrotron facility, which features a modified multi-anvil apparatus, to allow a strong and high-resolution x-ray beam to pass through the high-pressure assembly when a sample is being heated at pressure. We have also worked with the Argonne National Laboratory Advanced Photon Source (Argonne, Ill.) where we have simultaneously studied the compressibility and thermal expansion of metals and oxides, as well as the phase equilibria of planetary mantles (peridotite) and bulk compositions (chondrites) under extreme P-T [pressure and temperature] conditions.

Three models have been advanced to explain the origin of water on Earth (figure 2). The first of these is the traditional model in which the Earth's origin has been attributed to comets or another kind of volatile-bearing body that arrived late and well after accretion was complete. A second model proposes that water arrived just at the end of accretion, after the huge metallic core of the Earth had finished forming. The third model suggests that the Earth acquired its water early, during the accretion process.

The second hypothesis is linked to a class of elements called the highly siderophile elements; these elements are thought to reside mainly in the Earth's core. They are also present in the mantle at concentrations similar to those that would be expected if small amounts of chondritic material were added to the mantle after the core had formed. Because of this, the highly siderophile elements (HSEs) as well as the volatiles have commonly been linked in formation models for the Earth. This model was originally proposed in the 1970s, at a time at which relevant high P-T data were unavailable.

Fig. 1. *(from top): Sample is placed in white pressure medium between eight carbide cubes (four shown), placed between six steel wedges, and then placed in a hydraulic press. An Astromaterials Research and Exploration Science scientist is shown with the multi-anvil module and press at bottom.*

Fig. 2. *Did Earth have its water early, or did it acquire it later from comets? How did water survive a giant impact?*

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continued

To test this model more thoroughly, we studied the distribution of the HSE palladium (Pd) to test whether its abundance in the Earth's mantle requires the addition of later chondritic material, or whether its presence can be explained by simple metal-silicate equilibrium between the mantle and the core during accretion. The results, at pressures up to 15 GPa , have shown that the concentration of Pd in the Earth's mantle can be explained by high P-T distribution between the core and the mantle early in the history of the planet. The implications are that late additions of water- and HSE-bearing material are not necessary, and that water and HSE concentrations in the Earth's mantle were established very early during accretion. Other elements (e.g., gold, platinum, iridium, and rhodium) are being investigated to determine whether they are also compatible with this simple, and early, origin of water on Earth.

It has been known for some time that the surface of Mars contains sulfur, but the diversity and distribution of sulfates around the martian surface have been only more recently appreciated. The sulfur is thought to originate from interior degassing, but this hypothesis has not been rigorously tested with either experimental or more recent spacecraft data. If the sulfur comes from the martian interior, the main vehicle for transport would have to be magma, which is capable of dissolving significant amounts of sulfur. Although this process is well known for Earth basalts (e.g., mid-ocean ridges and Hawaii), it is relatively poorly understood for martian basalts such as the shergottites or those erupted from Olympus Mons (figure 3). Because magma generation in Mars likely takes place at pressures that are accessible in the Johnson Space Center High Pressure Laboratory, we have undertaken a study of sulfur solubility in martian magmas that includes the melting process in the mantle as well as later differentiation at shallower conditions at or near the surface. The results so far indicate that models based on terrestrial compositions and applied to martian systems are inadequate for predicting sulfur in magmas. The solubility of sulfur in martian magmas is perhaps two times higher than that predicted by Earth-based models. The results of this study will have fundamental implications for the total sulfur budget of Mars, as well as for our understanding of sulfur inputs into the martian atmosphere and the control of elements in the martian interior by sulfides.

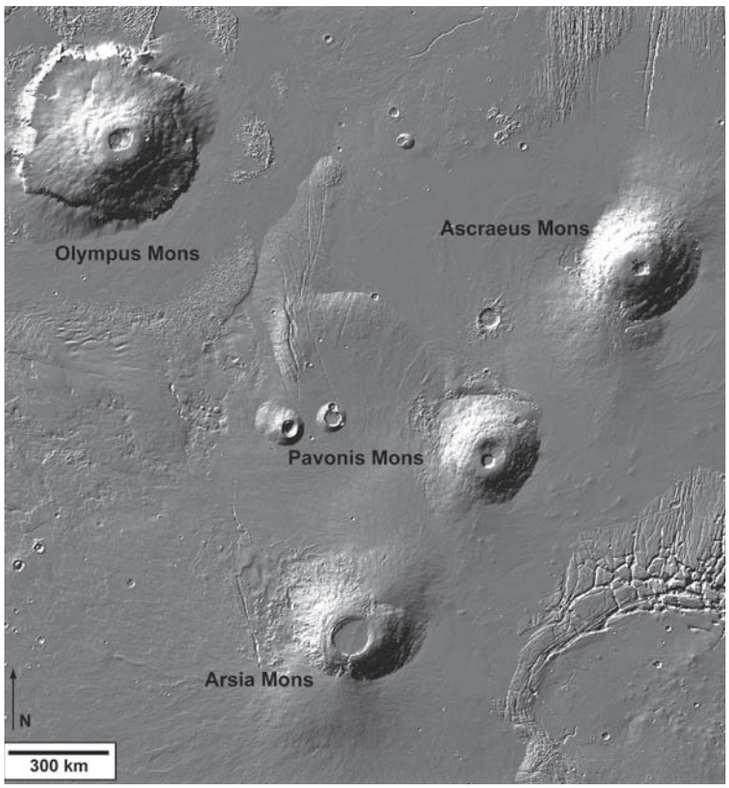

Fig. 3. *Did all the sulfur on the surface of Mars come from volcanic eruptions such as from Olympus Mons?*

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