DIFFERENTIATION OF WATER-RICH PLANETARY BODIES: DEHYDRATION, MAGMATISM AND WATER STORAGE.

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Introduction: Whereas in the Inner Solar System, most planetary bodies differentiated dry (or water-poor) into a basaltic protocrust, a peridotite mantle and an iron-rich core, in the Outer Solar System, the building blocks for planetesimals were water-rich, producing ice-bearing bodies. The role and fate of water during the differentiation process, however, remain unclear. As the temperature increases due to the extinct radioactivities (e.g. ^{26}Al) and to accretion energy, differentiation of icy-planetesimals probably follows three main steps: (1) Ice melting produces a two-layer body, with a water ocean (potentially partially frozen) above a rocky core. At the same time, interaction between liquid water and rock produces a large amount of hydrous silicates, mainly serpentines. (2) If temperature increases sufficiently, the rocky core undergoes metamorphism, and follows a series of dehydration reactions that progressively releases more water toward the ice layer. (3) With further temperature increase, metal- then silicate-solidii are reached, and the rocky core can undergo further differentiation into a metallic core, a silicate mantle, and possibly a silicate crust. Step (1) is mostly controlled by the melting curve of ice and is relatively well known. However, almost nothing is known about further differentiation steps, even if we know that some of the differentiated bodies in the outer solar system possess a metallic core (Io, Europa, Ganymede) and thus likely reached at least the metal melting curve. In this study, we use phase equilibrium diagrams of water-saturated Fe-rich compositions and thermal models for the evolution of small planetary bodies to discuss the influence of large amounts of water on planetary differentiation. The results are applied to the satellites of Jupiter and Saturn.

Water in planetary building blocks: In the main asteroid belt, the carbonaceous chondrites contain up to 17 wt% H_2O [1]. Ceres, the largest of all the asteroids possibly contains 17 to 27 wt% H_2O [2]. Higher concentrations are expected further out in the Solar Systems, with water finally becoming the major component in comets. Delivery of water to growing planetesimals can be hampered by dehydration and degassing. However, the impact pressures and surface temperatures are not sufficient for silicate dehydration on bodies smaller than 2000 km in radius [3], as investigated here. Most of the small planetary bodies in the Outer Solar system contain a large ice/ocean layer (e.g., Ganymede, Titan, Calysto, Europa) [4,5]. Such high water content indicate that small planetary bodies in the Outer Solar System grew under water-saturated conditions.

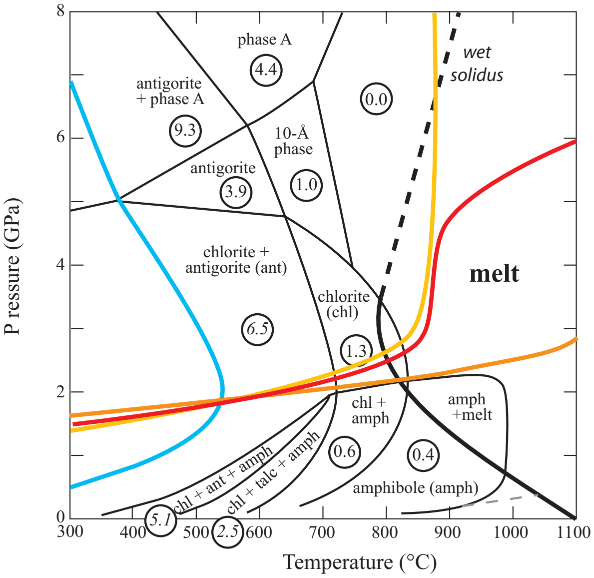

Fig. 1. Water saturated phase relations of an Fe-rich planetary body, redrawn after [6]. Water contents from [6,7,8]. Thermal profiles after accretion by [9] (in blue), actual thermal profiles after radioactive heating by [4] (in yellow, orange and red).

Ice/silicate differenciation and water concentrations in planetary mantles: Figure 1 presents the phase diagram of a water-saturated, FeO-rich peridotite composition [6]. If heating is solely due to successive planetesimal impacts as the planetary body grows [9], the thermal profile of a ~2000 km radius peridotitic body lies entirely in the chlorite + antigorite field (Figure 1., blue curve). The planetary body never melts, and ~6.5 wt% water is stored in its silicate part. More water can be stored in the innermost part of the larger bodies (up to ~9.3 wt%), but those values will not significantly change the bulk water content. If the building blocks contain more than 6.5 wt% water, then the rest will migrate to the surface, contributing to the outer ice layers of the planet. If carbonaceous chondrites are the main building blocks, the initial mantle density will be about 2.75 g/cm^3 [10]. However, progressive dehydration to form a mantle of chlorite-serpentinite is likely to increase this density.

Mantle dehydration and protocrust formation: After accretion, the temperature of the planetary body is expected to further increase as a consequence of extinct and extant radioactivities, and the dissipation of residual accretional energy [4,11]. If the temperature increases enough to cross the wet solidus (Figure 1), water-rich silicate melts are produced and migrate to the ocean bottom to form a protocrust. Melting of the anhydrous residual mantle is not possible unless exceptionally high temperatures are reached.

As an example, all thermal models of Titan proposed by [4] cross the wet solidus during the satellite history (Figure 1, yellow, orange and red curves). The interior of Titan above 2.5 GPa is fully dehydrated, and hydrous phases only subsist in the outer part of the mantle. Hydrous protocrusts and anhydrous lower mantles are likely present on Titan and Ganymede, possibly on Europa, and were probably present in the early history of Io. Due to the influence of Jupiter's tidal forces, Io is the only satellite of the outer planets where temperatures can cross the dry solidus and induce further melting of the residual anhydrous mantle.

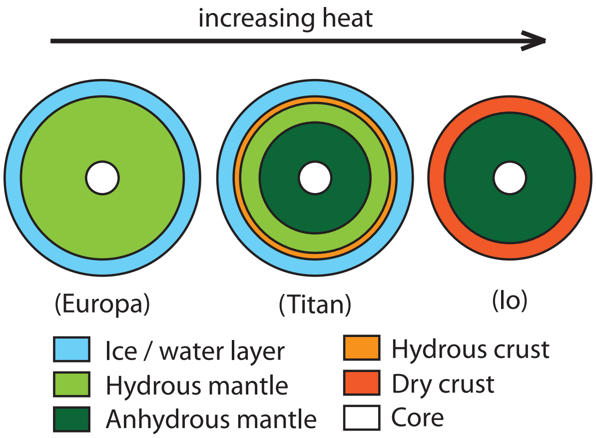

Fig. 2. Conceptual model for the evolution of water-rich planetary bodies. With increasing available heat, the mantle progressively dehydrates and melts, and the ice layer is sublimated and lost to space.

Protocrust compositions in the Outer Solar System: The composition of melts produced by water-saturated melting of an iron-rich peridotite composition have been experimentally investigated by [12]. Glasses from three experiments, saturated with olivine, orthopyroxene, clinopyroxene, spinel, and, for one experiment, amphibole, have been analyzed by electron microprobe. They have very similar andesitic compositions, with SiO_2 = 57-60 wt%, Al_2O_3 = 18-21 wt%, FeO = 2-6 wt%, MgO = 1-3 wt% and CaO = 8-10 wt% for melt fractions around 10 %. Similar silica rich melts are also produced on Earth by melting of a volatile-bearing lithosphere [13], and in subduction zones []. These results indicates that any protocrust formed on small, water-rich planetary body will be andesitic, and not basaltic. The presence of an andesitic ocean-floor on some of the ocean worlds, instead of the traditional basaltic or serpentinitic ocean-floors encountered on Earth will have consequences on the solute concentrations in the ocean, the crustal alteration processes, and the availability of minerals for the development of life.

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