Habitability of Icy Worlds: Electrochemical Capacitance of Serpentinizing Hydrothermal Systems

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Differentiated icy satellites and dwarf planets in the size range $R \approx 250 - 2000$ km constitute a special class of objects sufficiently large for anhydrous and chemically reducing rocky interiors to result from heats of formation, yet small enough to sustain fracturable mantle depths 10-100 times greater than Earth's crustal thickness. Hydration of rocky mantle minerals by serpentinization provides a means for sustaining the measured release of chemical energy in such worlds. Fluid percolation depths increase as radiogenic heating diminishes, providing a long-lived source of chemicals and energy for putative organisms. In tidally evolved systems such as Europa, periods of high forced eccentricity provide a means for dehydrating and sealing fractured mantle, thereby recharging the global reservoir of geochemical energy.

Serpentinization in Icy Worlds

The hydration of olivine and pyroxene has received much attention in recent decades as serpentinizing springs have been identified on the continent [1] and seafloor [2]. Reaction rate and extent are limited by factors of rock permeability, fluid flow rate and temperature [3]. During the overall lifetime of such systems, the depth of fluid percolation and corresponding volume of rock available for reaction are plausibly limited by the depth at which microfractures close under pressure [4]. Applying the same methods of estimation to the conductively cooled near surfaces of solar system objects, depths of fluid percolation are up to 100 times greater in the smallest objects as exemplified by Europa and Enceladus [5]. The present work also considers the dwarf planet Ceres, which, if differentiated, is an ideal place to search for deep hydrothermal chemistry.

Electrochemical Capacitance and Life's Origins

Depth of fluid percolation increases as the object ages and radiogenic heating diminishes. Progressive fracturing provides a means for slowly and continuously releasing chemical energy imparted during a prior era of intense heating (e.g. formation and differentiation). On a global basis, heat released by serpentinization is comparable to radiogenic heating for the smallest objects (Fig. 1). Hydrothermal convection would probably localize and intensify serpentinization heating, driving the exothermic reaction closer to its optimum temperature of 250 ^{o}C [6]. The mineral assemblages present in serpentinizing systems and hydrogen rich alkaline fluids enable the fixation of CO2-rich ocean fluids through the acethyl-Coa pathway — a plausible scenario for spawning more complex but more efficient living systems [7].

Recharge By Heating to Dehydration

Serpentine dehydrates above 500 ^{o}C, with little dependence on pressure for the depths considered here [10]. Objects larger than 1000 km in diameter should have obtained such temperatures during formation. Objects as small as Enceladus (R = 252 km) could have been heated sufficiently if their accretion preceded the decay of short-lived ^{26}Al [11]. Heating subsequent to formation might reset the serpentinized areas, providing a means for renewing and intensifying the long-term release of energy through serpentinization. Two such scenarios are envisioned here: creation of the Tharsis rise on Mars 3.5 Ga and a period of high tidal dissipation in Europa's rocky interior 3 Ga [12]. Increased heat and hydrogen output following these events are depicted as dashed curves in Figure 1.

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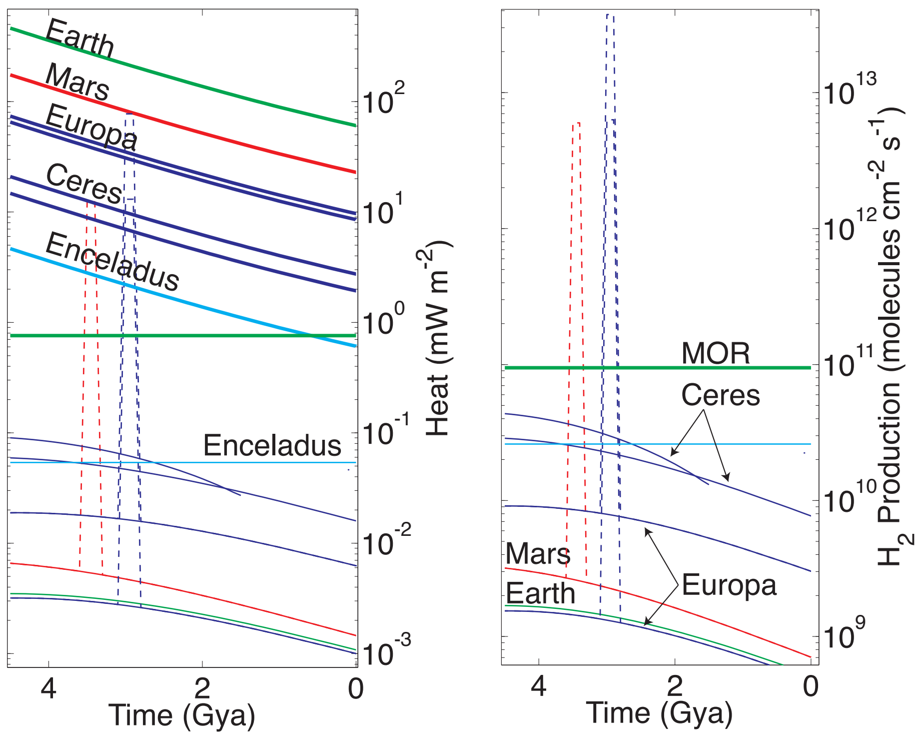

Figure 1: Surface heat hydrogen fluxes in planetary interiors through geologic time. On the left, heat from decay of long-lived radionuclides (upper lines) is compared with heat from the serpentinization of fractured magnesium- and iron-bearing olivine. On the right, molecular hydrogen production is shown for the same reaction. For comparison, a similar estimate is shown (MOR) for serpentinization of Earth's mid-ocean ridges (3.5 km depth) at present rates of spreading (2 mm yr^{-1}). Dashed lines indicate the increase in heat and hydrogen release from rehydration following epochs of heat-induced dehydration of previously serpentinized material. For Enceladus, the rocky interior is entirely fractureable from time zero. For Europa and Ceres, estimates are made for maximum and minimum water-rock interface depths (Ceres, 52 and 120 km: McCord and Sotin [8]; Europa, 80 and 170 km: Anderson et al. [9]. Rocks are assumed to be peridotite with 70% olivine, of which 10% is fayalite. Complete serpentinization is assumed to the fractureable mantle depth as calculated by Vance et al. [5].

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