ENCELADUS AND EUROPA: HOW DOES HYDROTHERMAL ACTIVITY BEGIN AT THE SURFACE?

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Introduction: The question of how the surface hydrothermal activity (e.g., eruptive plumes and heat flow) is initiated can be addressed within the framework of our *"Perrier Ocean" model* [1, 2]. This model delivers the necessary heat and chemicals to support the heat flow and plumes observed by *Cassini* in Enceladus' South Polar Region [3-5]. The model employs closed-loop circulation of water from a subsurface ocean. The ocean is the main reservoir of heat and chemicals, including dissolved gases. As ocean water moves up toward the surface, pressure is reduced and gases exsolve forming bubbles. This bubbly mixture is less dense than the icy crust and the buoyant ocean-water mixture rises toward the surface. Near the surface, heat and chemicals, including some volatiles, are delivered to the chambers in which plumes form and also to shallow reservoirs that keep the surface ice "warm". (Plume operations, *per se*, are as described by Schmidt et al. [6] and Postberg et al. [7] and are adopted by us.) After transferring heat, the water cools, bubbles contract and dissolve, and the mixture is now relatively dense. It descends through cracks in the crust and returns to the ocean. Once the closed-loop circulation has started it is self-sustaining. Loss of water via the erupting plumes is relatively negligible compared to the amount needed to maintain the heat flow.

We note that the activity described herein for the the "Perrier-Ocean" model could, *a priori*, apply to all small icy bodies that sheltered an interior ocean at some point in their history.

Processes for Starting Hydrothermal Activity at the Surface: Ocean water is denser than the icy crust and normally cannot rise to the surface. The circulation can be started either by making the water buoyant, such as by the introduction of gas bubbles, or by pressurizing the ocean and forcing the water up. In the latter case when the water has been raised high enough gas can exsolve and form bubbles. Once sufficient buoyancy has been established the process becomes self-sustaining.

Processes for starting circulation include: *1) Fracturing of the ice crust and opening void space* [8]- A crack opens in the ice (for example as a consequence of tidal stressing or an impact), and ocean water rushes in to fill it. As deeper water rises, gases exsolve and form bubbles that make the water buoyant [9]. *2) Ascending oceanic plumes*- If conditions in the ocean support plumes, these may erode "holes" in the crust.

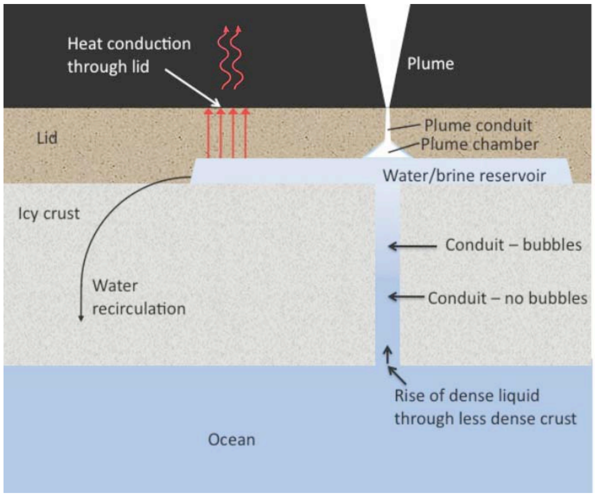

Fig. 1. Sketch of the "Perrier Ocean" model. Ocean water is circulated up to near the surface. It supplies the plume chamber with all the necessary chemicals. It transfers heat to near-surface ice that then radiates it to space. Depleted of its heat, the water returns to the ocean via cracks in the crust. For simplicity only one vertical conduit is shown. Enceladus may have many such conduits. (This cartoon is not drawn to scale. Crawford and Stevenson introduced the term "Perrier Ocean" [9].)

When the hydraulic pressure becomes low enough, gas will exsolve and may establish positive buoyancy that would start the circulation. Such plumes (without dissolved gas) were suggested for Europa by Thomson and Delaney [see 10, 11]. On a larger scale, hydrothermal activity can be started if the ocean becomes pressurized and water is forced to the surface. Processes using this approach include: *3) Magma from a rocky core intruding into an icy crust* [12], and similarly *4) magma intrusion directly into an ocean.* Both of these processes produce steam that provides the pressurization. *5) Freezing and thickening of the ice crust* [13]. This requires the crust to support hoop stresses. As the crust grows in thickness from the bottom downward, the ocean gets squeezed. Another volumetric change processes is *6) Expansion of the core by hydration*. Both 5 and 6 proceed slowly compared to the very rapid pressurization by hot magma in 3 and 4.

Cessation of Activity: The hydrothermal activity stops when the ocean water can no longer supply heat.

There can be a number of causes for this. These include: *1) Tectonic activity blocks the flow of water to the surface.* E.g., faulting displaces sections of the conduit such that the lengths are no longer aligned and cannot transport water to the surface. *2) Erosion of the supply conduit walls resulting in conduit enlargement*. With discharge fixed, enlargement of the conduit will reduce the flow rate. When the flow becomes too slow, the rising bubbles will outpace the liquid. Such phase separation can destroy the positive buoyancy of the upward-going column [9]. *3) Gas depletion*. This would apply when the system has lost so much gas that not enough bubbles are formed to achieve positive buoyancy. *4) Crust grows and becomes too thick.* A thick crust causes two difficulties. First more bubbles are required to attain positive buoyancy and raise the ocean water to the surface region. Second, below about twenty-five kilometers the lithostatic pressure will squeeze ice into the conduits. When this rate becomes faster than can be counterbalanced by erosion, the tube will be pinched shut. 5) *Temporary or permanent closure of cracks by clathration.* The severity of the blockage depends on the T-P relationship and abundance of guest species.

Future Spacecraft Observations: The available data are not sufficient to distinguish between the possible starting mechanisms of hydrothermal activity at Enceladus. Our model has, however, potential application to hydrothermal activity on Europa as well. The available data cannot rule out such Enceladus-like activity at Europa. New measurements from spacecraft will be necessary to resolve these issues. Greatly needed are 1) high spatial resolution thermal emission measurements over entire diurnal periods, 2) high precision mass spectrometry (allowing isotopic measurements) over an extended mass range so that large molecules will not be missed, on either Enceladus or Europa.

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