FORMING CO_2 ICE ON ENCELADUS' SURFACE. D. L. Matson[1], A. G. Davies[1] T. V. Johnson[1], J. C. Castillo-Rogez[1], and J. I. Lunine[2]. [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena CA 91101, dmatson@jpl.nasa.gov, [2]Department of Astronomy, Cornell University, Ithaca, NY 14853E.

Introduction: "We found traces of free CO_2 ice, trapped CO_2 (either as a liquid or gaseous inclusion), and simple organics in the tiger stripes." "Indeed, we found free CO_2 ice in small amounts globally and in higher concentrations near Enceladus' south polar regions…." (Brown et al., 2006 p. 1427 [1]). The profound puzzle for which Brown et al. did not have an answer is how did pure CO_2 ice come to be on the surface. We suggest that the CO_2 came from gas pockets trapped below the ice. We show that such pockets are a natural consequence of the circulation of Enceladus' gas-rich ocean water. We conclude by comparing gas pockets with plume chambers, both subsurface features of Enceladus.

Enceladus is an amazing satellite. It is the sixth-largest moon of Saturn, but at 500 km in diameter, was thought to be much too small to be geologically active. However, its South Polar Region has erupting plumes and numerous thermal anomalies that radiate a total of ~15 GW of power [2,3]. These anomalies have local "hot" spots where temperatures can be as high as one hundred degrees hotter than is possible by heating with absorbed sunlight alone. Furthermore, analysis of some of the tiny water-ice crystals lofted in the plumes found salts, including NaCl. This discovery and other evidence led Postberg et al. [4] to conclude that the erupting material came from "sea water".

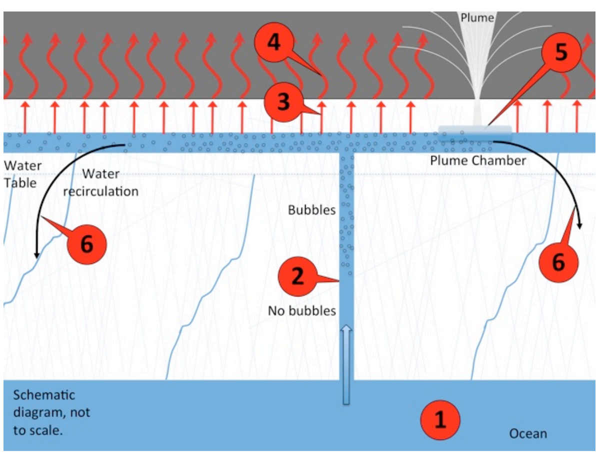

Fig. 1. A not-to-scale sketch illustrating the ocean water circulation hypothesis. Ocean water comes up and is circulated just below the surface. It supplies the plume chamber with the chemicals seen in the plumes. It transfers heat to near-surface ice that, in turn, radiates heat to space. Then the water returns to the ocean. This figure illustrates just one example of a situation that may occur at many localities in the South Polar Region. Matson et al. [7] used pressure relationships to demonstrate that ocean water can circulate in Enceladus.

Cassini flew through the plumes and the Ion and Neutral Mass Spectrometer (INMS) and the Cosmic Dust Analyzer (CDA) directly sampled the plume material. INMS measured the composition of the gas cloud. It was mostly water vapor but included ~5% mole fraction CO_2 and traces of other gases [5,6].

Ocean Water Circulation Hypothesis: We explain the CO_2 ice deposits in the context of the *Ocean Water Circulation Hypothesis* [7]. This hypothesis describes how water, chemicals, and heat come from a warm ocean at depth and are brought to the surface. A notional illustration is presented in Fig. 1. The figure schematically depicts six major features of a conjectured, ongoing, water circulation system below Enceladus' active south polar areas. The figure is a vertical section passing through plume chambers and thermal anomalies. The depicted, near-surface water layer is not necessarily continuous in the vertical plane perpendicular to the shown section (i.e., the direction in-and-out of the page), but exists where there is endogenic heat flow. At the bottom is the subsurface ocean (#1 in Fig. 1). It underlays the South Polar Region but its actual extent is unknown. The ocean is assumed to be below an average crustal thickness of 10 km. The ocean is a reservoir for the chemical species detected in the plumes. As ocean water is brought to the surface the pressure falls below the saturation pressure for each gas species and the corresponding gases then exsolve according to Henry's Law. CO_2 and the other much less abundant gases form tiny bubbles that reduce the overall density of the fluid. With the exsolution of enough gas, the ocean water becomes buoyant and rises towards the surface where fractures or fissures in the ice have provided conduits, shown schematically at #2 in Fig. 1.

Near the surface the water flows beneath a protective ice cap and spreads out laterally below the thermal anomalies. A symbolic surface thermal anomaly is indicated by #3 where heat from the water is being conducted through the ice cap to the surface. Areas of anomalously high surface temperature radiate this heat to space #4. Fissures, troughs, and other topographic relief in the bottom of the ice cap provide shortcuts for heat transfer to the surface (making these areas hotter). An example of such locations are the ''tiger stripes'' [2, 11]. Depending on the temperature of the surface, the thickness of the cap can be inferred to vary from a few tens of meters (surface temperature of ~100 K and higher) up to hundreds of meters (surface temperatures ~80–100 K).

The plume chambers are environments where some of the ocean water is converted into vapor and aerosols. A single symbolic example is shown at #5. We have adopted the plume model of Schmidt et al. [8]. The flow of ocean water through a plume chamber replenishes the chemicals that have erupted as well as the energy (through heat transfer) that powers the plume process. Bubbles coming into the chamber pop. This produces an aerosol spray of tiny droplets in the plume chamber. Some of these particles are then entrained in the erupting gas. Altogether the plumes erupt about 150–300 kg s^{-1} [9] most of which is water.

The water that has lost heat and gas is colder and denser. It returns to the ocean, indicated by #6, via available fissures or cracks in the icy crust. The ocean is warm (~0 °C) [7] and must have a source of heat or it will freeze on a time scale of ~30 million years [10].

Gas Pockets: The whole South Polar Region is crisscrossed by many scars, faults or fissures. It has a “fractured” and “disturbed” appearance. This suggests that cracks and other imperfections continue through the ice and are also expressed on its bottom. Such topography is conducive to the formation of gas pockets. As the ocean water nears the surface it spreads out laterally, following the pattern indicated by the thermal anomalies. Although the water is now streaming horizontally, the gas bubbles continue to rise vertically. Even though their vertical migration may be slow and even if the flow is relatively turbulent, some bubbles will still reach recesses in the bottom of the ice and, over time, pop and form gas pockets.

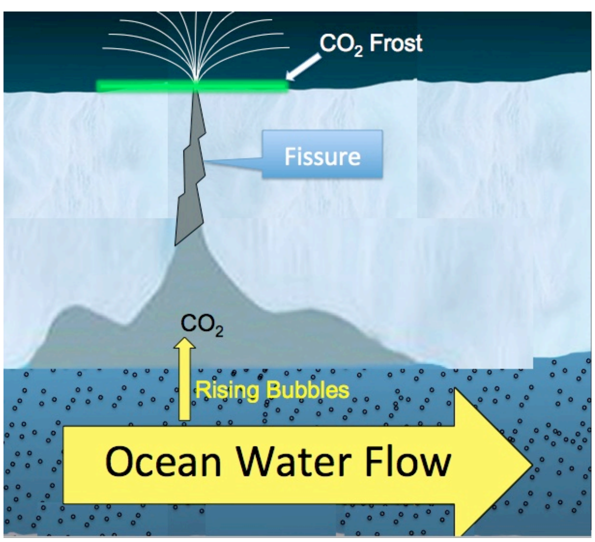

Fig. 2. A notional sketch of an Enceladus gas pocket. A transient fissure is indicated by dark gray. Its opening allows pocket gas to escape. Before it opens gas accumulates. At the surface the direction and speed of venting gas is not known.

The gas pockets are envisioned as being ruptured by the regular fissuring of ice in the South Polar Region. Hurford et al. [12] have modeled the tidally controlled periodic openings of rifts in Enceladus’ South Polar Region. If one of these rifts cuts into a gas pocket, CO_2 gas will be vented to the surface. By the time the vented gas reaches the surface its speed and direction are unknown. Whether or not a frost forms depends upon the amount of CO_2 released and the transient density of the cloud of emitted gas above the surface. The faster molecules that have a clear path will escape from Enceladus. If enough gas is vented and the mean free path of the molecules is short enough that they have many collisions, a fraction of them will be scattered to the surface and freeze. Possible locations for such frost are most favorable away from the stronger thermal anomalies. It was noted by Brown, et al. [1] that the frost deposits may not be permanent and that an active replenishment processes may be necessary. By way of comparison, studies of CO_2 frost on Iapetus suggest that migration can be significant [13].

Gas Pockets Compared with Plume Chambers: Both of these features lie below the icy surface. The plumes are contiuously erupting whereas the venting of gas pockets is suggested to be an intermitant or episodic phenomenon. The pockets vent CO_2 gas whereas the plume gas is 90% water vapor. The plumes also have entrained aerosols containing NaCl and other species characteristic of sea water.

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