CO_2 VENTING AND ICE FORMATION ON ENCELADUS' SURFACE. D. L. Matson[1], A. G. Davies[1], J. Ph. Combe[2], T. B. McCord[2], T. V. Johnson[1], J. C. Castillo-Rogez[1], and J. I. Lunine[3]. [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena CA 91101, dmatson@jpl.nasa.gov, [2] Bear Fight Institute, Winthrop, WA, [3]Department of Astronomy, Cornell University, Ithaca, NY 14853.

Traces of CO_2 ice were "…found in small amounts globally and in higher concentrations near Enceladus' south polar regions…." (Brown et al., 2006 p. 1427 [1]). Brown et al. noted that CO_2 ice sublimes and that over the long term the deposits would not last. Replenishment is necessary. Thus, these CO_2 deposits are indications of recent gas venting. However the puzzle is where did pure CO_2 ice come from? We explore the possibility that the CO_2 comes from pockets of gas below the ice. These pockets may be a natural consequence of the circulation of Enceladus' gas-rich ocean water. If so, then it is possible to infer the life cycle of a gas pocket.

The CO_2 ice can be identified by the wavelength of the center of its distinctive absorption band and recently such deposits on Enceladus have been mapped [2, 3].

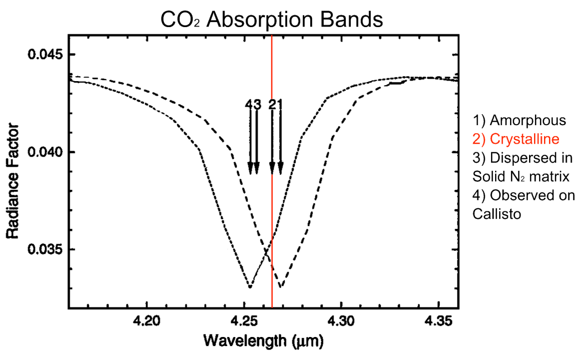

Fig. 1. CO_2 crystaline ice is identified by its absorption band center. Figure is from [2, 3].

Ocean Water Circulation Hypothesis: We explain the CO_2 ice deposits in the context of the *Ocean Water Circulation Hypothesis* as illustrated in Fig. 2 [4]. At the bottom of the figure is the subsurface ocean. It underlays much of the South Polar Region. The ocean is assumed to lie below 10 km of crust. 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.

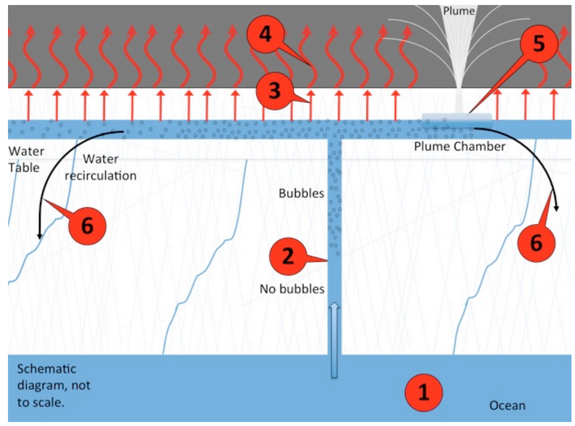

Fig. 2. A sketch illustrating the ocean water circulation hypothesis [4]. Water rises from the subsurface ocean and in some places flows just below the surface ice cap. The water supplies plume chambers with all necessary materials to support the eruptions and transfers heat to near-surface ice. The energy is conducted through the ice and radiates to space. The water returns to the ocean via fissures in the icy crust. The circulation is pressure driven. Pressures are published in [4].

Near the surface the water flows beneath a protective ice cap and spreads out laterally below the thermal anomalies. 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 ocean itself is warm (~0 °C) [4] and must have a source of heat or it will freeze on a time scale of ~30 million years [5].

Gas Pockets: The South Polar Region is criss-crossed by many scars, faults or fissures giving it a "fractured" and "disturbed" appearance. This suggests that cracks and other imperfections continue through the relative thin cap ice and also shape the bottom topography of the interface with the near-surface water. 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.

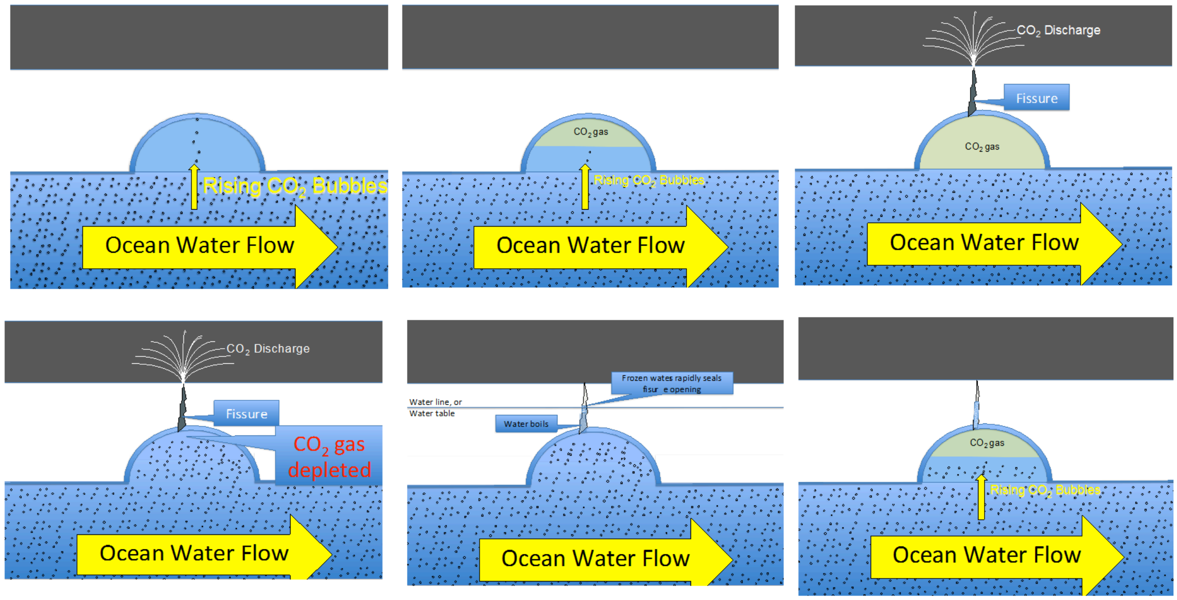

Fig. 3. Cartoon strip illustrating the life-cycle of an Enceladus gas pocket.

The above cartoon strip (Fig. 3) depicts a hypothetical life-cycle of a gas pocket. Once circulation starts, bubble-rich water flows below the ice cap. In the first frame some bubbles are shown as making their way into the protected recess. Gradually the ulage of the recess is filled by pressurized CO_2 gas.

The South Polar Region is continually being stressed by regular gravitational tides and sometimes these produce fissures in the ice cap [6]. Such an occurrence is indicated in the third frame by the dark gray rupture symbol. This opening enables the pressurized gas to escape to space. By the time of the fourth frame all of the CO_2 gas has escaped and seawater enters the fissure and proceeds up to the level of the water table. Under vacuum conditions, seawater boils and some of it freezes. This processe was studied by Cassen et al. [7]. Eventually an impermeable plug is formed and the recess is sealed-off from the vacuum of space, as shown in the fifth frame. In the last frame the cycle is starting again.

When the vented gas reaches the surface its speed and direction are unknown. The formation of a frost depends upon the amount of CO_2 released and the transient density of the gas cloud above the surface. Faster molecules that have a clear path will escape Enceladus. If enough gas is vented and the mean free path of the molecules is short enough that they have many collisions, many of them will be scattered to the surface and freeze. Locations for such frost are more favorable away from the stronger thermal anomalies. As was noted by Brown, et al. [1] the frost deposits were not likely to be permanent and comparison with studies of CO_2 frost on Iapetus indicate that migration can be significant [13].

Gas Pockets Compared with Plume Chambers: Both of these features lie below the icy surface. The plumes are continuously erupting whereas the venting of gas pockets is suggested to be an intermittent or episodic phenomenon. The pockets vent pressurized CO_2 gas whereas the plume gas is 90% low pressure water vapor. The plumes also have entrained aerosols containing NaCl and other species characteristic of sea water [8,9].

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References: [1] Brown R. H. et al. (2006) Science 311, 1425-1428. [2] Combe J. Ph. et al. (2013) EOS AGU Fall Mtg. Abstract P53B-1862. [3] McCord T. B. et al. McCord T. B. et al. (1997) Science 278, 271-275; McCord et al. (1998) JGR 103 8603-8626. [4] Matson D. L. et al. (2012) Icarus 221, 53–62. [5] Roberts J. H. and Nimmo F. (2008) Icarus 194, 675-689. [6] Hurford T. A. et al. (2007) Nature 447, 292-294. [7] Cassen, P. et al. (1979) GRL 6, 731–734. [8] Postberg F. et al. (2009) Nature 459, 1098-1101. [9] Schmidt J. et al. (2008) Nature 451, 685-688.