SUPPRESSION OF PENITENTE FORMATION AT TEMPERATURES AND PRESSURES ABOVE THE SUBLIMATION CURVE. L. Backman1, J. Foster2, D. Berisford2, T. A. Nordheim3, and K. P. Hand2, 1University of Virginia, Charlottesville, VA, lb2ty@virginia.edu, 2Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, Kevin.P.Hand@jpl.nasa.gov

Introduction: The formation of penitentes [1], or similar bladed ice structures, has been reported on Mars [2], Callisto [3], and Pluto [4]. Such features have been speculated for Europa [5], but as Hand et al. [6] have shown, these morphologies are unlikely to form on airless bodies where efficient sublimation yields large mean free paths instead of differential sublimation in an atmosphere dominated by fluid flow. The interest in the surface morphologies and geology of ice-covered ocean worlds provides a clear need to elucidate the factors that drive ice morphologies on the variety of icy worlds in our solar system.

Penitente formation is, in part, dependent on sublimation rates [5][7], which are in turn dependent on the equilibrium vapor density. Given the noon-time equator temperature on Europa of ~130K, Hobley et al [5] note that their calculations result in a sublimation rate that was six to nine times larger than previously calculated [8], and significant enough to promote the formation of penitentes. Their model calculates a slightly higher equilibrium pressure at 130K based on a fit to experimental data, relative to that predicted by Feistel and Wagner’s thermodynamic model [9]. However, a large scatter is noted [10] in the experimental data available for the equilibrium vapor pressure below 140K.

Bergeron and coworkers [11] found that penitente formation was suppressed at Earth ambient pressure and temperatures of -35°C (238K) and below. They hypothesized that the air near the ice was saturated with water vapor ($P_{vap}^{238K} \approx 20Pa$), reducing the driving force for sublimation. However, the hypothesis that penitente formation would be suppressed at conditions above the equilibrium sublimation pressure was not explored further in that work. In addition, the sensitivity of penitente formation on this pressure differential is not known. For a given temperature, how large does this pressure differential need to be to suppress penitente formation, and is this requisite differential larger than the uncertainty in the currently known sublimation curve?

The exploration of the dependence of penitente formation on pressure and temperature, relative to the sublimation curve for water, is therefore warranted. The work presented here seeks to provide preliminary experimental results to fill this knowledge gap and to probe the hypothesis that penitente formation is suppressed at pressures above the equilibrium vapor pressure.

Methodology: A variable temperature and pressure ice and solar irradiance testbed [12] in JPL’s Ocean Worlds Lab (http://oceanworldslab.jpl.nasa.gov) was used to expose bulk ice to temperatures from 250-268K and pressures close to the sublimation curve (a few torr). The chamber was filled with deionized water to a height of approximately 5 cm for each experiment. The water was degassed prior to freezing by using a roughing to evacuate the chamber for one minute. The chamber was then backfilled with ambient air. A recirculating fluid chiller was then used to cool and maintain the chamber at the desired temperature. The chiller set-point was estimated based on previously determined temperature gradients that would exist after the start of illumination. The roughing pump was used to evacuate and maintain the chamber at, or close to, the sublimation pressure. Pressures higher than the equilibrium vapor pressure were achieved by using a needle valve to allow a controlled leak of pure dry nitrogen gas into the chamber. Deviations from the target pressure during the elevated pressure experiments ranged from 0.003 to 0.03 torr.

Once the test temperature and pressure was reached, an 80W halogen lamp was positioned 30 cm above the surface of the ice. A vertical thermocouple array was used to monitor temperature gradients in the ice from the surface to the floor of the chamber. The temperature, pressure, and morphology of the ice were measured over several days, and tests were terminated before illumination-driven sublimation excavated to the bottom of the chamber. At the end of each test, the chamber was backfilled, opened, and direct examination of the resultant ice morphology was conducted.

Results and Discussion: Figure 1 plots the results from five experiments, each of which was conducted with temperature and pressure conditions on or above the vapor-pressure curve.

Two main morphological features were noted in the ice during and after the test. First, we noted the formation of micropenitentes at conditions that coincided with the sublimation curve, which is consistent with those described and documented by Bergeron et al [11]. Second, the area of illumination in all cases underwent excavation such that a bowl shaped depression was observed.

A clear trend is observed wherein temperature and pressure conditions at the sublimation curve result in micropenitentes, whereas conditions away from the sublimation curve result in only excavation. Figure 2 summarizes the ice morphology under conditions, with respect to the sublimation curve [10].
Figure 1: Observations of ice morphology at the temperatures and pressures tested. The dotted line indicates the constant pressure (4 torr) set of tests.

Penitente formation appears to be suppressed at 258K and 2 torr, where the differential is less than one torr ($P_{\text{vap}}^{258K} \approx 1.2$torr). At 268K and 4 torr, the pressure is very slightly above the sublimation pressure. Qualitatively, the micropenitentes formed under these conditions were smaller and spaced farther apart than those formed under conditions along the sublimation curve. As growth of penitentes are, in part, a function of sublimation rate and the vapor pressure differential from the equilibrium sublimation pressure, this is likely indicative of a reduction in driving force for sublimation. However, further experimental design updates, such as measurement of penitente height as a function of exposure time, would be needed to draw quantitative conclusions.

Conclusions: In this work, bulk ice was maintained under conditions at and above the vapor-pressure curve while exposed to irradiance from a static halogen lamp, used to simulate the solar flux. Our experimental evidence to date supports the hypothesis that penitente formation is suppressed at temperature and pressure conditions above the sublimation curve. This effect was noted even for pressure differential of less than one torr, which underscores the need to further examine the conditions under which surface ice morphologies change as a function of temperature, pressure, and irradiance.

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References: