A NEW HYPOTHESIS FOR THE ORIGIN OF MASS MOVEMENTS ON CALLISTO.

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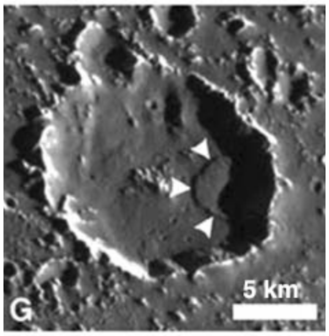

Fig. 1 - Lobate mass movement deposit on the floor of 15 km diameter crater on Callisto. [3]

Introduction: Callisto exhibits discrete mass movements that are larger and apparently more common than seen on other icy Galilean satellites (Fig. 1), as well as the most degraded surface [1,2]. While impact erosion and regolith formation are expected to operate with similar vigor on Callisto as on Ganymede, most of the areas observed at high resolution on Callisto have an appearance that implies that some additional process is at work, most likely sublimation-driven landform modification and mass wasting [1-3]. Moore *et al.* [1999] concluded that the extent of surface degradation indicates an ice more volatile than H_2O is probably involved; the most likely candidate being CO_2. Two mechanisms have been proposed - undermining/ oversteepening of slopes by sublimation erosion and seismic triggering - which may work together to trigger the mass movements [1-3].

Here we propose a different mechanism, whereby slope instability is created by *condensation* of CO_2 ice that gradually accumulates in the near-surface pore space on the coldest interior walls of impact craters. The source of this ice is a CO_2 vapor flux driven upward by the geothermal gradient through a porous megaregolith containing some fraction of CO_2 ice at depth. Based on previous theoretical work related to deep ground ice on Mars, we believe that this deep CO_2 ice would have developed a particular vertical distribution that we refer to as Steady-State Pore (SSP) ice.

Steady-State Pore Ice: SSP ice can be maintained in dynamic equilibrium anywhere that has the following attributes:

- A porous, permeable regolith,
- A reservoir of volatile condensate (ice or liquid) within or just beneath the regolith,
- A temperature gradient, and
- A surface where the ice is *not* thermally stable on a regional (>10 km) scale

The idea of SSP ice was first suggested in the planetary science literature by Clifford (1993) [4] in his comprehensive study of the subsurface hydrology of Mars. But the first explicit modeling and theoretical analysis of this phenomenon was presented in Mellon et al. (1997) [5]. They showed that in times or places where ground ice is undergoing long-term sublimation and diffusive loss, the ice table (the shallowest depth where any pore ice exists) will not continue to recede indefinitely to greater depths. While a geothermal temperature gradient will continue to drive vapor upward toward the surface, beyond a certain point it will

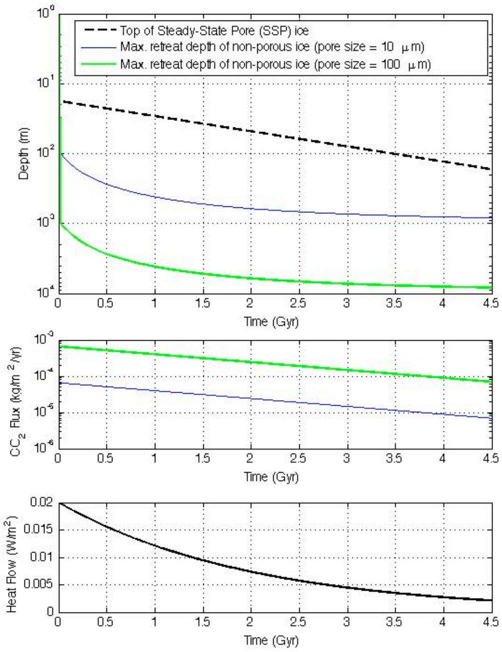

Fig. 2 - Possible evolution of subsurface CO_2 ice on Callisto assuming an initial CO_2 ice volume fraction of 10% and two different values of the CO_2-ice-free pore size. A non-porous CO_2 ice table would quickly retreat from its assumed initial depth of 1m to below z_{SSP0}, the SSP ice table (dotted line), after which its maximum retreat rate is controlled by conditions at z_{SSP0}. The depth of z_{SSP0} also increases with time due to a declining interior heat flux (assumed function shown in lower plot). At any given time, the CO_2 ice fraction increases with depth from zero just above z_{SSP0} to higher values below. We note that the CO_2 vapor flux predicted for the present day is close to the estimated minimum value of 1E-7 $kg/m^2/yr$ required to maintain Callisto's observed CO_2 atmosphere [6]

recondense at shallower colder depths, and persist in the regolith as interstitial ice partially filling the pore space as long as a source of vapor remains below. Once this occurs, a steady-state profile of ice volume fraction develops, with net mass loss only occurring from the base of the porous ice layer.

One of the reasons that SSP ice is important and useful is that as soon as this profile starts to develop it determines, and keeps constant, the loss rate of volatiles beneath it. The vapor flux at any depth with ice present can be written as

$$F_v = D_{eff} * d/dT(\rho_{v,eq}(T)) * dT/dz ,$$

where $\rho_{v,eq}(T)$ is the equilibrium vapor density. All else being equal, the middle term would cause the flux to increase with depth. But this would lead to secular ice accumulation in the pores as the flux from below each point exceeds the flux above so the pores become increasingly constricted, reducing D_{eff}. This self-regulating mechanism (negative feedback) enables the SSP profile to maintain a constant vapor flux throughout its depth with an ice content that increases gradually downward but remains constant in time as long as vapor is supplied from below. The value of F_v is therefore completely determined by the heat flow and the properties of the regolith at $z_{SSP,0}$, which is typically within meters of the surface. Using estimated values for Callisto's heat flow [ref] and near-surface pore size, our calculated F_v values are shown in **Fig. 2**.

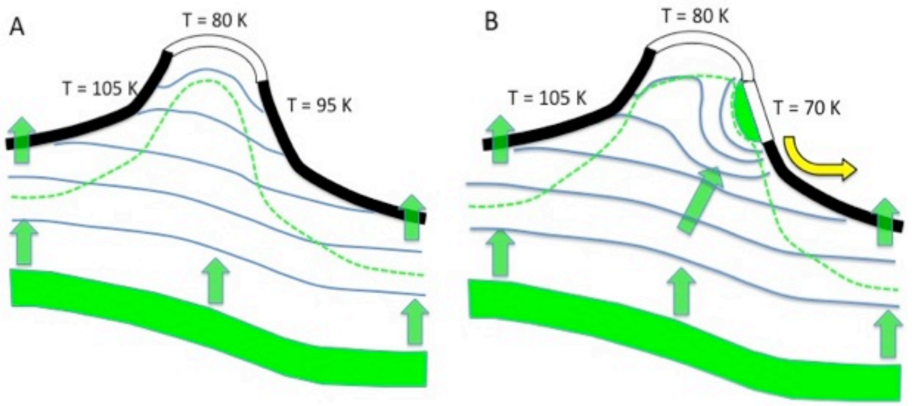

Fig. 3 - Hypothetical evolutionary scenario for landslide due to localized accumulation of near-surface CO_2 ice on the interior rim of an impact crater. Black marks surfaces covered with dark dust (white for frost) and labels indicate local diurnal average surface temperatures (T_{avg}). Blue contour lines are subsurface isotherms and dashed green line is the SSP CO_2 ice table. Green fill represents regions with high volume fractions of CO_2 ice, and green arrows represent CO_2 vapor flux, with length proportional to magnitude. Yellow arrow in panel B represents landslide path.

(A) Bright frost forms on top of crater rim (as observed in Galileo images, see Fig. 1), lowering T_{avg} and raising SSP ice table. Interior walls of crater rim are cooler than exterior due to more shadowing of adjacent surfaces (see **Fig. 4**). Also, steeper slopes can shed dust lag and expose high thermal inertia water ice "bedrock".

(B) Water frost can accumulate on most-frequently shadowed walls, raising albedo and lowering T_{avg}. Temperatures ≤75K, the CO_2 frost-point temperature corresponding to observed atmospheric CO_2 density [6], permit growth of stable near-surface CO_2 ice fed by vapor flux from below. Local compression of isotherms can also focus increased vapor flux to these locations. Gradual build-up of relatively dense (1.6 g/cc) near-surface CO_2 ice in pore space on steep slope eventually leads to landslide.

Implications of Surface Perturbation to SSP Ice: The behavior and required conditions for SSP Ice just described may apply regionally on Callisto, but small-scale local perturbations in surface temperature could have significant effects on landscape evolution, as described in **Fig. 3**. Further details and relevant model calculations will be presented.

References: [1] Moore et al. (1999), *Icarus, 140*, 294-312. [2] Chuang and Greeley (2000), *JGR, 105*, 20227-44. [3] Moore et al. (2004), Callisto, in Jupiter: The Planet, Satellites and Magnetosphere, ed. Bagenal et al., pp.397–426. [4] Clifford (1993), *JGR, 98*, 10973-11016. [5] Mellon et al. (1997), *JGR, 102*, 19357-69. [6] Carlson (1999), *Science 283*, 820. [7] Wood et al. (2007), Workshop on Ices, Oceans, and Fire: Sats. of the Outer S.S., LPI contrib. no. 1357, 151-152.

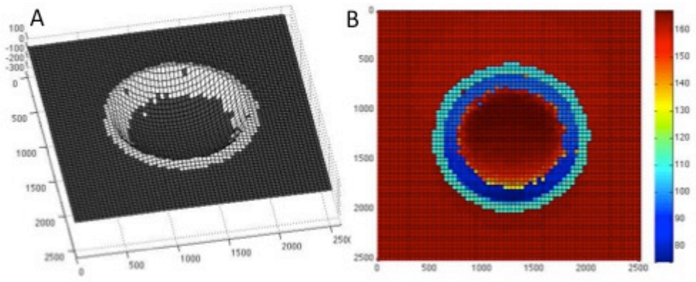

Fig. 4 – Supporting results from our 3-D Topographic Radiative Thermal Model [7] for Callistan crater at 20°N. (A) Assumed albedo map with dark gray (dust mantled) areas at 20% and white (frosty) areas at 80%. (B) Model-calculated diurnal max. temperatures. Interior slopes have T_{max} = 75-95K and exterior slopes have T_{max} = 106-113K.