DOME CRATERS ON GANYMEDE AND CALLISTO MAY FORM BY TOPOGRAPHIC RELAXATION OF PIT CRATERS AIDED BY REMNANT IMPACT HEAT. M. Caussi[1], A. J. Dombard[1], and D. G. Korycansky[2] [1]Dept. of Earth and Environmental Sciences, Univ. of Illinois at Chicago, Chicago, IL 60607 (mcauss2@uic.edu), [2]Dept. of Earth and Planetary Sciences, Univ. of California, Santa Cruz, CA 95064.

Introduction: The icy Galilean satellites host a variety of large impact features that are rare on other planetary and satellite surfaces in the Solar System. For Ganymede and Callisto, these features include impact basins with central pits and domes [1].Large complex craters on these two moons possess a central pit in place of central peaks seen elsewhere, and at larger crater sizes, these central pits host a dome (Fig. 1). The emergence of central dome craters occurs at diameters greater than ~60 km, which is also the approximate diameter at which central pit craters cease to occur [1]. It has been suggested [2, 3] that there could be a relationship between pit craters and dome craters. Understanding how these features formed can clarify our picture of outer-planet satellite evolution, and here, we focus on the formation of the central dome.

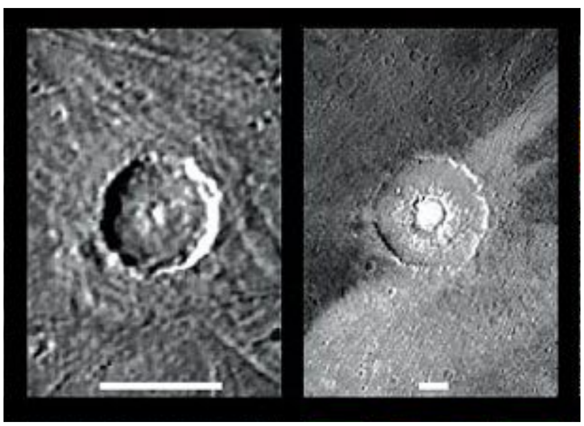

Figure 1: Central pit crater (left).Central dome crater (right). Scale bar: 30 km [4].

Several models for dome origin were developed after Voyager, including refrozen impact melt, post-impact intrusion, and uplift during impact. Following the acquisition of Galileo's higher resolution observations, the melt and intrusion hypotheses became less likely as no indications of flooding or fractures were found, which favors an origin by uplift[1].

Here, we explore whether central uplift could occur by topographic relaxation of an initial central pit, evolving a central pit crater to a central dome crater over longer, post-impact time scales. The mechanism of topographic relaxation has been used to explain the extreme uplift of some central peak craters on Saturn's moon Dione [5], in which a thermal anomaly in the center of the crater, left over from the impact, can enhance the creeping flow of ice and uplift the center of the crater on which the central peak lies. A similar mechanism thus could explain central dome craters.

Methods: The viscoelastic relaxation of a 100-km-diameter pit crater on Ganymede is investigated using the finite element method. These simulations are conducted using the commercially available Marc package, which we have used previously to explore crater relaxation on these moons [e.g.,6]. We simulate the evolution of a pit crater over 100 Myr. First, a thermal simulation that tracks the diffusion of the impact heat is performed. The results of the thermal simulation are then mapped into a mechanical simulation that solves the long-term evolution of the topography.

Crater shape. For the initial crater shape (black line in Fig. 2), we scale typical dimensions [2] of central pit craters to this larger crater diameter. The pit is modeled as an inverted truncated cone. The shape of the main crater depression is a 4th order polynomial, while the crater-rim and the pit-rim are modeled following an inverse 3rd power law [6].

Temperature structure. A thermal simulation is performed first, to determine the subsurface temperature evolution over 100 Myr as the remnant heat from the impact diffuses conductively over time. We start our simulations at the final solidification of any impact melt. The temperature field at each moment in time strongly determines the viscosity and hence the rate of relaxation. The dimensions and magnitudes of the impact-induced thermal anomaly are adapted from hydrocode simulations [7]. The thermal-anomaly maximum temperature is 270 K, located at the center of the crater, very near the surface. The excess temperatures decrease radially and with depth from the maximum value. A background heat flux is applied to the elements at the base of the mesh, with values expected at present (3 mW m^{-2}) and earlier in Solar System history (10 mW m^{-2}). The elements on the sides of the mesh are set to zero heat flux, and the surface temperature is fixed at 120 K. We apply a thermal conductivity of ice that follows an inversely proportional relationship with temperature [e.g., 6].

Viscoelastic relaxation. A mechanical simulation is next performed using the results from the thermal simulation. For the mechanical simulation, motions on the side and bottom boundaries are restricted to free-slip. A uniform gravity load is applied to all elements in the mesh, corresponding to Ganymede's gravitational acceleration of 1.44 ms^{-2}. This load, combined with a mass density corresponding to ice, provides the gravitational force that generates the deviatoric stresses driving relaxation. For the viscoelastic rheology, we use linear, isotropic elasticity with a Young's modulus of 9.33 GPa and a nominal Poisson's ratio of 0.33. Because of the long time scales, viscous flow is considered to be solely due to steady state creep [8] assuming a grain size of 1 mm.

Results and Discussion: Crater topography constitutes a perturbation in the near-surface, deviatoric stress state of the area. To relax the induced stresses and restore a flat surface, ice flows downward from the rim and upward from the crater depression and the pit over long timescales. Because viscosity decreases with increasing temperature, viscoelastic relaxation is enhanced if ice is warm [cf. 6]. Hence, both the heat left over from the impact and the background heat flux aid relaxation.

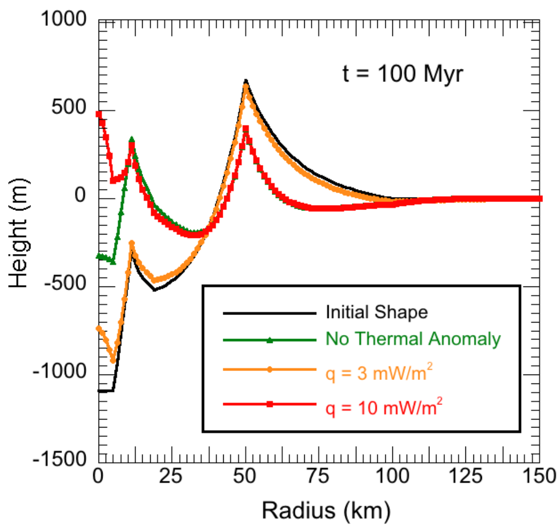

Figure 2: Topographic profiles of relaxing craters under low heat flux (3 mWm^{-2}) and high heat flux (10 mWm^{-2}) are shown in orange and red respectively. If a dome is created, then it forms early, before the thermal anomaly has dissipated. The topographic profile of a relaxing crater under high heat flow with no remnant impact heat is also shown in green. The initial crater shape is shown in black.

High heat flux cases (10 mW m^{-2}). The simulation results show that a central dome is formed within 100 Myr when the background heat flux is high and heat left over from impact is applied (red line in Fig.2). The thermal anomaly softens the ice below the pit, enhancing its upward flow as compared to the rest of the crater depression. Contrastingly, when no remnant impact heat is applied (green line in Fig. 2), there is an overall uplift of the crater depression but a dome does not form, indicating there is no preferential uplift of the material below the pit. The relatively small scale pit largely rides along with the relaxing basin.

Low heat flux case (3 mW m^{-2}). If the ice surrounding the thermal anomaly is stiff, such as when temperatures increase slowly with depth under lower heat flow conditions, the impact-heated ice cannot uplift as easily. When the background heat flux is low, the material in the vicinity of the anomaly is not soft enough to accommodate the enhanced uplift of the pit floor, and the anomaly dissipates while only forming a small dome. Simulation results (yellow line in Fig. 2) show there is a modest up-bowing of the pit floor, but not as pronounced as in the higher heat flow case. Thus, the morphology of dome craters might be used as a discriminator of background heat flow at the time of impact. Notably, pit craters of the 100-km scale may always relax a central dome, even under the lower modern heat flux.

Indeed, because of the interplay of heat flux with remnant heat, larger craters like the size explored here should be more prone to dome formation than smaller craters. Additional simulations will explore smaller sizes, particularly around the transition diameter between the observed central pit and central dome craters (~60 km). Furthermore, hydrocode simulations will also be performed to constrain better the thermal anomaly for craters on Ganymede and Callisto, as well as explore why craters on these moons form central pits in the first place, instead of central peaks.

Conclusions: This model for dome formation could potentially solve one of the long-standing problems regarding large impact features on Ganymede and Callisto. Given that this model for dome formation occurs over a long timescale and is heat flux dependent, it could also be used to constrain the thermal histories of these moons.

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