LARGE SHALLOW CRATERS ON CALLISTO AND GANYMEDE AS AN INEVITABLE RESULT OF VISCOUS RELAXATION. M. T. Bland[1] and V. J. Bray[2], [1]U. S. Geological Survey, Astrogeology Science Center, Flagstaff AZ (mbland@usgs.gov), [2]Lunar and Planetary Laboratory, University of Arizona, Tucson AZ.

Crater depths on Callisto and Ganymede: Impact craters on Callisto and Ganymede with diameters (D) >40 km have shallower depths (d) than predicted by simply extrapolating the d-D trend from smaller complex craters [1] (Fig. 1). [1] attributed the shallow depths (and changes in crater morphology) to structural layering within the ice shell, including the influence of an ocean. Subsequent numerical simulations of impacts into icy bodies have reproduced the shallow depths by imposing a temperature gradient (which results in a strength gradient) in the ice shell [2, 3, 4]. Those simulations require heat fluxes (F) of 35-70 mW m^{-2} to match observed crater depths [2, 4], which exceed the radiogenic heat flux for both Ganymede and Callisto (e.g., [5] and discussed below). Whereas ample evidence exists for elevated heat flow in Ganymede's ancient past, the lack of present-day tidal heating implies current heat flows are now much lower. Callisto, which effectively lacks tectonic deformation [6] and may be undifferentiated [7], likely never experienced heat fluxes in excess of radiogenic ($25 \geq F \geq 3$ mW m^{-2}). Thus, Callisto's lithosphere has been cold over most of its history and impact craters formed in the last ~2 Gyrs should have formed deep crater cavities [2,4]. Here we suggest an alternative explanation for the shallow depths of craters with D > 40 km on Callisto and Ganymede: viscous relaxation under radiogenic heating.

Modeling Viscous Relaxation: Viscous relaxation is the process by which non-hydrostatic stresses induced by impact crater topography drive viscous flow that reduces that topography over time. The resulting craters have preserved rims but reduced depth or even up-bowed floors [8]. We forward model the viscous relaxation of impact craters on Callisto and Ganymede using the finite element code Tekton [9], which solves the non-Newtonian viscoelastic constitutive equations for both stress and displacement on a deforming grid of nodes. For simplicity we assume conditions most-relevant to Callisto (surface gravity of 1.24 m s^{-2}, and above radiogenic flux) but the insight applies equally well to Ganymede. We use the rheological parameters for water ice of [10] and optionally account for rock-ice mixtures (especially relevant for Callisto) by increasing the ice viscosity by 100x [11, 12]. The rheology of water ice is a strong function of temperature, and we therefore investigate surface temperatures (T_s) ranging from 130 K (the maximum diurnally averaged temperature at Callisto's equator) to 100 K. We find that below 100 K minimal viscous relaxation occurs for the heat fluxes evaluated. We assume a temperature dependent thermal conductivity for pure water ice and a time dependent radiogenic heat flux (values above). We investigate relaxation for crater ages of 500 Myrs to 4 Gyrs - older craters experience both higher fluxes and have had longer to relax. Here we assume a standard crater shape that does not include a central structure (we are currently investigating how such structures are modified by relaxation) and investigate craters with diameters ranging from 10 to 100 km. We assume the initial depth of each crater by extrapolating the d-D trend from complex craters with D < 20 km to larger D (Fig. 1).

Results: Viscous relaxation under radiogenic heat flow occurs rapidly for craters with $D \geq 60$ km on Callisto and Ganymede (as already demonstrated by [13]). The depths of our simulated craters are consistent with those measured by [1] (Fig. 1). Thus, the observed present-day depth of craters on Callisto and Ganymede may be a natural consequence of craters forming deep and then relaxing to their present shallower depth over 500 Myrs to 3 Gyrs.

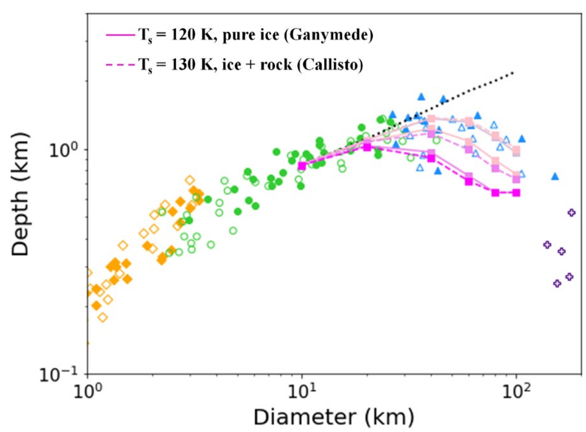

Fig. 1: Comparison of measured and simulated crater depths on Callisto (filled) and Ganymede (open) Simulated craters were initialized with depths extrapolated from the d-D curve for complex craters (dotted black line). Orange diamonds = simple, green circles = complex, blue triangles = central pit/dome, purple crosses = anomalous dome craters. The pink curves (square symbols) are simulated crater depths for crater ages of 500 Ma (lightest) to 3 Gyrs (darkest) and for pure ice at 120 K (solid lines - Ganymede's equator) and ice-rock mixture at 130 K (dashed line – Callisto's equator).

The results shown in Fig. 1 hold for equatorial and mid-latitudes on each body (~70% of the surface). For colder T_s, viscous relaxation is substantially reduced. Figure 2 shows the fractional change in d of 1-Gyr old impact craters (relative to their initial d) for different T_s and pure water ice. At $T_s \leq 110$ K, only craters with $D \geq 80$ km are significantly viscously relaxed. Near the poles (100 K) essentially no relaxation occurs.

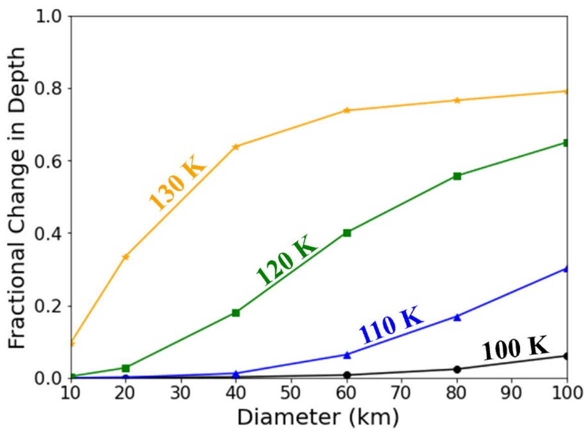

Fig. 2: The fractional change in the rim-to-floor depth (relative to initial depth) of 1-Gyr old craters on Callisto. Curves are for the T_s indicated.

The effect of initial crater depth. Viscous relaxation is driven by topographically generated stresses. Deeper initial craters induce larger stresses and therefore experience more rapid relaxation. We tested whether substantial relaxation occurs if we assume the craters formed at the depths observed by [1] and modelled by [2, 4]. In that scenario, we find that craters with $D \geq 60$ km would have present-day depths that are much shallower than is observed. Furthermore, given that the models of [2, 4] require heat fluxes well in excess of radiogenic to explain Callisto and Ganymede's craters, viscous relaxation would be further enhanced and present-day crater depths even shallower.

The effect of particulates in the ice shell. Much of Callisto's surface is covered by a dark lag, suggesting a significant fraction of non-ice material in the near surface. Rock-ice mixtures have viscosities 10-100x higher than pure water ice [11, 14]. To assess viscous relaxation in a mixed ice-rock layer, we repeated our simulations but assumed a viscosity 100x that of pure water ice [e.g., 12]. We find that for a T_s of 130 K (Callisto's equator) the resulting depths are an excellent match to observations (dashed curves in Fig. 1). That is, not only does viscous relaxation still occur when an ice-rock mixture is assumed, such a layer is actually required to match the observed crater depths. Otherwise, crater depths become too shallow.

Testable Predictions: Our results predict that craters with $D \geq 60$ km at Callisto's high latitudes should be deeper than similarly sized craters at lower latitudes. A comprehensive assessment of crater depths on Callisto has not yet been published and the available topographic data are sparse [but see 15]. Data returned by the JUICE and Europa Clipper missions may permit a more robust test of this prediction. More data are available for Ganymede, but that moon's high-latitude craters have been modified by viscous relaxation under high heat flow [16] so the potential latitudinal pattern has been lost. If crater depths on Callisto are uniform with latitude, then the viscosity of the lithosphere must be high – implying that either the rock-ice fraction in the upper few kilometers exceeds 50% or else grain boundary sliding is completely inhibited [17]. The latter possibility is challenged by Ganymede, where substantial viscous relaxation is observed [5, 16].

We also predict that recently formed craters (aged > 500 Myrs) should be very deep; however, such craters are rare on these moons. Using the cratering rates of [18] we expect only 3-4 craters with $80 \leq D \leq 100$ km to have formed in the last 500 Myrs, and it is plausible that those craters simply are not in the sample of [1], which only includes ~5 craters in this size range for Callisto and Ganymede combined.

Conclusion: The depth-diameter trends for craters with $D > 30$ km observed on Callisto and Ganymede can be explained by assuming the craters formed deep cavities (consistent with extrapolating the *d-D* curve from smaller complex craters) and have viscously relaxed under radiogenic heat flow over time.

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