CONVECTION IN CALLISTO'S ICE SHELL: IMPLICATIONS FOR DIFFERENTIATION.

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Introduction: Of the four Galilean moons, Callisto's interior seems to be the least constrained. The state of the body's differentiation is not well understood [1–3], but there is strong evidence that Callisto, like Europa and Ganymede, has a subsurface ocean beneath an icy shell [4]. Correct interior models of these ocean worlds help to construct accurate thermal models which aid in elucidating longevity of oceans and their potential habitability. For the case of Callisto, the state of differentiation beneath the ocean is needed to create such a model. Another important factor for thermal models of ocean worlds is how heat travels through the overlying ice shell. That is, will a layer of ice shell above the ocean be convective, or will the shell be purely conductive?

[5] proposed that a non-Newtonian rheology (i.e., grain boundary sliding (GBS) and dislocation creep) in Callisto's ice shell would cause it to be stable against convection. Later, [6] proposed that Newtonian flow laws (i.e., diffusion creep, which is theoretical in ice) would allow convection to occur. [6] also used updated rheologic values to argue that GBS (the more dominant of the non-Newtonian deformation mechanisms) would allow convection to occur, which was supported by [7] who focused on non-Newtonian flow. The low fraction of impurities possibly within Callisto's ice shell was taken to be negligible in these models [5–7], however, after these studies, an experimental laboratory study found that at a silicate impurity fraction of ≥6%, ice behaves much more rigidly than previously thought [8]. Specifically, the deformation mechanism GBS is effectively made inoperable at silicate contents beyond this threshold. This new rheology has not been applied to Callisto's ice shell and may determine whether or not convection is possible.

The compositional structure of Callisto's ice shell (and therefore, its rheology) is likely a consequence of the mechanism of differentiation. [6] proposed that if Callisto differentiated without melting water ice (hereafter, cold differentiation), impurities likely would not fully separate and form a "dirty" ice shell, but if the ice melted during differentiation (hereafter, warm differentiation), impurities would have completely separated forming a "clean" ice shell. Another shell formation theory that has been proposed for other icy bodies is that an ocean formed (via warm differentiation) but then froze top-down with impurities [9] (hereafter, warm differentiation with impure freezing). In this scenario, impurities would both be trapped in freezing ice and fall back to the liquid water below, making the ocean more impurity rich through time and the shell more impurity rich with depth, also yielding a "dirty" ice shell. It is possible that if Callisto has a "dirty" ice shell, this new, more rigid rheology would make it stable against convection. This state would mean that the heat flow through Callisto's ice shell (and other icy bodies) may depend on how the body differentiated.

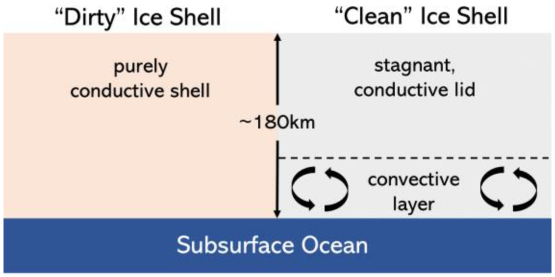

Figure 1: *Diagram of our scenarios. Left: Callisto underwent either cold differentiation or warm differentiation with freezing impurities and resists convection in a "dirty" ice shell. Right: warm differentiation occurred and a "clean" ice shell is able to convect.*

Dirty Ice Shell Structure: To apply the rheology proposed by [8], Callisto's ice shell would need to contain ≥6% silicates by volume. Taking a hydrated silicate and ice density of 2500 kg/m^3 and 917 kg/m^3 respectively, a uniform mixture of 6% hydrated silicates and 94% ice yields a shell density of 1012 kg/m^3 (Fig. 1). While this is more dense than the typical density of liquid water (1000 kg/m^3), salts can be dissolved within the ocean that decrease freezing temperature and increase density [10]. Indeed, it was argued that a subsurface ocean on Callisto must have a salinity close to Earth's ocean (1027 kg/m^3, on average) to explain the induced magnetic field detected by the Galileo spacecraft [4]. Ammonia would decrease ocean density and has been proposed as an excellent antifreeze to ensure the longevity of oceans, but it has not been spectroscopically identified in the Galilean system as it has elsewhere in the solar system [11]. Therefore, it is gravitationally possible for Callisto to support enough silicate impurities within its ice shell to apply this new rheology.

Convection in an Ice Shell: To test if convection is possible in a "dirty" or "clean" ice shell, we computed the Rayleigh number (Ra) for each condition:

$$\mathrm{Ra} = \frac{g \alpha \rho D^3 \Delta T}{\kappa \eta}.$$

Ra is defined as the ratio of buoyancy forces to resisting forces and determines if convection will occur. We treat all parameters as constants with values taken from [6] except D, the convective layer thickness, and ρ, the density of our "dirty" ice shell scenario, which we computed to be 1012 kg/m^3. For both differentiation cases, η, the effective viscosity, is computed from power law relations and rheological values from [12], with grain sizes for GBS (dislocation creep is independent of grain size) taken from [6]. The critical Rayleigh number needed to achieve convection was taken as 1.2×10^5 [7]. Using the surface temperature, adiabatic temperature of the convective layer, and the estimated heat flow through the rigid lid above [13], the total thickness of the shell can be determined. We plot the effective viscosity against total shell thickness to determine if our calculated viscosities yield realistic thicknesses, which allow us to assess if convection is plausible for our "dirty" and "clean" cases.

Results and Discussion: We found that a "clean" ice shell favors convection. This scenario allows GBS to occur, which is the dominant deformation mechanism at the base of Callisto's shell (GBS viscosity, η_{GBS} ~10^{16} Pa·s; dislocation creep viscosity, η_{disl} ~10^{29} Pa·s). Because GBS is grain size dependent, we calculated the effective viscosity for a set of likely grain sizes and found the necessary shell thickness for each (Fig. 2). The thicknesses necessary to allow convection in a "clean" shell are reasonable for all grain sizes (between 130–200 km) and suggest that convection would occur if Callisto underwent warm differentiation without subsequent impure freezing.

However, our results show that a "dirty" ice shell would not favor convection. Dislocation creep would be the only deformation mechanism in this scenario, which is negligible in a "clean" ice shell. The necessary shell thickness to allow convection in this setting is entirely unrealistic (~1.5×10^6 km). This result implies that if Callisto's shell formed without melting all of its water ice, it may be purely conductive.

A product of convection in an ice shell is its thickness. A purely conductive shell will be thinner than a convective one as convection is a much more efficient cooling mechanism [10]. Crater morphology of the Galilean satellites suggests that Callisto and Ganymede have similarly thick ice shells compared to Europa [14], which agrees with thermal models predicting convection above the ocean. For these thermal models to be correct, our results imply the shell would need to be "clean." However, Callisto also receives less tidal energy from Jupiter than Ganymede and Europa, and it is unclear if only conduction and lack of tidal energy could explain the thickness implied by crater measurements of [14].

Conclusions: We applied a new, rigid ice rheology to Callisto's ice shell to assess how it would affect convection. We find that convection likely only occurs on Callisto if the ice shell is clean, and the icy satellite experienced warm differentiation (i.e., water ice melted and separated from the silicate material) without impurities getting trapped in the freezing shell. However, if convection is unable to occur in the ice shell, it may be a result of a cold differentiation process or an impurity content that has shut off GBS. If Callisto indeed has thick shell, it is possible that convection was favored at one point in time, however, a better understanding of the thermal evolution and shell thickness would allow a better understanding of the state of convection in Callisto's shell.

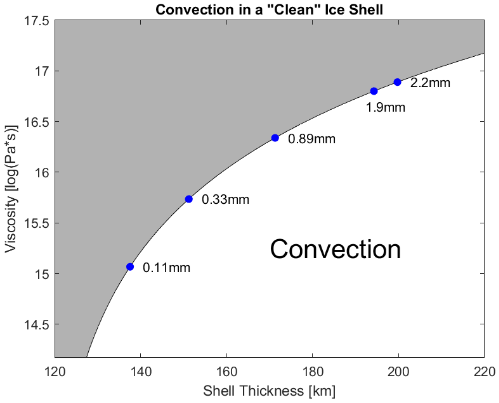

Figure 2: *Conditions necessary for convection in a "clean" ice shell. The white area is where convection will readily occur, the grey section it will not, and the black line between is where the* $Ra=1.2\times10^5$. *With GBS, the necessary shell thickness needed to induce convection is near the estimated shell thickness (~180 km) for all grain sizes, which are shown as blue dots. With the more rigid rheology (i.e., the only deformation mechanism is dislocation creep) applied, the necessary thickness to allow convection is ~*1.5×10^6 *km and is not shown on this figure due to its implausibility.*

References: [1] Anderson, J. et al. Nature 387, 264–266 (1997). [2] McKinnon, W. Icarus Notes 130, 540–543 (1997). [3] Anderson, J. et al. Icarus 153(1), 157–161 (2001). [4] Khurana et al. Nature 395, 777–780 (1998). [5] Ruiz, J. Nature 412, 409–411 (2001). [6] McKinnon, W. Icarus, 183(2), 435–450, (2006). [7] Barr, A. et al. JGR Planets 109, E12008 (2004). [8] Qi, C. et al. GRL 45(23), 12,757–12,765 (2018). [9] Castillo-Rogez, J. et al. GRL 46, 1963–1972 (2019). [10] Hussmann, H et al. Treatise of Geophys. 2, 605–635 (2015). [11] Clark, R. et al. Reviews in Min. and Geochem., 78, 399–446 (2014). [12] Durham, W. & Stern, L. Annu. Rev. Earth Planet. Sci. 29, 295–330 (2001). [13] Kuskov, O, & Kronrod, V Icarus 177(2), 550–569 (2005). [14] Schenk, P. M. Nature 417, 419–421 (2002).