PROBLEMS PERTAINING TO THE INTERNAL STRUCTURES OF GANYMEDE AND CALLISTO. William B. McKinnon, Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721.

Two of the fundamental issues concerning Ganymede and Callisto are the determination of their internal structures and the origin of grooved terrain on Ganymede. Both of these are ultimately tied to the general question of why planetary objects take the evolutionary directions they do. Ganymede and Callisto put this question into sharp focus, for it is not immediately obvious why they should diverge at all. Gas-free accretion models (1) do not naturally lead to any dichotomy between the two satellites. A silicate core (whose state of hydration is not well determined) is overlain by a mixed zone of rock and water ice, which is in turn surrounded by a nearly silicate free upper mantle of ice. Explicit inclusion of a proto-Jovian nebula may largely prevent the differentiation of Callisto (2).

One way to test these models, and others that may arise, is to use impact craters as experimental probes of the thermal and physical structure of the "crusts" and upper mantles of the two bodies. The largest craters are sensitive to structure to depths of the same order as their diameters (several hundred km). This size class commonly exhibits a tectonic signature recognized as multiple rings. It is the form and extent of these multiringed structures and their place in the cratering record that provides constraints on the interior (3,4,5,6).

The evidence points to "icy" mantles that are hot, in a homologous sense, with a colder stiffer outer layer, or lithosphere, circa 4.0 GYA. "Icy" may mean an admixture of ice and some rock, for ring systems do not determine a mantle composition and thermal structure uniquely. They are most sensitive to rheologic structure. Therefore, if either composition or temperature is known independently, then limits can be placed on the other.

The lithospheric evolution of Ganymede and Callisto may be compared. Callisto's lithosphere is seen to be thicker at an earlier time (3). This in itself is not surprising, but at least at the time of furrow formation in Galileo (and Marius) Regio on Ganymede, Callisto's lithosphere was more than 1.5-2.0 times as thick (7). The problem is that this exceeds the thickness ratio, 1.26, predicted in equilibrium with radiogenic heat production (8). This assumes that the conductivities for both lithospheres are the same. But, it is unlikely that the conductivity of an undifferentiated Callistoan lithosphere (~25% silicate by volume) sufficiently exceeds that of clean ice to account for this difference. Silicate conductivities are highly variable (9) and 2.5 Wm⁻¹K⁻¹ is typical of igneous rock at ~300 K (10). The conductivity of ice Ih is 2.25 Wm⁻¹K⁻¹ at 273 K (11) and may show a stronger increase with decreasing temperature than most silicates (12).

The simplest explanation is that Ganymede started off hotter and thus its heat flow and lithosphere thickness were not in equilibrium with radionuclide heat release. There was a component of secular cooling in the global heat budget. Complicating this situation is the possibility that an undetermined amount of tidal dissipation may be invoked for Ganymede (8). It is difficult to understand the origin of the necessary large eccentricities, however. Heat contributed by continued core and lower mantle differentiation was probably minor.
If Callisto's mantle is undifferentiated and Ganymede's is not, the two-phase mixture will be stiffer than clean ice and will convect at a higher self-regulated temperature. For a given heat flow, the lithosphere of Callisto must be thicker. The viscosity increase may be more than an order of magnitude at the same temperature if the silicates are dispersed as fine grains smaller than the average ice grain size. In this case the silicate crystals obstruct the movement of dislocations through the ice. However, the silicate grains are just as likely to be much larger. If so, the volumetric dominance of the ice for small silicate packing factors drastically mitigates the viscosity increase. An order of magnitude increase in viscosity may be counteracted by a temperature increase of \(0.05 T_M\), where \(T_M\) is the melting temperature, unless the ice grain size is small (see 15). In terms of lithosphere thickness, augmentation of the lithospheric temperature drop (\(0.2-0.4 T_M\)) by 0.05 \(T_M\) is marginally able to account for Callisto's excess.

The Callistoan heat flow may be evaluated at the time of formation of Valhalla. Estimates for surface temperature, sub-lithosphere (asthenosphere) temperature, lithosphere thickness, and average thermal conductivity are 120 \(\pm\) 10K, 0.7 \(\pm\) 0.1 \(T_M\), 15-20 km, and 4.5 \(Wm^{-1}K^{-1}\), respectively (7,11). The resulting heat flow is 0.018 \(\pm\) 0.008 \(Wm^{-2}\). The estimated chondritic heat flow at 4.0 GYA is 0.025 \(Wm^{-2}\) (8). This may be construed as a lack of evidence for any other heat source within Callisto except a radiogenic one.

While tantalizing, a conclusive case for Callisto's state of differentiation cannot yet be made. However, the multiringed systems contain additional information. The major problem there is explaining the differing tectonic elements of the various ring structures. Foremost are the differences between Valhalla and Galileo Regio. The outer rings of Valhalla are mostly outward facing scarps, interpreted as normal faults (6). The rings of Galileo Regio are entirely graben (to the limit of photographic coverage). Fault blocks may be rotated to face outward in the far field (i.e., several crater radii away) when the lithosphere is dragged over an asthenosphere that is either stagnant or flowing slowly away from the filling crater (4). Graben should be produced if the asthenosphere continues to flow weakly inward, even in the far field. Potentially, one way for this to be accomplished is for the flow to be channeled in an upper layer. Whether the plausible layering of the upper mantle of Ganymede relates to this problem is not known at present. Generally, the rotation of a lithospheric block, or lack thereof, depends on the force couple between lithosphere and asthenosphere.

The present effort is to model collapse of the transient basin cavity and ring formation using a non-Newtonian viscoelastic finite element code (16) recently modified for axial symmetry. The effects of different scales of impact, different lithospheric thicknesses and strengths, and various internal models will be explored. First results should be presented.

References