ON CONVECTION IN ICE I SHELLS OF OUTER SOLAR SYSTEM BODIES — APPLICATION TO CALLISTO AND TITAN. William B. McKinnon, Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, Saint Louis, MO 63130, mckinnon@wustl.edu.

Introduction: It has been argued that the dominant non-Newtonian creep mechanisms of water ice make the ice shell above Callisto's ocean, and by inference all radiogenically heated ice I shells in the outer solar system, stable against solid-state convective overturn [1]. Conductive heat transport and internal melting (oceans) are therefore predicted to be, or have been, widespread among midsize and larger icy satellites and Kuiper Belt objects. Alternatively, at low stresses (where non-Newtonian viscosities can be arbitrarily large), convective instabilities may arise in the diffusional creep regime for arbitrarily small temperature perturbations. For Callisto, ice viscosities are low enough that convection is expected over most of geologic time above the internal liquid layer for plausible ice grain sizes (≤ a few mm [2,3]).

The alternative for early Callisto, a conducting shell over a very deep ocean (> 400 km), is *not compatible* with Callisto's present partially differentiated state. Moreover, if convection is occurring today, the stagnant lid would be quite thick (~100 km) and compatible with the lack of active geology. Nevertheless, Callisto's steady-state heat flow may have fallen below the convective minimum for its ice I shell. In this case convection ends, the ice shell melts back at its base, and the internal ocean widens considerably. The presence of such an ocean, of order 200 km thick, is compatible with Callisto's moment-of-inertia, but its formation would have caused an ~2.5% radial expansion. The tectonic effects of such a late expansion are not observed on Callisto. Ganymede, due to its greater size, rock fraction and full differentiation, has a substantially higher heat flow than Callisto and has not reached this tectonic end state. Titan, if differentiated, should be similar to Ganymede in this regard [3].

Convection on Callisto: Stagnant lid scaling for temperature- and pressure-dependent viscosity convection [4-6] is applied to Callisto. The effects of temperature-dependent thermal conductivity, spherical geometry, and the pressure dependence of the ice-I melting temperature are incorporated. The critical Raleigh number for convective overturn, defined with the viscosity at the base of the shell (η_b) and for an effective temperature drop across the shell, is ≈ 3 x 10^6. For a given shell thickness (D), up to the maximum possible for a floating ice shell on Callisto (≈175 km), this imposes a maximum η_b and thus a maximum grain size (d) for convection to occur.

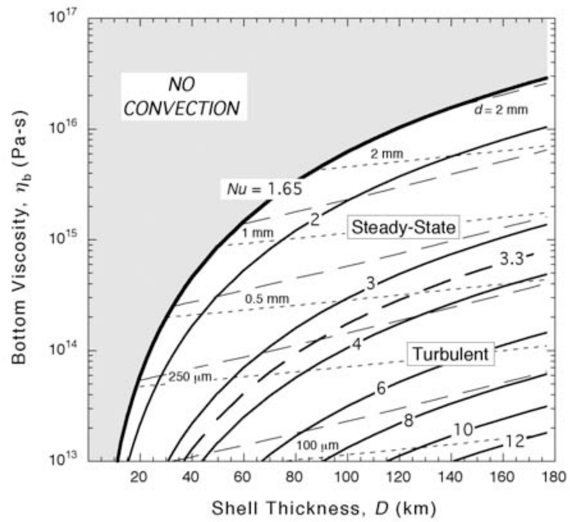

Fig. 1. Combinations of basal viscosity and shell thickness on Callisto unstable to convective overturn, contoured in terms of Nusselt number. Overlaid on the solid *Nu* contours are thin dashed contours of ice grain size that correspond to a given basal viscosity and shell thickness (through the *P*, *T* of the ice solidus). Dashed contours indicate zero activation volume, *V** (no pressure effect on viscosity), whereas the short dashes incorporate a *V** = -13 cm^3 mol^{-1}.

Combinations of η_b and D that are unstable to convective overturn are illustrated in Fig. 1, contoured in terms of effective basal Rayleigh number. The contours are, however, labeled in terms of their equivalent Nusselt numbers, *Nu*. The upper solid curve is the critical viscosity curve for convection to occur at all (*Nu* = 1.65), and the thick, dashed curve indicates the approximate boundary between steady-state and turbulent convection (*Nu* = 3.3) [5,6].

Grain sizes <2-4 mm are necessary for convection to occur by diffusional creep. Strictly speaking, the *Nu* contours in Fig. 2 apply to *V** = 0, which may be more appropriate for diffusion in ice I [3]; a negative *V** affects the scaling such that d < 3 mm is probably a more precise upper limit. This grain size limit compares favorably with observations in terrestrial polar ice sheets undergoing strain, especially when contaminated with trace impurities and microparticles [7]. Callisto's ice is arguably dirtier than this, so the grain size in its mantle may be smaller still.

I conclude that convection is permitted if not likely within Callisto's floating ice shell, and by implication, plausible in the ice shells of Ganymede [8] and Titan [9] as well. These analytical results complement the numerical results of Barr et al. [10], who recently showed that convection by non-Newtonian creep could result from a suitably large, long wavelength, imposed temperature perturbation. The source of such a temperature perturbation within Callisto is far from clear, however, so diffusion-creep-mediated convection is likely to be the dominant mode.

Thermal Evolution: Surface heat flow contours are plotted in a similar manner in Fig. 2, with most of the constant *Nu* curves omitted for clarity. Based on

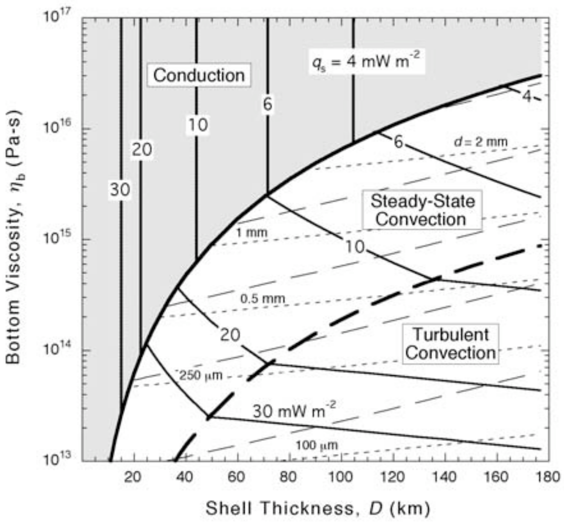

Fig. 2. Combinations of basal viscosity and shell thickness on Callisto unstable to convective overturn, with overlaid contours of surface heat flow in each heat transport regime: conduction, steady-state convection, and turbulent convection. Conductive heat flow contours are disjoint from those in the convective regions. Contours of ice grain size are plotted in the convective regions as in Fig. 1.

its rock fraction, Callisto's steady-state heat flow at >4 Ga was likely in excess of 20 mW m^{-2}. A steadily growing ice shell in conductive steady state, over an internal ocean, thus implies a thin ice shell and a very deeply melted and differentiated Callisto early-on. Deep differentiation is incompatible with Callisto's moment-of-inertia [11]. Either convection occurred in a thicker ice shell, keeping the ocean thickness within acceptable bounds, or the interpretation of Callisto's degree-2 gravity field in is error. Thus I conclude that not only is convection permitted for Callisto, it is apparently required early in Solar System history.

Conductive-convective turn-on. The heat flow transition from steady-state to turbulent convection is continuous (Fig. 2). The transition from conduction to steady-state convection is not: q_s contours are discontinuous, and the transition represents a profound thermomechanical reorganization of the ice shell. Convective "turn-on" is accompanied by a "heat pulse" that is at least 50% above the pre-existing conductive background (Fig. 2). It would last as long as necessary to thicken the ice shell, freeze out some of the ocean at its base, and cool the overall ice-ocean-ice system. Heat flow would not decline monotonically across the transition, as in older parameterized convection models. The increased heat flow, accompanied by convective stresses, would have had the potential to fracture the lithosphere and melt or mobilize hot ice, water, or low-melting-point volcanic fluids. Although argued to not be applicable to Callisto, bodies generally regarded as being deeply accretionally melted, such as Ganymede [e.g., 11] or Titan [e.g., 9] may have evolved through just a transition. The resulting substantial thermal and tectonic changes may bear on the formation of Ganymede's bright smooth and grooved terrains.

Tectonic end game. If the heat flow from Callisto's interior drops below the minimum value that a critically convecting ice I layer can transport (~3.5 mW m^{-2}; Fig. 2), then convection must stop. Given greater heat transport across the shell than is supplied from below, the shell cools, but this increases the viscosity so that the Rayleigh number becomes sub-critical. The thermally stable solution is now a conductive one, but the conductive shell is thinner than the convective one (i.e., the ocean thickens as the ice shell "dies"). Callisto is close to this marginal state, which is acerbated by significant non-Newtonian contributions to creep and heat transport for larger *d* [3,10]. The lack of any tectonic signature from the resulting satellite expansion implies that this transition has not occurred, and perhaps amazingly, that convection continues to the present day in Callisto (and Ganymede and Titan are in no danger if they have rock+metal cores). This is best accomplished if *d* is somewhat smaller (< 1 mm) and the ice shell and ocean below colder (<235 K). The smaller grain size suppresses the non-Newtonian contribution and this and the lower temperature reduce the convective heat flux. Such an ocean requires an antifreeze.

References: [1] Ruiz J. (2001) *Nature, 412*, 409-411. [2] McKinnon W.B. (2001) *BAAS, 33*, 1090. [3] McKinnon W.B. (2005) *submitted*. [4] Solomatov V.S. (1995) *Phys. Fluids, 7*, 266-274. [5] Dumoulin C. et al. (1995) *JGR*, 12,759-12,777. [6] Solomatov V.S. and Moresi L.-N. (2000) *JGR, 105*, 21,795-21,817. [7] De La Chappelle, S. et al. (1998) *JGR, 103*, 5091-5105. [8] Kivelson M.G. et al. (2002) *Icarus, 157*, 507-522. [9] Grasset O. and Sotin C. (1996) *Icarus, 123*, 101-121. [10] Barr, A.C. et al. (2004) *JGR, 109*, E12008. [11] Schubert G. et al. (2004) in *Jupiter-The Planet, Satellites, and Magnetosphere* (Bagenal, Dowling & McKinnon, eds.), 281-306.