CONDUCTIVE-CONVECTIVE SWITCHES OF THE ICE SHELL OF EUROPA: IMPLICATIONS FOR THE SURFACES STRUCTURES. G. Mitri and A.P. Showman , *Department of Planetary Sciences and Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, 85721, USA (mitri@lpl.arizona.edu).*

Introduction: We investigate the response of a conductive and convective ice shell to changes of heat production in the silicate mantle and in the ice shell of Jupiter's satellite Europa. This abstract is a summary of Mitri and Showman, recently submitted to *Icarus* [1]. Estimates of Europa's ice-shell thickness range from $\sim$ 3–50 km [2-7]. This uncertainty in thickness translates directly into an uncertainty in the heat-transfer mechanism: if the shell is thick, the rigid surface could be underlain by a layer of convecting water ice [5, 8-11], whereas a thin shell would instead transport the heat by conduction [7]. Interestingly, most estimates of the shell thickness (10–40 km) imply that the ice-shell Rayleigh number is near the critical Rayleigh number, which is $\sim 10^6$ for realistic temperature-dependent viscosities [e.g., 9].

The implications of surface landforms for the configuration of the ice shell remain controversial [10]. Numerous small (3-30 km-diameter) pits, uplifts, and disrupted spots, as well as larger chaos terrains such as Conamara Chaos and the Mitten, have been attributed to convection in an ice shell at least 10 km thick [10, 12-14]. But other authors have suggested that chaos results instead from melt-through of a thin ice shell [6, 7]. Similarly, some formation mechanisms for ridges require a thin-ice shell [15], while other ridge-formation mechanisms allow a thicker shell [16]. *Figueredo and Greeley* [17], *Pappalardo et al.* [9], and others have shown that tectonic resurfacing decreased rapidly after ridged-plains formation and that chaos formation has increased with time. These authors suggest that the transition from tectonic- to chaos resurfacing resulted from the gradual thickening of the ice shell. On the other hand, *Greenberg et al.* [7] suggests a different scenario where the chaos and tectonic terrains form concurrently and continually resurface Europa.

The assumption is often made that the heat flux near the conductive-convective transition is a continuous function of the layer thickness. However, laboratory experiments in a fluid with temperature-dependent viscosity indicate that, at the critical Rayleigh number, the convection jumps directly to a finite-amplitude regime [18], implying that the heat flux for a layer that is barely supercritical to convection *greatly exceeds* that for a barely subcritical, nonconvecting layer. Because thinner conductive layers transport greater heat flux, this result implies that the heat flux for a barely supercritical convective layer will be *equal* to the heat flux for a conductive layer that is much thinner. Therefore, for a range of conditions near the critical Rayleigh number, two solutions — one a thin, conductive shell and the other a thick, convective shell — exist for a given basal heat flux. The existence of two solutions for a given heat flux raises an obvious question: what determines which of the two states Europa occupies? And can Europa switch between these states? Answers to these questions have important implications for the time history of Europa's ice-shell thickness, and hence for Europa's surface geology, especially because Europa's heat-production rate may vary in time.

Here, we present two-dimensional numerical simulations of convection in Europa's ice shell to determine whether perturbations in heat flux or tidal-heating rate can cause the shell to switch between conductive and convective states, and we discuss the implications for Europa's evolution.

Model: We performed numerical simulations of subsolidus convection with temperature-dependent Newtonian viscosity and a range of tidal-heating rates, ice-shell thicknesses, and melting-temperature viscosities using the ConMan finite-element code [19]. The viscosity contrast was chosen to maintain the convection in the stagnant-lid regime, and the tidal-heating rate depends on temperature. The ConMan code assumes that the ice-layer thickness δ is constant throughout each simulation, so there is no direct way to account for ice-shell thickness fluctuations in response to thermal perturbations. However, we can perform constant-thickness simulations to determine the equilibrium heat flux for a given shell thickness and tidal-flexing amplitude; we then use these results to *infer* how the thickness will change if the basal heat flux or tidal-flexing amplitude change. The approach is valid as long as the perturbations in heat flux or tidal-flexing amplitude occur on timescales long compared to the convective timescale, which is $\sim 10^4$–10^5 yr for viscosities of 10^{14}–10^{15} Pa s. In contrast, the expected changes in shell thickness associated with coupled orbital-geophysical feedbacks are $\sim 10^7$–10^8 yr.

Results: Our simulations confirm that, at the critical Rayleigh number, convection jumps immediately into a finite-amplitude state (Fig. 1), in agreement with laboratory experiments [18] for a fluid with strongly temperature-dependent viscosity. This result implies that, for a range of basal-heat fluxes and ice-shell tidal-flexing amplitudes relevant to Europa, *two equilibrium states* exist: one for a thin, conductive ice shell and the other for a thick, convective ice shell (Fig. 1). To our knowledge this phenomenon has never previously been discussed in the icy-satellite context. The primary relevance for Europa is that, under appropriate conditions, small changes in heat flux or tidal-flexing amplitude can force the ice shell to switch between these two states, leading to large — and *rapid* — changes in the ice-shell thickness.

These switches occur as follows. Consider a thin, conductive shell that transports great heat flux, and suppose the heat flux supplied to the base of the shell from the silicate layer declines over time. The shell would gradually thicken, sliding down the conductive trajectory in the left half of Fig. 1. When the shell thickened sufficiently to reach the critical Rayleigh number (18-km thickness in Fig. 1), convection would initiate. The convected heat flux then jumps — implying that the shell is suddenly transporting a much greater heat flux than that supplied by the silicate layer. Therefore, the shell rapidly thickens (to 35 km in Fig. 1) until its convected flux again matches that supplied from below. Similarly, a gradually increasing basal heat flux would force a convective shell to gradually thin; when the shell reaches the critical Rayleigh number (18-km thickness in Fig. 1), any further increases in basal-heat flux would force the shell to jump to the 10-km-thick conductive state.

When such switches occur, global expansion or contraction of Europa would result, depending on whether the shell thickened or thinned. Conductive-to-convective switches causes ice-shell thickening of $\sim$ 8–30 km, depending on the tidal-heating rate, whereas convective-to-conductive switches lead to thinning of $\sim$ 5–10 km. The timescale of these conductive-convective switches, $\sim$ 5–10 Myr, is much less than probable timescales for the orbital fluctuations (10^8 years) and changes in radiogenic heat flux (10^9 years) that allow the switches to occur. The rapidity of these switches implies that stress buildup, hence extensive fracture, of Europa's surface would occur during such a switch; in contrast, gradual $\sim 10^8$-year changes in the ice-shell thickness would allow the expansion or contraction to be accomodated by viscous deformation rather than fracture.

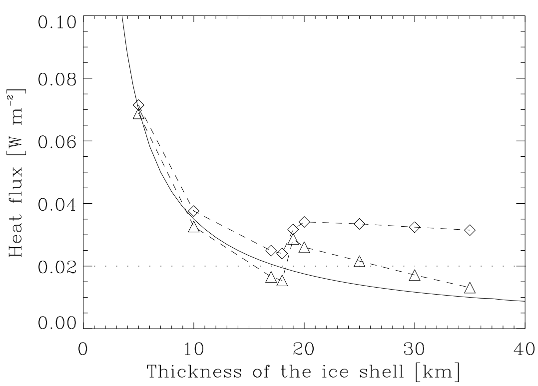

Figure 1: Relation between the heat flux calculated in the hot boundary layer of the convective ice shell (triangles) and in the stagnant lid (diamonds) vs the thickness of the ice shell δ. Here, each pair of points at a given ice-shell thickness gives the results of a single numerical simulation. The shell is conductive for $\delta \leq 18$ km and convective for $\delta \geq 19$ km. The radiogenic heat flux ranges from 0.005-0.020 W m^{-2}; the dotted line shows the maximum radiogenic heat flux. For reference, the solid curve illustrates the relationship between heat flux and δ for a conductive ice shell without internal heating. For these simulations the melting-temperature viscosity is 10^{14} Pa s and the tidal-flexing amplitude of the ice shell is $\epsilon_0 = 1.1 \cdot 10^{-5}$.

Several studies have shown that Europa's resurfacing has shifted from a tectonic regime (i.e., ridge-building) to chaos and lenticulae formation throughout the course of the $\sim$ 50 Myr observational record [eg., 10, 17]. Based on the interpretation that chaos and lenticulae result from convection in the ice shell [e.g., 13], several of these authors have interpreted this shift as evidence for a thickening of the ice shell with time, resulting in the onset of convection sometime within the past $\sim$ 50 Myr (see [10] for a review). A possible dilemma in explaining chaos is that, if convection has only just initiated, one might expect the convection to be relatively low-amplitude, which makes it difficult to understand how surface disruption would result from the convection. Our simulations provide a mechanism for producing a rapid ($\sim 10^7$ year) shift from a conductive state to a high-amplitude, vigorously convecting state potentially capable of forming chaos, pits, and domes. Furthermore, the rapidity of the shift would allow lithospheric fracture and band formation, which is broadly consistent with the inference that bands are often intermediate in age between the ridged plains and chaos [17]. Finally, our model shows that, under the right conditions, the shift from conductive to vigorous-convective states can occur with only modest perturbations in the basal heat flux and tidal-flexing amplitude. If Europa's heat flux varies cyclically in time, such switches could occur repeatedly during Europa's history.

Even if no such switches occur, our simulations describe how the ice-shell thickness responds to changes in the heat flux and tidal-heating rate. Because of the weak dependence of the heat flux on the thickness, a convective ice shell responds to modest variations in heat flux with large variations in thickness. In a convective ice shell without internal heating, a variation of heat flux of 0.01 W m^{-2} involves changes of thickness $\geq$10 km. In contrast, large variations of heat flux involves relatively small variations of thickness in a conductive ice shell. Tidal heating in the ice shell lessens the sensitivity of ice-shell thickness to variations in basal heat flux, however.

Conclusions: Our simulations show that heat-production variations in Europa's silicate interior can produce large variations in the thickness of a convective ice shell. Moreover, modest variation in the heat flux supplied from below can produce repeated switches from a conductive to a convective configuration of the ice shell during Europa's history, with rapid and large variations in thickness. Based on interpretations for how features such as chaos, ridges and bands are formed, several authors have suggested that Europa's ice shell has recently undergone changes in thickness. Our model provides a mechanism for such changes to occur.

References: **[1].** Mitri G., A.P. Showman, Icarus, submitted (2005). **[2].** Turtle, Ivanov, LPSC XXXIII, 1431 ab. (2002). **[3].** Schenk, Nature, 417, 419 (2002). **[4].** Hussmann et al. Icarus, 156, 143 (2004). **[5].** Tobie et al., GRL, 108, 5124, (2004). **[6].** Williams and Greeley, GRL, 25, 4273 (1998). **[7].** Greenberg et al., Icarus, 141, 263 (1999). **[8].** Cassen et al., GRL, 6, 731 (1999). **[9].** McKinnon, GRL, 26, 951 (1999). **[10].** Pappalardo et al., Nature, 391, 365 (1999). **[11].** Showman, Han, GRL, 109, 1010, (2004). **[12].** Head, Pappalardo, JGR, 104, 27143 (1999). **[13].** Collins, JGR, 105, 1709 (2000). **[14].** Figueredo et al. (2002). **[15].** Greenberg et al., Icarus, 135, 64 (1998). **[16].** Nimmo, Gaidos, JGR, 107, 5021 (2002). **[17].** Figueredo, Greeley, 167, 287 (2004). **[18].** Stengel et al., J. Fluid Mech., 120, 411 (1982). **[19].** King et al., Phys. Earth Inter., 59, 195 (1990). **[20].** Dumolin et al., JGR, 104, 12,759 (1999). **[21].** Solomatov, Phys. Fluids, 7, 266 (1995).