Flow-like features on Europa: geometric patterns and relation to topography collectively constrain material properties and effusion rates. H. Miyamoto[1], G.Mitri[2], J.M. Dohm[3], and A.P. Showman[2], [1]Department of Geosystem Engineering, University of Tokyo (Dept Geosystem Engineering, Univ Tokyo, Tokyo 113-8656, Japan; miyamoto@geosys.t.u-tokyo.ac.jp), [2]Lunar and Planetary Laboratory, University of Arizona, [3] Department of Hydrology and Water Resources, University of Arizona

Introduction: Processes that result in the formation of a variety of surface features on Europa may involve surface flows of viscous materials, including both ice and slurry flows [e.g.. 1-5]. Theoretical investigations of cryovolcanism suggest that an eruption of ice/water is a viable, though not unequivocal, explanation for these features [5]. Although most of these flow-like features can also be explained by other processes, such as thermal or compositional diapirism [6-8] or melt-through of a thin ice shell [9,10], even in these cases, surface flows may be involved; for example, ascending diapirs may fracture the surface and discharge materials that flow onto the surface [4,5]. Here, we present numerical simulations of surface-ice flows on Europa to better illuminate whether putative flow-like features actually resulted from flows and, for probable flow candidates, to constrain the eruption conditions and flow rheology during emplacement. The primary constraint on the modeling is the relationship between the flow-like features and surrounding topography, which affords a unique opportunity to test the flow hypothesis. Overall, our results support the view of Fagents [5] that, while cryovolcanic flows appear to be present on Europa, they are not a dominating factor in shaping the surface.

Putative flow-like features: Several types of features have been proposed to result from flow emplacement processes, including (1) thin flow-like features that infill topographic lows and, in some cases, are routed by positive topography, (2) lobate, lava-like features, and (3) circular to elongate dome-like features that cut across/overlap topography (Fig. 1).

Numerical model: In order to estimate the movement of ice flows, we employ a composite constitutive equation of ice rheology [11], which includes individual flow laws for four specific creep mechanisms. We adopt a simple, two-dimensional model that integrates over the vertical dimension, leading to equations for the flow thickness and vertically averaged horizontal flow speed as a function of horizontal position. This model will allow short computation times, and hence a much greater exploration of parameter space, than would be possible with three-dimensional simulations. In these preliminary Europa simulations we utilize an isothermal version of the model, keeping in mind the caveat that the results are only valid for timescales less than the thermal diffusion time H^2/k.

Results and discussions: We perform two groups of systematic calculations of ice flows using an inclined plane with and without irregular topography [12].

From the calculations without irregular topography, we find that the thickness of a flow strongly depends on the effusion rate: a higher effusion rate generally results in a thicker flow. Importantly, this effect is enhanced for a more viscous flow. This suggests that the thickness of a flow-like feature is a good indicator of both the rheology and the effusion rate of the ice. For example, a thin flow (<100m) is likely formed by less viscous flow, such as a warm ice flow with temperatures exceeding 200K and grain size less than 50 μm. Further constraints on flow evolution can be obtained by considering the cooling times, since the formation time must be less than the cooling time, $\sim H^2/\kappa$, of an ice flow. Our simulations suggest that flow-like features can form only with effusion rates exceeding $\sim 10^6 m^3$ year^{-1}. In general, a lower viscosity flow becomes thinner at a lower effusion rate. As such, maintaining a given flow thickness means that flows of low viscosity (i.e., warm flows with small grain sizes) require greater effusion rates than flows of high viscosity (i.e., cold flows with large grain sizes). Even at high effusion rates (10^7-10^8 m^3 year^{-1}), however, only solid-ice flows with temperatures exceeding ~200 K and grain sizes less than ~50 μm can form flows with thicknesses appropriate to Europa (<~300 m).

The systematic simulations with irregular topography show that there are three distinct patterns that result from the interactions between a flow and a ridge. We categorized these flow pattern types as (Fig. 2): (1) "A-type", which is completely or partially blocked by the ridge; the pattern is significantly confined by the existence of the ridge. This type of interaction is observed only when the thickness of the flow is less than or almost the same as that of the ridge; (2) "B-type", which is partially but not significantly affected by the ridge. This is commonly observed for a flow whose thickness is on the same order of the thickness as the ridge; (3) "C-type", which cuts across the ridge without any apparent modification in the large-scale flow morphology (e.g., shape). In order for a C-type flow to occur, the average thickness of the flow must exceed the height of the ridge by at least an order of magnitude.

More than 150 simulations were performed to systematically explore the range of conditions that lead to A, B, and C-type flows. A summary of these simulations is presented in Fig. 3. Simulations of A- and B-type are most relevant for Europa, whereas C-type are ruled out because the thicknesses required for C-type flows greatly exceed observed thicknesses of Europan flow-like features. In summary, our simulations show that most combinations of plausible temperatures, grain sizes, and effusion rates produce flow morphologies that do not resemble Europan landforms. However, observed flow-like features that show modest influence from pre-existing topography could result from ice flows with temperatures >230 K, effusion rates $>10^7$ m^3 $year^{-1}$, and a wide range of grain sizes. Completely confined flow-like features (i.e., flows unable to surmount ridges) must have had such low viscosities that, if they resulted from solid flows, the grain sizes during emplacement were < 2 mm. Although the grain size on Europa is unknown, values often assumed for ice shell on Europa are much larger than this value. Thus, this grain size seems unlikely. If these features resulted from flows, they probably involved liquids or slurries. Importantly, there exists a class of flow-like features, with heights comparable to that of surrounding topography, which show no influence from the topography. Our simulations suggest that these features did not result from flows; only flows at least ten times thicker than the pre-existing topography are able to defy the influence of such pre-existing topography, but the features in question on Europa have heights comparable to those of the surrounding ridges. Note that this conclusion is mainly derived from a lack of discernable interaction among the flow-like feature and the ridge, which is more readily interpreted from the limited-resolution images. The rheology of ice on Europa might be different from that of pure water ice. However, even in this case, most impurities tend to increase the viscosity of ice, which will only worsen the case for solid-state flows; thus the generally negative conclusion for the solid-state flows on Europa might be enforced by considering the impurities of ice.

Our results provide theoretical support for the view that many of Europa's lobate features are not cryovolcanismic in origin, and that, while some cryovolcanism has undoubtedly occurred, that cryovolcanims is not a major factor in shaping the surface.

References: [1] Wilson, L. et al (1997) JGR, 102, 9263-9272 [2] Carr, M. H. (1998) Nature, 391, 363-365 [3] Head, J. W. et al (1999) JGR, 104, 27,143-27,155 [4] Figueredo, P.H. et al. (2002), JGR, 107, 5026 [5] Fargents, S.A. (2003), JGR, 108, 5139, [6] Pappalardo, R. T. et al. (1998) Nature, 391, 365-368 [7] Collins et al. (2000) JGR, 105, 1709-1716 [8] Showmann, A.P. and Han, L. (2004), JGR, 109, doi:10.1029/2003JE002103 [9] Greenberg, R. et al. (1999) Icarus, 141, 263-286 [10] Tomson, R.E. and Dalaney, J.R. (2001) JGR, 106, 12,355-12,365 [11] Goldsby, D.L. and Kohlstedt, D.L. (2001) JGR, 106, 11,017-11,030 [12] Miyamoto, H. et al., Icarus, in revision.

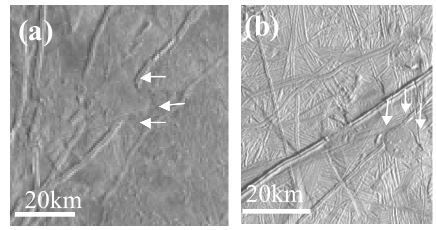

Figure 1. Examples of flow-like features: (a) 374667300 and (b) 38713701

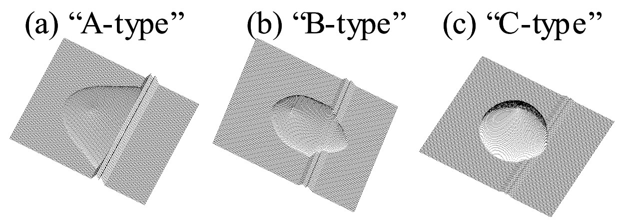

Figure 2. Examples of three distinct patterns that result from the interactions between a flow and a ridge.

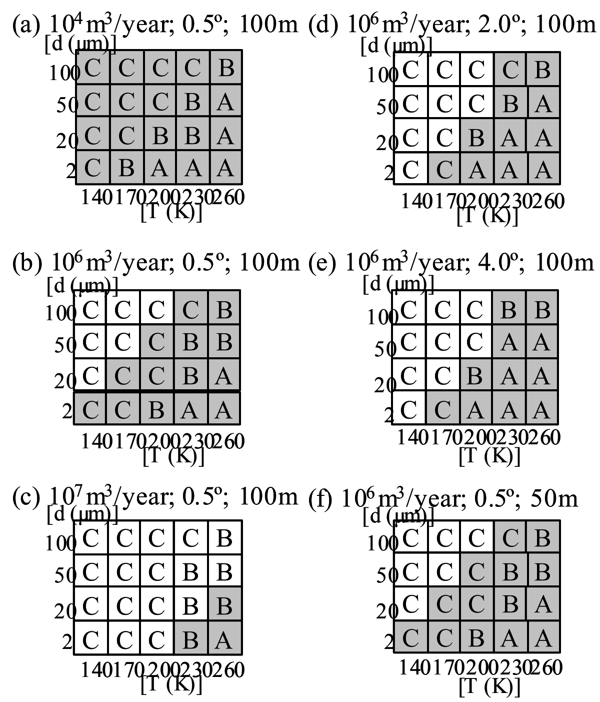

Figure 3. Summary of systematic simulations over 150 cases. White boxes correspond to flows able to expand to 10-km diameter over a timescale less than the cooling timescale, whereas gray boxes correspond to flows that can only expand to 10-km diameter over times exceeding the cooling timescale. A- and B- types in white boxes are most relevant for Europa: most of the results do not fit the features on Europa.