Putative ice flows on Europa: Geometric patterns and relation to topography collectively constrain material properties and effusion rates

Hideaki Miyamoto a,b,*, Giuseppe Mitri a,c, Adam P. Showman a, James M. Dohm d

a Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA
b Department of Geosystem Engineering, University of Tokyo, Tokyo 113-8656, Japan
c International Research School of Planetary Sciences, University G. d’Annunzio, Pescara, Italy
d Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ, USA

Received 11 July 2004; revised 9 March 2005
Available online 17 May 2005

Abstract

Europa’s surface exhibits numerous small dome-like and lobate features, some of which have been attributed to fluid emplacement of ice or slush on the surface. We perform numerical simulations of non-Newtonian flows to assess the physical conditions required for these features to result from viscous flows. Our simulations indicate that the morphology of an ice flow on Europa will be, at least partially, influenced by pre-existing topography unless the thickness of the flow exceeds that of the underlying topography by at least an order of magnitude. Three classes of features can be identified on Europa. First, some (possibly most) putative flow-like features exhibit no influence from the pre-existing topography such as ridges, although their thicknesses are generally on the same order as those of ridges. Therefore, flow processes probably cannot explain the formation of these features. Second, some observed features show modest influence from the underlying topography. These might be explained by ice flows with wide ranges of parameters (ice temperatures >230 K, effusion rates >10^7 m^3 year^-1, and a wide range of grain sizes), although surface uplift (e.g., by diapirism) and in situ disaggregation provide an equally compelling explanation. Third, several observed features are completely confined by pre-existing topographic structures on at least one side; these are the best known candidates for flow features on Europa. If these features resulted from solid-ice flows, then temperatures >260 K and grain sizes <2 µm are required. Such small grain sizes seem unlikely; low-viscosity flows such as ice slurries or brines provide a better explanation for these features. Our results provide theoretical support for the view that many of Europa’s lobate features have not resulted from solid-ice flows.

© 2005 Elsevier Inc. All rights reserved.

Keywords: Europa; Satellites of Jupiter; Surfaces; Ices; Volcanism

1. 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. A variety of possible flow types have been reported (e.g., Wilson et al., 1997; Carr et al., 1998; Head et al., 1998, 1999; Figueredo et al., 2002; Fagents, 2003). These include irregular and elongate structures with lobate fronts, elliptical/circular dome-like structures, features that embay or partially bury pre-existing landforms, and smooth plains-forming materials that infill topographic lows (Head et al., 1999; Fagents, 2003). Theoretical investigations suggest that an eruption of ice/water is a viable, though not unequivocal, explanation for these features (Fagents, 2003). However, most of these flow-like features can also be explained by other processes, such as thermal or compositional diapirism (Pappalardo et al., 1998; Collins et al., 2000; Showman and Han, 2004a, 2004b; Pappalardo and Barr, 2004).
or melt-through of a thin ice shell (Greenberg et al., 1999; Tomson and Delaney, 2001; O’Brien et al., 2002). But 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 (Fagents, 2003). Just this process has been invoked for a large-scale, elevated, and chaos-like “Mitten” feature (Murias Chaos; Figueredo et al., 2002).

Numerical and theoretical studies have focused primarily on convection in the underlying ice to explain some of the features discussed above (Rathbun et al., 1998; Nimmo and Manga, 2002; Showman and Han, 2004a, 2004b; Pappalardo and Barr, 2004). However, only a few quantitative studies have investigated the potential for flow-related processes. Fagents (2003) discusses mechanisms that could allow effusive eruptions and presents simple analytical models for the spreading of cylindrically symmetric, Newtonian flows outward from an initial point source. Because of her model assumptions, she was unable to directly investigate the interaction between surface flows and pre-existing topography such as ridges. However, as we will discuss, many putative flow features show strong interactions with surrounding topography, and the observed interactions may provide clues to help constrain the properties of these flows (or indeed, whether they are flows at all). Moreover, while analytical model of Fagents (2003) emplaced the flow material instantaneously at the surface (i.e., no effusion was allowed), real flows may be fed by continuing eruptions and furthermore may exhibit non-Newtonian ice rheology (e.g., Durham et al., 1997; Goldsby and Kohlstedt, 2001). Thus, there is merit in considering a more detailed, numerical flow model that allows sustained effusion, non-Newtonian rheology, and interaction with topography.

In this work, 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 (e.g., the extent to which topography controls the flow shapes), which affords a unique opportunity to test the flow hypothesis. Some of the observed features do not exhibit the interaction with nearby topography that is predicted from our simulations, and thus can be argued to have resulted instead from another process (e.g., intrusive doming followed by in situ disaggregation of the surface). Other observed features, however, exhibit structural control by topography that is well represented in our simulations, and we argue that these features are best explained by the emplacement of viscous flow material. Overall, our results support the view of Fagents (2003) that, while solid-ice flows appear to be present on Europa, they are not a dominating factor in shaping the surface.

2. Putative flow-like features

Several types of features have been proposed to result from flow emplacement processes (Fagents, 2003), 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. Here we briefly describe the relevant details of these features.

Thin flow-like features appear to occupy topographic lows with either dark or bright albedos. In addition, they occasionally exhibit lobate flow fronts (Greeley et al., 2000). This particular feature type has been interpreted to result from small-volume fluid effusion. For example, low-albedo features at the margins of Thrace Macula (Fig. 1a) appear to embay ridged terrain, suggesting confinement of a fluid by topography (Fagents, 2003). Other examples are smooth-surface features delimited by ridges (Figs. 1b and 1c), which are explained by a fluid flowing up against and/or being constrained by topographic barriers (Fagents, 2003).

Flow-like features with lobate fronts may suggest the emplacement of viscous flows onto the surface of Europa (Finnerty et al., 1981; Lucchitta and Soderblom, 1982; Wilson et al., 1997). Lobate features of a few tens of kilometers scale (Fig. 2) were identified in some images from Galileo orbit E4 and G7 (Fagents, 2003). However, because of inadequate image resolution, these features do not provide compelling evidence for surface flows (Fagents, 2003). It is sometimes difficult to determine whether the flow-like features have positive relief with respect to the ridges, and thus remains uncertain in some cases (e.g., Fig. 2b).

Europa exhibits many positive topographic features including domes, platforms, irregular uplifts, and disrupted micro-chaos regions (Pappalardo et al., 1998; Greeley et al., 1998; Greenberg et al., 2003). Some of them show positive elevations reaching 100–200 m or more (Fagents et al., 2000; Figueredo et al., 2002; Greenberg et al., 2003; Schenk and Pappalardo, 2004) and have surface textures bearing no relation to the surrounding terrain (Fig. 3), appearing to have obscured and spread over the pre-existing surface as a viscous flow (Carr et al., 1998; Fagents, 2003). A range of sizes is observed (e.g., Riley et al., 2000; Greenberg and Geissler, 2002; Spaun, 2002; Greenberg et al., 2003). Fagents (2003) measured 11 domes in the orbit E6 data and reported that heights, diameters, and volumes are typically on the order of 40 to <100 m, ~3 to 10 km, and 0.3 to 3 km³, respectively. Since these features are rarely disrupted by tectonic structures such as ridges, they are some of the youngest features on the surface of Europa (Nimmo and Manga, 2002; Figueredo and Greeley, 2004). A distinct example is an approximately 100-km-wide dome-like mass referred to as “Mitten” (Murias Chaos; 21° N, 84° W; Fig. 3c), which is interpreted to be the result of a mobile ice diapir that subsequently underwent viscous, solid-state flow over the surface (Figueredo et al., 2002).
Putative ice flows on Europa

Fig. 1. (a) High-resolution image (466669765; 466669778) of Thrace Macula (42° S, 172° W) with inset showing the lobate morphology in a greater scale (466664413). Low-albedo material around the margin of the feature display patterns which are strongly influenced by pre-existing topography. (b) Fluid-like smooth material at the flank of a ridge embays irregular topography (15° N, 273° W; 383718613). (c) High-resolution image of smooth material, which embays irregular topography (374685452).

Fig. 2. Flow-like features with lobate fronts. (a) Flow-like feature appears to be influenced by the ridge (374667300). (b) Flow-like feature does not have topographic influence (389780563). (c) Flow-like feature appears to be confined by ridges (389780563).

The thickness estimations of flow-like features are especially difficult due to the limited image resolution. A flow-like feature may have thicknesses of ~200 m, while many others might be less than 100 m. We emphasize that exact thickness estimations are not our intention of this work, and that our conclusions do not depend on the exact values of flow thicknesses.

3. Numerical model

3.1. Approach

In this paper, we investigate the emplacement patterns of the flow-like features to constrain the material properties and the effusion rates. In order to estimate the movement of ice
flows, we have modified an existing numerical code used for calculating a variety of viscous flow types (Miyamoto and Sasaki, 1997, 1998, 2000; Miyamoto et al., 2004a, 2004b).

A rigorous description of a surface flow would require full, coupled three-dimensional numerical simulations of the heat, mass, and momentum equations. Such an approach would introduce many complexities, which in our view are unwarranted by the current paucity of data for europian flows. Our approach is instead to adopt a simpler, 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. A difficulty is that heat loss from the top of the flow (which depends on the vertical temperature profile inside the flow) can no longer be accurately represented. We expect the bulk lateral movement of any given column of ice within the flow to be controlled by the interior region of the flow that has the greatest temperature and strain rate, and so the peak temperature within any given column will be the primary parameter determining the flow behavior. If the thermal diffusion timescale, $H^2/\kappa$, exceeds the characteristic time, $L/2U$, for the flow to grow to its final size, then the interior regions of the flow will undergo only minimal cooling during the growth of the flow. (Here $L$ is the final flow diameter, $U$ is the horizontal flow speed, $H$ is the mean flow thickness, and $\kappa \sim 10^{-6} \text{ m}^2 \text{s}^{-1}$ is the thermal diffusivity.) For a final flow diameter of $\sim 10 \text{ km}$ and flow thicknesses of $\sim 200 \text{ m}$, the flow will therefore expand to its final size with minimal interior cooling if $U > \kappa L/2H^2 \sim 4 \text{ m year}^{-1}$. Under conditions where the flow expansion speed exceeds this critical value, the bulk properties of the flow may be approximately described by assuming the flow is isothermal. For comparison, terrestrial lava flows/domes have strongly temperature-dependent rheologies, but many aspects of their morphologies are crudely explained by isothermal models (e.g., Hulme, 1974; Huppert et al., 1982; McKenzie et al., 1992; Dragoni et al., 1986). Therefore, 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 $H^2/\kappa$.

### 3.2. Ice rheology

Numerous laboratory experiments of ice have shown that the best fit among shear strain rate, $\dot{\varepsilon}$, and the shear stress, $\sigma$, is expressed by Glen’s law (e.g., Paterson, 1994):

$$\dot{\varepsilon} = B\sigma^n, \quad (1)$$

where $B$ and $n$ are parameters that depend on many factors such as ice temperature, crystal orientation, impurity, and creep regime. This may be rewritten in the style of the Arrhenius equation as given by Goldsby and Kohlstedt (2001):

$$\dot{\varepsilon} = A \sigma^n \exp\left(-\frac{Q}{RT}\right), \quad (2)$$

where $A$ is a material parameter, $d$ is the grain size, $n$ is the stress exponent, $Q$ is the activation energy, $R$ is the gas constant, and $T$ is temperature. Based on creep experiments of fine-grained ice, Goldsby and Kohlstedt (2001) proposed a composite constitutive equation, which includes individual flow laws for four specific creep mechanisms:

$$\dot{\varepsilon} = \dot{\varepsilon}_{\text{diff}} + \left(\frac{1}{\dot{\varepsilon}_{\text{basal}}} + \frac{1}{\dot{\varepsilon}_{\text{gbs}}}\right)^{-1} + \dot{\varepsilon}_{\text{disl}}, \quad (3)$$

where the subscripts refer to diffusional flow (diff), basal or easy slip (basal), grain boundary sliding (gbs), and dislocation creep (disl). However, it is unlikely that the flow laws are applicable to all physical conditions (e.g., Budd and Jacka, 1989). For example, the internal structure of ice masses/sheets may be highly variable due to complex deformational histories (Duval and Montagnat, 2002). Nevertheless, the above equation is applied here because it is derived from recent systematic laboratory experiments, and it agrees well with the flow behavior determined from field measurements on glaciers and ice sheets (Goldsby and Kohlstedt, 2002). However, further understanding of ice rheology in the future may lead to modifications in this equation.
We use the parameters given by Goldsby and Kohlstedt (2001) for ice rheology, shown in Tables 1 and 2. The ice-grain size on Europa is unknown, but McKinnon (1999) argues that the cyclical tidal strain limits grain sizes to 1 mm, and the grain size may be even smaller if grain growth is controlled by the presence of impurities (Kirk and Stevenson, 1987; Nimmo and Manga, 2002). We considered grain sizes from 1 µm to 1 mm. Since grains as large as 1 mm produce viscosities so large that no flows can occur, only grain sizes of 1–100 µm are used in the flow simulations of this work.

In this work, wide ranges of stress and strain curves were calculated with parameters shown in Tables 1 and 2. In particular, Fig. 4a shows the importance of the regimes of diffusional flow and basal-slip-accommodated GBS for ice flows on Europa. We calculated stress-strain curves both with and without the effect of the GBS-accommodated basal slip (Fig. 4b), observing that the effect of the GBS-accommodated basal slip may be neglected at the fixed grain size even for a wide range of temperatures. Therefore, we use the following equation for our constitutive equation of ice rheology instead of Eq. (3):

\[ \dot{\epsilon} \sim \dot{\epsilon}_{\text{diff}} + \dot{\epsilon}_{\text{gbs}} + \dot{\epsilon}_{\text{disl}}. \]  

(4)

In this case, using the same subscripts as above, we can rewrite the above equation with Eq. (2) as:

\[ \dot{\epsilon} = D_{\text{disl}} \sigma^{n_{\text{disl}}} + D_{\text{gbs}} \sigma^{n_{\text{gbs}}} + D_{\text{diff}} \sigma^{n_{\text{diff}}} \]

\[ \equiv \sum_{i=\text{diff, gbs, disl}} (D_i \sigma^{n_i}), \]

(5)

where D is a component with the subscripts rule introduced above. For example, \( D_{\text{diff}} \) is expressed as:

\[ D_{\text{diff}} = A_{\text{diff}} \tau^p_{\text{diff}} \exp(-Q_{\text{diff}}/RT). \]  

(6)

---

**Table 1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration due to gravity (g)</td>
<td>1.32 m s(^{-2})</td>
</tr>
<tr>
<td>Grain size (d)</td>
<td>1–100 µm</td>
</tr>
<tr>
<td>Basal velocity (u_b)</td>
<td>0.0 m s(^{-1})</td>
</tr>
<tr>
<td>Density (ρ)</td>
<td>917 kg m(^{-3})</td>
</tr>
<tr>
<td>Slope angle (α)</td>
<td>0.0°–6.0°</td>
</tr>
<tr>
<td>Ridge width</td>
<td>4 km</td>
</tr>
<tr>
<td>Mesh size</td>
<td>200 m</td>
</tr>
</tbody>
</table>

**Table 2**

Parameters for ice rheology (from Goldsby and Kohlstedt, 2001)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burgers vector</td>
<td>4.52 × 10(^{-10}) m</td>
</tr>
<tr>
<td>Molar volume</td>
<td>1.97 × 10(^{-5}) m(^3)</td>
</tr>
<tr>
<td>Pre-exponential, volume diffusion</td>
<td>9.10 × 10(^{-4}) m(^2) s(^{-1})</td>
</tr>
<tr>
<td>Pre-exponential, grain boundary diffusion</td>
<td>5.80 × 10(^{-4}) m(^2) s(^{-1})</td>
</tr>
<tr>
<td>Activation energy, volume diffusion</td>
<td>59.4 kJ mol(^{-1})</td>
</tr>
<tr>
<td>Grain boundary width</td>
<td>9.04 × 10(^{-10}) m</td>
</tr>
<tr>
<td>Activation energy, boundary diffusion</td>
<td>49 kJ mol(^{-1})</td>
</tr>
</tbody>
</table>

\[ A \]

- Dislocation creep: 4.0 × 10\(^5\) MPa\(^{-4}\) s\(^{-1}\)
- GBS-accommodated basal slip: 3.9 × 10\(^{-3}\) MPa\(^{-1}\) s\(^{-1}\)
- Basal-slip accommodated GBS: 5.5 × 10\(^{-7}\) MPa\(^{-2}\) s\(^{-1}\)

\[ n \]

- Dislocation creep: 4.0
- GBS-accommodated basal slip: 1.8
- Basal-slip accommodated GBS: 2.4

\[ Q \]

- Dislocation creep: 60 kJ mol\(^{-1}\)
- GBS-accommodated basal slip: 49 kJ mol\(^{-1}\)
- Basal-slip accommodated GBS: 60 kJ mol\(^{-1}\)

---

Fig. 4. (a) Log–log plots of strain rate versus shear stress curves of ice (temperature 200 K, grain size 20 µm) for different flow regimes and the constitutive equation. (b) Log–log plots of the strain rate and the shear stress of both the full constitutive equation (solid line) and the approximated equation (dash line).
3.3. Flow model

We assume that the horizontal scale of the flow is much larger than its vertical scale, which is appropriate for europa flows. Assuming a simple shear flow, the strain rate may be written as:

\[ \dot{\epsilon} = \frac{1}{2} \frac{\partial u}{\partial z}, \]

where \( u \) is the velocity along the direction of the shear stress (this direction is taken as the \( x \) axis). For a gravity-driven flow on a shallow slope, the shear stress at depth \( (h - z) \), where \( h \) is the thickness of the flow and \( z \) is the height measured from the base of the flow, can be written as (e.g., Miyamoto and Sasaki, 1997):

\[ \sigma = (\rho g \sin \alpha - \rho g \frac{\partial h}{\partial x} \cos \alpha) (h - z), \]

where \( \rho \) is the density of the flow, \( g \) is the acceleration due to gravity, and \( \alpha \) is the angle of the slope from the horizontal. Equation (8) explicitly includes horizontal pressure gradients caused both by regional surface slope (first term) and lateral variations in flow thickness (second term). Integrating Eq. (7) using Eqs. (5), (8) and the free surface boundary-condition, we obtain an expression for the velocity as:

\[ u = \sum_{i,diff, \text{basal}, \text{disl}} \frac{2D_i G^nh_{n+1}}{n_i + 1} - 2D_i G^n(h - z)_{n+1}, \]

where \( G \) is \((\rho g \sin \alpha - \rho g \frac{\partial h}{\partial x} \cos \alpha)\) and \( u_b \) is the velocity due to the slip at the base. By vertically integrating the above equation again, we obtain the flux \( Q \) per unit width as:

\[ Q = \sum_{i,diff, \text{gbs}, \text{disl}} \frac{2D_i G^n h_{n+2}}{n_i + 2} + hu_b, \]

The above equation is valid for a one-dimensional flow. For a two-dimensional flow, Eq. (10) still correctly describes the magnitude of the flux at any given point. If we choose arbitrary horizontal coordinate axes \( x' \) and \( y' \), the components of the flux projected along these axes can be written as follows:

\[ Q_{x'} = Q \frac{\sigma_{x'}}{\sigma} = Q \frac{\sigma_{x'}}{\sqrt{\sigma_{x'}^2 + \sigma_{y'}^2}}, \]

\[ Q_{y'} = Q \frac{\sigma_{y'}}{\sigma} = Q \frac{\sigma_{y'}}{\sqrt{\sigma_{x'}^2 + \sigma_{y'}^2}}, \]

where \( \sigma_{x'} \) and \( \sigma_{y'} \) are the shear stress components in the \( x' \) and \( y' \) directions, respectively.

We calculate fluxes in the \( x' \) and \( y' \) directions from the above equations and insert them into the following continuity equation to calculate a time sequential movement of the flow:

\[ \text{grad} Q = \frac{\partial Q_{x'}}{\partial x'} + \frac{\partial Q_{y'}}{\partial y'} = S - \frac{\partial h}{\partial t}, \]

where \( S \) (units m s\(^{-1}\)) is the effusion rate. Note that this method is not fully two-dimensional in the strict sense. However, errors caused by this method are small, especially when we apply an implicit method. We took the finite difference method with the fully implicit expansion of one-point upstream to solve this equation.

4. Results and discussions

We perform two groups of systematic calculations of ice flows. The first calculates flows over an inclined plane without irregular topography, while the second calculates flows over an inclined plane including a double ridge (Fig. 5). These two groups are necessary to observe how viscous flows with diverse rheological properties and physical conditions behave with and without topographic obstructions.

4.1. Simulations on flat planes

We calculate time-dependent movements of ice flows on a slightly inclined plane with wide ranges of rheological properties and effusion rates. In this group of calculations, a flow is erupted from a point source with a constant effusion rate, though our numerical model can handle a time-dependent effusion rate and a complicated vent geometry. The simulated flow spreads over the plane; this process is illustrated in Fig. 6 for a slope of 0.5°. The calculation is stopped when the diameter of the flow becomes 10 km, which is considered to be a good scale for flow-like features on Europa (Section 2). Because observational evidence cannot alone constrain the eruption parameters including ice temperature and the grain size of ice on Europa, we consider a wide range of parameter values to understand their general influences on the flow patterns.

Results from a broad series of calculations are summarized in Fig. 7, again assuming a 0.5° slope. As expected, a less viscous flow is generally thinner than a more viscous flow. Note the term “viscous” is used for convenience, although the model employs non-Newtonian rheology as discussed above (a less viscous flow may have a lower temperature and/or a larger grain size). We also 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.
Fig. 6. Example result on a plane (0.5° slope, inclined to the right) without irregular topography. Ice temperature, grain size, and the effusion rate are 230 K and 10 µm, $10^7$ m³ year⁻¹, respectively. Snap shots at 3000 (a), 6000 (b), and 10,000 years (c). The source is located at the central part of the 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 (<100 m) is likely formed by less viscous flow, such as a warm ice flow with temperatures exceeding 200 K and grain size less than 50 µm.

Further constraints on flow evolution can be obtained by considering the cooling times. The formation time must be less than the cooling time, $\sim H^2/\kappa$, of an ice flow. Because the cooling time scale increases with the square of the thickness, a thicker flow can survive for a greater time period before it is completely immobilized due to the onset of an increasingly high viscosity. However, since a more viscous flow requires greater time for emplacement, a balance between the rheology, the effusion rate, and the cooling time scale becomes an important issue. In Fig. 7b, we compare the formation time and the cooling time scale, and highlight the cases when the formation time is less than the cooling time scale (gray highlighted areas). Our simulations suggest that flow-like features can form only with effusion rates exceeding $\sim 10^6$ m³ 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 ($10^7–10^8$ m³ year⁻¹), however, Fig. 7 implies that only solid-ice flows with temperatures exceeding $\sim 200$ K and grain sizes less than $\sim 50$ µm can form flows with thicknesses appropriate to Europa (here we assume 200 m for the upper limit of their thicknesses, however, note again that the thickness estimation is technically difficult due to the image resolution).

Since the slope angles at which the formations of these features occur on Europa are unknown, we systematically tested the dependence of flow morphology on slope angles. Some of these results are summarized in Fig. 8. Based on these calculations, we find that with an increasing slope angle, the thickness becomes smaller, depending on the ice rheology and effusion rate. Generally, the effect of the slope is larger for a less viscous flow with a lower effusion rate.
Importantly, even for the case with high temperature (260 K) and low effusion rate (10^6 m^3 year^{-1}), the thickness difference between flows on slopes ranging from 0 to 3° is only about 20%. Because this range of slopes encompasses the range of interest for Europa, the behaviors of europan ice flows are largely unaffected by the exact value of the slope angle.

As shown in Section 2, some flow-like features are distinctly non-circular, with aspect ratios ranging up to ~3–10. Fig. 9 shows the length/width ratio for flows whose maximum lengths are 10 km. As expected, the length/width ratio generally becomes larger for a flow on a steeper slope. More importantly, we note that a larger effusion rate and a more viscous rheology make the length/width less sensitive to the slope angle. In other words, an oblong feature may suggest a smaller effusion rate and a less viscous ice rheology in cases when the flow shape results primarily from slope rather than elongated or oddly shaped eruption vents.

4.2. Simulations with ridge structures

The systematic calculations described above yield several important constraints on flow parameters, including the combinations of rheological properties and effusion rates that allow the formation of flows that are broadly consistent with observed europaen features. Even stronger constraints on the flow properties can be obtained by considering the interaction of flows with surrounding topographic structures (Miyamoto and Papp, 2004) such as ridges. For example, many flow-like features of Europa appear to cut across and/or partly bury ridges. Here we present numerical simulations of the interactions between flows and ridges and summarize the different classes of flows that can result.

Photoclinometric data suggest that ridges are up to about 200 m in height (Sullivan et al., 1998; Greenberg et al., 1998; Head et al., 1999) and that the maximum average slope of the outer flank of the ridge is about 12° (Kadel et al., 1998). Though there is a continuum of morphological classes among ridges (e.g., Greenberg et al., 1998; Greenberg and Geissler, 2002), observed flow-like features most commonly interact with double ridges, so we consider a double ridge here. Therefore, we generate hypothetical topography with 50–200-m-thick ridges (Fig. 5b) and perform systematic simulations of flows with wide-ranging parameters over this manufactured topography.

The systematic simulations 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. 10): (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. 11, illustrating the flow type that results from each considered combination of effusion rate, slope angle, ridge height, temperature, and ice-grain size. 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. We consider this to be a significant insight,
since it is valid regardless of the uncertainty in the thickness assessment: even if the exact thicknesses of flows and ridges remain uncertain, we can safely rule out the flow hypothesis for flow-like features that show no influence with underlying ridges as long as they have thicknesses less than ten times that of the ridges. In the figure, white boxes correspond to flows able to expand to 10-km diameter over a timescale less than the cooling timescale $H^2/\kappa$, whereas gray boxes correspond to flows that would only theoretically expand to 10-km diameter over times exceeding the cooling timescale. These gray-marked flows are therefore ruled out as an explanation for features of $\sim$10-km diameter or larger (e.g., Figs. 2c and 3a), at least for flows with a source area much smaller than the flow size. A- and B-type flows in white boxes are most possible for Europa, because they match both morphological and thermal constraints. At low effusion rates of $10^6$ m$^3$ year$^{-1}$, A- and B-type flows can result from a wide range of flow temperatures and ice-grain sizes. However, because of the low effusion rate, the time for these flows to reach $\sim$10-km diameter (typical for europen flows) exceeds the thermal diffusion timescale (Fig. 11). Large effusion rates of $10^8$ m$^3$ year$^{-1}$ also produce a range of A- and B-type flows (though over a small range of temperatures and grain sizes than flows at smaller effusion rates), but the rapid effusion rate allows all of these flows to expand to 10-km diameter over timescales less than the cooling timescale. Intermediate effusion rates of $10^6$–$10^7$ m$^3$ year$^{-1}$ show both behaviors—some flows can expand to 10-km diameter before freezing, while others cannot. Interestingly, at these intermediate effusion rates, the flows that can expand to 10 km tend to be C-type flows, while all A-type and most B-type flows would cool and stall before reaching 10-km diameter. These arguments suggest that for flows to both (i) match the observed morphology of europen flow-like features, and (ii) satisfy the thermal constraint that the flow must expand before it cools and stalls, the effusion rate must be at least $10^7$–$10^8$ m$^3$ year$^{-1}$.

Lobate features that are modestly affected by topography (e.g., Figs. 2c and 3a) may be classified as B-type flows. Our simulations indicate that solid-ice flows can only explain these features if the flow temperatures exceed 230 K (Fig. 11) and effusion rate exceeds $10^7$ m$^3$ year$^{-1}$. A wide range of grain sizes up to $\sim$100 µm is allowed.

Some flow-like features are topographically confined by ridges (e.g., several structures along the margin of the dark region in Fig. 1a that appear unable to cross ridges), so if these features actually resulted from flows, they are of A type. Within the ranges of parameters we considered, only effusion rates of $10^8$ m$^3$ year$^{-1}$, temperatures $>260$ K, and grain sizes $<2$ µm can explain these features as solid-ice flows (Fig. 11). These restrictions seem extreme, which suggests that, if these features resulted from flows, then the flows must have been liquid or slurry flows.

Several observed flow-like features cannot be classified as A- or B-type features, which argues against a flow origin for these features. For example, the chaotic, dome-like feature in Fig. 3b overlaps several ridges without influence from them; similarly, the lobate feature in Fig. 2b appears to cross several ridges with no obvious changes in width or morphology. Our simulated flows can only reproduce these characteristics when the flow thicknesses exceed that of the overlapped ridges by at least an order of magnitude (C type); in contrast, the features in Figs. 2b and 3b have heights comparable to the surrounding terrains (e.g., Carr et al., 1998; Figueredo et al., 2002; Fagents, 2003).

Furthermore, the feature in Fig. 2b has a length/width ratio of $\sim$5; our simulations can only reproduce such ob-long features when the effusion rate and ice viscosity are extremely small (Fig. 9), which is ruled out by the thermal considerations discussed previously (such flows would cool

![Fig. 10. Examples of three distinct patterns that result from the interactions between a flow and a ridge. (a) A-type feature (temperature 260 K, grain size 10 µm, inclination angle 0.5°, effusion rate $10^6$ m$^3$ year$^{-1}$, snap shot at $3 \times 10^3$ years). A flow is completely blocked or significantly affected by the ridge. (b) B-type feature (temperature 260 K, grain size 100 µm, inclination angle 2.0°, effusion rate $10^6$ m$^3$ year$^{-1}$, snap shot at $2.5 \times 10^3$ years). A flow is affected by the ridge but not significantly. (c) C-type feature (temperature 180 K, grain size 50 µm, inclination angle 0.5°, effusion rate $10^6$ m$^3$ year$^{-1}$, snap shot at $3.5 \times 10^4$ years). A flow cross over the ridge without any effect from the ridge.](image-url)
Fig. 11. Summary of systematic simulations over 150 cases. Temperature and grain size are 140–260 K (columns), and 2–100 µm (lines), respectively. Effusion rate, slope angle, and ridge thickness are, respectively, (a) $10^4 \text{ m}^3/\text{year}$, 0.5°, 100 m, (b) $10^6 \text{ m}^3/\text{year}$, 0.5°, 100 m, (c) $10^7 \text{ m}^3/\text{year}$, 0.5°, 100 m, (d) $10^7 \text{ m}^3/\text{year}$, 0.5°, 100 m, (e) $10^7 \text{ m}^3/\text{year}$, 4.0°, 100 m, (f) $10^8 \text{ m}^3/\text{year}$, 0.5°, 100 m, (g) $10^7 \text{ m}^3/\text{year}$, 0.5°, 50 m, and (h) $10^8 \text{ m}^3/\text{year}$, 0.5°, 200 m.

A, B, and C refer to A-type, B-type, and C-type features discussed in Fig. 10. 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. Some thin, flow-like features show topographically confined patterns only at their margins, and often display isolated and/or clustered promontories (knobs) inside (e.g., Fig. 1a). These structures suggest a complex formational process including heating and melting from the subsurface. Even so, the marginal features, which are clearly confined by topography, are most easily explained by fluid emplacements.

5. Conclusions

We performed numerical simulations of surface flows of ice to constrain the range of ice temperatures, effusion rates, and grain sizes that can explain the morphology of europa flow-like features. Most combinations of plausible temperatures, grain sizes, and effusion rates produce flow morphologies that do not resemble europa 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 $>10^7 \text{ m}^3/\text{year}$, 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 $<2 \mu$m. Although the grain size on Europa is unknown, values often assumed for ice shell on Europa are much larger than this value (see, e.g., McKinnon, 1999; Nimmo and Manga, 2002). 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 do not appear to be influenced by the surrounding 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.

For flows to expand to \(~10\text{-km}~\) diameter before cooling and stalling, the effusion rates must be \(10^7–10^8\text{ m}^3\text{ year}^{-1}\). Is this plausible? Suppose that a flow ascends from the ice-shell interior onto the surface through a vertical, cylindrical conduit of width \(d\). The vertical (Stokes) ascent speed of the material through the conduit is \(w \sim \Delta \rho g d^2/\eta\), where \(g\) is gravity and \(\Delta \rho\) is the density contrast and viscosity of the ascending material, respectively. Equating the effusion rate \(E \sim w d^2\), we find that

\[
d \sim \left(\frac{\eta E}{\Delta \rho g}\right)^{1/4}.
\]

If the density contrast results from thermal buoyancy alone, then \(\Delta \rho \sim \rho \alpha \Delta T \sim 5\text{ kg m}^{-3}\), where \(\rho \sim 1000\text{ kg m}^{-3}\) is the density, \(\alpha \sim 10^{-4}\text{ K}^{-1}\) is thermal expansivity, and \(\Delta T \sim 50\text{ K}\) is the thermal contrast between the ascending material and the surrounding cold lithosphere. If the density contrast results instead from compositional differences (e.g., fresh ice ascending through a salty ice lithosphere) then \(\Delta \rho\) would be larger, perhaps with an upper limit of \(200\text{ kg m}^{-3}\). Assuming \(\eta \sim 10^{14}\text{ Pas}\), \(g = 1.3\text{ m s}^{-2}\), and \(E \sim 10^7–10^8\text{ m}^3\text{ year}^{-1}\) implies that \(d \sim 1.5–2.7\text{ km}\) if the buoyancy is thermal and \(d \sim 0.6–1\text{ km}\) if the buoyancy is compositional. Creating such wide conduits would require wholesale collapse of km-wide portions of the lithosphere (as opposed to formation of simple dikes), and at present it is unclear whether this is feasible. Therefore, effusion rates of \(10^7–10^8\text{ m}^3\text{ year}^{-1}\), while large, cannot be fully ruled out.

Surface deformations due to diapirism may provide better explanations for the formations of dome-like features.

Although the model presented here provides valuable insights into icy-satellite flow processes, there are several areas where improvement is warranted. Most importantly, the model neglects thermal cooling of the flows, and we were only crudely able to determine the final flow size and morphology by postulating that the flow lifetime is approximately equal to the thermal-diffusion timescale. In the future, we plan to include vertical structure and thermal cooling of the flows, which will allow improved determination of flow behavior. We also plan to consider the possibility of finite-sized and irregularly shaped eruption vents, which could have an impact on flow morphology. A further caveat regarding the results presented here is that some flow-like features on Europa may result from multiple generations of relatively small flows; however, our constraints on flow rheology and effusion rate were derived assuming that each feature resulted from only a single flow event. Future, more detailed studies will allow a better characterization of whether multiple-flow events can help explain some of Europa’s flow-like features.

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 (e.g., Durham et al., 1992; Mangold et al., 2002), 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.

Acknowledgments

We thank William Durham for his constructive review, including valuable comments related to the impurities of ice, and an anonymous reviewer, whose comments greatly improved and significantly tightened the manuscript. This work was supported in part by JSPS Postdoctoral Fellowship for Research Abroad (to H.M.), the Italian Space Agency ASI (to G.M.), and NSF Planetary Astronomy Grant no. AST-0206269 and the NASA PG&G program (to A.P.S.).

References


