RESURFACING OF GANYMEDE BY LIQUID-WATER VOLCANISM. A.P. Showman, *Department of Planetary Sciences and Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, 85721, USA (showman@lpl.arizona.edu)*, I. Mosqueira, *NASA Ames Research Center 245-3, Moffett Field, CA 94035*, J.W. Head III, *Department of Geological Sciences, Brown University, Providence, RI 02912*.

Summary: A long-popular model for producing Ganymede's bright terrain involves flooding of low-lying graben with liquid water, slush, or warm, soft ice. The model suffers from major problems, however, including the absence of obvious near-surface heat sources, the negative buoyancy of liquid water, and the lack of a mechanism for confining the flows to graben floors. We show that topography — such as a global set of graben — causes subsurface (ahydrostatic) pressure gradients that can "suck" subsurface liquid water upward onto the floors of topographic lows (graben). As the low areas become full, the pressure gradients disappear and the resurfacing ceases. This provides an explanation for the observed straight dark-bright terrain boundaries: water cannot overflow the graben, so surfacing rarely embays craters and other rough topography. Subsurface liquid water must exist for the scenario to exist, of course, and is plausibly provided by tidal heating during an ancient orbital resonance. This abstract is a summary of Showman et al. [1] recently submitted to *Icarus*.

Introduction: About 65% of Ganymede's surface consists of bright terrain with relatively low crater densities, indicating that intense geological activity occurred between $\sim$ 1–3 Ga ago [2]. The prevailing Voyager-era view was that the bright terrain formed by flooding of a global set of graben — i.e., low-lying, fault-bounded blocks produced by lithospheric extension — with liquid water, slush, or warm, soft ice. The problem is that liquid water is denser than ice, so any liquid produced at even shallow depths will percolate downward, away from the surface, and be unavailable for volcanic resurfacing. Although resurfacing by tectonic deformation has occurred in some places [3, 4], it has difficulty explaining regions of smooth bright terrain unless cryovolcanism occurred concurrently with the tectonism, so a mechanism for cryvolcanism is still needed. Resurfacing by solid ice is possible [5], but regions of very flat, smooth bright terrain [6] are better explained by a low-viscosity agent such as liquid water or slush.

For cryovolcanism to explain Ganymede's bright terrain, two conditions must be met: First, the *eruption locations* must be confined to the graben floors. Any mechanism that allows eruption of cryvolcanic materials within topographic highs is inconsistent with observations, because the erupted materials would flow downhill toward topographic lows, leaving rilles or other obvious flow markings, which are lacking within Ganymede's dark terrain. Second, the eruptions must not overflow the graben — otherwise, chaotic bright-dark terrain boundaries that embay topography would be produced. This suggests the existence of a shut-off mechanism that terminated the eruptions before the graben overflowed.

Here we investigate how near-surface liquid water produced during ancient tidal heating events can be delivered to Ganymede surface.

Model for Melt Migration: Melting takes place first along grain boundaries, and we envision that the liquid water produced during tidal heating initially exists within an interconnected network of melt-filled pores, at grain boundaries, that constitute only a small fraction of the total volume. This melt can be flushed from the matrix in response to melt-matrix buoyancy or external forces.

The equations governing the coupled flow of a melt and matrix have been derived by several groups [7, 8]. The momentum equation governing the relative flow of melt and matrix, essentially Darcy's law, can be written in general form as [8]

$$f(v_i^{liq} - v_i^{sol}) = -\frac{k}{\eta^{liq}}\left[\frac{\partial p^{liq}}{\partial x_i} + g\rho^{liq}\delta_{iz}\right] \qquad (1)$$

where f is the melt fraction (equivalent to porosity), k is the permeability, g is gravity, p^{liq}, η^{liq}, and ρ^{liq} are the pressure, viscosity, and density of the melt, δ_{ij} is the Kronecker delta, v_i^{liq} and v_i^{sol} are the true velocities of the melt and matrix, respectively, x_i are the spatial coordinates, z is height, and $i = 1$, 2, and 3 are the coordinate indeces. Using a viscous constitutive law for the matrix, we can write Darcy's law solely in terms of the velocity fields [8]. In vector notation, the equation becomes

$$f(\mathbf{v}^{liq} - \mathbf{v}^{sol}) = \frac{k}{\eta^{liq}}[-(1-f)g\Delta\rho\mathbf{z}$$
$$-\nabla\left\{(\zeta + \frac{1}{3}\eta)\nabla\cdot\mathbf{v}^{sol}\right\} - \nabla(\eta\nabla\mathbf{v}^{sol})] \qquad (2)$$

where $\mathbf{v}^{liq}$ and $\mathbf{v}^{sol}$ are the vector velocities of the melt and matrix, $\mathbf{z}$ is the upward unit vector, and η and ζ are the shear and bulk viscosities of the matrix, respectively. Three factors affect the migration of melt relative to solid: the melt-matrix buoyancy (first term), the pressure gradient caused by gradients of matrix volume changes due to expansion and compaction (second term), and the pressure gradient caused by volume-conserving shear deformation of the matrix (third term). For Ganymede, $\Delta\rho$ is positive and the buoyancy term causes downward percolation of the melt. However, under appropriate conditions the matrix deformation terms can counteract the negative buoyancy, allowing liquid water to rise upward through the ice.

Consider the effects of surface topography. Topography causes subsurface stress fields that induce upward motion of the solid ice underneath topographic lows and downward motion underneath topographic highs, which lessens the topography over time (crater relaxation and post-glacial rebound being standard examples). The flow is effectively driven by an ahydrostatic pressure-gradient force $-\nabla(\eta\nabla\mathbf{v}^{sol})$ that points downward beneath topographic highs and upward beneath topographic lows. Through Eq. (2), this pressure-gradient force associated with matrix flow beneath topographic lows *counteracts* the negative buoyancy of the liquid water.

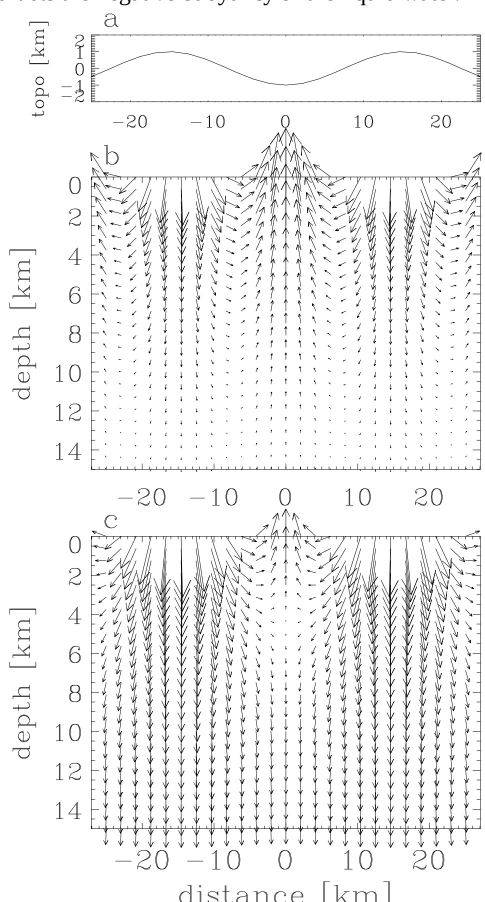

Figure 1: Subsurface pressure gradients $-\nabla p$ caused by the topography shown in (a). (b) shows pressure gradients in matrix. (c) shows pressure gradients in pore-space liquid water.

A simple two-dimensional analytical solution, assuming constant viscosity, illustrates this process. When melt fraction is constant and melting is ignored, the matrix flow is incompressible. In the limit where the melt fraction f goes toward zero, the melt has negligible influence on the matrix force balance and $\mathbf{v}^{sol}$ is governed by pressure-gradient, viscous, and gravity forces in the matrix alone. The velocity $\mathbf{v}^{sol}$ is then just determined by a standard solution for gravitational relaxation of a one-phase, viscous fluid [ref. 9, Chapter 6]. Let the satellite interior and surface correspond to an infinite half-space with a sinusoidal surface topography $h = h_0 \cos(mx)$, where m is the wavenumber equal to 2π over the wavelength, x is horizontal distance, and $h_0 m \ll 1$ (the height of the topography is much less than its wavelength). The topography provides a crude representation of horst and graben formed by lithospheric extension. We apply a no-slip boundary condition (horizontal speed equals zero) at the surface, appropriate because a stiff lithosphere overlies the partially molten region. With this condition, the matrix velocity $\mathbf{v}^{sol}$ is given by [ref. 9, pp. 238-240]

$$\mathbf{v}^{sol} = -\frac{\rho g h_0}{2\eta} z e^{mz} \sin(mx)\,\mathbf{x} - \frac{\rho g h_0}{2\eta m} e^{mz}[1 - mz]\cos(mx)\,\mathbf{z} \tag{3}$$

where $\mathbf{x}$ and $\mathbf{z}$ are the horizontal and upward unit vectors, respectively. The pressure gradients associated with the topographically induced flow are

$$-\eta\nabla^2\mathbf{v}^{sol} = \rho g h_0 m e^{mz}\left[\sin(mx)\mathbf{x} - \cos(mx)\mathbf{z}\right] \tag{4}$$

where z is height; z is zero at the surface and negative within the interior. These pressure gradients are illustrated in Fig. 1b for the two-km peak-to-peak sinusoidal topography ($h_0 = -1$ km) shown in Fig. 1a. As expected, the pressure gradients indicate that the ice flows upward underneath topographic lows and downward underneath topographic highs. From Eq. (2), the net pressure gradient affecting the melt (i.e., the quantity in square brackets in Eq. 2) is that in Fig. 1b plus the negative buoyancy of the melt. This is shown in Fig. 1c assuming $\Delta\rho = 80$ kg m^{-3}, relevant for pure liquid water and ice. The topographic pressure gradients underneath topographic lows can overwhelm the negative buoyancy of the liquid water, resulting in a net pressure gradient that drives liquid water *upward* into the topographic lows despite the liquid's negative buoyancy. Eruptions are confined solely to topographic lows (graben); furthermore, as the graben fill, the topography — hence pressure gradients — disappear and the resurfacing automatically ceases. Water therefore cannot overflow the graben. Therefore, the straight bright-dark terrain boundaries and absence of cryovolcanic flow features extending from high-altitude dark terrain into lower-altitude bright terrain can be naturally explained.

A range of calculations [1] shows that liquid can be pumped from up to ∼10 km depth. Plausible ancient tidal heating events [1, 10] could cause melting at 5–10 km depth, at least in some regions, suggesting that liquid was available to be pumped upward to the surface. Alternately, if open extension fractures can form during graben formation, the pressure gradients might act to drive slush onto the graben floors. Because slush is almost neutrally buoyant, the relevant pressure gradients are those in Fig. 1b, and so slush can be pumped from depths exceeding 20 km. A challenge for these models is the short predicted gravitational relaxation timescales of topographic features at high heat flows; the resurfacing must occur before the topography disappears.

References: **[1].** Showman, A.P., I. Mosqueira, and J.W. Head III, submitted to Icarus (2004). **[2].** Pappalardo, R.T., et al, in *Jupiter: Planet, Satellites, and Magnetosphere* (2004). **[3].** Pappalardo, R.T., et al., Icarus 135, 276-302 (1998). **[4].** Head, J.W., R. Pappalardo, G. Collins, and R. Greeley, LPSC XXVIII, 535-536 (1997). **[5].** Kirk, R.L. and D.J. Stevenson, Icarus 69, 91-134 (1987). **[6].** Schenk, P.M., W.B. McKinnon, D. Gwynn, and J.M. Moore, Nature 410, 57-60 (2001). **[7].** McKenzie, D., J. Petrology 25, 713-765 (1984). **[8].** Scott, D.R., JGR 93, 6451-6462 (1988). **[9].** Turcotte, D.L. and G. Schubert, *Geodynamics*, 2nd ed (2002). **[10].** Showman, A.P. and R. Malhotra, Icarus 127, 93-111 (1997).