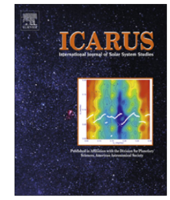
Icarus 227 (2014) 206–209

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus



Note

Formation of Ganymede's grooved terrain by convection-driven resurfacing

Noah P. Hammond *, Amy C. Barr

Department of Geological Sciences, Brown University, Providence, RI 02912, USA

ARTICLE INFO

Article history:
Received 3 July 2013
Revised 20 August 2013
Accepted 21 August 2013
Available online 3 September 2013

Keywords:
Ganymede
Jupiter
Tectonics

ABSTRACT

The heat flux and strain rate inferred for grooved terrain formation on Ganymede can be produced in a convecting ice shell 10–100 km thick with weak near-surface ice. Smooth linear grooves may have formed by convection-driven lithospheric spreading and long-wavelength compressional folds may form atop convective downwellings, and would possibly be detectable with mapping from ESA's upcoming Jupiter-Icy Moon Explorer Mission.

1. Introduction

Over half the surface of Ganymede, Jupiter's largest satellite, is covered in grooved terrain, composed of 10–100 km wide linear and polygonal swaths (Collins et al., 1998) of sub-parallel ridges and troughs (Murchie et al., 1986; Pappalardo, 1998). The ridge and trough spacing is ∼7 km, though they are often subdivided by narrower grooves 100 m −1 km wide (Pappalardo, 1998). A subset of groove lanes, which we refer to as "subdued grooves", have straight margins and relatively constant widths over large distances (Head, 2002) and are characterized by subdued light material (Patterson et al., 2010).

Grooved terrain is thought to have formed during an era of global surface expansion (Smith, 1979) resulting from satellite differentiation (Squyres, 1980) or from the melting of the ice I shell when Ganymede entered a possible Laplace-like resonance with Europa and Io (Showman et al., 1997; Bland et al., 2009). Subparallel grooves may form by tilt-block style normal faulting (Pappalardo, 1998) due to tensional stresses in the lithosphere.

Convection in the ice shell has been suggested as a driving mechanism for grooved terrain formation (Lucchitta, 1980; Parmentier et al., 1982), because it can operate globally and generate zones of intense local deformation (Shoemaker et al., 1982). Head (2002) argued that subdued grooves form in a similar way to extensional bands on Europa, which likely form by a convection-driven midocean rift-type mechanism (Prockter et al., 2002).

Previous work argues that convective stresses were not strong enough to drive surface deformation on Ganymede (Squyres and Croft, 1986); convective plumes were thought to be confined below a "stagnant lid", a highly viscous layer of ice which inhibits resurfacing (Solomatov, 1995). However, if the near-surface has a yield stress comparable to the thermal buoyancy stresses from convection, plumes can approach the surface, leading to deformation and efficient heat transport (Trompert and Hansen, 1998; Tackley, 2000; Solomatov, 2004; Showman and Han, 2005). This style of "sluggish lid" convection may be occurring beneath the active South Polar Terrain (SPT) of Enceladus (Barr, 2008). The observed heat flow and surface age of the Enceladus SPT are consistent with heat flows and deformation rates associated with sluggish lid convection (Barr, 2008; Han et al., 2012).

On Ganymede, surface conditions may also have been consistent with sluggish lid convection. Models of flexural uplift estimate a heat flux of 100–200 mW m^{-2} for grooved terrain (Nimmo et al., 2002), and a heat flux of 60–80 mW m^{-2} for the adjacent dark terrain (Nimmo and Pappalardo, 2004). While heat flow estimates based on flexure are somewhat uncertain, independent estimates based on models of groove terrain formation by extensional necking predict a similar heat flux of ∼50 mW m^{-2} (Bland et al., 2010). Extensional necking models also predict strain rates between 10^{-16} and 10^{-13} s^{-1} for high-relief grooved material (Dombard and McKinnon, 2001; Bland and Showman, 2007), close to strain rates inferred from folds observed in between the tiger stripes of the SPT (Barr and Preuss, 2010).

Here, we simulate solid-state convection in an ice shell with a weak upper surface to show that the heat flow and deformation rates arising from sluggish lid convection are consistent with the

* Corresponding author. Address: Department of Geological Sciences, Brown University, 324 Brook Street, Box 1846, Providence, RI 02912, USA. Fax: +1 (401) 863 2058.

E-mail address: noah_hammond@brown.edu (N.P. Hammond).

0019-1035/$ - see front matter
http://dx.doi.org/10.1016/j.icarus.2013.08.024

conditions inferred for grooved terrain formation. Subdued grooves may be areas where convection drove complete lithospheric separation, whereas other grooves may form in response to subsurface flow above a convective upwelling (Lucchitta, 1980).

2. Methods

We use the two-dimensional Cartesian finite element model CITCOM (Moresi and Solomatov, 1995) to simulate solid state convection in Ganymede's ice shell. We explore a wide range of ice shell conditions by varying the basal Rayleigh number, Ra_1, which governs the vigor of convection and is related to D, the ice shell thickness,

$$Ra_1 = \frac{\rho g \alpha \Delta T D^3}{\kappa \eta_1}, \tag{1}$$

with ice density ρ = 1000 kg m^{-3}, surface gravity g = 1.4 m s^{-2}, coefficient of thermal expansion $\alpha = 10^{-4}$ K^{-1}, basal viscosity η_1, thermal diffusivity $\kappa = 10^{-6}$ m^2 s^{-1}, and ΔT = 150 K is the difference between the temperature at the base (260 K) and the surface (110 K) of the ice shell. With these parameters, $Ra_1 = 2.1 \times 10^8 (D/100\ \text{km})^3 (10^{14}\ \text{Pa s}/\eta_1)$.

We use a simple temperature dependent viscosity (Solomatov and Moresi, 2000), $\eta(T) = \eta_0 \exp(-\gamma T)$, where $\gamma = \theta/\Delta T$, $\theta = \ln(\Delta\eta)$, and $\Delta\eta = \eta_0/\eta_1$ is the viscosity contrast between ice at the surface (η_0), and ice at the base of the shell. On Ganymede, the $\Delta\eta$ predicted for an ice shell deforming by Newtonian volume diffusion is very large (Goldsby and Kohlstedt, 2001), and convection is predicted to occur in the stagnant lid regime. However, the effective viscosity of the surface can be dramatically reduced if convective stresses exceed the lithospheric yield stress (Solomatov, 2004), leading to so-called "sluggish lid" convection. Previous work shows that sluggish lid behavior can occur on Enceladus and Europa for surface yield stress <100 kPa (Showman and Han, 2005; Barr, 2008; O'Neill and Nimmo, 2010). Here, we limit the effective viscosity of surface by imposing a low $\Delta\eta$, which is the simplest way of mimicking the effect of brittle surface ice with a low yield stress (Barr, 2008). We use $\eta_1 = 10^{14}$ Pa s, for an ice grain size ~0.1 mm (Barr and McKinnon, 2007).

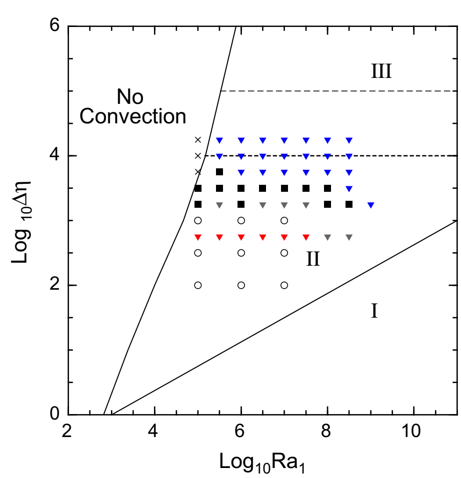


Fig. 1. Values of Rayleigh number (Ra_1) and viscosity contrast ($\Delta\eta$) explored in this study. Black squares represent simulations which successfully match heat flux estimates based on flexure for grooved terrain and dark terrain at strain rates inferred from models of extensional necking. Inverted triangles show simulations that do not meet these criterion, with blue showing those with a heat flow that is too low, gray showing those with an average strain rate exceeding 10^{-13} s^{-1}, and red showing simulations with an average heat flux exceeding 200 mW m^{-2} in regions of extension. "x" symbols show simulations that do not convect and empty circles represent simulations run for the Enceladus SPT by Barr (2008). Lines indicate the boundaries between convective regimes: isoviscous (I), sluggish lid (II), and stagnant lid (III). Dashed lines indicate gradual transition from sluggish lid regime to stagnant lid regime.

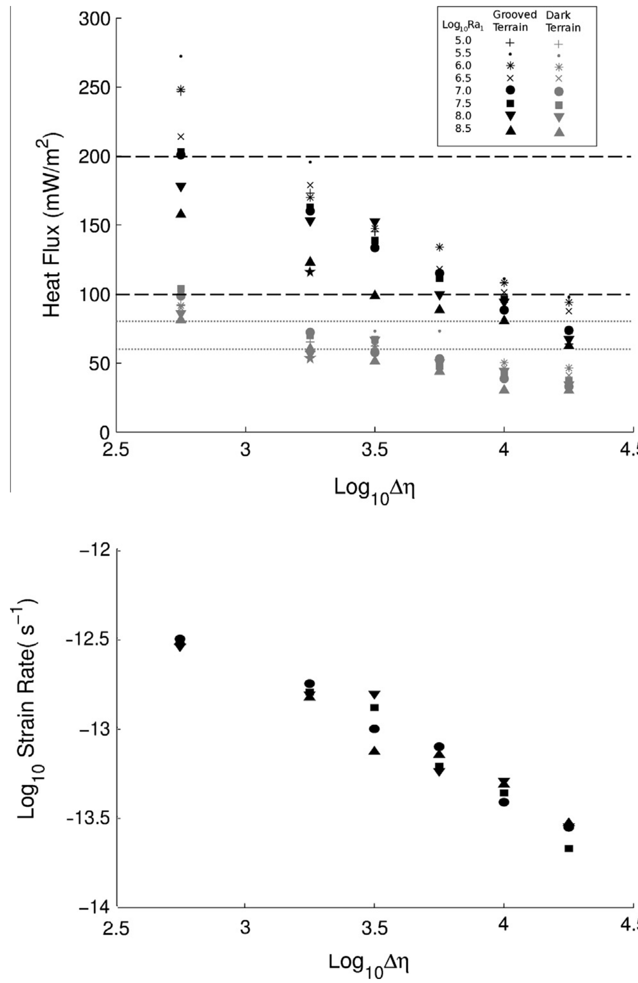


Fig. 2. (top) Heat flux of convection simulations plotted as a function of viscosity contrast. Basal Rayleigh numbers of $\log_{10}(Ra_1)$ = (5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5) are plotted with the symbols, (indicated in legend), plus, dot, asterisk, cross, circle, square, inverted triangle and upright triangle, respectively. Star symbols represent one simulation for $Ra_1 = 10^9$. Black symbols represent average heat flux in regions of extension, and gray symbols show the average heat flux in regions of contraction. Black dashed lines show estimated heat flux for grooved terrain. Gray dotted lines show estimate heat flux for dark terrain. (Bottom) Surface strain rate of convection simulations plotted as a function of viscosity contrast. Basal Rayleigh numbers represented by same symbols as above, although many overlap and are not visible.

We simulate convection for $\Delta\eta$ between $10^{2.75}$–$10^{4.25}$, close to the boundary between the sluggish lid regime and stagnant lid regime, $\Delta\eta \sim 10^4$–10^5 (Solomatov, 1995). We model convection in an 8 × 1 domain, with 512 × 64 elements, with periodic boundary conditions at the sides to minimize edge effects. We use a basally heated ice shell because the spatial distribution of tidal dissipation in a convecting ice shell is not fully understood (Han and Showman, 2010). Additionally, surface deformation rates and heat flow are likely insensitive to the precise mode of heating (Solomatov and Moresi, 2000). We allow all our simulations to reach a steady state, then measure how strain rate and heat flux vary at the surface.

The convective heat flux, $F = \frac{k\Delta T}{D} Nu$, where k = 3.3 W m^{-1} K^{-1} is the thermal conductivity and Nu is the Nusselt number, which describes the efficiency of convective versus conductive heat transport. The strain rate is approximated by $\dot{\varepsilon} = (\partial v_{xsf}/\partial x)$, where v_{xsf}