grain sizes, but negative feedbacks occur for small grain sizes.

5.2.2. The difficulty of fracturing the surface. Thermal convection causes typical stresses of 10^{-3}–10^{-2} MPa, which is much smaller than the ~1–3-MPa failure strength of unfractured ice. This discrepancy raises difficulties for understanding how solid-state convection can induce surface disruption.

However, several factors could ameliorate this difficulty. First, Europa's surface shows abundant evidence that *tidal* stresses, which reach ~0.1 MPa at Europa's current eccentricity, have fractured the surface (*Greenberg et al.,* 1998; *Hoppa et al.,* 1999). For example, models for the formation of Europa's cycloidal ridges suggest a fracture yield stress of just 0.04 MPa (*Hoppa et al.,* 1999). Field studies on the Ross Ice Shelf, one of Earth's closest analogs to Europa's ice shell, also exhibit failure strengths of order 0.1 MPa (*Kehle,* 1964). While not definitive, these studies are consistent with the idea that Europa's near-surface ice is weak, but it is not clear whether these estimates are appropriate for the failure of Europa's entire lithosphere. If, for example, cycloids are relatively shallow phenomena, the relatively low stress associated with cycloid propagation may be relevant to Europa's near-surface ice only. If Europa's band topography forms in a manner similar to terrestrial mid-ocean ridges (*Prockter et al.,* 2002), the yield strength of Europa's lithosphere at the time and location of band formation is ~0.4 to 2 MPa (*Stempel et al.,* 2005). Another approach may be to consider the effects of microcracking on the rheology of near-surface ice (*Tobie et al.,* 2004). Between a depth of ~15–40 km on Earth, microcracks are expected to play a role in accommodating deformation, and facilitate semibrittle-plastic behavior that is conductive to forming zones of weakness in the crust (*Kohlstedt et al.,* 1995; *Tackley,* 2000a; *Bercovici,* 2003). Further field characterization of relevant terrestrial analogs and studies of flexure and failure on Europa constrained by new spacecraft data are needed to shed light upon this issue.

Second, *Showman and Han* (2005) pointed out that stresses can become greatly enhanced within a thin "stress boundary layer" near the surface, promoting the likelihood of surface fracture. This phenomenon results from the need to balance forces in a lithosphere whose width far exceeds its thickness (*Melosh,* 1977; *Fowler,* 1985, 1993; *McKinnon,* 1998; *Solomatov,* 2004a,b). To illustrate, consider a two-dimensional lithosphere with horizontal dimension x and vertical dimension z. Horizontal force balance in the lithosphere leads to the stress equilibrium condition

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xz}}{\partial z} = 0 \qquad (33)$$

where σ_{xx} and σ_{xz} are the horizontal normal and shear stresses, respectively. The shear stress is zero at the surface but due to convection (or other processes) is nonzero in the interior. Suppose the shear stress at the base of the stress boundary layer is σ_b. For a stress boundary layer of thickness h that experiences this shear stress over a horizonal distance L, we have to order of magnitude

$$\sigma_{xx} \sim \frac{L}{h}\sigma_b \qquad (34)$$

The appropriate value for h is the viscosity scale height in the lithosphere (*Solomatov,* 2004a), which is ~1 km for europan conditions. The interior convective stresses should remain coherent over distances L comparable to the interplume spacing, which is similar to the ice-shell thickness. Adopting L ~ 20 km, we thus see that stresses can become enhanced by a factor of ~20 within the stress boundary layer. In agreement with this estimate, numerical simulations by *Showman and Han* (2005) show that, although convective stresses within the ice-shell interior are typically ~10^{-3}–10^{-2} MPa, the normal stresses due to thermal convection can exceed ~0.1 MPa near the surface.

Third, the stresses that occur during compositional convection in a heterogeneous salty ice shell would far exceed those due to thermal convection alone. For the density contrasts needed to explain ~300 m-tall uplifts ($\Delta\rho \sim 30$ kg m^{-3} over a height range h ~ 10 km), typical convective stresses are ~$\Delta\rho g h \sim 0.4$ MPa. In the presence of a stress boundary layer, near-surface stresses could be enhanced by an additional order of magnitude or more. These values exceed those needed to fracture ice. Thus, the idea that convection can fracture the surface seems reasonable.

5.2.3. Can convection produce a chaos-like morphology? To test the hypothesis that convection can cause formation of chaos-type terrains, *Showman and Han* (2005) performed two-dimensional numerical simulations of thermal convection in Europa's ice shell including the effects of plasticity, which is a continuum representation for deformation by brittle failure. Plastic deformation occurs when the deviatoric stresses reach a specified yield stress σ_Y; at lower stresses, the rheology corresponds to a Newtonian, temperature-dependent viscosity (cf. *Trompert and Hansen,* 1998; *Moresi and Solomatov,* 1998; *Tackley,* 2000b). Partial melting and salinity were not considered. These simulations showed four regimes of behavior depending on the yield stress, thickness of the ice shell, and other parameters. At large yield stresses (≥0.1 MPa), the stresses never attain necessary values for plastic deformation, and so stagnant-lid convection occurs. At modestly smaller yield stresses (~0.03–0.08 MPa), a thick, cold upper lid remains, but it deforms via plastic deformation (see Fig. 5). *Showman and Han* (2005) dubbed this the "pliable lid" regime. Most of the plastic deformation is confined near the surface, as a result of the stress boundary layer. At even smaller yield stresses (<0.05 MPa), the convection moves away from stagnant-lid regime, exhibiting either episodic foundering and regrowth of the lid (see Fig. 6) or continual recycling of the lid.

What is the connection between these simulations and Europa's chaotic terrain? The formation of chaos requires not only surface fracture but sufficient strains to rotate and translate surviving chaos rafts and disaggregate the inter-