**CAN CONVECTION START IN ENCELADUS' ICE SHELL?** Amy C. Barr[1] and William B. McKinnon[2], [1]Department of Space Studies, Southwest Research Institute, 1050 Walnut St., Suite 400, Boulder, CO 80302 (amy@boulder.swri.edu); [2]Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, Saint Louis, MO 63130.

**Introduction:** Observations of Enceladus by *Cassini* indicate that this tiny Saturnian moon is geologically active, with plumes of water vapor and dust erupting from its southern polar region [1,2]. The activity near Enceladus' south pole suggests that tidal dissipation has become spatially localized in this region, perhaps due to a compositional, rheological, and/or thermal anomaly in its ice shell (and which may have led to its reorientation [3]). Here we examine the role that solid-state convection may have played in driving Enceladus' prolific activity by creating a suitable rheological and thermal anomaly. We find convection can initiate in a pure ice I shell of a differentiated Enceladus if the ice grain size is <1 mm. This grain-size restriction becomes more severe for lower basal temperatures, which argues against a cold, ammonia-rich ocean. We discuss the likely interior structure of Enceladus, ice rheology, the conditions required for convection, and expected convective heat flux [4].

**Interior Structure:** Enceladus' mean density is 1608.3 kg $m^{-3}$ and its mean radius 252.1 km [2]. We assume that tidal heating in the past provided enough heat for Enceladus to differentiate. Calculations with ICYMOON [5] suggest two possible structures for a differentiated Enceladus: a hydrated silicate core of radius 170 km and density 3200 kg $m^{-3}$ overlain by a solid $H_2O$ layer 85 km thick, or a smaller dehydrated silicate core (density 3700 kg $m^{-3}$) overlain by an ice shell 95 km thick (Fig. 1.).

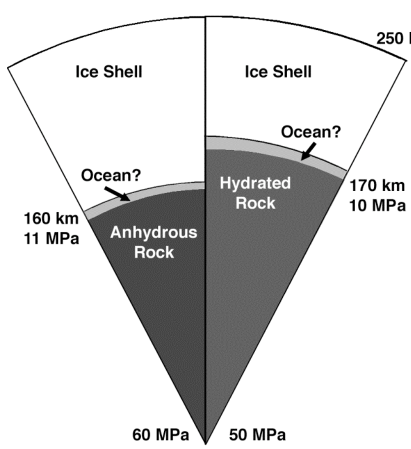


Figure 1. Interior of a differentiated Enceladus based on solar-composition rock [5] and an updated iron abundance [6]. An internal liquid layer may exist at the base of the pure ice I ice shell, but the thicker the ocean, the smaller the rock core.

**Can Convection Initiate?** We examine the likelihood of triggering convection on Enceladus' ice shell, following [7–9], who investigate the conditions under which convection may start in an icy satellite given the complex Newtonian and non-Newtonian rheology for ice I. Strain in ice I is accommodated by volume diffusion, grain-size-sensitive (GSS) creep, and dislocation creep [e.g., 10]. The strain rate for each deformation mechanism depends on temperature, grain size (for GSS creep and volume diffusion), and stress (GSS and dislocation creep).

A thermal anomaly of amplitude $\delta T$, plausibly caused by tidal heating, acting over a vertical length scale $h$ in Enceladus' ice shell will give rise to a thermal buoyancy stress,

$$\sigma_{th} \sim \rho g \alpha \delta T h = 1.6 \left(\frac{g}{0.11 \text{ m s}^{-2}}\right)\left(\frac{h}{10 \text{ km}}\right) \text{kPa}, \quad (1)$$

where $\alpha$ = coefficient of thermal expansion $\rho$ = ice density, and $g$ = local gravity (0.11 m $s^{-2}$ at the surface). Because such driving stresses are low, strain during the onset of convection is likely accommodated by volume diffusion for relatively small ice grain sizes ($d$). For larger $d$, strain should be accommodated by GSS creep. Dislocation creep requires much larger stresses to activate, so we neglect it here.

In an ice shell of thickness $D$ with a composite rheology, deformation during the onset of convection is controlled by the microphysical deformation mechanism that predicts the largest strain rate (or equivalently, the smallest viscosity) close to the base of the shell [7]. The convective stability criterion for the shell's base, and by extension, the entire ice shell is, $Ra_1 > min(Ra_{cr,diff}, Ra_{cr,GSS})$. Because the Rayleigh number $Ra \propto D^3$, the minimum ice shell thickness where convection can occur is $D_{cr} = min(D_{cr,diff}, D_{cr,GSS})$. We can ignore spherical geometric effects, or correct for them [8], because near the critical $Ra$, the thickness of the convecting sublayer is small compared to $D$.

For volume diffusion, $Ra_{cr,diff} = 20.9\theta^4$, where $\theta = 1.2Q^*\Delta T/RT_i^2$, $Q^*$ = activation energy, $\Delta T$ is the temperature drop across the shell, $R$ the gas constant, and the 1.2 roughly corrects for the F-K approximation [4]. If the basal temperature of the ice shell ($T_b$) is the melting point of pure water ice I (~270 K), and the surface temperature of Enceladus is 70 K, $\theta$~24, and $Ra_{cr,diff}$ = 7 x $10^7$. The critical $D$ where convection may start is given by setting $Ra_{cr,diff} = Ra_1$, where $Ra_1 = (3A\rho g\alpha\Delta TD^3)/(\kappa d^p \exp(Q^*/RT_b))$, $A = 1.1 \times 10^{-10}$ m$^2$ Pa$^{-1}$ s$^{-1}$ for $T_b = 270$ K, grain size exponent $p = 2$, and $\kappa$ = thermal diffusivity. The ice grain size $d$ is considered a free parameter.

We assume that grain-size-sensitive creep occurs due to grain boundary sliding in ice I [10]. If strain during the onset of convection is accommodated by GSS creep, a finite-amplitude perturbation is *required* to start convection in the ice shell. The critical Rayleigh number for GSS creep, therefore, represents the absolute minimum *Ra* where convection can *continue*, or where convection can be triggered from a large temperature perturbation [7,9]. For rheological parameters appropriate for GBS [10], $Ra_{cr,gss}=4.2 \times 10^4$.

Putting it all together for volume diffusion, the critical ice shell thickness where convection can occur in a differentiated Enceladus is

$$D_{cr,diff} = 134 \text{ km} \left(\frac{d}{1 \text{ mm}}\right)^{2/3} . \quad (2)$$

For GSS creep, the absolute critical ice shell thickness where convection may continue or may be triggered from a large temperature fluctuation is, for Enceladus-specific parameters and $T_b$=270 K,

$$D_{cr,GSS} = 105 \text{ km} \left(\frac{d}{1 \text{ mm}}\right)^{(1.4/3.8)} . \quad (3)$$

Figure 2 summarizes the relationship between the critical ice shell thickness for convection, ice grain size, and ice rheology for Enceladus' ice shell. We note that if the basal temperature of the ice shell is depressed by the presence of non-water-ice materials with low melting points, such as ammonia and sulfate salts, this decreases the likelihood that convection can occur, because the critical Rayleigh number increases sharply as $T_b$ decreases.

**Convective Heat Flux:** If volume diffusion accommodates convective strain in an actively flowing ice shell, the convective heat flux depends solely on ice grain size: $F_{conv} \sim 4.8$ mW m$^{-2}$ $(d/1 \text{ mm})^{-2/3}$.

**Conclusions:** We find that convection can occur in the pure water ice I shell of a differentiated Enceladus if the ice grain size is less than 1 mm, which may be realistic if non-water-ice impurities keep grains small. Grain sizes can be kept this small by tiny rock particles (as in terrestrial ice cores [11]). Enceladus plume particles do contain a very small rock fraction (H. Waite, pers. comm.). Other plausible second-phase "pinning" contaminants are clathrates and hydrated sulfates. We note that if the ice shell is dominated by clathrate, as recently proposed [12], it would be too stiff to convect (based on existing rheological measurements and the expectation that diffusion is more difficult given the large clathrate unit cell and guest molecules).

The grain-size restriction becomes more severe for lower basal ice temperatures, which implies that any ammonia in Enceladus' interior has not become strongly concentrated in a thin basal ocean. For a pure ice shell, convective heat flows are low compared with the ~250 mW m$^{-2}$ measured for Enceladus' south polar terrain [1]. Thus whereas solid-state convection may be a prerequisite for Enceladus' geological activity, the observed heat flow requires strong tidal dissipation within the convecting region. The persistence of convection in the presence of strong internal (tidal) heating may not require such small ice grains.

**Acknowledgement:** This work supported by NASA Outer Planet Research Program grant NNG05GI15G.

**References:** [1] Spencer J. R. et al. (2006) *Science 311*, 1401-1405. [2] Porco C. C. et al. (2006) *Science 311*, 1393-1401. [3] Nimmo, F. and Pappalardo R.T. (2006) *Nature 441*, 614-616. [4] Barr A. C. and McKinnon W.B. (2006) *GRL*, submitted. [5] Mueller S. and McKinnon W.B. (1988) *Icarus 76*, 437-464. [6] Lodders K. (2003) *Astrophys. J. 591*, 1220-1247. [7] Barr A.C. and Pappalardo R.T. (2005) *JGR 110*, E12005. [8] McKinnon W. B. (2006) *Icarus 183*, 435-450. [9] Solomatov V. S. and Barr A.C. (2006) *PEPI 155*, 140-145 (2006). [10] Durham W. B. and Stern L.A. (2001). *AREPS 29*, 295-330. [11] Barr A.C. and McKinnon W.B. (2007), *JGR 112*, in press. [12] Kieffer S.W. et al. (2006) *Science 314*, 1764-1766.

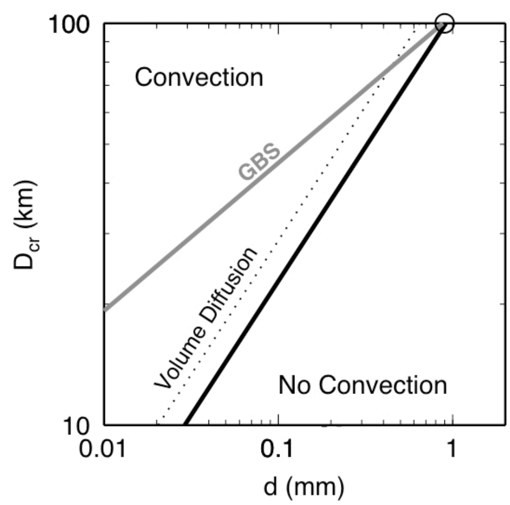


Figure 2. Critical ice shell thickness ($D_{cr}$) in a pure water ice shell ($T_b$ = 270 K) with a composite Newtonian and non-Newtonian rheology for ice I as a function of grain size $d$. For a given $d$, convection can be triggered from small temperature fluctuations in an ice shell where $Ra_1 > Ra_{cr,diff}$ for volume diffusion (dotted line), or may continue in a slightly thinner ice shell (black line). In ice shells with $d > 0.9$ mm, strain during the onset of convection is controlled by GSS creep, so convection can occur if $Ra_1 > Ra_{cr,gss}$ (gray line), provided a optimal, finite-amplitude initial temperature perturbation is generated in the shell to lower its viscosity, e.g., by tidal dissipation.