NON-NEWTONIAN DIAPIRISM IN THE ICY SATELLITES; P.J. Thomas, NASA Ames Research Center, Moffett Field, CA 94035, and G. Schubert, Department of Earth and Space Sciences, UCLA, Los Angeles, CA 90024

Resurfacing is observed on a number of the icy satellites (1). If it is to be an endogenic process, the presence of a minor constituent volatile (such as NH_3) is required for partial melting to occur (2,3). Diapirism may then occur if the temperature is sufficiently high for ice to deform in a viscous manner. The strong stress-dependence of ice rheology at temperatures appropriate to icy satellite interiors ($\dot{\varepsilon} \propto \tau^n$, where $\dot{\varepsilon}$ is strain-rate, τ is effective stress and $n \approx 4.0$ (4)) is likely to significantly influence the drag forces acting on rising diapirs. We examine here only the isothermal case, appropriate to a rapidly rising diapir (without time to cool or heat the surroundings) or a diapir with buoyancy due to a compositional difference. Table 1 compares rise times for diapirs with radius 10 km and density difference with the surroundings 300 kg m^{-3} with non-Newtonian (4) and Newtonian (5) rheologies. The power-law rheology can, at sufficiently high temperatures, reduce the rise times of diapirs compared to those of a Newtonian and facilitate the occurence of diapirism on the small Saturnian satellites in short geological times.

A simple assessment of diapirism in a power-law fluid can be obtained by using the variation of stress τ in the simple constant viscosity Stokes law case to estimate the variation of viscosity with radial distance from the center of a spherical diapir. Detailed numerical modelling of the mechanical flow of power-law fluids gives stresses that are at least in order-of-magnitude agreement with those in corresponding Newtonian cases (6). Perpendicular to the diapir's motion, $\tau \propto Ua^3r^{-4}$ where U is the diapir's speed, r is the radial distance from the center of the diapir, and a is the diapir radius. Given the power-law rheology above, $\eta \propto (Ua^3r^{-4})^{1-n}$.

The tendency of the power-law rheology to produce low viscosities in response to high stresses has been examined previously for crater relaxation (6). For diapirism, power-law rheology favors the motion of large, low density diapirs on satellites with high gravitational acceleration. Thus, diapirism may be more important on the larger icy satellites. Furthermore, large melt volumes may occur due to incorporation of smaller, slower diapirs within larger, faster diapirs.

In a power-law fluid, a rising diapir will be surrounded by a lubricating layer with substantially lower viscosity than that of the fluid at some distance. This layer will only be able to effectively reduce the drag on the diapir provided that its thickness δ is not too small compared to a (8). The variation of viscosity close to the diapir is illustrated in Fig. 1. The thickness of the lubricating layer varies as $\delta \propto e^{1/(4(n-1))}-1$. For $n = 4.8$, appropriate h ice at icy satellite temperatures (4) $\delta \approx 0.1a$. A value of $\delta/a \approx 0.1$ appears to be too small for effective lubrication (8,9), but detailed numerical simulations are underway to confirm this. A more complete understanding of diapirism in power-law fluids is important for models of differentiation of the icy satellites (10) and proposed large scale diapirism below multi-ring basins (11,12).

Table 1. Ascent times of 10 km radius spherical diapirs in the icy satellites. $T = 0.6T_m = 164K$

	Ganymede ($g = 1.5\ ms^{-2}$)	Dione, Rhea ($g = 0.2\ ms^{-2}$)	Mimas, Enceladus ($g = 0.08\ ms^{-2}$)
τ(Pa)	4.5×10^6	6×10^5	2.4×10^5
$\eta_{n=1}$(Pa s)	1.68×10^{21}	1.68×10^{21}	1.68×10^{21}
$\eta_{n=4.8}$(Pa s)	1.90×10^{17}	4.02×10^{20}	1.31×10^{22}
$t_{r\ n=1}$ (yr)	3.6×10^8	2.7×10^9	6.7×10^9
$t_{r\ n=4.8}$ (yr)	4.0×10^4 *	6.4×10^8	5.2×10^{10}

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$T = 0.8T_m = 218K$			
τ (Pa)	4.5×10^6	6×10^5	2.4×10^5
$\eta_{n=1}$ (Pa s)	5.58×10^{16}	5.58×10^{16}	5.58×10^{16}
$\eta_{n=4.0}$ (Pa s)	1.20×10^{13}	5.06×10^{15}	7.90×10^{16}
$t_{r\ n=1}$ (yr)	1.18×10^4 *	8.84×10^4 *	2.21×10^5 *
$t_{r\ n=4.0}$ (yr)	2.54 *	8.02×10^3 *	3.13×10^5 *

The viscosity laws adopted here are $\eta_{n=1} = 10^{14} \exp\left[25\left(\frac{273}{T} - 1\right) \right]$ (5) and $\eta_{n>1} = \frac{1}{3A} \exp\left(\frac{Q}{RT}\right)\tau^{1-n}$.

For $T < 195K$, $n = 4.8$, $Q = 29 \text{kJ mol}^{-1}$, $A = 1.58 \times 10^{-34} \text{Pa}^{-4.8}\text{s}^{-1}$.
For $195K < T < 240K$, $n = 4.0$, $Q = 61 \text{ kJ mol}^{-1}$, $A = 1.26 \times 10^{-19} \text{Pa}^{-4.0}\text{s}^{-1}$ (4).
$\tau = \Delta\rho g a$, where $\Delta\rho = 300 \text{kg m}^{-3}$ and $a = 10^4$ m. $t_r = \frac{3\eta\ell}{a^2 g\Delta\rho}$, where $\ell = 10^5$ m.

* Ascent time is less than or equal to the conduction cooling time $a^2/\kappa \simeq 10^8 \text{ m}^2/10^{-6}\text{m}^2\text{s}^{-1} \simeq 3.2 \times 10^6$ yr.

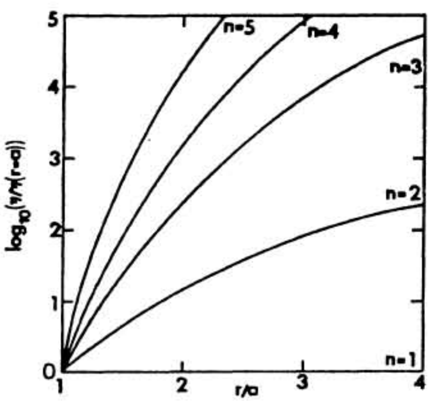

Fig. 1 Viscosity (normalized to its value at the diapir's surface) vs. radius for various values of stress exponent.

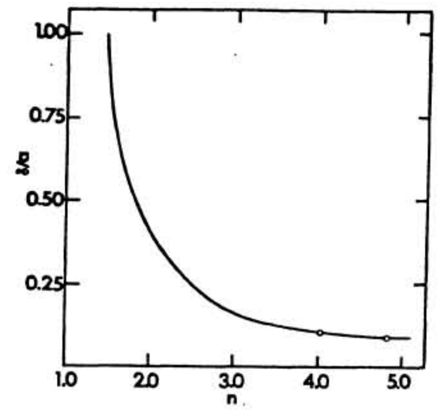

Fig. 2 Lubrication layer thickness (normalized to diapir radius) vs. stress exponent. The curve is marked at n = 4.0 and n = 4.8, values appropriate to the ice rheologies in this study.

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