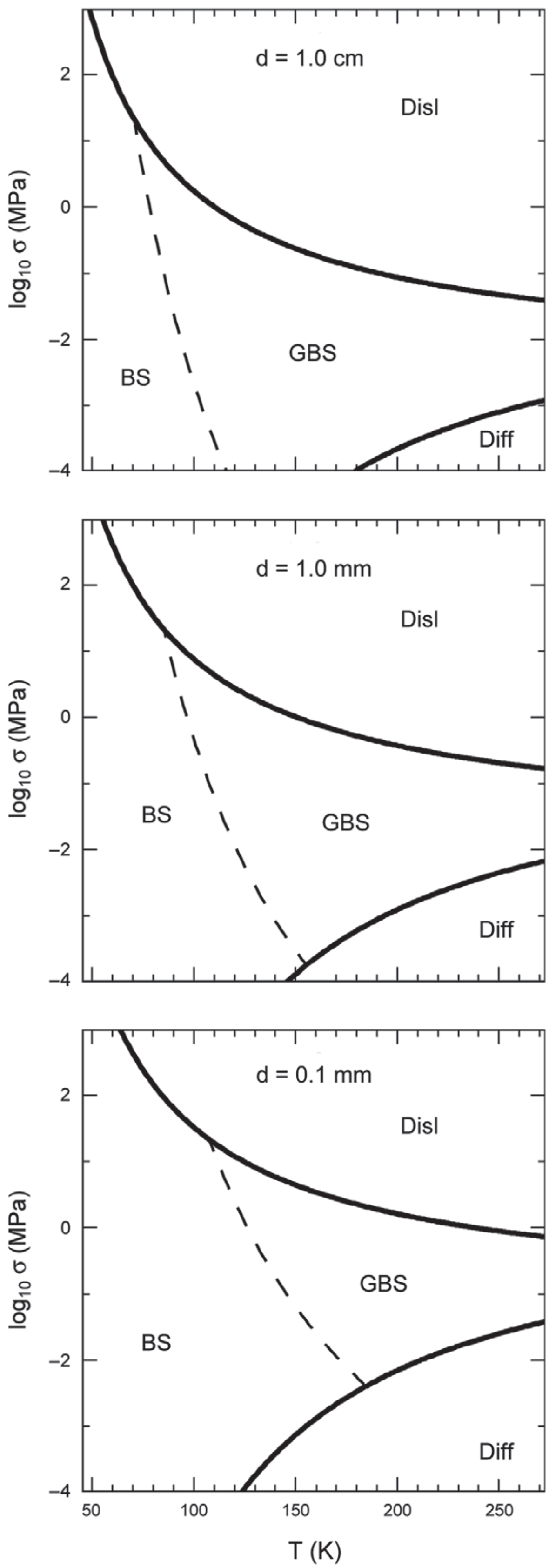

Fig. 2. Deformation maps for ice I using the rheology of *Goldsby and Kohlstedt* (2001), for ice with grain sizes of 1.0 cm, 1.0 mm, and 0.1 mm. Lines on the deformation map represent the transition stress between mechanisms as a function of temperature. From *Barr et al.* (2004).

Moresi, 2000) ~O(1 km). Like most rock-forming minerals, ice is thought to deform by diffusion creep at low stresses, high temperatures, and in materials with small grain size. Diffusion creep occurs by two processes: volume diffusion creep (Nabarro-Herring creep) and grain boundary diffusion creep (Coble creep) (*Goodman et al.,* 1981)

$$\dot{\varepsilon}_{diff} = \frac{42V_m\sigma}{3RTd^2}\left(D_v + \frac{\pi\delta}{d}D_b\right) \tag{12}$$

where σ is differential stress, R = 8.314 J mol^{-1} K^{-1} is the gas constant, d is grain size, D_v is the rate of volume diffusion, δ = 2b is the grain boundary width, b is Burger's vector for ice, V_m is the molar volume, and D_b is the rate of grain boundary diffusion (*Goldsby and Kohlstedt,* 2001). Each diffusion coefficient is strongly temperature-dependent, $D_v = D_{o,v}\exp(-Q_v/RT)$, and $D_b = D_{o,b}\exp(-Q_b/RT)$. Note also that the strain rate from diffusion creep is grain-size dependent.

To date, diffusion creep in ice has not been directly observed in laboratory experiments, so values of its governing parameters (summarized in Table 1) are calculated based on microphysical models of the diffusion processes. *Goodman et al.* (1981) provide a comprehensive discussion of diffusion processes in ice, section 5.5 of *Goldsby and Kohlstedt* (2001) gives recent updates for governing parameters, and *Goldsby* (2007) provides an update on efforts to observe diffusion creep in the laboratory. At conditions appropriate for a warm convecting ice shell with reasonable grain sizes ~0.1 mm to 1 mm, the deformation rate from diffusion creep is overwhelmingly dominated by the volume diffusion term. At T > 258 K, the rate of Coble creep in ice is expected to increase by a factor of 1000, due to premelting along grain boundaries and triple junctions, which allows for more efficient grain boundary diffusion than a purely solid grain boundary (*Goldsby and Kohlstedt,* 2001). This results in a marked decrease in the viscosity of ice within 10 K of the melting point (see deformation maps of *Durham and Stern,* 2001), an effect that has been largely overlooked in current numerical studies (with the noted exception of *Tobie et al.,* 2003).

An effective viscosity can be calculated from the stress-strain rate relationship (*Durham and Stern,* 2001; *Ranalli*, 1987)

$$\eta = \frac{1}{3^{(n+1)/2}}\frac{\sigma}{\dot{\varepsilon}} \tag{13}$$

where the factor of $3^{(n+1)/2}$, where n is the rheological stress exponent, is included because the stresses that drive deformation have not been resolved into shear and normal components (*Ranalli,* 1987). For diffusion creep, n = 1. This gives an effective viscosity due to volume diffusion

$$\eta_{diff} = \frac{RTd^2}{42V_mD_{o,v}}\exp\left(\frac{Q_v^*}{RT}\right) \tag{14}$$

The resulting behavior of ice is said to be "Newtonian," meaning that the effective viscosity is independent of stress,