TABLE 1. Rheological parameters for ice I after *Goldsby and Kohlstedt* (2001).

Parameter	Basal Slip	Grain Boundary Sliding	Dislocation Creep
B (m^p Pa^{-n} s^{-1})	2.2×10^{-7}	6.2×10^{-14}	4.0×10^{-19}
n	2.4	1.8	4.0
p	0	1.4	0
Q^* (kJ mol^{-1})	60	49	60
Parameter	**Name**	**Volume Diffusion**	
V_m (m^3 mol^{-1})	Molar volume	1.97×10^{-5}	
b (m)	Burger's vector	4.52×10^{-10}	
δ (m) = 2b	Grain boundary width	9.04×10^{-10}	
$D_{o,v}$ (m^2 s^{-1})	Volume diffusion constant	9.10×10^{-4}	
Q_v^* (kJ mol^{-1})	Volume diffusion activation energy	59.4	
$D_{o,b}$ (m^2 s^{-1})	GB diffusion constant	7.0×10^{-4}	
Q_b^* (kJ mol^{-1})	GB diffusion activation energy	49	

and that stress and strain rate are linearly related. The volume diffusion flow law and variants of it have been widely applied to study of the interior of Europa's icy shell since the 1980s. It is common to rewrite the flow law as

$$\eta = \eta_o \exp\left[A\left(\frac{T_m}{T} - 1\right)\right] \quad (15)$$

which is equivalent to equation (14) if $A = Q^*/RT_m \sim 26$ for pure water ice and η_o is equal to $\eta_{diff}(d_o, T_m)$, where d_o is an assumed grain size. The value η_o is commonly assumed to be a free parameter ranging from $\eta_o \sim 10^{13}$ to 10^{15} Pa s, corresponding to grain sizes of 0.1 mm and 1 mm, respectively (using equation (14)). The volume diffusion rheology has been used in all existing calculations of tidal dissipation within Europa's icy shell (*Ojakangas and Stevenson,* 1989; *Tobie et al.,* 2003*; Showman and Han,* 2004; *Mitri and Showman,* 2005, 2008b). We note that, at the stresses associated with Europa's daily tidal flexing, ~0.1 MPa, or during the onset of convection, non-Newtonian deformation mechanisms could be relevant (*Barr et al.,* 2004).

3.1.2. High stress regime: Grain-size-sensitive and dislocation creep. The behavior of ice I at relatively high stresses $\sigma > 0.01$ MPa is well-characterized by laboratory experiments and glacial measurements. Although the stresses in a convecting ice shell on Europa are relatively low, larger stresses ($\sigma \sim 0.01$ MPa) may build up in the icy shell during the onset of convection (see section 4.2.1) or by lithospheric deformation. In ice with a grain size d > 1 mm, flow driven by stresses of this magnitude is accommodated by dislocation creep and grain-size-sensitive creep.

In this regime, the stress-strain rate relationship for water ice is described as

$$\dot{\varepsilon} = \frac{B}{d^p}\sigma^n \exp\left(\frac{-Q^*}{RT}\right) \quad (16)$$

where B and n are constants determined in laboratory experiments, or from measuring glacial flow, and p is the grain size exponent. A summary of flow laws determined between 1952 and 1979 by *Weertman* (1983) reveals the level of uncertainty in ice rheology during the Voyager era. Values of n ranging from 1.6 to 4 had been measured in different contexts: Creep in polycrystalline ice at low temperature (perhaps most appropriate for Europa) suggested n ~ 3 and activation energies between 60 to 80 kJ mol^{-1} (*Weertman* (1983). Because n > 1, the effective ice viscosity in the high-stress regime depends on stress (i.e., ice is "non-Newtonian," meaning that strain rate depends nonlinearly on stress).

Laboratory experiments reveal that for $\sigma > 1$ MPa, deformation in ice occurs by dislocation creep, characterized by equation (16) with n = 4 and $Q^* = 60$ kJ mol^{-1} (*Goldsby and Kohlstedt,* 2001). Dislocation creep has a high stress exponent n = 4, so the strain rate in cold ice with a large grain size depends strongly on the applied stress (i.e., the ice is highly non-Newtonian) and its strain rate is independent of grain size. Similar to the low-stress regime, strain rates from dislocation creep in ice with T > 258 K are also increased due to premelting at grain boundaries and three- and four-grain junctions in ice (see section 5.4 of *Goldsby and Kohlstedt,* 2001).

Recent laboratory experiments suggest the existence of an intermediate regime for 0.01 MPa < σ < 1 MPa (see Fig. 5 of *Goldsby and Kohlstedt,* 2001), wherein deformation occurs by weakly non-Newtonian deformation mechanism(s) referred to collectively as "grain-size-sensitive" (GSS) creep. GSS creep is characterized by a relatively low-stress exponent n ~ 2, a relatively low grain-size exponent 1 < p < 2, and a modest activation energy $Q^* \sim 49$–60 kJ mol^{-1} (*Goldsby and Kohlstedt,* 2001; *Durham et al.,* 2001). GSS creep is of particular interest to the glacial community, because most large ice bodies on Earth, which have grain sizes ~1–10 mm and driving stresses ~0.1 MPa, are deforming in the intermediate stress regime.

Although the governing parameters of GSS creep are generally agreed upon, identification of the specific microphysical process that accommodates strain in this regime is an open area of debate. The values of the governing parameters strongly suggest that easy slip (equivalently basal slip), where ice grains deform along the basal planes of their hex-