agonal crystals, occurs in the intermediate regime (*Goldsby and Kohlstedt,* 2001; *Duval et al.,* 2000). A secondary process such as dislocation creep or grain boundary sliding must operate in tandem with basal slip to accommodate deformation in crystals whose planes are not oriented properly for basal slip to occur (*Goldsby and Kohlstedt,* 2002). The identification of this secondary process has been problematic. Scanning electron microscopy of deformed ice samples allowed *Goldsby and Kohlstedt* (2001) to identify instances of grain switching and occurrence of straight grain boundaries and four-grain junctions, providing evidence that grain boundary sliding accommodates easy slip. This gives rise to a combined flow law in the intermediate regime (*Goldsby and Kohlstedt,* 2001)

$$\dot{\varepsilon}_{gss} = \left(\frac{1}{\dot{\varepsilon}_{gbs}} + \frac{1}{\dot{\varepsilon}_{bs}} \right)^{-1} \qquad (17)$$

where gbs stands for grain boundary sliding, and bs stands for basal slip, with the strain rate from grain boundary sliding ($\dot{\varepsilon}_{gbs}$) dominating at conditions relevant to the interior of Europa's ice shell (*Barr et al.,* 2004). Governing parameters for GSS creep effectively controlled by GBS are summarized in Table 1.

However, it has been suggested that grain boundary sliding and basal slip acting together are not able produce the crystal fabric (the coalignment of crystal lattices in adjacent grains) observed in deformed sections of terrestrial ice sheets (*Duval et al.,* 2000; *Duval and Montagnat,* 2002). *Montagnat and Duval* (2000) suggest an alternate hypothesis: that grain boundary migration (essentially, grain growth) and associated recrystallization accommodates basal slip. However, *Goldsby and Kohlstedt* (2002) point out that grain boundary migration does not produce strain and thus is not a deformation mechanism. The identification of the microphysical process accommodating deformation in ice at moderate stresses remains an active area of research.

3.1.3. A combined flow law. *Goldsby and Kohlstedt* (2001) propose that the behavior of ice I across the high-, intermediate-, and low-stress regimes can be described by a single governing equation

$$\dot{\varepsilon}_{total} = \dot{\varepsilon}_{diff} + \dot{\varepsilon}_{gss} + \dot{\varepsilon}_{disl} \qquad (18)$$

where, in application to Europa's icy shell, the strain rate due to GSS may be approximated by the governing parameters of grain boundary sliding (*Barr et al.,* 2004). Despite uncertainties in the microphysical mechanisms at work in GSS creep, a combined flow law including both GSS and dislocation creep using governing parameters summarized in Table 1 provides a good match to stress/strain rate/grain size relationships deduced from previous laboratory experiments (*Goldsby and Kohlstedt,* 2001) and glacial measurements (*Peltier et al.,* 2000). The composite flow law can be used to determine the regimes of dominance in stress, temperature, and grain size space for each constituent deformation mechanism. By equating strain rates between pairs of mechanisms, one can construct a deformation map for ice that can be used to predict which rheology is appropriate for a given application (see Fig. 2 and deformation maps of *Durham and Stern,* 2001).

3.2. Effect of Impurities

The presence of substances other than water ice in Europa's icy shell can have an important effect on its rheology. Here we summarize how the presence of various materials, including ammonia, sulfate salts, and dispersed particulates, may affect the rheology of Europa's icy shell.

Ammonia dihydrate, $NH_3 \cdot 2H_2O$, the stable phase in the water-rich, low-pressure region of phase space in the ammonia-water system, melts at $T_m = 176$ K. Ammonia has been suggested as a possible means to thermodynamically stabilize liquid water oceans beneath convecting ice shells (e.g., *Spohn and Schubert,* 2003) and implicated as a possible component of cryovolcanic magmas on icy satellites. The rheology of ammonia dihydrate has been measured in laboratory experiments by *Durham et al.* (1993). The flow law for ammonia dihydrate, with mole fraction $x_{NH_3} = 0.3$ (corresponding to a mole fraction of 90% dihydrate), can be expressed in similar form as equation (16), with $B = 10^{-15}$ $Pa^{-5.8}$ s^{-1}, $n = 5.8$, and $Q^* = 102$ kJ mol^{-1}. At its melting point and a nominal stress of 0.01 MPa, ammonia dihydrate is 2 orders of magnitude less viscous than water ice, but its large activation energy leads to a rapid increase in viscosity as the temperature is decreased.

Galileo NIMS data suggest that the surface of Europa's icy shell is composed predominantly of water ice and nonice materials that include one or more hydrated materials. Candidates for the latter include hydrated magnesium and/or sodium salts (*McCord et al.,* 1999) or hydrated solidified sulfuric acid (*Carson et al.,* 2005). Geochemical modeling of water-rock chemistry in Europa's ocean also suggest the formation of magnesium and/or sodium salts, supporting the view that the icy shell may be salty throughout (*Zolotov and Shock,* 2001; *McKinnon and Zolensky,* 2003). The sulfate salts were found to have much higher viscosities than pure water ice at comparable temperatures (*Durham et al.,* 2005). For example, the difference in hardness between mirabilite grains and water ice is so high that the dispersed mirabilite particles can act as hard secondary phases, and have a similar effect on the rheology of the bulk material as silicate grains.

Recent laboratory experiments by, e.g., *McCarthy et al.* (2007) have explored dissipation in mixtures of ice and magnesium sulfate. Frozen eutectic mixtures of ice and magnesium sulfate form a lamellar structure with layers of ice and magnesium sulfate sandwiched together. The resulting mixture is stiff but highly dissipative due to the microscale boundaries between layers of magnesium sulfate and water ice. Future laboratory experiments on pure water ice and water ice mixed with other materials may provide alternate models for dissipation than the Maxwell model, and