near the surface of the ice shell. In this study, numerical cut-offs to limit the viscosity values near the surface of $max(\eta) = 10^7 - 10^{10}$ are used to prevent essentially infinite viscosities in the near-surface ice.

In Chapter 2, a single term from the composite rheology for ice I (equation 1.4) for grain boundary sliding or basal slip is implemented. The viscosity due to GBS or basal slip in ice is calculated as a strain rate-dependent viscosity,

$$\eta = \left(\frac{d^p}{A}\right)^{1/n} \dot{\varepsilon}_{II}^{(1-n)/n} \exp\left(\frac{Q^*}{nRT}\right), \tag{1.34}$$

where $\dot{\varepsilon}_{II}$ is the second invariant of the strain rate tensor:

$$\dot{\varepsilon}_{II} = \frac{1}{2}\Big(\sum_{i,j}\Big(\frac{\partial v_i}{\partial v_j} + \frac{\partial v_j}{\partial v_i}\Big)\Big)^{1/2}. \tag{1.35}$$

This form of viscosity function approximates the behavior of a true stress-dependent rheology, but is more numerically tractable in Citcom than a stress-dependent viscosity function.

When the viscosity is stress- or strain rate-dependent, the velocity and viscosity fields are coupled. The fields must be solved iteratively until convergence is achieved. This introduces further non-linearity to the convection problem and can result in very low viscosities in the convecting region where the ice is flowing, and large viscosities in the near surface ice where convective motions are negligible. The requirement to iterate to find self-consistent viscosity and velocity fields makes simulations of convection in non-Newtonian fluids computationally expensive compared to Newtonian models. As a result, before this thesis, implementation of the strain rate- or stress-dependence has so far been ignored in numerical convection models of icy satellites.

1.5.4 Composite Rheology for Ice I

The full composite rheology for ice I (equation 1.4) is implemented in simulations presented in Chapters 3, 4, and 5. In the composite rheology determined by *Goldsby*