DUCTILE SHEAR ZONES ON ICY SATELLITES ENABLED BY GRAIN SIZE EVOLUTION N. P. Hammond[1] and T. E. Caswell[2], [1]Centre for Planetary Sciences, Department of Physical and Environmental Sciences, University of Toronto, 1785 Military Trail, Toronto ON, Canada, noah.hammond@utoronto.ca, [2]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, USA.

Introduction: On Earth, ductile shear zones are thought to underlie major strike-slip faults [1]. Ductile shear zones cause deformation in the lower crust to localize into narrow bands [2], and are suggested to be essential in enabling plate-like behavior and plate tectonics [3]. The rocks in ductile shear zones, mylonites, are characterized by extremely fine grain sizes and strong crystallographic fabrics [4,5].

Many strike-slip faults have been observed on icy satellites, such as Ganymede and Europa, with lateral offsets of over 50 km (e.g. [6]). We propose that ductile shear zones with fine grain sizes may underlie major strike-slip faults on icy satellites. Previous investigators have explored the potential for shear heating beneath strike-slip faults [7,8]. Reduced grain size beneath the fault would further reduce the viscosity of the shear zone, enhancing shear localization and lowering the stress required to drive strike-slip motion.

Here we explore the potential for ice mylonite formation beneath strike-slip faults on Europa using a new model of grain size evolution [9]. As discussed below, small grain sizes in icy ductile shear zones could be maintained if the ice is deforming by grain boundary sliding (GBS). Below, we outline how the grain size evolves for ice creeping by GBS. We also numerically model the development of a ductile shear zone on Europa and discuss the geodynamic consequences for shear localization.

Approach: Grain size in a deforming ice shell is influenced by dynamic recrystallization, which serves to reduce grain size, and grain growth, which causes grain size to increase [10]. Previous models of grain size evolution in a convecting ice shell [11] assumed the ice shell reached steady-state between these two competing processes.

Recent experimental work [12] shows that during deformation by GBS in water ice (the regime of "GBS-accommodated basal slip" of *Goldsby & Kohlstedt,* 2001[13]), dynamic recrystallization does not occur. This is an important discovery, as GBS may be the dominant deformation mechanism for a broad range of temperatures and stresses expected in the ductile portion of an ice shell [14].

Lack of dynamic recrystallization during GBS does not necessarily mean that grain growth proceeds unchecked. Grain growth can be inhibited in the GBS regime if the energy dissipation rate by plastic flow exceeds that which would be achieved by grain growth [9]. Thus, grain size may be pinned during deformation by GBS.

A hypothetical path of grain size evolution is illustrated on the deformation mechanism map in Figure 1 for a temperature of T=250 K [9]. An initially large (1 mm) grain size is reduced to ~300 μm by dynamic recrystallization when a stress perturbation (due to fault slip) drives deformation via dislocation creep. When the stress perturbation decays to the background stress, deformation by GBS is sufficient to inhibit grain growth, resulting in a constant, and reduced grain size.

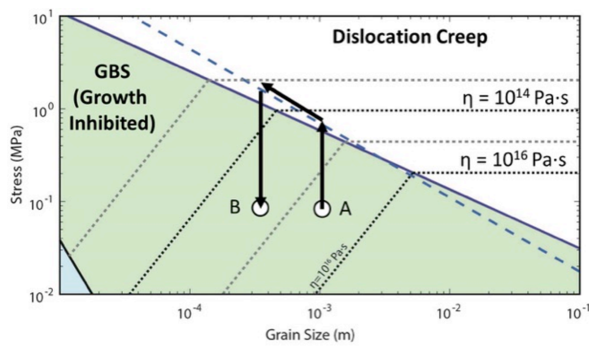

Figure 1: A model of ice grain size evolution during creep, after [9]. The region where GBS is the fastest deformation mechanism is indicated in green. Thin, black, dashed lines indicate viscosity isochrones and the thick blue dashed line the recrystallized grain size piezometer of [15]. Point A indicates an initial grain size. A stress increase due to fault slip drives deformation in the dislocation creep regime, which reduces the grain size before the stress decays to the background value. The result is grain size B, associated with a reduced viscosity.

Models of Ductile Shear Zone Evolution: We model the evolution of a ductile shear zone beneath a strike-slip fault on Europa to calculate the evolution of temperature, strain rate and grain size. We use a two-dimensional finite difference code, similar to Nimmo and Gaidos (2002) [7], with a 2 km thick elastic layer above an 18 km thick ductile layer. The initial temperature profile is conductive with a surface temperature T_s= 100 K, and a melting temperature of T_m= 270 K.

We use a composite creep rheology to calculate the viscosity in the ductile layer [13] and solve for the strain rate as shear proceeds in the elastic layer. A right lateral shear is imposed by applying a constant velocity boundary condition at the sides and in the elastic layer of $u = \pm u_0$, where u is the out-of plane velocity. We include viscous heating in the ductile layer and frictional heating along the fault in the elastic layer assuming a coefficient of friction of $\mu = 0.1$ [7,16].

As deformation proceeds we allow grain size to evolve such that either: 1) the grain size reduces according to the field boundary approach [10] if dislocation creep is the dominant mechanism, 2) the grain size remains constant if GBS is dominant and the energy dissipation rate from GBS is higher than the dissipation rate for grain growth or 3) grains grow if the dissipation rate from grain growth is higher.

An example calculation is shown in Fig. 2 for a shear strain rate at the surface of $\dot{\varepsilon} = 2\text{x}10^{-11}$ s^{-1}. Beneath the fault, deformation is extremely localized with a local shear strain rate $\dot{\varepsilon} = 2\text{x}10^{-9}$ s^{-1}. Reduced grain size and higher temperatures in this region lowers the viscosity, which promotes strain localization. Lower viscosity due to smaller grain size reduces the magnitude of viscous heating, however, and no near-surface melting occurs in this example. Further work will evaluate the feedbacks between grain size, strain rate, viscosity, temperature, and melt generation.

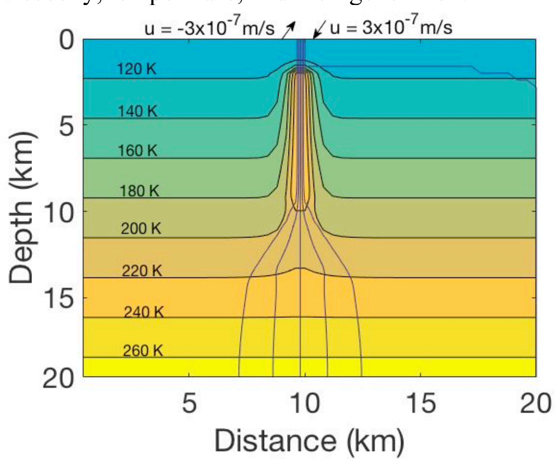

Figure 2: Numerical modeling results showing the temperature beneath a 2 km deep strike-slip fault on Europa. Blue vertical lines show contours of the out-of plane velocity with intervals $u=1\text{x}10^{-7}$ m/s. Arrows at the top indicate the direction of shear.

Using this model we shall constrain the conditions under which "ice mylonite" ductile shear zones may form and be sustained. We shall identify candidate regions of shear localization on icy satellites and discuss the geophysical implications, including how ductile shear zones could affect the strength of an ice shell, the distribution of tectonic deformation, and distribution of tidal heating.

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