ICE GRAIN SIZE AND THE RHEOLOGY OF THE MARTIAN POLAR DEPOSITS. Amy C. Barr[1] and Sarah M. Milkovich[2], [1]Department of Space Studies, Southwest Research Institute, 1050 Walnut St., Suite 400, Boulder, CO 80302 (amy@boulder.swri.edu), [2]Jet Propulsion Laboratory, Pasadena, CA 91101 (sarah.m.milkovich@jpl.nasa.gov).

Introduction: The martian polar deposits (MPD) (Figure 1) are made up of kilometers-thick layered deposits of water ice and dust covered by residual ice (water ice in the north, carbon dioxide in the south). The history and dynamics of these deposits are of great interest because they are the largest known water reservoirs on the planet, and because their layers are thought to contain the record of recent climate variations [e.g., 1]. Interpretations of the morphology of the MPD, their formation and evolution over time, and the link between climatic history and the individual layers, depend in part on how large a role ice flow has played over time.

Current efforts to model flow in the MPD are hampered by uncertainties in the physical properties of the deposits, chiefly, the rheology, ice grain size, and dust content. Recent models assume either dust-free and constant grain size [e.g., 2,3,4], dust contents of at least 10% by volume and constant ice grain size [5] or that there is enough dust in the deposits to prevent grain growth and maintain constant grain size with depth [6]. Here we examine the microphysical processes that control grain size in terrestrial ice sheets to provide physically motivated estimates of grain size in the MPD. Our analysis constrains possible grain sizes in the MPD and provides a framework in which new information about the MPD (i.e. dust content and strain estimates based on geomorphology) can be used to refine grain size estimates in the future.

Approach: We use estimates of ice grain size and microphysical models of the processes that control grain sizes in the terrestrial GRIP and Dome Concordia ice cores to constrain grain size in the MPD. We apply a simple model of Zener pinning to place a lower limit on ice grain size in the deposits based on estimates of dust content from the MARSIS radar experiment.

If the MPD have flowed over geologic time, their grain size and crystal fabric may have evolved over time. We use estimates of the temperature and differential stress in the polar deposits to place an upper bound on grain size assuming it is controlled by dynamic recrystallization, a process in which the mean grain size of the ice is modified due to flow.

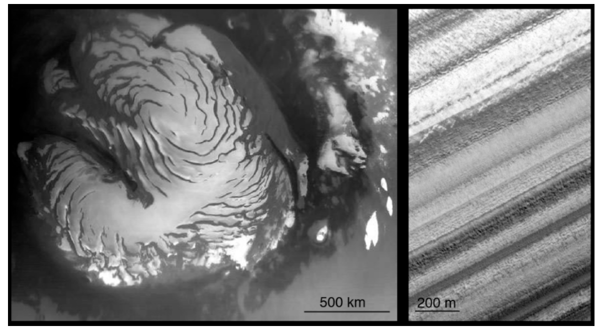

Fig 1. Martian North Polar Deposits. Left: residual ice cap on top of layered deposits. Right: polar layered deposits (MOC M00/02100).

Finally, we suggest a rheology for modeling the MPD that self-consistently describes grain size modification by dynamic recrystallization and flow due to grain boundary sliding.

Observations and Previous Work: Recent spectral observations by Mars Express' OMEGA are consistent with surface ice grains of ~ 1 mm [7]. Close to the surface of the deposits, ice grains grow by sintering, and increase with depth, or equivalently, time [8.9]. Detailed modeling of this process suggests grains between 200 μm and 1 mm at a depth of 60 m, consistent with OMEGA observations.

MARSIS results provide a glimpse into the composition of the deposits at depth, and suggest that the deposits are relatively pure ice (<2% impurities). This result is based on the ratio between the reflectivity of the surface layer and the bedrock contact, and may be consistent with pure ice layered with relatively dusty ice [10].

Grain Sizes in Terrestrial Ice Cores: Terrestrial ice sheets provide a natural laboratory in which to study ice grain size and processes that control grain size and ice crystal orientation. In the absence of non-water-ice impurities, and in low-stress environments where the ice does not flow, grains grow with time as [11]

$$R^2 - R_0^2 = 2K_g t \quad (1)$$

where R is the grain radius, R_o is the initial grain radius, K_g is a temperature-dependent constant. Grain growth occurs due to grain boundary migration, which is driven by the free energy decrease associated with a decrease in grain boundary curvature.

In terrestrial ice cores, however, ice grain size is roughly constant with depth (or equivalently, time), suggesting that other processes affect grain growth rates and/or modify the mean grain size. To understand the processes that might control grain size in the MPD, we examine grain sizes and physical processes inferred to control grain size in terrestrial ice cores, in particular, the GRIP core from central Greenland (Fig. 2).

The GRIP ice core samples ~3 km of ice up to 100 kyr old from the Greenland Ice Sheet. Ice above 1625 m depth was deposited during the current interglacial epoch and has low levels of non-water-ice impurities. Ice below this depth was deposited during the Wisconsin glaciation and has substantially larger levels of impurities [12, 13].

However, below a depth of ~1 km in GRIP, ice grain sizes are kept approximately constant, between 2-4 mm, due to two processes: 1) in glacial ice, with large impurity content, grain boundary pinning due to the presence of silicate microparticles [13,14,15,16,17] and 2) in relatively impurity-free interglacial ice, grain size is kept constant by a process called dynamic recrystallization [13] where the average grain size of the ice changes as the ice is strained.

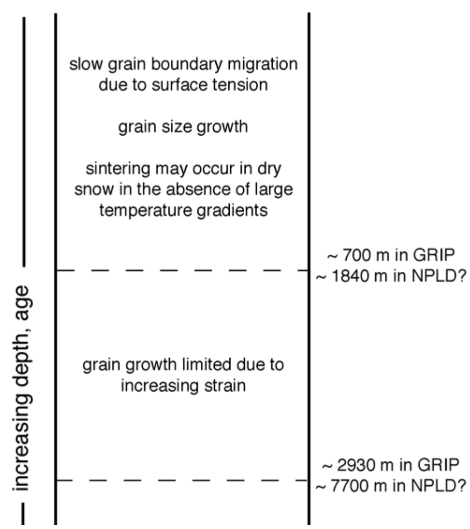

Fig. 2. Summary of processes controlling grain size in the GRIP ice core and the MPD [after 19].

Grain Boundary Pinning: Observations of impurity-laden portions of terrestrial ice cores, including GRIP and Dome C in Antarctica, indicate that grain sizes in "dirty" or "dusty" ice is smaller than grain size in clear ice [14,15]. SEM imaging of sections of the GRIP and other ice cores suggest that silicate particles pin grain boundaries and inhibit grain growth [16,17], which allows grain sizes in dusty parts of glaciers to remain small in spite of high temperatures and significant shearing.

Silicate and clathrate particles mixed in with ice serve as hard secondary phases that exert a drag force on grain boundaries and in some cases, can halt grain growth completely. We focus on grain boundary pinning due to silicate particles, but note that clathrate particles may be of equal importance in controlling grain size in the MPD.

The effect of pinning particles on grain size was first modeled by Zener, who related the drag force exerted by hard secondary phases on grain boundaries to the rate of grain growth (dR/dt) [11]

$$\frac{dR}{dt} = K_{g,0} \exp\left(\frac{-E_A}{R_G T}\right)\left(\frac{1}{R} - \frac{P_Z}{\alpha\gamma}\right) \qquad (2)$$

where E_A=46 kJ/mol is the activation energy for grain boundary migration, R_G =8.314 J/mol-K is the gas constant, T is temperature, γ=0.065 J/m^2 is the grain boundary free energy [13], and α=0.25 is a geometric factor. P_Z is the pinning pressure exerted on the grain boundary, which is related to the number of particles on the boundary (N_x) as [11]

$$P_Z = \frac{\pi\gamma r_x R N_x}{3} \ . \qquad (3)$$

Grain growth is stopped completely when the r.h.s. of equation (5) is equal to zero, which gives rise to the Zener limiting grain size [11],

$$R_Z = \left(\frac{3\alpha}{\pi r_x f N_x}\right)^{(1/2)} \qquad (4)$$

where f is the fraction of particles residing on grain boundaries.

The MPD are inferred to be < 2% dust by weight. Assuming that the dust is silicate with a density of 3000 kg m^{-3}, this implies N_x~ 10^{12} dust particles per cubic meter of MPD ice. SEM imaging of terrestrial ice samples with similar dust concentrations suggest that in glacial ice, f ~ 25% [16,17]. The limiting grain size can be related to the assumed dust particle size and weight percent of dust (w) as,

$$R_Z = 0.7 \text{ mm} \left(\frac{1\ \mu\text{m}}{r_x}\right)^{(1/2)} \left(\frac{0.02}{w}\right)^{(1/2)} \qquad (5)$$

If the polar deposits have 2% dust by weight (w=0.02), R_z~0.7 mm. If the dust content is significantly less than 2%, for example, 0.1%, the plausible value of grain size increases to 3 mm. Although the dust content in the deposits is not yet tightly constrained from radar data, our calculations provide method to link dust content to ice grain size.

Dynamic Recrystallization: If the ice in the martian polar deposits has flowed over time, its grain size may be controlled by a process called dynamic recrystallization. In this process, grain growth, driven by the free energy decrease associated with reduction of grain boundary curvature, is balanced by subgrain rotation, where heterogeneous deformation within grains leads to the formation of new grain boundaries [20]. The balance of grain growth and destruction by these processes leads to an equilibrium recrystallized grain size that depends on stress (σ) as [20]

$$d = K\,b\left(\frac{\sigma}{\mu}\right)^{-m}, \qquad (6)$$

where b=4.52 x 10^{-10} m is the Burger's vector for ice, μ=3.5x10^9 Pa is the shear modulus for ice, and m=1.25 [20]. The ice can only achieve this equilibrium recrystallized grain size if it has experienced > 25% strain [12]. Therefore, our grain size estimate holds only for regions of the polar deposits where deformation has occurred. In regions where deformation has occurred, in the absence of impurities, ice grains could grow to somewhat larger values.

The stresses that drive flow on terrestrial glaciers are proportional to the shear stress, $\sigma \sim \rho g z \alpha$, where g is gravity, and $\alpha \sim 10^{-3}$ is the surface slope. Surface slopes in the polar flats on Mars (i.e. away from the troughs) are of similar magnitude ~4x10^{-3}, but the gravity on Mars is 1/3 less. As a result, we expect grain sizes in the flat part of the polar deposits to be smaller than measured grain sizes in GRIP by a factor of

$$\frac{d_{Mars}}{d_{Earth}} = \left(\frac{\sigma_{Mars}}{\sigma_{Earth}}\right)^{-m} \sim \left(\frac{\alpha_{Mars} g_{Mars}}{\alpha_{Earth} g_{Earth}}\right)^{-1.25} \sim 0.6 \qquad (7)$$

which implies grain sizes in the deep interior of the polar flats of ~2 mm, regardless of impurity content. This implies that even in the absence of impurities (as suggested by MARSIS), grain sizes in the polar flats could be as small as 2 mm as a result of dynamic recrystallization.

Self-Consistent Flow Law and Grain Size Model: At the modest stresses associated with flow in the MPD, we expect deformation to occur by the grain size sensitive creep mechanism described by Goldsby & Kohlstedt [2001] [21]. If grain size in the ice deposits is dictated by dynamic recrystallization, eq. (6) can be combined with the ice flow law to yield a strongly non-Newtonian rheology for ice I,

$$\dot{\varepsilon} = A'\sigma^{n'} \exp\left(\frac{-Q^*}{RT}\right) \qquad (8)$$

where $A'=(A/(Kb\mu^m))$ is a reduced pre-exponential constant, A=6.2x10^{-14} Pa$^{-1.8}$ m$^{1.4}$ s^{-1}, p=1.4 is the grain size exponent, 13 < K < 21 is a material parameter describing polycrystalline ice, which is obtained from fitting ice grain size as a function of temperature and strain rate in the GRIP ice core [22], $n'=n+mp$=3.55, and Q^*=49 kJ mol^{-1} is the activation energy, R is the gas constant, and T is temperature [21, 22, 23, 24].

Implications for RADAR interpretation: Consideration of ice grain sizes and ice crystal orientation is of key importance for the interpretation of imaging and radar datasets. Small variations in albedo of pure ice at visible wavelengths may be due to changes in grain size (e.g., [25]); variations in ice grain size with depth may be a contribution to varying brightnesses of the individual layers of the polar layered deposits [19]. Weakly-reflecting layers within ice deposits have been observed with radar sounding both on Earth (e.g., [26]) and Mars [27, 28, 29].

Three different mechanisms are thought to cause these internal reflections in terrestrial ice sheets: ice density variations due to pore spaces or bubbles, conductivity variations due to varying impurity content, and variations in crystal-fabric orientation. In a region of high shear, ice grains can become aligned with the c-axis vertical; the boundary between such a layer and a layer with disordered ice grains can cause a radar reflection ([30] and references therein). While the first mechanism is confined to the very upper regions of an ice sheet where firn is present, the last two mechanisms can occur at depth and may be at work within the martian polar deposits as well. Theoretical studies indicate that at frequencies of tens to 100 MHz, both mechanisms equally dominate the production of radar reflection, while at lower frequencies reflections are predominately due to changes in acidity while at higher frequencies reflections are predominately due to changes in the ice fabric [31]. While MARSIS frequencies are within the range dominated by impurity changes (1.8-5.0 MHz, [10]), SHARAD operates at 20 MHz [32], and a layer of ice with the correct grain orientation may cause a detectable reflection. If such a reflection were observed, it would place new constraints on models of the flow history of the MPD.

Conclusions: An examination of the physical processes controlling ice grain size in terrestrial ice sheets allows us to place constraints on the grain size within the MPD (Fig 3). The methods we describe will allow us to refine our physically-motivated estimates of grain size as we learn more about the properties of the MPD.

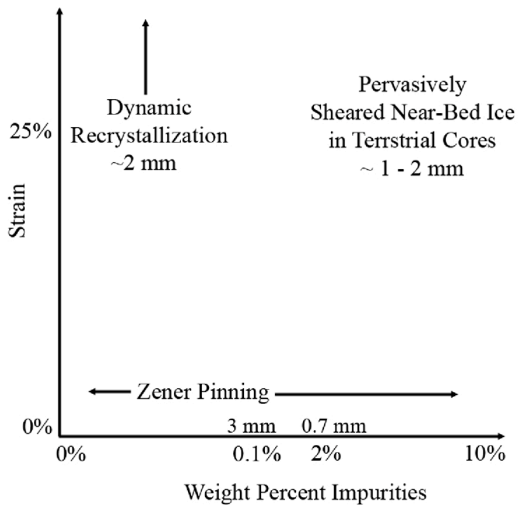

Fig. 3. Conceptual graph of the processes controlling ice grain size in the MPD.

In the absence of non-water-ice impurities (left side of Fig 3), modest stresses driving flow in the martian polar flats leads to an equilibrium recrystallized grain size of ~2 mm. The grain size evolves to this value as the ice accumulates strain, achieving the recrystallized value after a strain of 25%. The amount of strain experienced by the MPD over their evolution is not well-constrained, so an equilibrium may not have been achieved.

If grain sizes have reached their equilibrium values, the ice grain size and strain rate in the deposits may be self-consistently modeled simultaneously using equation (8), which combines an expression for the recystallized grain size from [20] and the GSS creep rheology from [21].

If impurities are present in the MPD at similar weight % levels as terrestrial glaciers (right side of Fig. 3), grain sizes are ~1-5 mm. As a result, *regardless* of whether impurities or dynamic recrystallization controls ice grain size, we converge on an estimate of d~1-5 mm in the MPD. Only in the case of no strain and very pure (< 0.1% impurities) ice will larger grains exist.

The presence of clathrates which act as hard secondary phases (and inhibit grain growth in a similar manner as silicate microparticles [18]) or CO_2 ice may modify conclusions here. Theoretical estimates limit the CO_2 content of the MPD under realistic conditions to a few tens of mbar [33]. The extent to which clathrate and/or CO_2 affects grain size and rheology depends on its distribution and length scale over which it is mixed in (i.e., intimately mixed vs. in discrete layers). Further laboratory experiments to characterize the behavior of mixed ices are required to determine how these materials may affect grain size.

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