RHEOLOGICAL BEHAVIOR OF CO_2 ICE WITH APPLICATION TO GLACIAL FLOW ON MARS

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Introduction: Recent radar soundings by the Mars Reconnaissance Orbiter provide evidence for large carbon dioxide (CO_2) deposits contained within the South Polar Layered Deposits (SPLD) of Mars [1–2]. The deposits are up to 1 km thick, may be up to 16,500 km^3 in volume [3], and exhibit morphological features similar to those observed in terrestrial glacial settings. To better understand glacial flow on Mars, we present results from an ongoing experimental investigation into the creep behavior of CO_2 ice. Our experiments complement two earlier experimental studies of solid CO_2 rheology [4–5], both of which found CO_2 ice to be a) up to two orders of magnitude weaker than H_2O ice at comparable conditions and b) too weak to sustain the glacial topographies observed at the Martian poles [6]. However, these studies used impure, commercially-available CO_2 ice as a starting material and explored a range of conditions not entirely consistent with current knowledge of the SPLD.

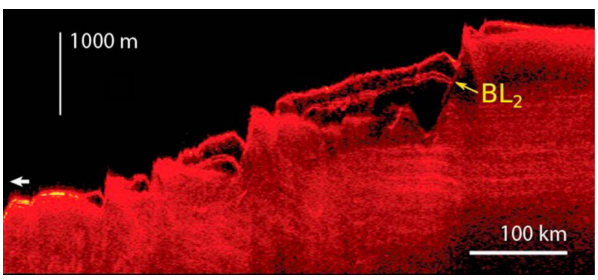

Figure 1. *Shallow radar data across the Martian south polar ice cap (modified after [2]). CO_2 deposits (dark layers) are up to 1 km in total thickness, separated by bounding layers (BL; light layers) composed of water ice and sediment.*

We quantify the creep behavior of pure, synthetic CO_2 ice using a constitutive equation of the form:

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

where $\dot{\varepsilon}$ is strain rate, A is a material constant, σ is flow stress, d is grain size, Q is the activation energy for creep, R is the gas constant, T is temperature, and n and p are the stress and grain-size exponents, respectively. In compressional creep experiments, we find our pure CO_2 samples to be modestly stronger than those in the previous experimental studies [4–5]. Moreover, experiments performed over a broad range of temperature and strain rate conditions show evidence for more than one dominant creep mechanism.

Experiments: Fine-grained (<100 μm), pure CO_2 powders were synthesized by deposition from CO_2 vapor onto a liquid-nitrogen-cooled aluminum plate in a sealed Perspex chamber, shown in Figure 2. Powders were packed by hand into a thin-walled indium jacket, which was then welded onto the end of a force gauge that resides within the high-pressure gas medium during the experiments. To prevent sublimation during sample handling, each sample was kept below 194.5 K at all times by submersion in liquid nitrogen. Jacketed samples were loaded into a cryogenic, gas-confining-medium apparatus [7], and 'hot-pressed' at experimental conditions (10 MPa confining pressure, and temperature in the range 155–195 K) to produce fully-densified cylinders, ~5 cm in length and 2.54 cm in diameter.

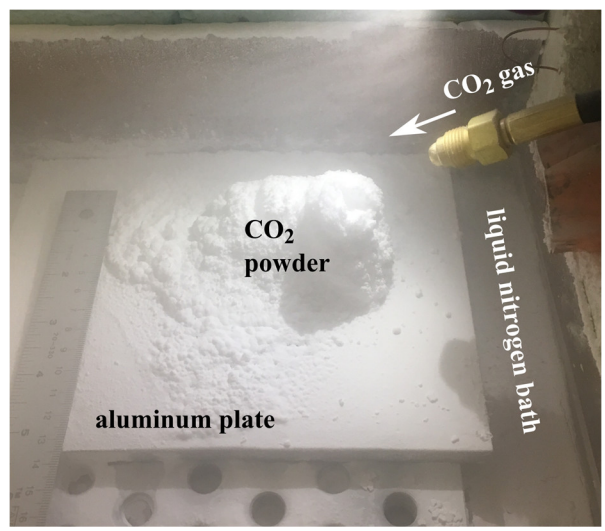

Figure 2. *CO_2 powders synthesized by deposition from CO_2 vapor onto an aluminum plate half-submerged in liquid nitrogen. Powders are subsequently packed into a thin-walled indium jacket, densified, and deformed.*

Samples were subsequently deformed in uniaxial compression to strains $\varepsilon \leq 0.2$ ($\leq$ 20% axial shortening) under constant-temperature conditions. During each test, multiple rate steps were imposed on the sample in order to determine the stress exponent, n. Stress measurements were corrected to account for the strength of the indium jacket, and the increasing cross-sectional

area of the sample during shortening. At the end of each experiment, samples were rapidly extracted from the apparatus and quenched in liquid nitrogen to preserve their microstructure. Due to the difficulty of stabilizing solid CO_2 in an optical or scanning electron microscope, microstructures were examined indirectly by peeling the soft indium jacket away from each sample, which replicates the underlying CO_2 grain structure – a technique previously used by [8].

Results/Discussion: Steady-state stresses and strain rates at T = 184–194 K are plotted in Figure 3. The data show that pure CO_2 is up to two times stronger than the previously-studied samples of commercially-available CO_2 ice [4–5], which contains propylene glycol and oil – impurities that may lubricate grain boundaries or otherwise affect the rheological behavior. As in [5], we find a large value of the stress exponent, $n = 8.5 \pm 1.5$, at relatively high stresses, indicating a much greater stress-sensitivity than observed in water ice, for which $n \leq 4$ [9]. However, at higher temperatures and lower strain rates – *i.e.*, at lower stresses – the steady-state data diverge from this high-n trend, transitioning to a lower-n regime where n is closer to 3 (Figure 3).

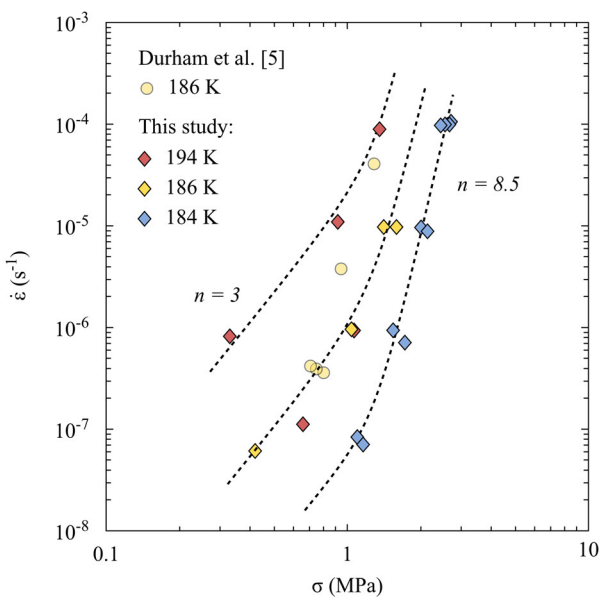

Figure 3. *Steady-state stresses versus strain rates for solid CO_2 at 184–194 K. For comparison, the previous CO_2 creep data of Durham et al. [5] are shown (faded circles) alongside our data (colored diamonds). Scatter in the 194 K data may be due to grain growth and/or thermal drift of the apparatus.*

By performing experiments over a range of temperatures, we are also able to derive a value for the creep activation energy, Q. These data, plotted as strain rate versus inverse temperature, are shown in Figure 4.

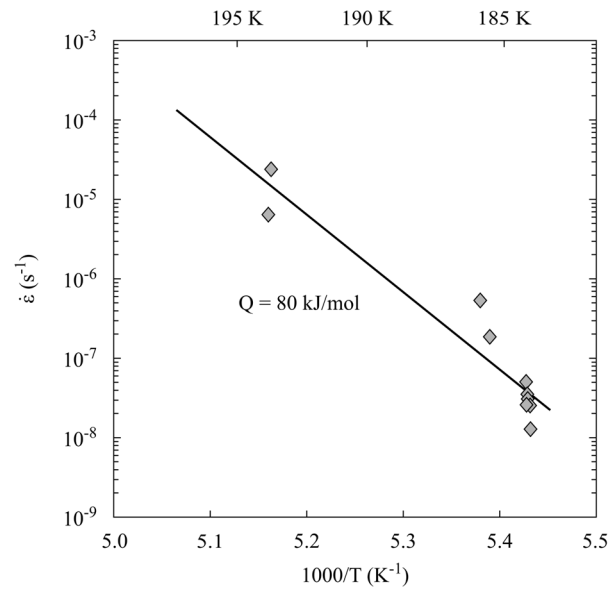

Figure 4. *Plot of strain rate versus inverse temperature. Only the data characterized by a high stress exponent are shown. These points are normalized to a stress of 1 MPa using the stress exponent, n = 8.5.*

From linear regression, we obtain $Q = 80 \pm 10$ kJ/mol for the high-n data (normalized to a stress of 1 MPa), which is higher than both of the previously reported values, 51 kJ/mol [4] and 33 kJ/mol [5].

Our results thus far indicate that CO_2 deforms by at least two distinct creep mechanisms under conditions applicable to the Martian south polar ice cap. Further experiments will be aimed at more tightly constraining these constitutive parameters and exploring a broader range of conditions, including the near-solidus ($195 \leq T \leq 215$ K) behavior of CO_2 ice, which may be important near the base of the SPLD where overburden pressures can stabilize solid CO_2 at higher temperatures.

References: [1] Phillips, R. J. et al. (2011) *Science*, *332*, 838-941. [2] Bierson, C. J., et al. (2016) *Geophys. Res. Lett.*, *43*(9), 4172-4179. [3] Putzig, N. E. et al. (2018) *Icarus*, *308*, 138-147. [4] Clark, B. and Mullin, R. (1976) *Icarus*, *27*, 215-228. [5] Durham, W. B. et al. (1999) *Geophys. Res. Lett.*, *26(23)*, 3493-3496. [6] Nye, J. F. et al. (2000) *Icarus*, *144*, 2, 449-455. [7] Heard, H. C. et al. (1990) *Geophys. Monogr. Ser.*, *56*, 225-228. [8] Durham, W. B. et al. (1996) *J. Geophys. Res. Solid Earth*, *101(B2)*, 2989-3001. [9] Goldsby, D. L. and Kohlstedt, D. L. (2001) *J. Geophys. Res. Solid Earth*, *106(B6)*, 11017-11030.