A Step in Understanding Glacial Flow: Exploring the effects of entrained insoluble debris on mechanical properties of polycrystalline ice

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Abstract

An improved understanding of the mechanisms and factors affecting glacial flow is crucial to better predict sea level rise. Glacial ice often contains impurities such as the presence of small insoluble particles. Mixtures of ice and dust can be found in many places throughout the world, specifically in areas of high latitude and altitude (Moore, 2014). This study aims to understand the effect of entrained insoluble debris on processes of glacial motion. Glaciers move through a combination of internal ice deformation and basal sliding. Internal ice deformation, the flow of individual ice grains, has been found to be grain-size dependent in both field and laboratory studies (Goldsby and Kohlstedt, 2001). In an attempt to better understand ice grain size, this study considers the effect of debris on grain growth. Samples of pure ice and ice with debris were fabricated with a standard protocol and maintained at -5°C for controlled annealing. Microstructural characterization was preformed using a light microscope to image the samples, and calculating the average grain sizes using a linear-intercept method. The ice with debris was found to have smaller grain sizes, thought to be associated with grain-boundary pinning. Extrapolated values were used with a flow law, projecting that ice with debris will have lower viscosity, thus flow faster. To address basal sliding, the other form of glacial movement, we conducted a second phase of study. Basal sliding, the process of a glacier sliding over the bedrock, is influenced by the presence of meltwater at the base of the glacier (Hoffman et al., 2011). Frictional heating, from ice-on-rock friction, was studied as a factor affecting meltwater production. We conducted a simple 1D computer model using laboratory friction measurements of ice with entrained debris (Zoet et al., 2013). We find that debris content and frictional heating are directly proportional. Trials run at faster glacial velocities also show larger amounts of frictional heating. As frictional heating may increase meltwater, glaciers with debris may slide faster over bedrock. Overall, by better understanding the motion of debris-rich glaciers, we can focus our attention to areas around the world at risk, and better predict/prepare for sea level rise.

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ARDSLEY Science Research

Introduction and Review of Literature

- Study by NASA noted an acceleration in the rise of global sea level (Blumberg, 2018)
  - One direct cause = melting terrestrial ice
- Efforts to better predict/prepare for sea level rise
  - **Need stronger understanding of glaciers, mechanisms of ice flow**
- Glaciers = large masses of ice
  - Move through internal ice deformation and basal sliding

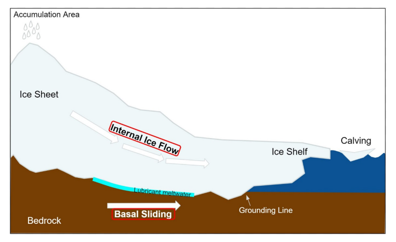


Fig 1: Diagram of a glacier

Internal Ice Deformation

- Grain boundary sliding dominant mechanism at glacial conditions (Goldsby and Kohlstedt, 2001)
- Flow of individual ice crystals (grains) in relation to each other

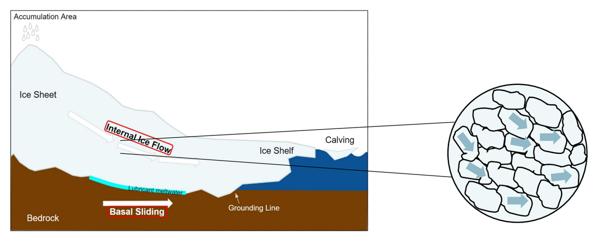


Fig 2: Diagram of a glacier and internal ice flow

- Atoms oriented in hexagonal rings, layers of rings form basal planes
  - Grains with atoms in hexagonal rings, layers of grains form basal planes
  - Under stress grains align and slide past each other on basal planes (Tarbuck and Lutgens, 2015)

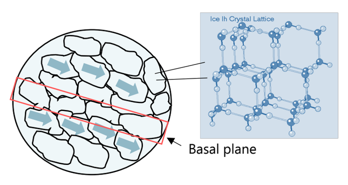


Fig 3: Grain microstructure

- Grain boundary migration theorized to be grain size-dependent (Goldsby and Kohlstedt, 2001)
  - Smaller grains = faster flow (Dahl-Jensen et al., 1987, Fisher et al., 1986)
  - Method to study factors affecting grain size: observing **grain growth**

Grain Growth

- Growth through grain boundary migration
  - Larger grains expand and consume smaller grains over time

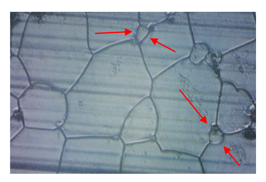


Fig 4: Model of grain growth through boundary migration

- Previous study monitored pure ice grain growth in varying temps in a controlled laboratory setting (Nielson, 2015)
  - Colder temperatures, smaller grain sizes
- **Grain growth is a way to understand the larger mechanism of internal ice deformation, since deformation is grain-sized dependent**

Basal Sliding

- Glacier sliding over the bedrock
- Influenced by presence of meltwater
  - Layer of water that forms between glacier and bedrock
  - Glacier velocity increases with meltwater (Hoffman et al., 2011)
  - Can be influenced by **frictional heating**

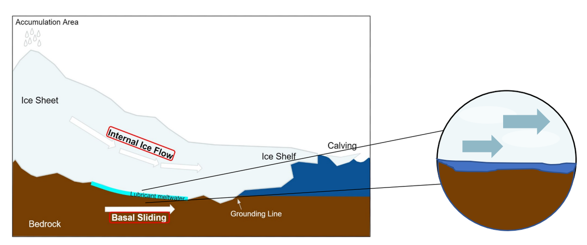


Fig 5: Diagram of a glacier and basal sliding

Frictional Heating

- Ice-on-rock friction occurring at base of glacier generates heat
  - Can lead to the creation of meltwater
- Previous study modeled frictional heating based on given depth and stress in a fault (Lachenbruch, 1986)
  - Frictional heating dependent on friction coefficient
- **Studying frictional heating is one way to better understand basal sliding, since meltwater generated influences glacial movement**

Gap in Literature

- Glacier impurities such as entrained insoluble debris particles
  - From atmosphere or from contact with bedrock at bottom of glacier

Grains

Field studies noted ice with debris having small grain sizes (Dahl-Jensen et al., 1987, Fisher et al., 1986)
Relationship not studied in controlled laboratory setting

Previous study observing grain growth in a controlled laboratory setting (Nielson, 2015)
Did not examine ice with impurities such as entrained debris

Frictional Heating

Previous study noted friction coefficient increases with debris (Zoet et al., 2013)
Did not emphasize relationship between debris content and frictional heating

Problem	Goals	Hypotheses
Necessary to study effects of debris on ice mechanics in relation to glacial movement	To compare grain growth in pure ice and ice with debris	Ice with debris will have smaller grain sizes
	To model the effect of entrained debris on frictional heating	Frictional heating increases with debris content

Methodology

(1a) Grain Growth Study: Fabricating Ice Samples (Cole, 1979)

Fabricating bulk ice
- Deionized water in a metal bucket
- Directional freezing unit (Fig 6) in chest freezer (-5°C)

Fabricating seed ice
- Shaved using a ½" crosscut burr bit
- Sieved using mesh pans (250μm and 106μm)

Filling mold
- Press sieved ice into mold (Figs 7 & 8)
- If debris: mix with sieved ice before filling mold

Flooding mold
- Air out with vacuum, DI water flooding through (Fig 9)
- Crystallized molds in chest freezer (-22°C)

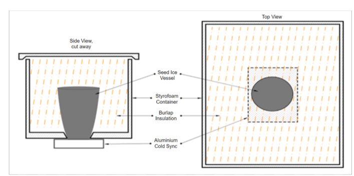
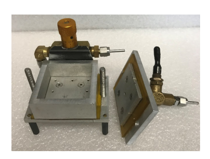


Fig 6: Directional freezing unit (Nielson, 2015)


Figs 7 & 8: Ice molds

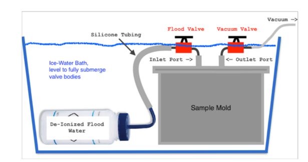
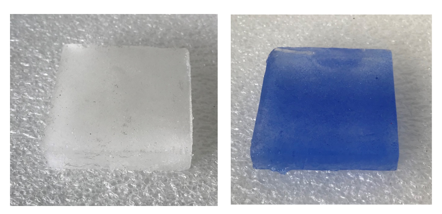



Fig 9: Vacuum mold-flooding (Nielson, 2015)

(1b) Grain Growth Study: Microstructural Analysis

Preparing for Observation	Microtome used to create flat surface for imaging
Observing Samples	Leica Light microscope; obj. lens 2.5x "Dinoeye" camera; Images saved with "DinoCapture 2.0"
Grain Size Analysis	Avg. grain size calculated (linear intercept method) Recorded grain sizes over time; compared samples


Figs 10 & 11: Pure ice & ice with debris samples

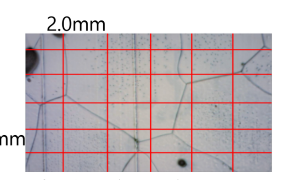


Fig 12: Linear-intercept analysis methodology

(2) Modeling Frictional Heating

MATLAB Program
1D Model, previously made by a lab member
Based off methodology of Lachenbruch, 1986

Variables Redefined
- μ = friction coefficient based on debris-rich ice-on-rock friction (Zoet et al., 2013).
- Ambient temp (T) = -3°C or -6°C
- Glacial velocity (v) = average (1.16x10^-5 m/s) or faster (5.6x10^-4m/s)

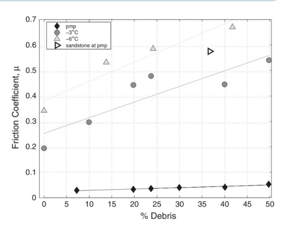


Fig 13: Friction coefficient based on debris content (Zoet et al., 2013)

Extrapolating the Δ in temp.
Graph of depth vs. temperature after frictional heating
- Used temp at depth of 140m (simulates actual glacier; Zoet, et al. 2013)

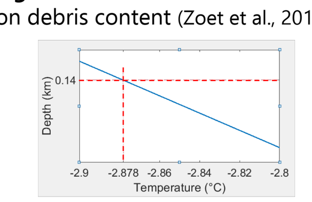


Fig 14: Determining temp. from MATLAB graphs

Results

Grain Growth Results

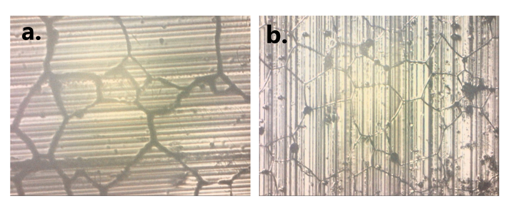


Fig 15: Ice microstructure taken with "DinoEye" camera

a. Pure ice day 3. Grain boundaries are the visible lines between the crystals. Horizontal lines are marks from the microtome.
b. Ice with debris day 2. Debris particles recognizable as small dots in between grain boundaries. Vertical lines are marks from the microtome.

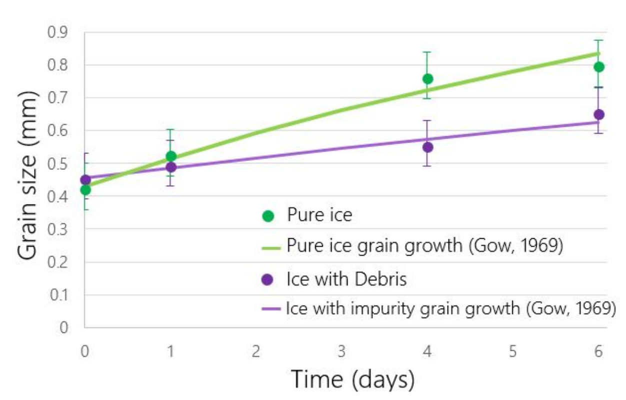


Fig 16: Time duration study of grain growth for pure ice and ice with debris

- Measured values overlain with $D^n = D_0^n + kt$ (Gow, 1969)
- $k = 1.12 \times 10^{-6.05}$ for pure ice, $8.57 \times 10^{-7.38}$ for ice with debris (Azuma, 2012)

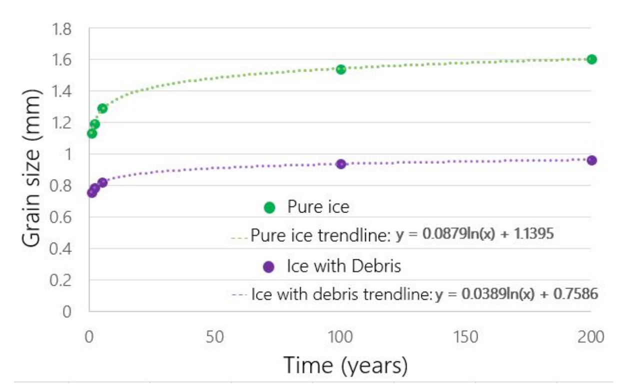


Fig 17: Extrapolated growth trends for pure ice and ice with debris

- Trendlines from measured values extrapolated to T=1, 2, 5, 100 & 200 yrs

Frictional Heating Results

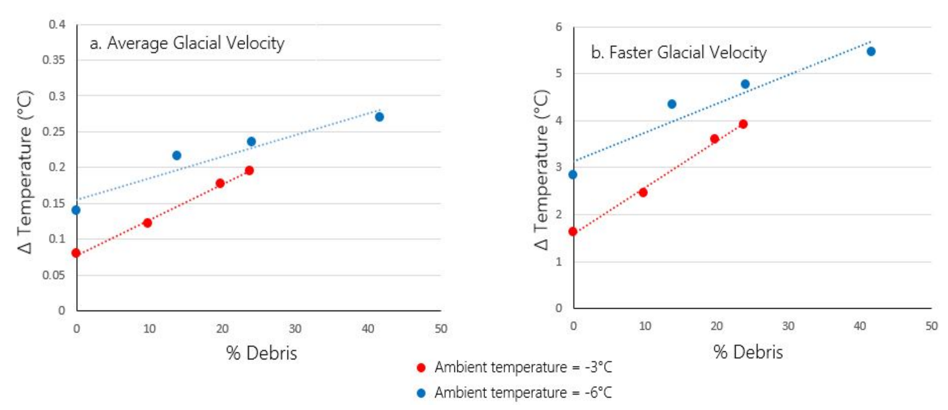


Fig 18: Change in temperature due to frictional heating as a function of debris content
a. Trial run at average glacial velocity
b. Trial run at faster glacial velocity

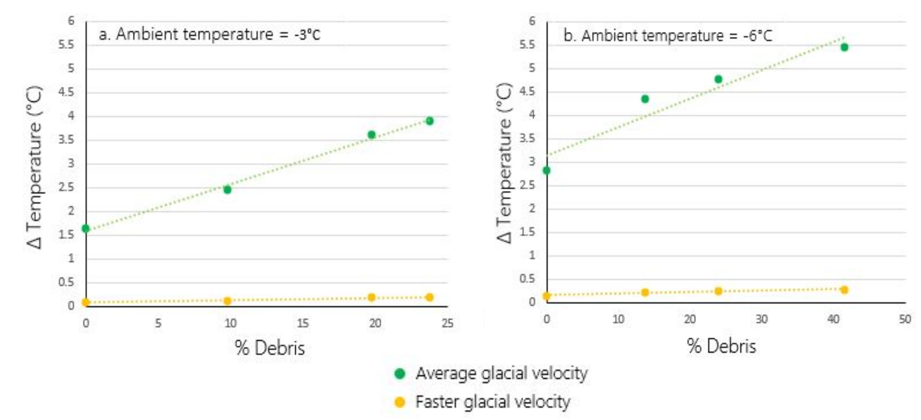


Fig 19: Change in temperature due to frictional heating as a function of debris content; comparing glacial velocities
a. Trial run at -3 °C ambient temperature
b. Trial run at -6 °C ambient temperature

Discussion

Grain Growth Study

- Grains smaller in ice with debris
  - Hypothesized to be result of grain boundary pinning: debris "pin" grains into place, restricting their movement / growth (Warren, 2006)
- Extrapolated grain sizes used with flow law (Goldsby and Kohlstedt, 2001)
  - Trend: ice with debris has lower viscosity (will flow faster)
  - Trend seems to augment over time

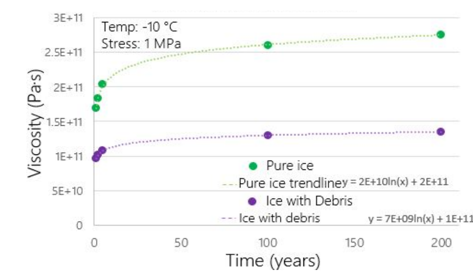


Fig 20: Extrapolated viscosities using flow law from Goldsby and Kohlstedt, 2001.

Modeling Frictional Heating

- Frictional heating and % debris directly proportional
- Faster velocities had larger amounts of temperature increase due to frictional heating
  - Faster velocities are consistent with stick-slip events
    - Stick-slip thought to be dominant in debris-rich glaciers (Zoet et al., 2013)

Applications

- Better accounting for ice impurities in glacial models will help understand which glaciers are at larger risk of melting
  - Prioritize attention to regions at higher risk, and address subsequent habitat changes
- Air pollution: contaminants may enter ice and affect flow in the future
- Improved sea level rise predictions will help coastal regions prepare for future climate

Conclusions

Hypothesis: ice with debris will have smaller grain sizes ✓
Other findings: Ice with fine-grained debris has lower viscosity

Ice entrained with insoluble fine-grained debris may flow faster than pure ice

Hypothesis: Frictional heating directly proportional to debris content ✓
Other findings: As velocity increases, frictional heating increases

Glaciers with debris-rich beds experiencing stick-slip may create more melt. Lubrication may cause the glacier to move faster.

Future Research

Goal: To obtain a more comprehensive understanding of the effect of debris on polycrystalline ice

Continuation of this study

- **Grain Growth Study**
  - Repeat with various types and sizes of debris
  - Create ice with different layers; pure ice & ice with debris
- **Modeling Frictional Heating**
  - Use cryogenic biaxial friction apparatus (Fig. 21) to find own friction coefficients of debris-rich ice-on-rock friction to use in model

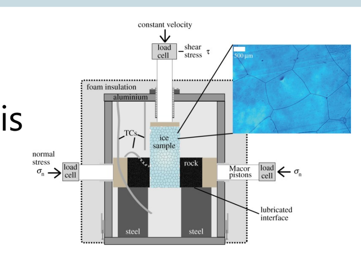


Fig 21: Cryogenic biaxial friction apparatus (McCarthy, 2017)

Calculate Young's Modulus

- The measure of the stiffness of a solid material
- Measure P- and S- waves through sample

$$E = \frac{\rho V_S^2 (3V_P^2 - 4V_S^2)}{V_P^2 - V_S^2}$$

- Strength of ice can relate to calving events

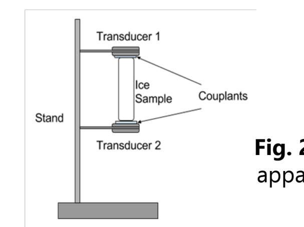


Fig. 22: P and S wave apparatus (K. Huang)

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