Environment and Processes of Subglacial Lake Whillans, West Antarctica

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Main Points

SLW sediment:
- comes from upstream and local marine sources
- shows evidence of various degrees of subglacial shear
- also evidence of recent dissolution (microbial mediation?)
- water saturated to compacted till - appears normally consolidated
- vertical clast fabric formed by decoupling during refilling
- last loading effect now over-printed

Lake discharge-recharge at low velocity
- ice recouples with lake bed at some lowstands
- till deformed into lake basin
- then ice re-floats and unloads
- no evidence of fluvial erosion or transport in subglacial flooding events
- flood velocities too low (<0.4 m/s) to entrain significant volumes of sediment
- water flow likely occurs in broad anastomosing sheets
A dynamic hydrological system
Lake is on a branch of a network of subglacial drainage

Carter et al., 2013
A dynamic hydrological system
Lake discharges and refills on a period of a few years

SLW has drained twice during the ICESat mission (2006 & 2009)

The 2009 discharge was captured during the last two ICESat campaigns

Now refilling

Fricker & Scambos 2009; Fricker et al. 2010
Geophysical team provided definition of the lake
and best site to access.

Hydrostatic pressure

Seismic reflection

Christianson et al. 2012

Horgan et al. 2012

Christner et al. 2014
Traversing from McMurdo
Camp set up by SLW
Lake bottom sediment rucked-up in front of camera

Image: Alberto Behar
Major WISSARD borehole science goals were achieved

Three ~0.4 liter water samples

Suspended sediment filtered from lake water onto a 0.2 micron filter

Sediment from percussion, piston and multi-cores
Sediment core analyses

- ITRAX XRF scanner & XRF
- Geotek physical props scanner
- X-radiography
- Grain Mineralogy
- Clast lithology
- Biomarkers
- Particle size
- Clast fabric
- Paleomag NRM and AMS
- Grain & clast surface microtextures
- Thin section micromorphology
- Moisture content
- Strength tests

shell fragment

Core degassing

Sediment strength tests
Below ~1m of turbid water

Local basal melting + flow from upstream

Structureless, clast-poor (<10%) muddy diamicton

Water saturated to compacted

Appears very homogeneous

Compare with upstream (“UpB”)
X-radiographs

- homogeneous - some weak layering?
- clast abundance - variable, < 10%
- clast orientation - locally preferred
Homogeneity shown by ITRAX XRF
(Percussion core)

Holes from clasts
Provenance analysis

Methods
- Clast lithology
- Sand mineralogy
- Major/trace element chemistry
- Molecular biomarkers

Clast lithologies
1158 clasts - mostly from granules to fine pebbles

Composition of plutonic clasts
- Felsic: 798
- Intermediate: 228
- Mafic: 79

Clast lithologies:
- Sedimentary
- Metasedimentary
- Plutonic
- Volcanic
Clasts and sands indicate similar sources to UpB
But there are differences
Molecular Biomarkers

Appears to suggest
• Downstream increase in marine biomarkers
• Local source of related marine sediment that has not been fully homogenized

Polar compounds found in sediments:
- Brassicasterol – specific to diatoms
- Dinostanol – thought to be specific to dinoflagellates
SLW water column geochemistry

- Consistency in chemical composition between three casts
- Nutrients N and P present in water column
- $\delta^{18}$O indicates glacial meltwater as dominant water source
- Br/Cl indicate a diluted seawater signal

<table>
<thead>
<tr>
<th></th>
<th>pH</th>
<th>Na+</th>
<th>K+</th>
<th>Mg$^{2+}$</th>
<th>Ca$^{2+}$</th>
<th>F$^-$</th>
<th>Cl$^-$</th>
<th>Br$^-$</th>
<th>NO$_3^-$</th>
<th>SO$_4^{2-}$</th>
<th>PO$_4^{3-}$</th>
<th>DIC (HCO$_3^-$)</th>
<th>$\delta^{18}$O</th>
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<tbody>
<tr>
<td>Cast 1</td>
<td>8.0</td>
<td>5118</td>
<td>175</td>
<td>473</td>
<td>1034</td>
<td>28</td>
<td>3657</td>
<td>5.1</td>
<td>1.4</td>
<td>1228</td>
<td>4.5</td>
<td>2095</td>
<td>-38.0</td>
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<tr>
<td>Cast 2</td>
<td>8.2</td>
<td>5285</td>
<td>177</td>
<td>477</td>
<td>1020</td>
<td>31</td>
<td>3827</td>
<td>5.8</td>
<td>0.7</td>
<td>1255</td>
<td>4.3</td>
<td>2130</td>
<td>-38.0</td>
</tr>
<tr>
<td>Cast 3</td>
<td>8.1</td>
<td>5389</td>
<td>178</td>
<td>486</td>
<td>1023</td>
<td>31</td>
<td>3904</td>
<td>6.6</td>
<td>0.4</td>
<td>1272</td>
<td>5.5</td>
<td>2109</td>
<td>-38.1</td>
</tr>
</tbody>
</table>

Units are ueq l$^{-1}$ except for $\delta^{18}$O and pH

Br/Cl ratio of SLW is 0.00153, seawater is 0.00155 (Holland 1978)

3.8 mM Cl = 1/144 strength seawater
Particle shapes and surface textures to assess subglacial processes and dynamics

Clast Shape
1158 clasts

Dominant lithology – igneous & metasedimentary

Typical glacial shape for lithology
Clasts angular, facetted and striated

Typical of subglacial till – not fluvial

<table>
<thead>
<tr>
<th>Feature</th>
<th>Percentage of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faceted</td>
<td>10%</td>
</tr>
<tr>
<td>Striated</td>
<td>28%</td>
</tr>
</tbody>
</table>

Roundness

- 0.7: 2
- 0.6: 10
- 0.5: 52
- 0.4: 220
- 0.3: 604
- 0.2: 255
- 0.1: 15

Clast numbers
## Clast features compared

<table>
<thead>
<tr>
<th>UpB</th>
<th>SLW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Striae: ~0.9% (?)</td>
<td>Striae: 28%</td>
</tr>
<tr>
<td>Facets: 50%</td>
<td>Facets: 10%</td>
</tr>
<tr>
<td>Roundness: subangular</td>
<td>Roundness: subangular</td>
</tr>
</tbody>
</table>

More striae but fewer facets downstream

less bedrock interaction
more in-till contacts

Tulaczyk et al. 1998
Surface microtexture of quartz grains

chatter marks
fresh surface

etched surface
conchoidal fractures

preweathered surface
chatter fractures

by SEM on 120 grains 125-1000 μm in size

Rebecca Putkammen
- Microtextures differ from UpB
- Infer a more complex history
  - weathering $\rightarrow$ crushing $\rightarrow$ fracture
  - $\rightarrow$ abrasion $\rightarrow$ dissolution
  - $\rightarrow$ variable shear
SLW till particle size distribution

Finer (silt) mode to UpB
Texture of sediment infers

- no sorted sediments
- may be larger volumes of water moving around during discharge-recharge events
- but given gradients and inferred conduit size
- velocities likely to be low at <0.4 ms\(^{-1}\) in 1 m deep water column
Clast fabric

Core section shows >4mm diameter clasts
Measure apparent long-axis on 82 clasts

- weak vertical fabric
- not typical sheared till fabric
- formed with decoupling?
Till microfabric

Fractures

Skelsepic

Lattispeic

van der Meer 1993
Physical properties

perhaps most interesting is water content and inferred consolidation
Consolidation vs depth

SLW till normally consolidated

appears any loading effect from last ice touch-down during lake drainage has been compensated

For hydrostatically consolidated sediment:

\[ e = e_o - C_p \log \frac{N_o}{N_{eo}} \]

\( e \): void ratio
\( e_o \): ref. void ratio
\( C \): compressibility
\( N_o \): effective normal pressure
\( N_{eo} \): ref. effective normal pressure

\[ N_o = N_{eb} + (\rho_t - \rho_w)gz \]

\[ \frac{dN_e}{dz} = (\rho_t - \rho_w)g \approx 10 \text{ kPa m}^{-1} \]

converted water content to void ratio
Environmental Interpretation

No signs of sorting or lag surfaces
- quiescent conditions in the lake
- negligible deposition or erosion of lake sediment
- "floods" not typical floods – flow only at cm/s due to low surface gradients and wide conduits

But during ‘lowstands’ ice recouples with bed
- deforming new till into the lake
- mixes any older thin lake sediment into till

Fricker et al. 2010
Conclusions

SLW sediment
- homogeneous, structureless, clast poor, muddy till
- water saturated to compacted

Sediment sources
- minor differences with those of UpB
- at least a local marine component

Clasts, grains and microfabric
- a more complex transport history than UpB
- strong (but variable) glacial shear and recent dissolution

Lake discharge-recharge at low velocity (<0.4ms\(^{-1}\))
- floods move across WIP but no sign of fluvial erosion or transport
- flow unlikely via persistent conduits, most likely in braided sheets

At some lowstands ice recouples with lake bed (last 2004?)
- till deformed into lake basin
- then re-floats and unloads
- common for lakes on ice plains but unlikely in deeper interior lakes

Till appears normally consolidated
- loading effect from last lake drainage now compensated

Clasts have weak vertical fabric
- formed with decoupling during lake refilling