Under The Ice: Studying one of the last unexplored aquatic environments on Earth

Presented by: Dr. Slawek Tulaczyk and Dr. Brent Christner

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Under the Ice: Studying one of the last unexplored aquatic environments on Earth

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University of California, Santa Cruz, CA, USA
Old view (book titles):

“The Crystal Desert”
“Big Dead Place”
Ice base seen from a subglacial water cavity below a mile of ice
The largest wetland on Earth surrounding lakes and rivers (NSF images)
Was Antarctica always covered by ice?

<table>
<thead>
<tr>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
</table>

When did Antarctica become covered by ice?

- (A) 30,000 years ago
- (B) 300,000 years ago
- (C) 3 mln years ago
- (D) 30 mln years ago
- (E) 300 mln years ago
Before 35 million years ago this used to be a continent like any other.
Antarctica before glaciation (Wilson and Luyendyke, 2009)

Restored elevation (m above modern sea level)
Let’s Pause for Questions
Where does the water come from?

Ice sheet melts at its base (Llubes et al., 2006)
What are sources of heat beneath ice?

(A) Sunlight
(B) Radioactive heat
(C) Geothermal heat
(D) Frictional heating during motion
Water is being squeezed towards the ocean but gets trapped in lakes
The largest subglacial lake in Antarctica is Lake Vostok.
Subglacial Lake Whillans has drained twice.

Some lakes are active.
>100 active subglacial lakes mapped out in 2003-08
Ice velocity map from Dr. Ian Joughin, UW
red ~1000 m/yr,
blue ~100 m/yr,
yellowish-green ~10 m/yr
mass gain
mass loss

snowfall

iceberg calving
surface melt
basal melt

ice flow
Why are Antarctic subglacial lakes worth studying?

(A) They may be microbial habitats
(B) Subglacial water bodies help control ice flow
(C) Lake sediments may be archives of past events in Antarctic climate history
(D) All of the above
Ice base seen from a subglacial water cavity below a mile of ice
Difficulties with drilling into subglacial environments

(NRC 2007 report on Exploration of Antarctic Subglacial Aquatic Environments)
Let’s Pause for Questions
Website http://www.wissard.org
Project Schedule

2009-10
Tool development

2010-11
Tool development

Surface geophysics

2011-12
Surface geophysics

Test drilling (McM)

2012-13
Lake and ice stream drilling

2013-14
Grounding zone drilling

2014-15
End of project
A new science traverse platform similar to the South Pole traverse

(SP traverse image from Antarctic Sun)
A new, mobile, and clean hot-water drill integrated into the traverse platform
(Enhanced Hot-Water Drill image from Antarctic Sun)
Conceptual field operational lay out of hot-water drill components (ICDS)
WISSARD Team (14 PIs, 9 Institutions)

Ross Powell  
RAGES Lead PI  
LISSARD PI

Sridhar Anandakrishnan  
LISSARD/RAGES PI

Slawek Tulaczyk  
LISSARD Lead PI  
RAGES PI

Helen Fricker  
LISSARD/RAGES PI

Brent Christner  
GBASE PI

John Priscu  
GBASE Lead PI

David Holland  
RAGES PI

Andrew Mitchell  
GBASE PI

Jeff Severinghaus  
LISSARD PI

Project Partners:
Ice Core Drilling Services (UW-Madison)
Raytheon Polar Services Company (Logistics/Traverse)
Deep Ocean Exploration and Research (Sub-Ice Robot etc.)
Subglacial Lake Ellsworth Project (UK initiative)
Antarctic subglacial hydrologic systems are complicated (wetlands, active/passive subglacial lakes, rivers)

Active subglacial lakes are widespread

Their activity may perturb ice flow

They support deep subglacial biosphere that needs to be explored
Let’s Pause for Questions
Under The Ice: Part II

Brent Christner
Department of Biological Sciences
Louisiana State University
Webinar talk points

• The extent of the biosphere
• Life in the cold
• A habitat for microbial life in solid ice
• Large quantities of water beneath the Antarctic ice sheets
• The icy implications for astrobiology
The extent of the biosphere

- Life inhabits a relatively small portion of the planet.

- Biosphere = portion of Earth where life exists and interacts with the lithosphere, hydrosphere, and atmosphere.

- Most of the life on Earth is a few kilometers above and below the surface.
Q1: Which of the following regarding life in the biosphere is FALSE?

A) Microbial life existed for billions of years before plants and animals.
B) There is more life in the Earth’s subsurface than on the surface.
C) The amount of global microbial carbon is about the same as the carbon in all plants.
D) There are 1,000,000,000 times more microbes on Earth than stars in the Universe.
E) All of the above statements are true.
### The microbial world is immense

<table>
<thead>
<tr>
<th>Environment</th>
<th># of cells (^a)</th>
<th>Pg of Carbon (^a) (1 Pg=10(^{15}) g=(~10^{12}) lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquatic habitats</td>
<td>1.2 x 10(^{29})</td>
<td>2.2</td>
</tr>
<tr>
<td>Soil</td>
<td>2.6 x 10(^{29})</td>
<td>26</td>
</tr>
<tr>
<td>Oceanic subsurface</td>
<td>3.6 x 10(^{30})</td>
<td>303</td>
</tr>
<tr>
<td>Terrestrial subsurface</td>
<td>2.5-25 x 10(^{29})</td>
<td>22-215</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>4-6 x 10(^{30})</td>
<td><strong>350-550</strong></td>
</tr>
</tbody>
</table>

- Prokaryotic carbon: 60-100% of the estimated carbon in plants.
- >10 times more cells and biomass in subsurface than the surface
- 1,000,000,000 times more microbes on Earth than stars in the Universe!

Data from: \(^a\)Whitman et al. 1998, PNAS 95:6578-6583
Geological timescale and major events in Earth’s history

- Origin of life
- O₂ accumulates in the atmosphere
- Eukaryotes appear in fossil record
- Higher plants and animals
- Homo sapiens
Most of the genetic diversity resides in the microbial world

- Life is classified into 3 domains
- Two of the domains are exclusively microbial (Bacteria and Archaea)
- Most of life’s genetic diversity resides in the microbial world
- The “crown radiation”: a peripheral branch on the tree of life

The hydrologic cycle: water = life

<table>
<thead>
<tr>
<th>H2O reservoir</th>
<th>Percent of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceans</td>
<td>97.25</td>
</tr>
<tr>
<td>Ice caps &amp; glaciers†</td>
<td>2.05</td>
</tr>
<tr>
<td>Groundwater</td>
<td>0.68</td>
</tr>
<tr>
<td>Lakes</td>
<td>0.01</td>
</tr>
<tr>
<td>Soil moisture</td>
<td>0.005</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>0.001</td>
</tr>
<tr>
<td>Streams &amp; rivers</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

†Contain 75% of the world’s freshwater

http://www.jek2004.com
Q2: Which most accurately describes conditions in the biosphere?

A) The biosphere is hot.
B) The biosphere is warm.
C) The biosphere is cold.
The biosphere is cold

• 90% (by volume) is cold ocean <5°C
• 70% of Earth’s freshwater is ice
• 14% of the Earth’s surface is polar
• 25% of soils are permafrost
“We have seen no living thing, not even a moss or a lichen... it is certainly a valley of the dead.”

R. F. Scott (1903)
“The biology of Antarctica is almost wholly a marine biology. Other than a few cryoalgae, who colonize melting snowfields, no organisms live on land ice exclusively; *there is no terrestrial cryoecosphere*. 

*In: The Ice: A Journey to Antarctica, S.J. Pyne (1986)*
98% of the Antarctic continent is covered in ice

90% of Earth’s ice is in Antarctica

70% of the planet’s freshwater is frozen in Antarctic ice
A habitat for microbial life in solid ice

Source: Lonnie Thompson
Environmental Data Include:

A. Temperature ($\delta^{18}O$)
B. Atmospheric Chemistry
C. Net Accumulation
D. Dustiness of Atmosphere
E. Vegetation Changes
F. Volcanic History
G. Anthropogenic Emissions
H. Entrapped Microorganisms
Bacteria cultured from an ancient glacial ice sample
<table>
<thead>
<tr>
<th>Investigators</th>
<th>Material</th>
<th>Age (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miteva &amp; Brenchley 2005</td>
<td>Glacial ice; GISP2, Greenland</td>
<td>120,000</td>
</tr>
<tr>
<td>Abyzov 1993</td>
<td>Glacial ice; Vostok, Antarctica</td>
<td>200,000</td>
</tr>
<tr>
<td>Christner et al. 2006</td>
<td>Glacial ice; Vostok, Antarctica</td>
<td>&gt;420,000</td>
</tr>
<tr>
<td>Christner et al. 2003</td>
<td>Glacial ice; Guliya, China</td>
<td>~750,000</td>
</tr>
<tr>
<td>Bidle et al. 2007</td>
<td>Glacial ice; Beacon Valley, Antarctica</td>
<td>~8,000,000</td>
</tr>
<tr>
<td>Cano and Borucki 1995</td>
<td>Amber</td>
<td>25,000,000</td>
</tr>
<tr>
<td>Greenblatt et al. 1999</td>
<td>Amber</td>
<td>120,000,000</td>
</tr>
<tr>
<td>Vreeland et al. 2000</td>
<td>Salt crystal</td>
<td>250,000,000</td>
</tr>
</tbody>
</table>
Q3: What do you think is the biggest challenge to microbial survival in ancient ice?

A) Cells require liquid water to sustain biochemical reactions, and there is no liquid water in ice.
B) Macromolecules are damaged over extended periods of dormancy, eventually killing the cells.
C) The process of freezing results in physical and mechanical damage to cells.
D) Extremely cold temperatures are inherently damaging to biological macromolecules.
E) Acclimating to 21st century popular music.
“Microbial habitat consisting of solid ice grains bounded by liquid veins. Two microbes are depicted as living in the vein of diameter $d_{\text{vein}}$ surrounding a single grain of diameter $D$."

Cryostage Microscopic Image at -20°C of Microbial Cells at the Ice Grain Boundaries

A thin section of glacial ice from the Taylor Glacier (McMurdo Dry Valleys, Antarctica) (A) Bright field image of the ice; (B) the same area under epifluorescence showing DNA-containing cells in the interstitial habitat between ice crystals. Each micrograph is ~1000 μm in width.
Protein synthesis at -15°C in the cold-adapted bacterium *Psychrobacter cryohalolentis* K5

The persistence of metabolism in ice at low temperatures raises an intriguing question: Are the World’s glaciers and ice sheets active biomes?
Let’s Pause for Questions
Large quantities of water exist beneath the Antarctic ice sheets.
Suglacial Lake Vostok, Antarctica

Studinger et al. 2003
Maintenance of Warm Subglacial Conditions in East Antarctica due to Geothermal Heating

Liquid water in the lake is stable due to the combined effect of:

• Geothermal heating

• Insulating properties of a thick ice sheet

• Decreased melting point of H$_2$O at high pressure
Microbes in Vostok Accretion Ice

Priscu et al. 1999; Christner and Priscu, unpublished.
A general equation of life can be represented as:

\[ \text{A}_{\text{red}} + \text{B}_{\text{ox}} \rightarrow \text{A}_{\text{ox}} + \text{B}_{\text{red}} \]

- **A\textsubscript{red}** – a reduced organic (e.g., glucose) or inorganic (e.g., Fe\textsuperscript{+2}) compound.

- **B\textsubscript{ox}** – an oxidized compound such as O\textsubscript{2}, NO\textsubscript{3}\textsuperscript{-}, SO\textsubscript{4}\textsuperscript{2-}, CO\textsubscript{2}, Fe\textsuperscript{+3}, Mn\textsuperscript{+4}, etc.

A continuous supply of reductants and oxidants is essential to maintain an ecosystem and life.

Life = e\textsuperscript{-} transfer
Q4: Which energy source is most important to life on Earth’s surface?

A) Solar
B) Chemical
C) Fusion
D) Wind
Energy flow in ecosystems

ATP = the energy “currency” for life

Substrates produced via autotrophic activity (CO₂-fixation)
Hypothetical scenario for lithotrophy in Subglacial Lake Vostok

\[ 4\text{FeS}_2 + 15\text{O}_2 + 14\text{H}_2\text{O} \rightarrow 16\text{H}^+ + 8\text{SO}_4^{2-} + 4\text{Fe(OH)}_3 \]

\[ \text{FeS}_2 + 14\text{Fe}^{3+} + 8\text{H}_2\text{O} \rightarrow 15\text{Fe}^{2+} + 2\text{SO}_4^{2-} + 16\text{H}^+ \]
Let’s Pause for Questions
A) Icy environments are a significant component of the Earth’s biosphere.

B) Studying life in cold environs on Earth provides information on the possibility of ET life on icy worlds.

C) Microbes isolated from cold environs synthesize biomolecules that have medical and industrial applications.

D) There really is no point.

E) A, B, and C
### Estimated concentration of cells and organic carbon in the Antarctic cryoecosphere

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Antarctica</th>
<th>Global</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Subglacial lakes, ice sheets, and ground water</td>
<td>Fresh Waters</td>
</tr>
<tr>
<td>Cell number</td>
<td>$4.00 \times 10^{28}$</td>
<td>1.31 $\times 10^{26}$</td>
</tr>
<tr>
<td>Cell-C (Pg)</td>
<td>$1.15 \times 10^{0}$</td>
<td>3.63 $\times 10^{-3}$</td>
</tr>
<tr>
<td>DOC (Pg)</td>
<td>$1.00 \times 10^{1}$</td>
<td>1.16 $\times 10^{0}$</td>
</tr>
</tbody>
</table>

All carbon values in petagrams (Pg = $10^{15}$ g = ~$10^{12}$ pounds)

Source: Priscu et al. 2007; Priscu and Christner 2004; Whitman et al. 1998; Lanoil et al. 2009
The icy implications for astrobiology

**Ski Mars?** - Recent and recurring glacial activity in tropical and mid-latitude regions.

**Europa** - If there is life, europans may share many similarities with microbial communities found in subglacial aquatic environments.
### Average Surface Temperature at Vostok, Antarctica

<table>
<thead>
<tr>
<th>Month</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>-32.1</td>
</tr>
<tr>
<td>Feb</td>
<td>-44.3</td>
</tr>
<tr>
<td>Mar</td>
<td>-57.9</td>
</tr>
<tr>
<td>Apr</td>
<td>-64.7</td>
</tr>
<tr>
<td>May</td>
<td>-65.6</td>
</tr>
<tr>
<td>Jun</td>
<td>-65.2</td>
</tr>
<tr>
<td>Jul</td>
<td>-66.9</td>
</tr>
<tr>
<td>Aug</td>
<td>-67.6</td>
</tr>
<tr>
<td>Sep</td>
<td>-66.0</td>
</tr>
<tr>
<td>Oct</td>
<td>-57.1</td>
</tr>
<tr>
<td>Nov</td>
<td>-43.3</td>
</tr>
<tr>
<td>Dec</td>
<td>-32.1</td>
</tr>
</tbody>
</table>

**YEAR**

- **Average**: -55.1

**Minimum** (CO₂ ice; high elevations at winter poles)

- **-133**

**Maximum** (dark tropical regions in summer)

- **27**

### Temperatures on the Surface of Mars

- **WORLD RECORD**: -89.5 °C (July 21, 1983)
LAKE VOSTOK
(Ride in the dark layers)

Ice flow

Chaotic Ice layer: thickness ~1.5-150 km

Water, microbes, inorganic particles, gases, ions

-180 °C

0 °C

Subice Ocean: a habitat for life and a reservoir of endogenous and exogenous substances

Cored 3623 m
Tide crack (10^3 y lifetime)
Loss of accreted ice and associated matter

Sunshine = photosynthesis

Comets = organics

~EUROPA
(life in the dark?)
(after Greenberg & Geissler, 2002)

Loss of accreted ice and associated matter

Clathrates?

LAKE VOSTOK
(Ride in the dark layers)

Water, microbes, inorganic particles, gases, ions

-180 °C

0 °C

Subice Ocean: a habitat for life and a reservoir of endogenous and exogenous substances

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Comets = organics

~EUROPA
(life in the dark?)
(after Greenberg & Geissler, 2002)
Is surficial liquid water (Earth-like conditions) a prerequisite for habitability?

- Mass of star relative to Sun
- Radius of orbit relative to Earth’s

“Habitable Zone”

- Mars
- Earth
- Venus
Lessons learned from icy environments on Earth are broadening the search for ET life
Conclusions

• From an evolutionary and ecological perspective, the Earth is a microbial planet.

• The majority of the biosphere is permanently cold.

• Biological processes persist under frozen conditions, implying that the World’s glaciers may be active biomes.

• Subglacial microbiota and ecosystems are expected to be unique from those found on Earth’s surface.

• The Antarctic cryoecosphere contains a significant pool of microbial cells and carbon.

• Subglacial environs provide tractable analogs to evaluate the possibility of life in icy extraterrestrial environments.
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