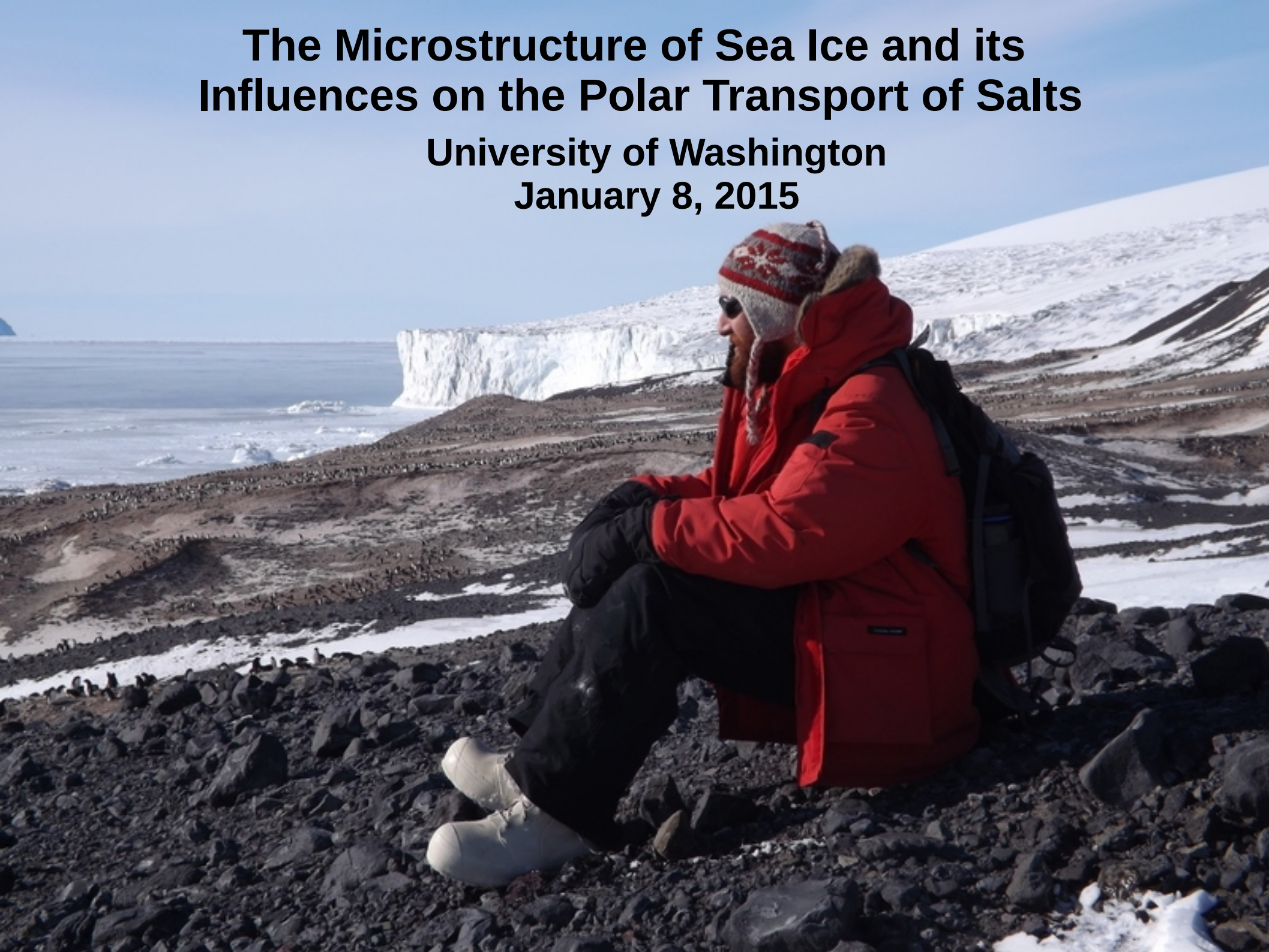
The Microstructure of Sea Ice and its Influences on the Polar Transport of Salts

University of Washington

January 8, 2015

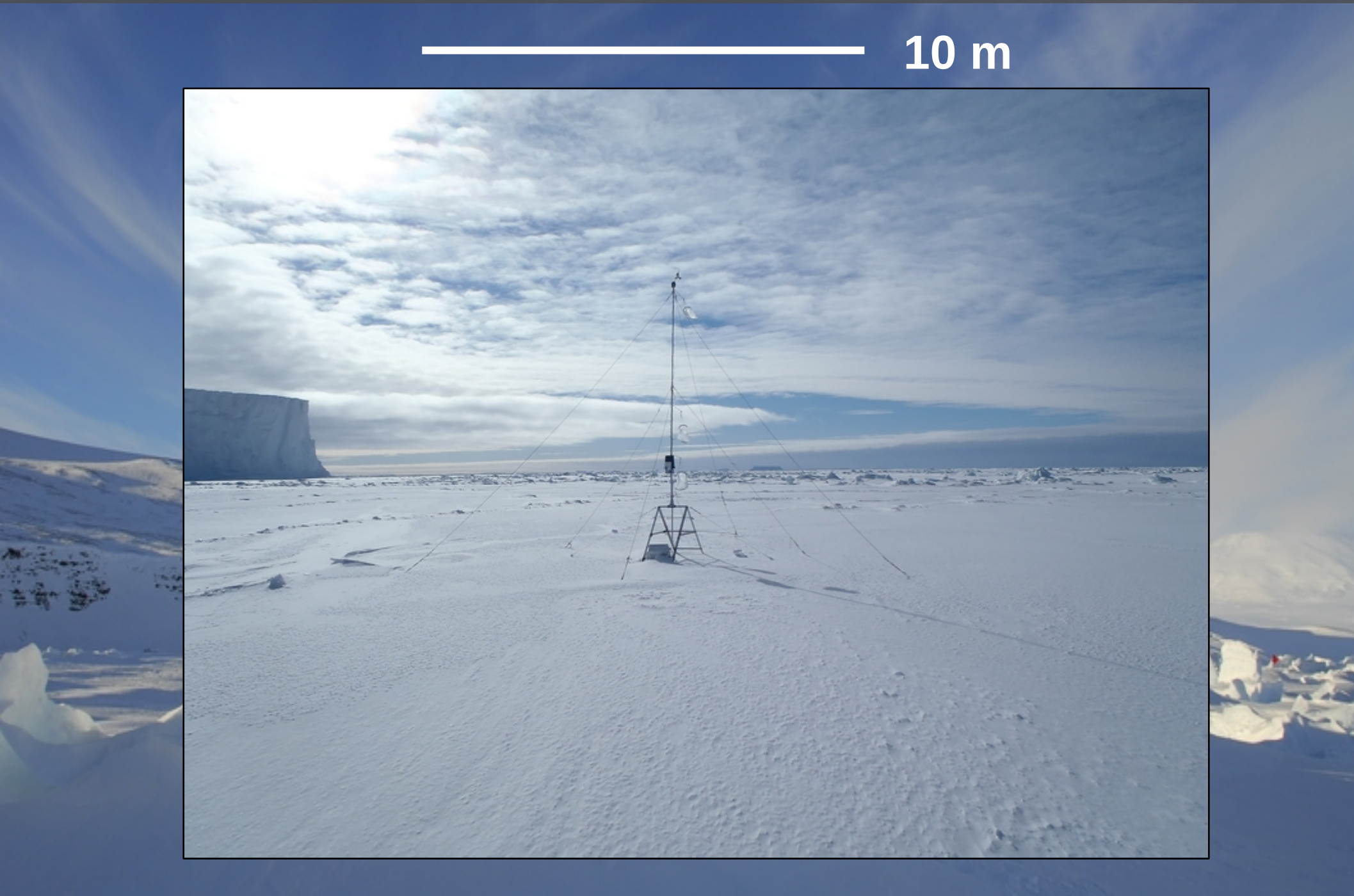


Scale of Sea Ice

Sea Ice

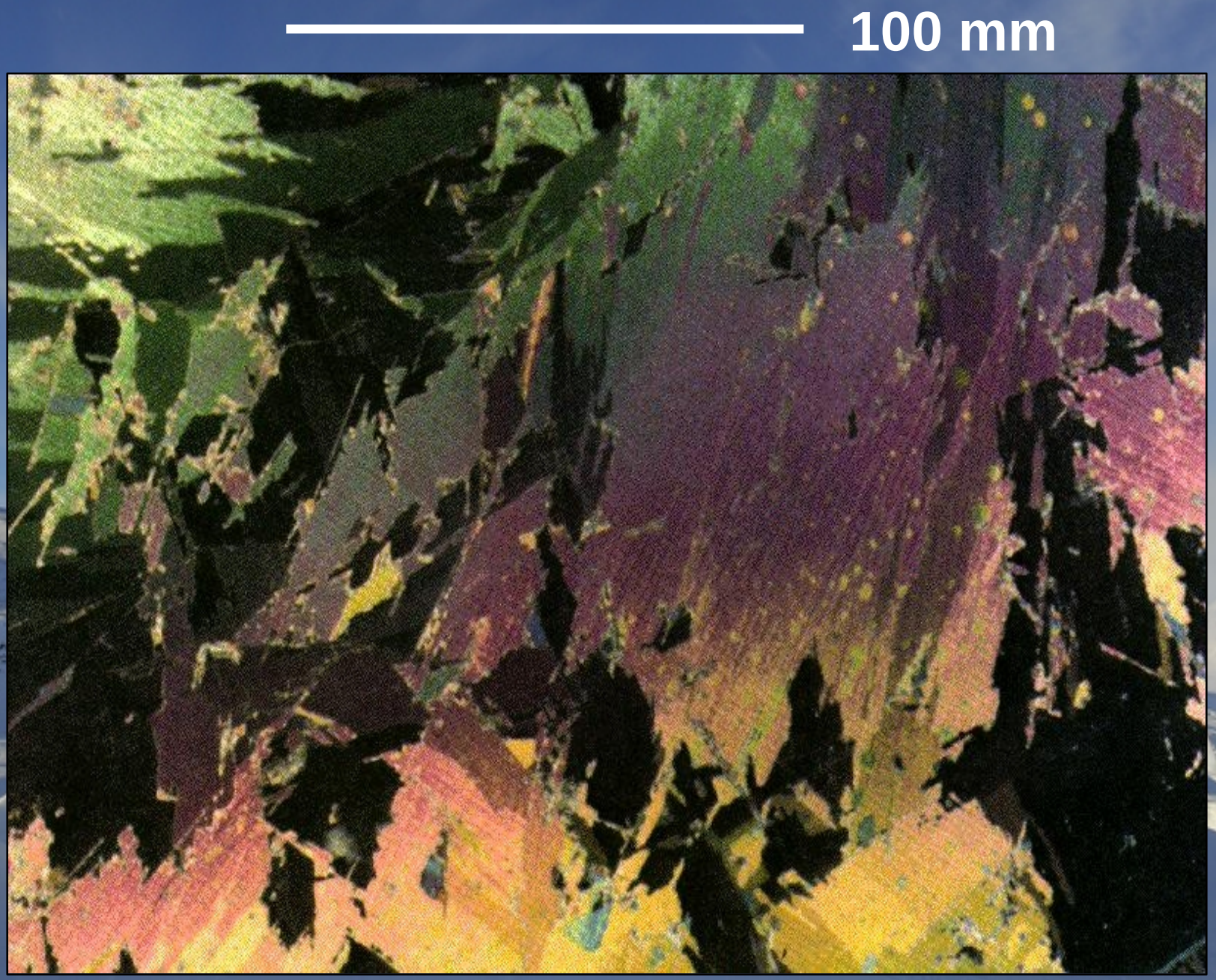
Sea Ice

Sea Ice

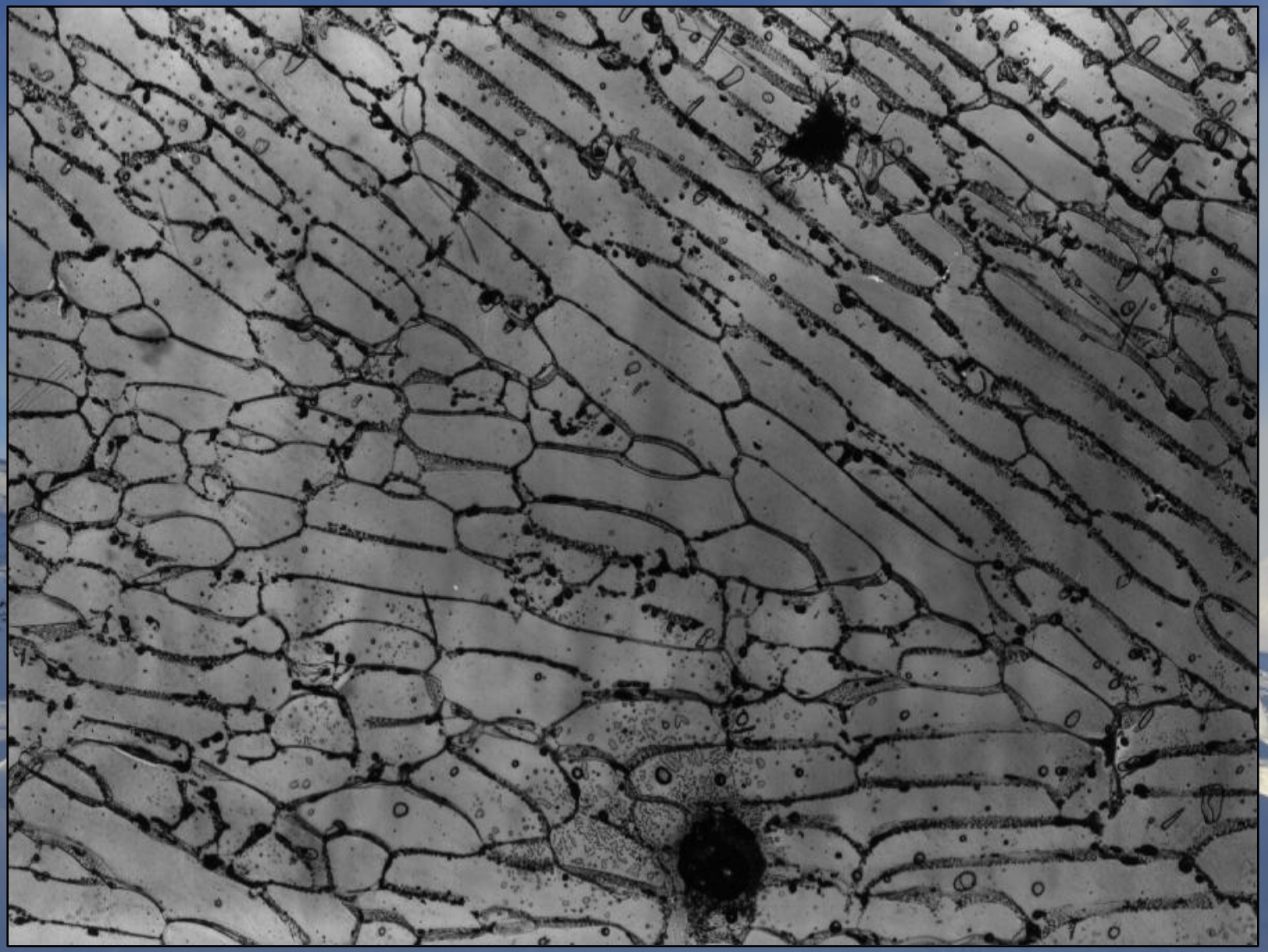


Sea Ice

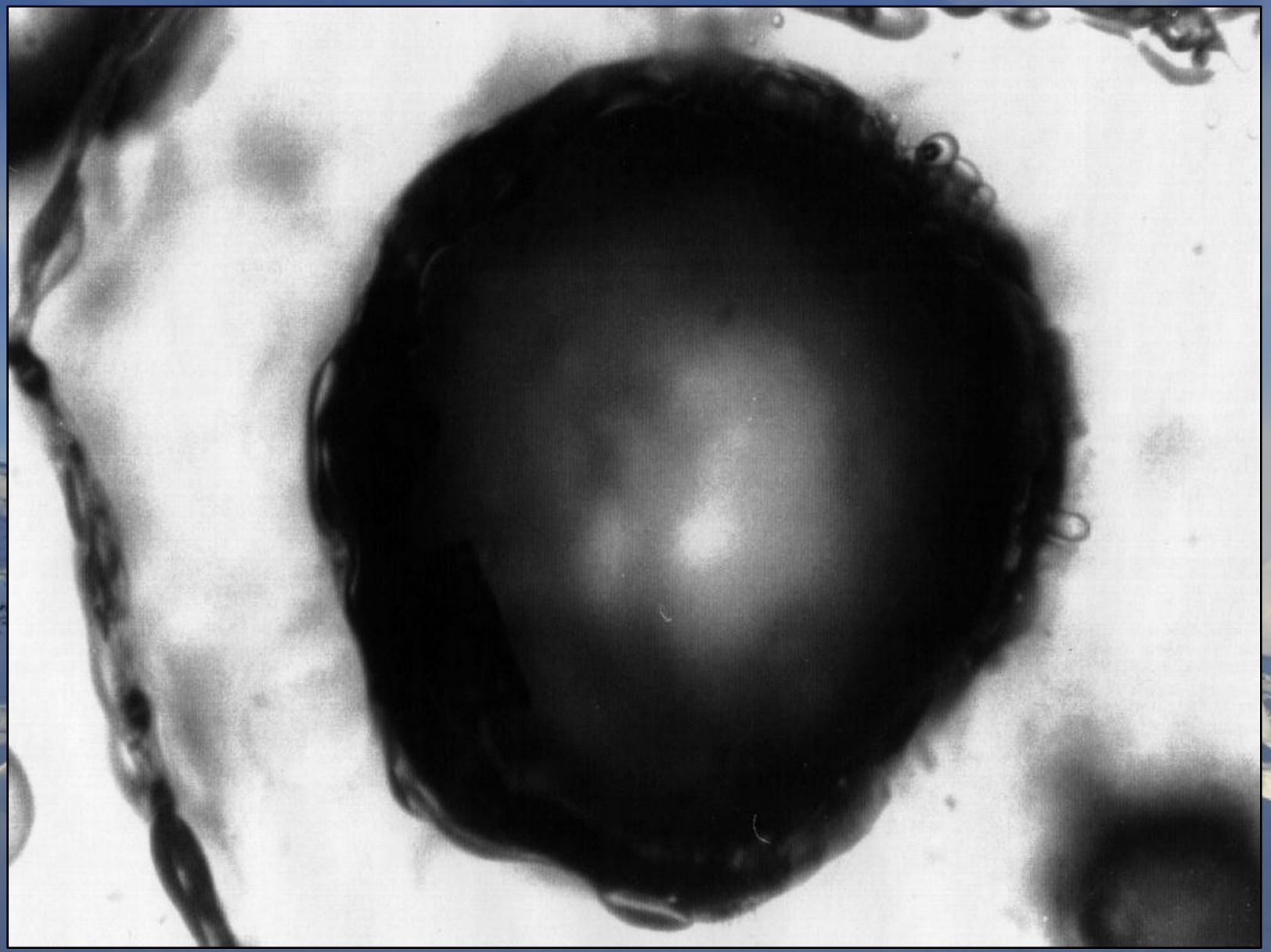
Sea Ice



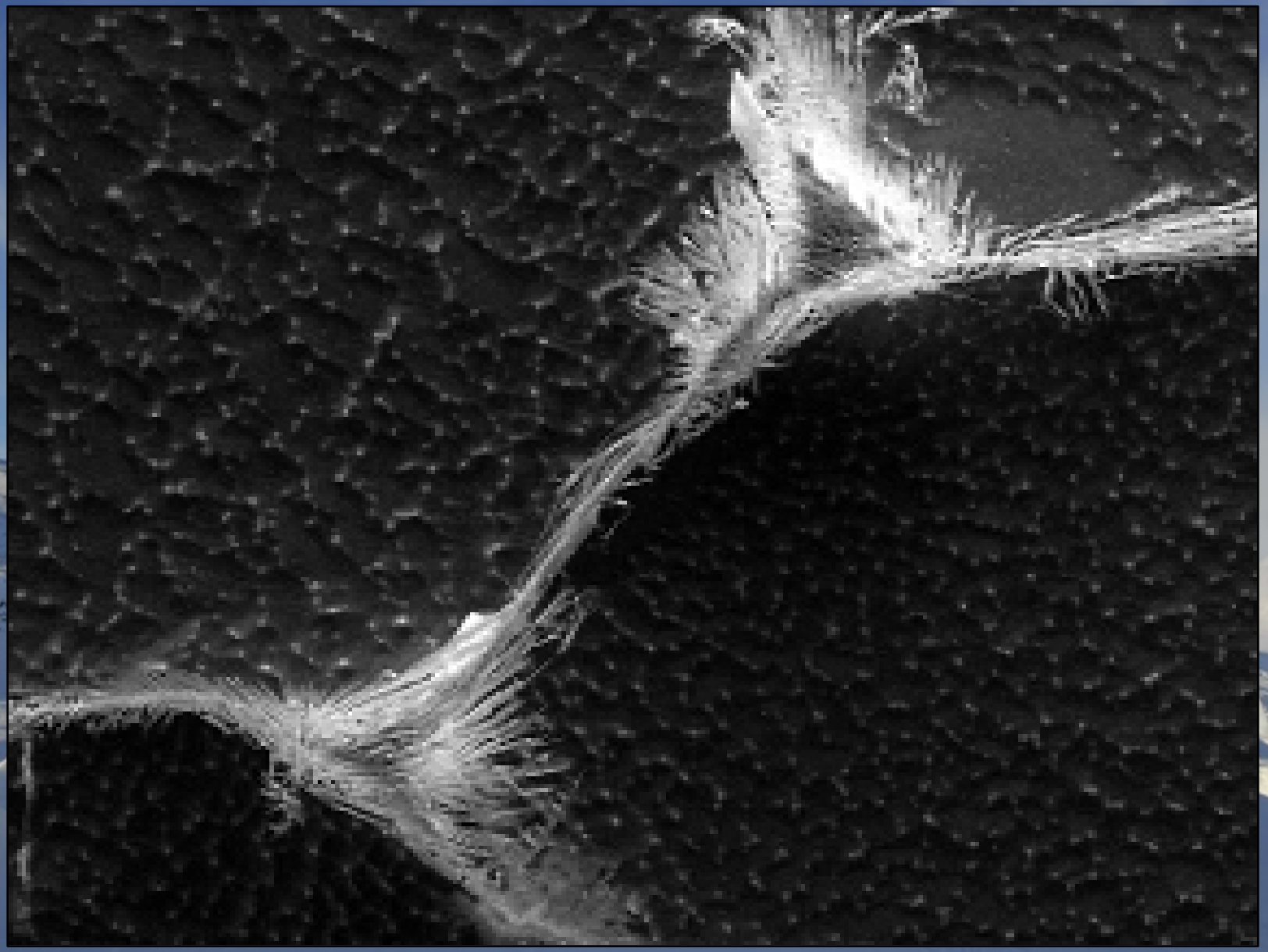
Sea Ice



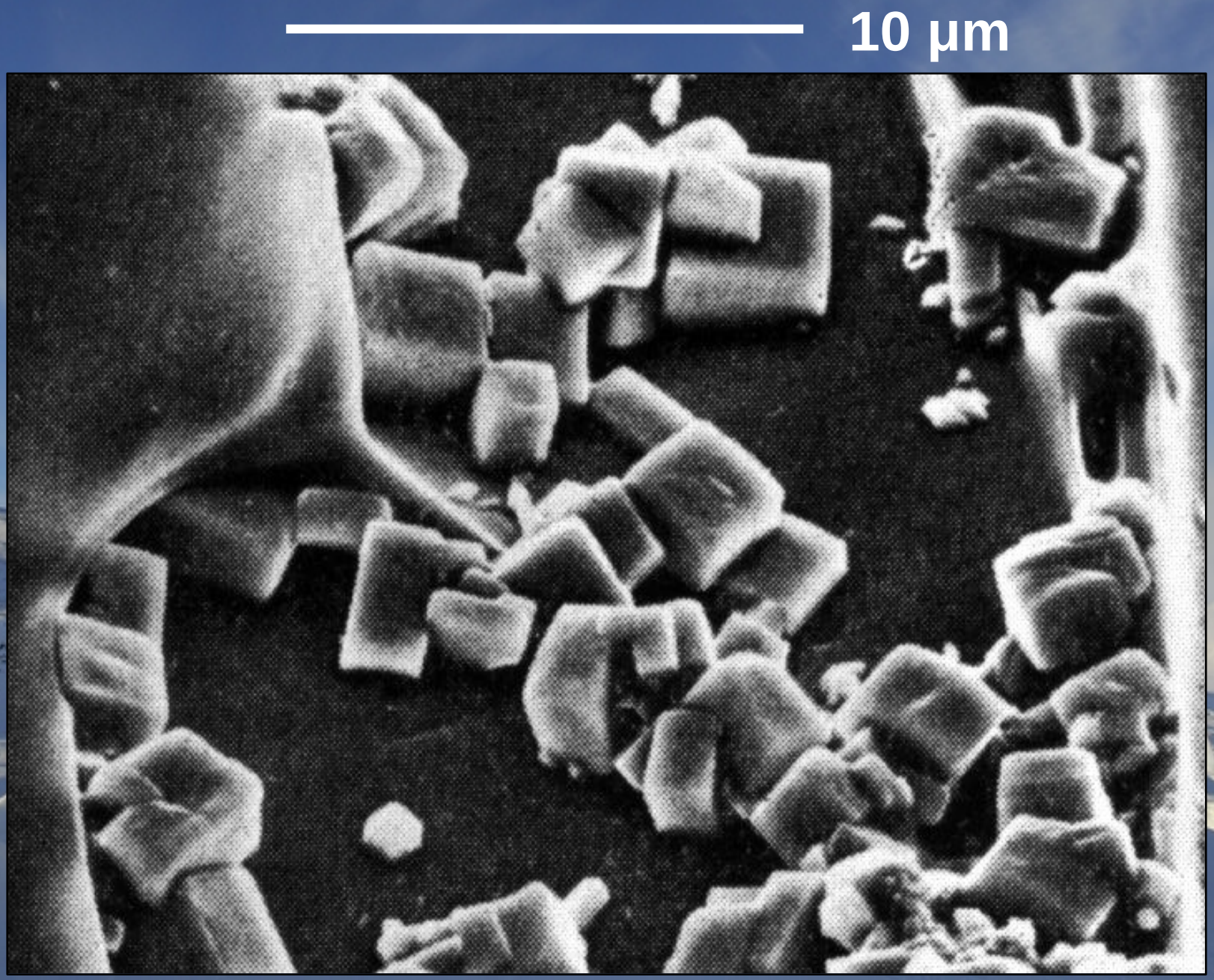
Sea Ice



Sea Ice

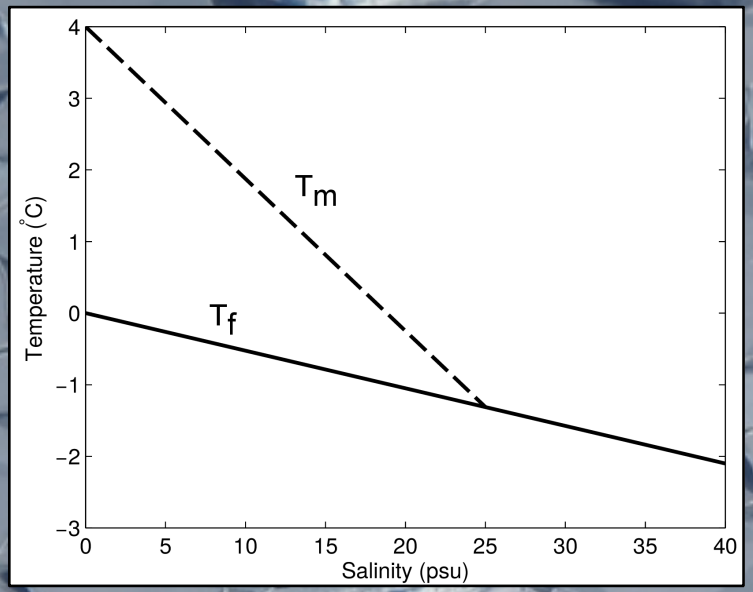


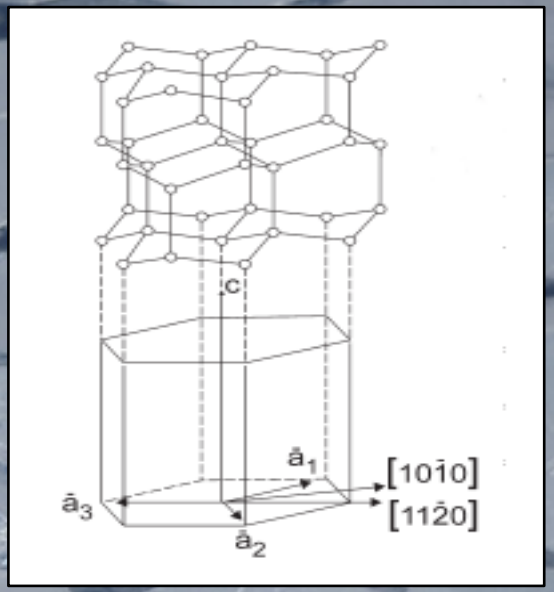
Sea Ice



Growth & Structure

Growth & Structure

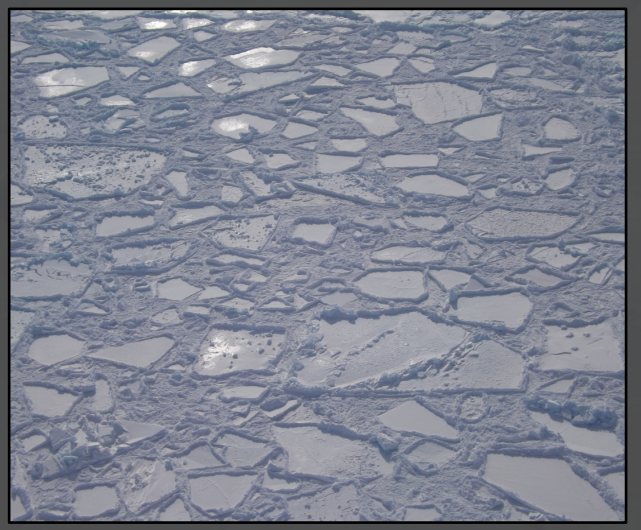




Frazil Ice

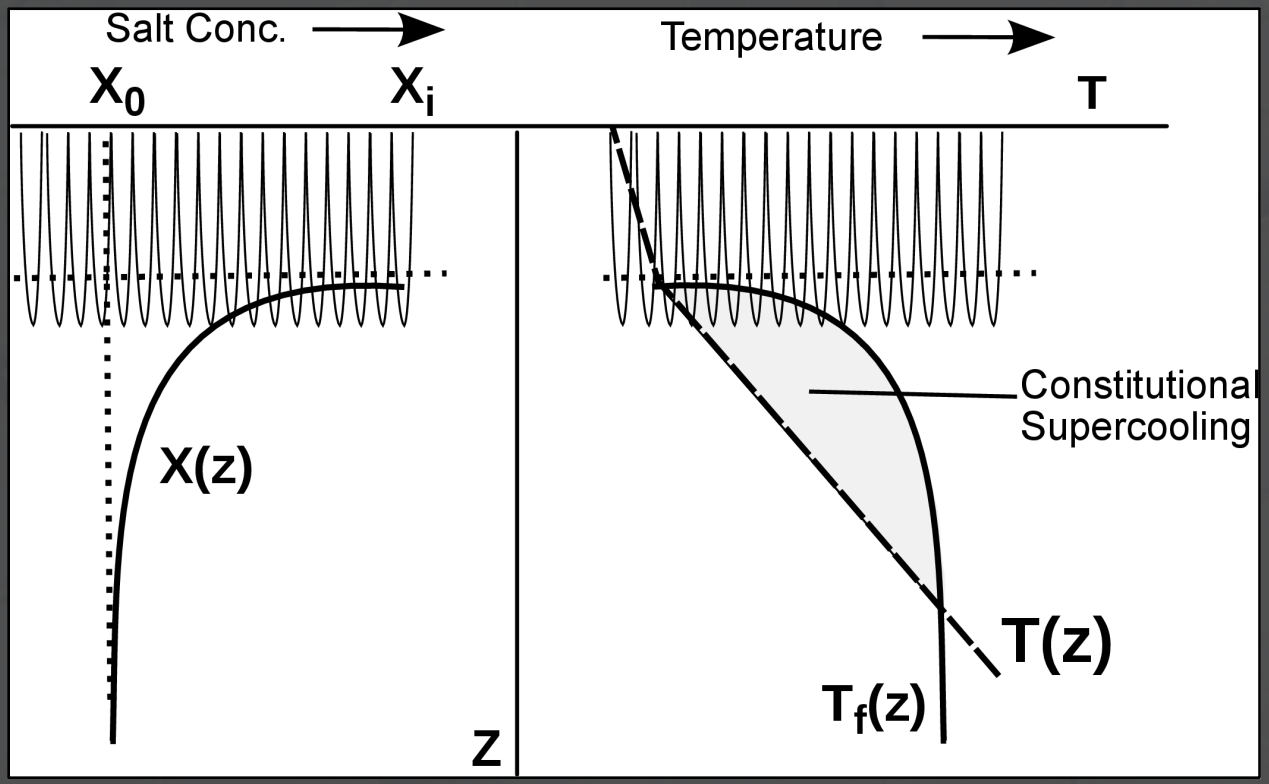
Grease Ice

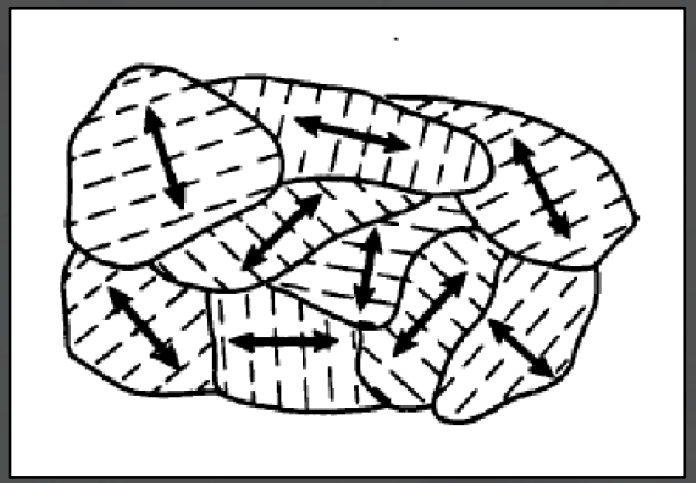
Pancake Ice



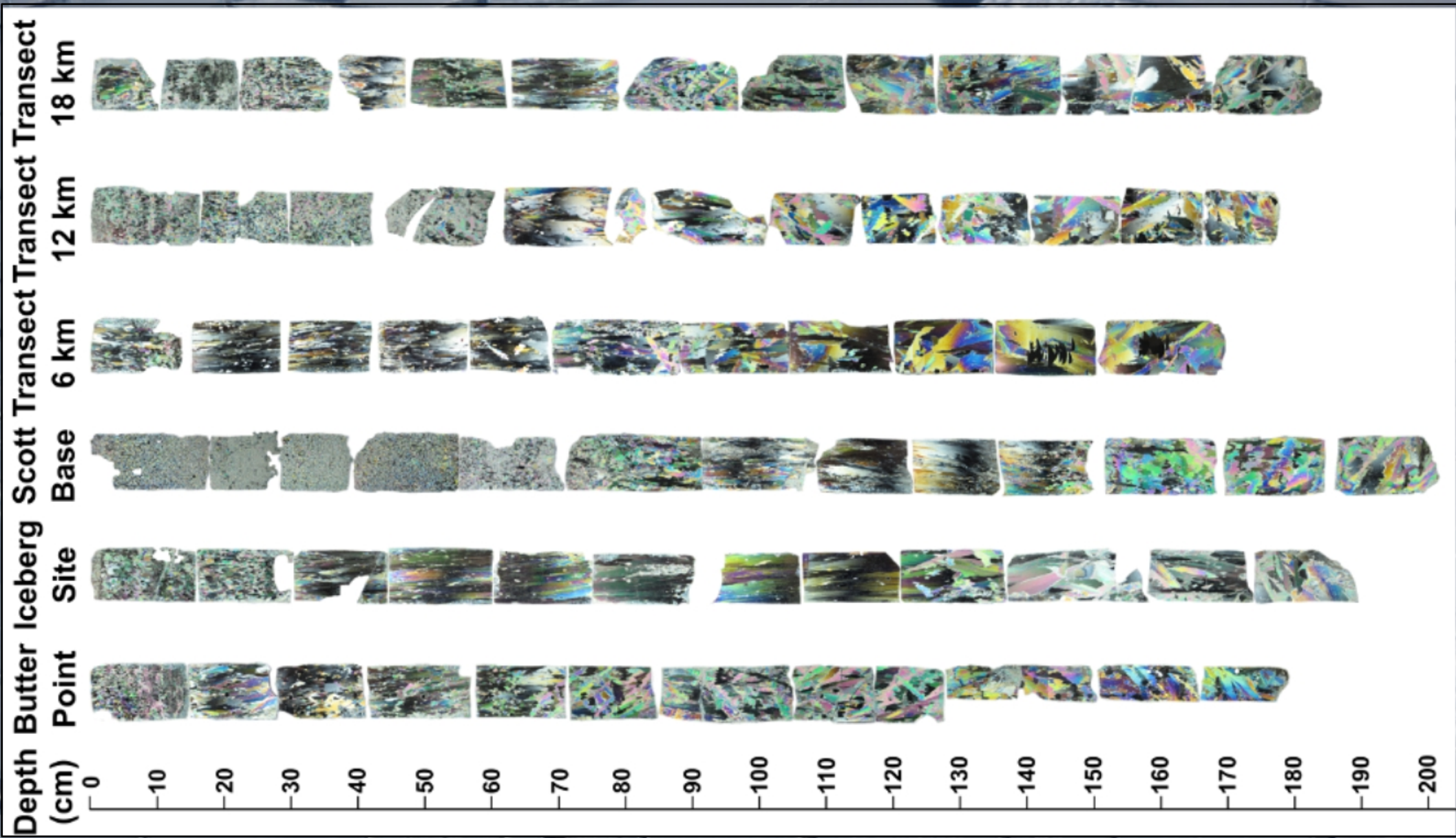
Growth & Structure

Constitutional Supercooling



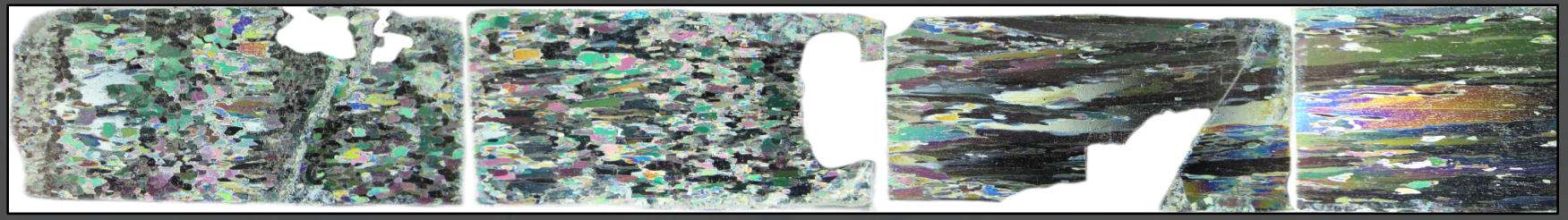


Growth & Structure

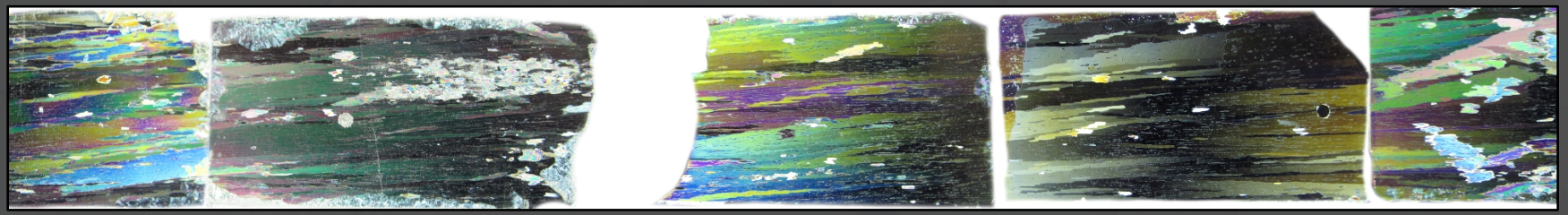


Growth & Structure

Top



Middle



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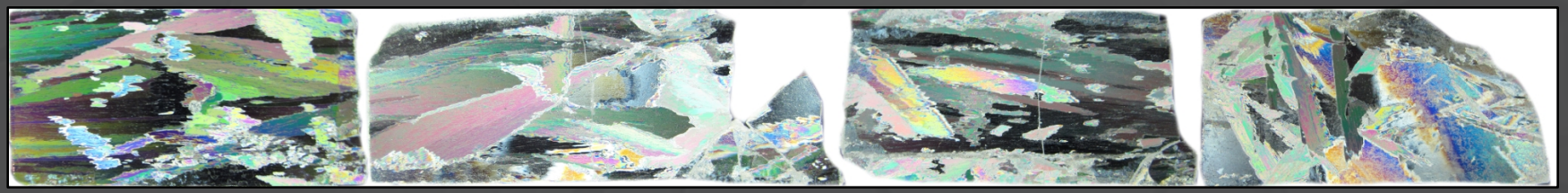
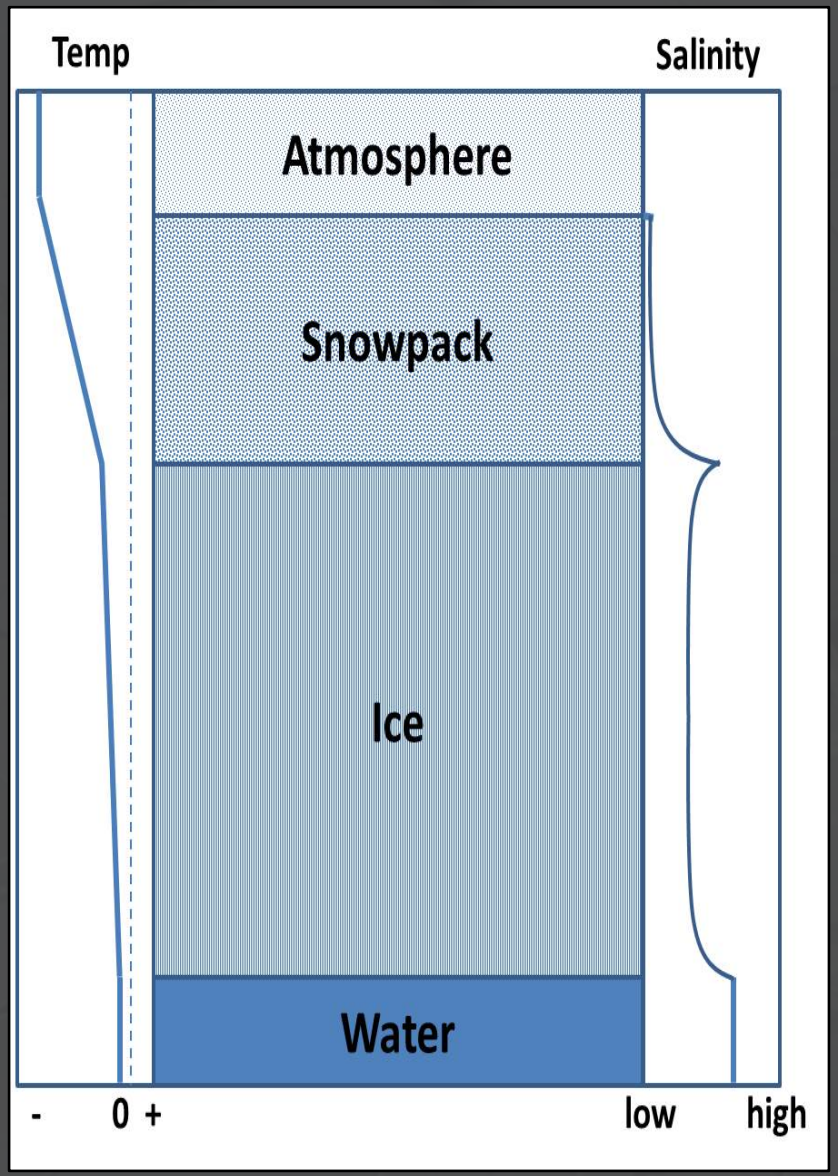
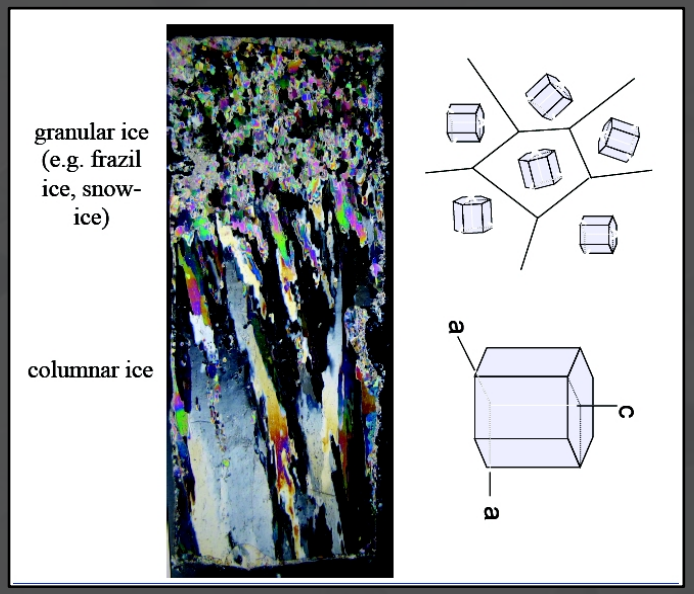


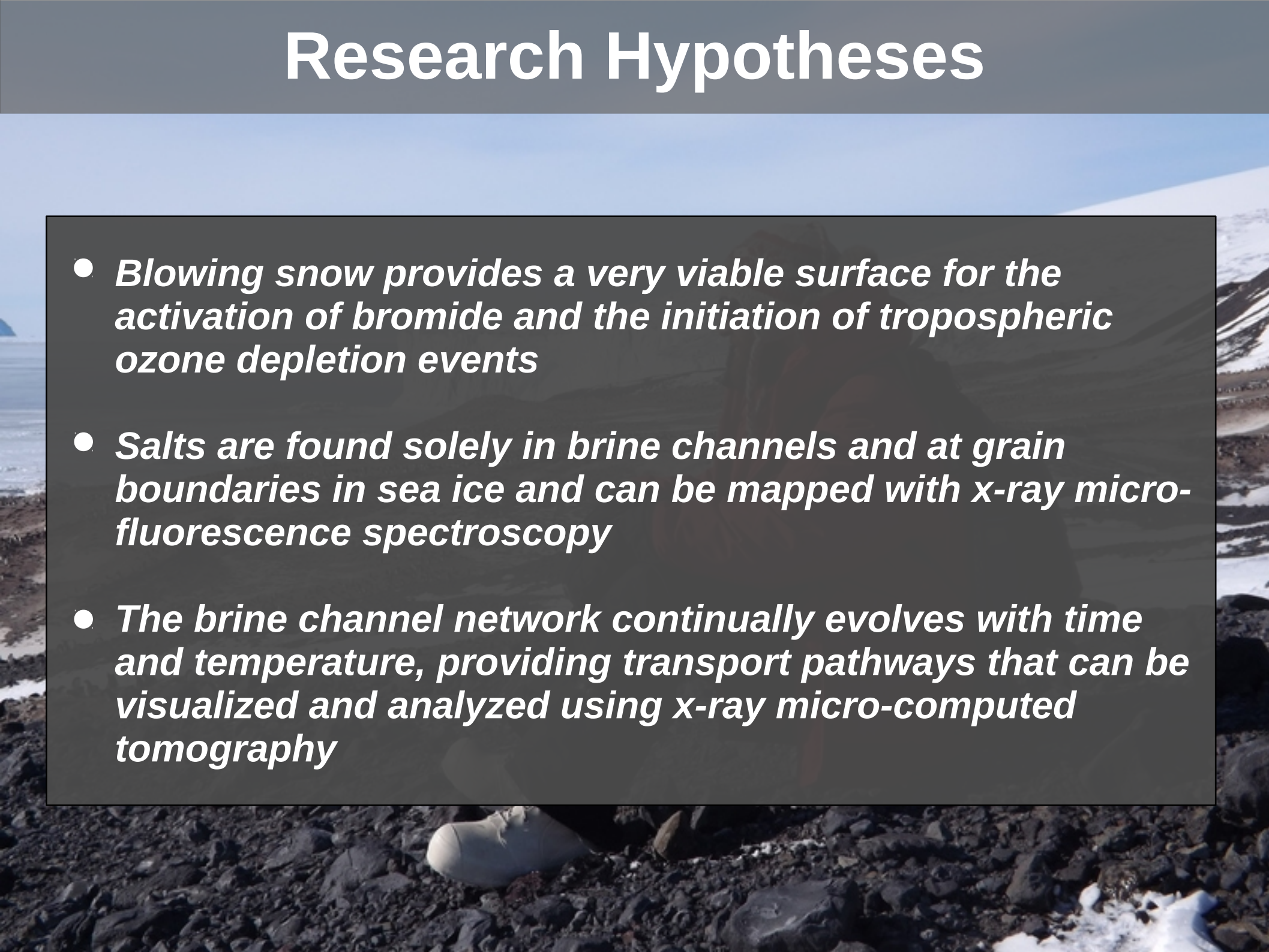
Growth & Structure



- ★ Sea ice structure reflects the original growth mechanisms
- ★ Warm on the bottom and cold on top
- ★ Salinity has “c-shape” profile



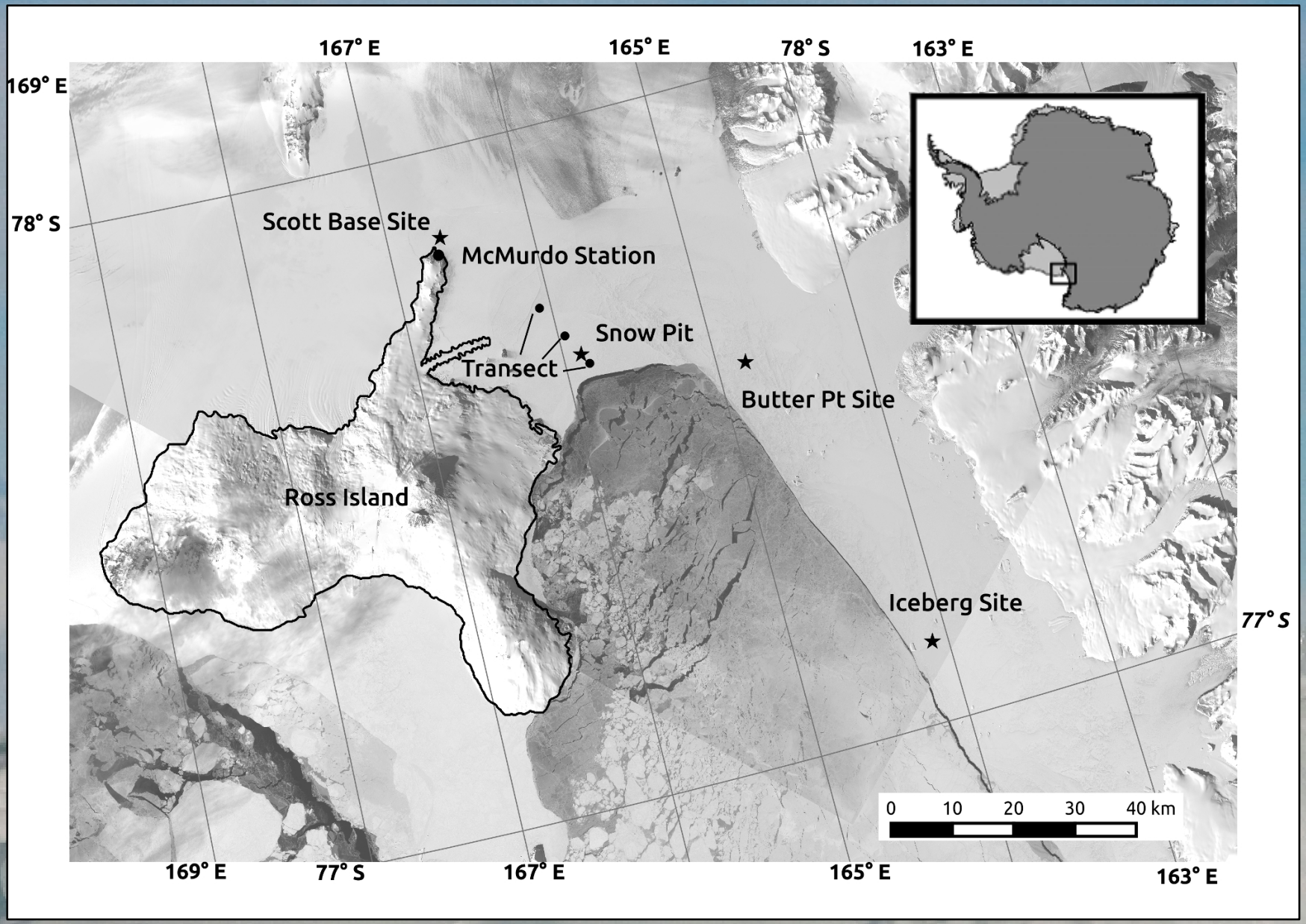
Research Hypotheses



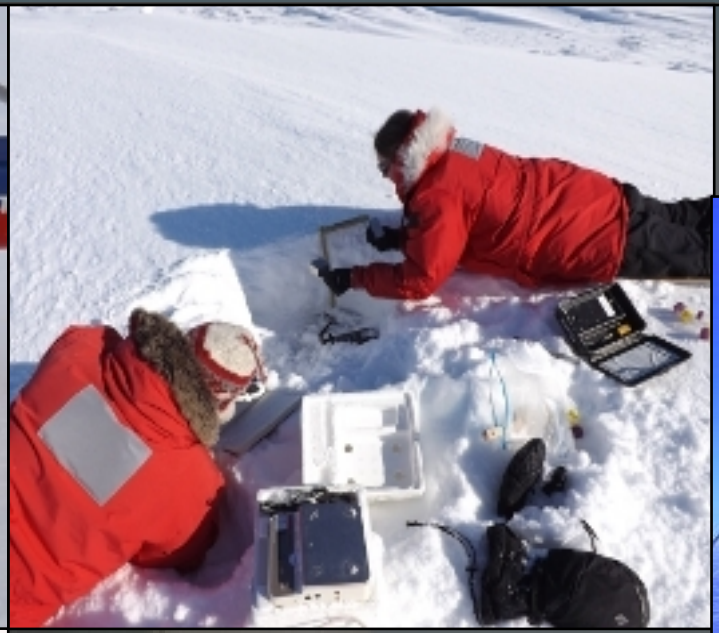
- ***Blowing snow provides a very viable surface for the activation of bromide and the initiation of tropospheric ozone depletion events***
- ***Salts are found solely in brine channels and at grain boundaries in sea ice and can be mapped with x-ray micro-fluorescence spectroscopy***
- ***The brine channel network continually evolves with time and temperature, providing transport pathways that can be visualized and analyzed using x-ray micro-computed tomography***

Ross Sea, Antarctica: 2012

Ross Sea, Antarctica



Ross Sea, Antarctica



Blowing Snow

Snow Pits

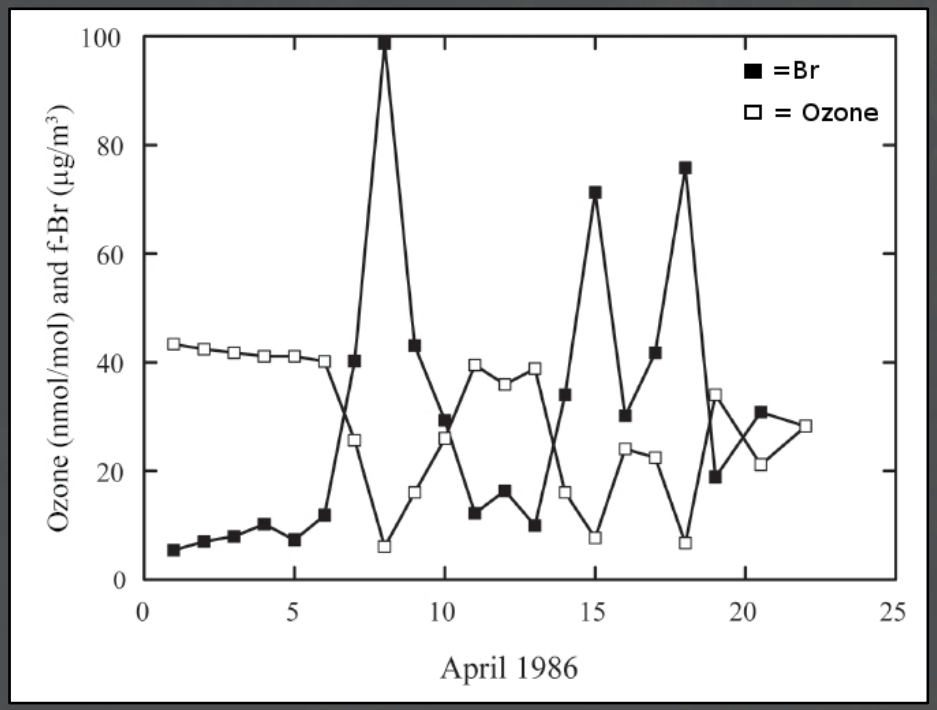
Sea Ice Cores

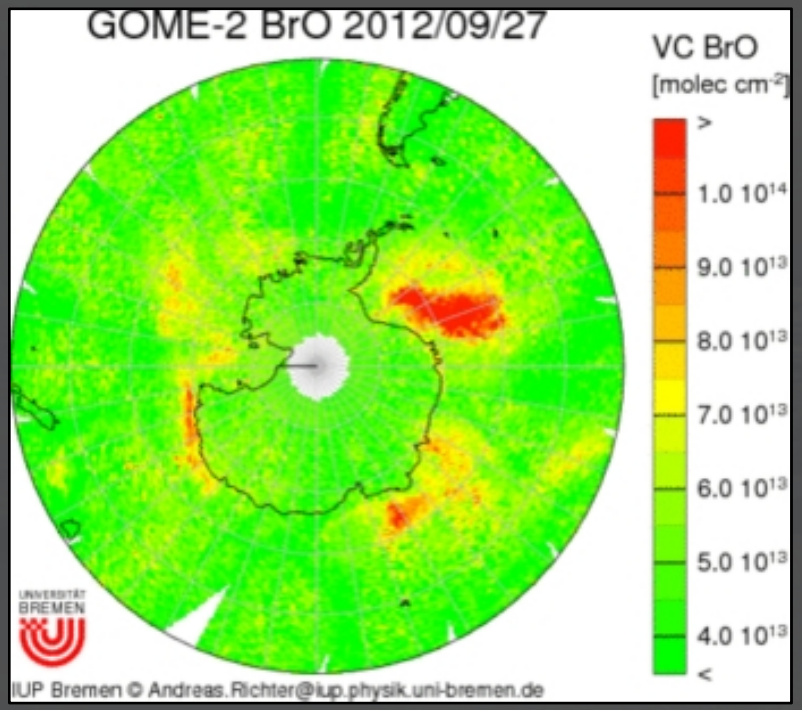
Blowing Snow & Br Activation

Salts

Polar Tropospheric Chemistry

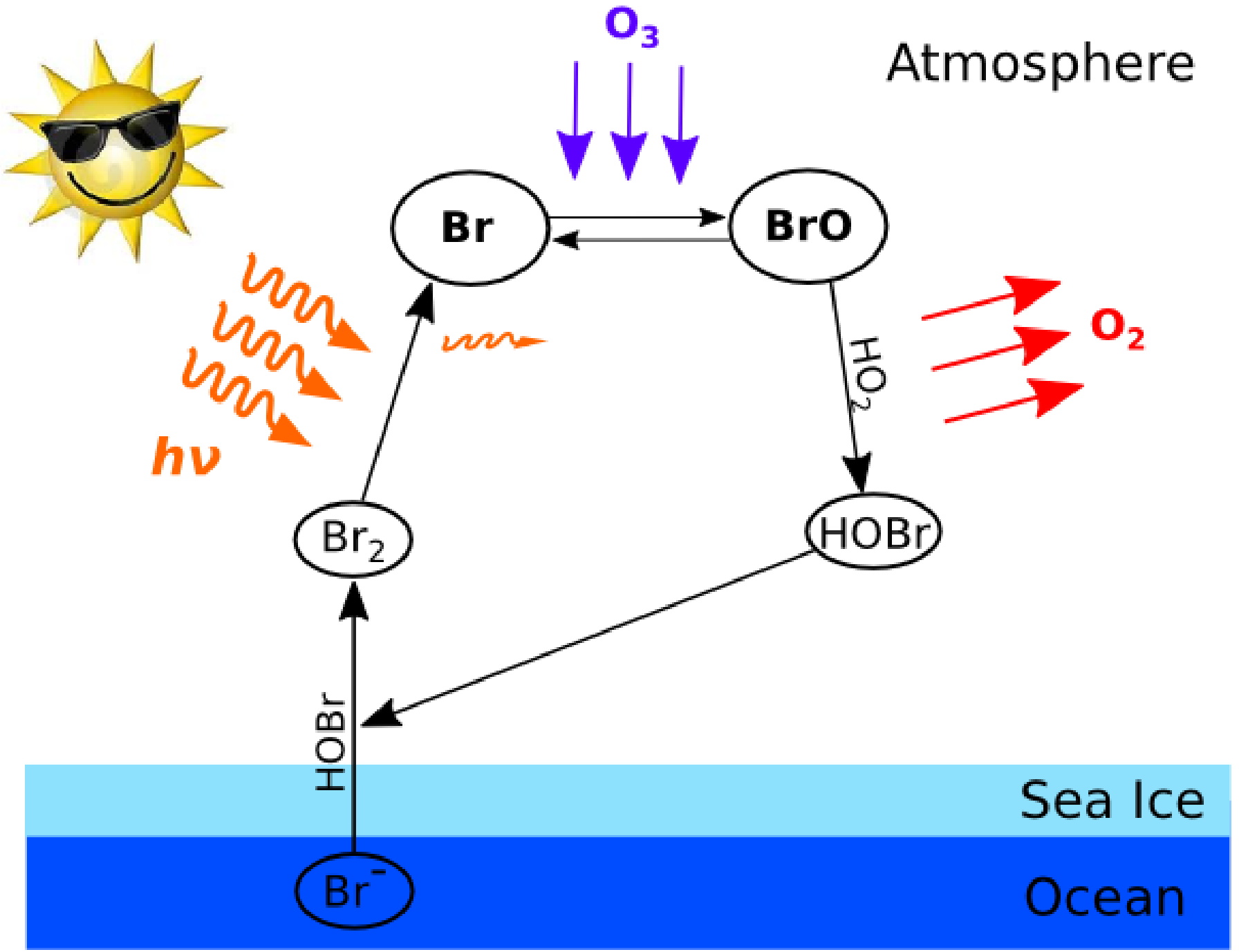
Increased BrO is highly correlated with decreased O_3





Barrie, L. A. et al. 1989. *J. Atmos. Chem.*, 9: 101-127

The Bromine Explosion



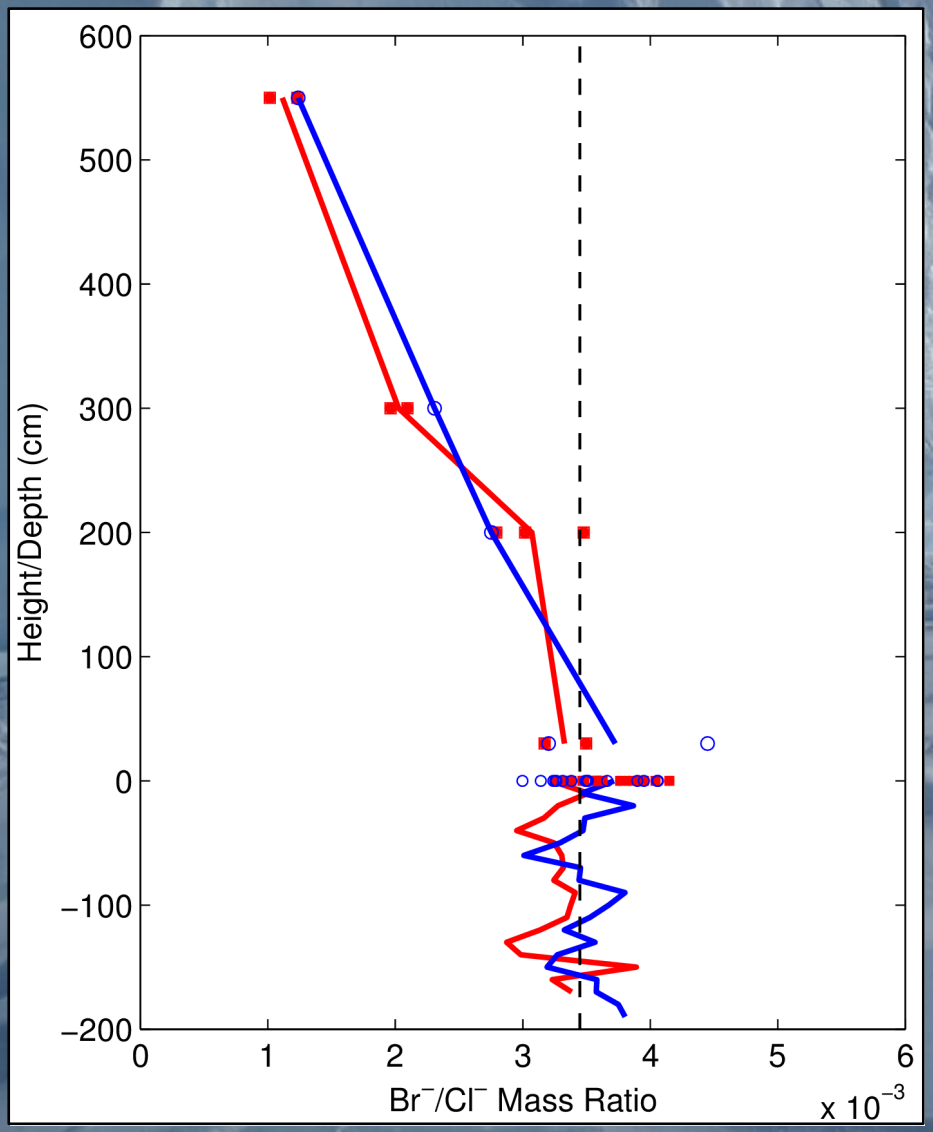
Blowing Snow & Br Activation

How does bromine get from the ocean, into the sea ice and snow, and eventually into the atmosphere?

Precisely where does bromine activation occur?

Blowing Snow & Br Activation

The chloride/bromide ratio is constant until the snow becomes lofted, at which point Br becomes increasingly depleted relative to Cl



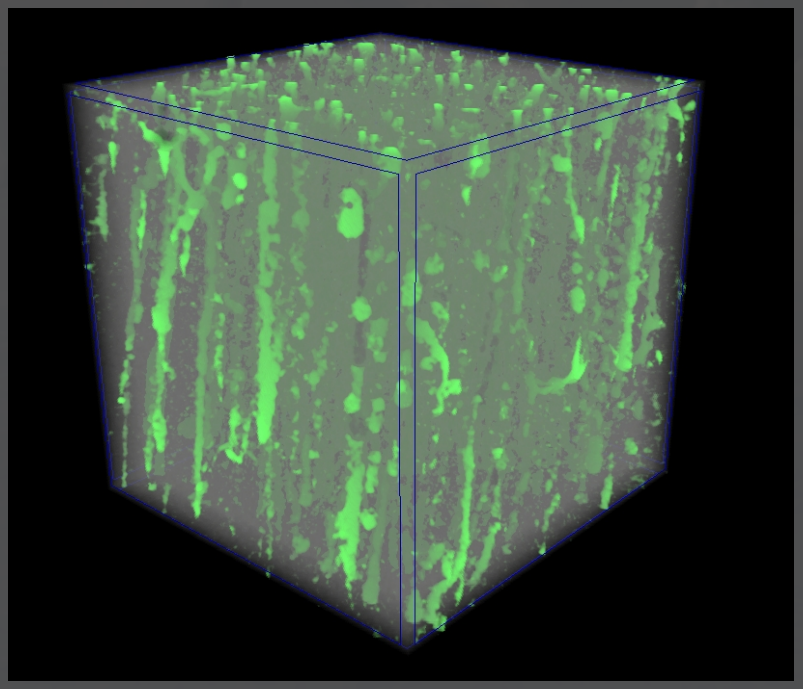
Citation: Lieb-Lappen, R. M. and Obbard, R. W. The role of blowing snow in the activation of bromine over Antarctic sea ice. Atmos. Chem. Phys., 15, 7537-7545, doi:10.5194/acp-15-7537-2015.

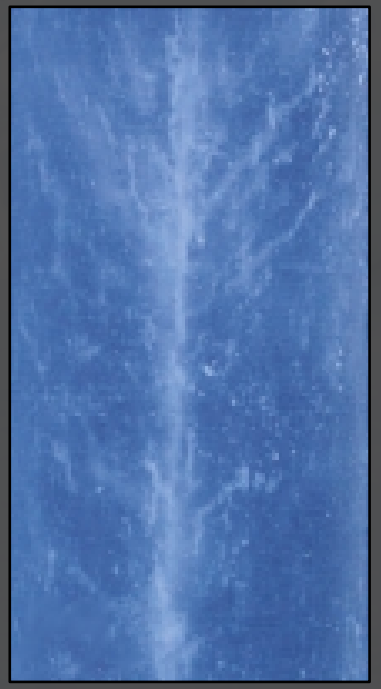
Brine Channel Morphology

Brine Channel Morphology

What is the morphology of the brine channel network and can it be described mathematically?

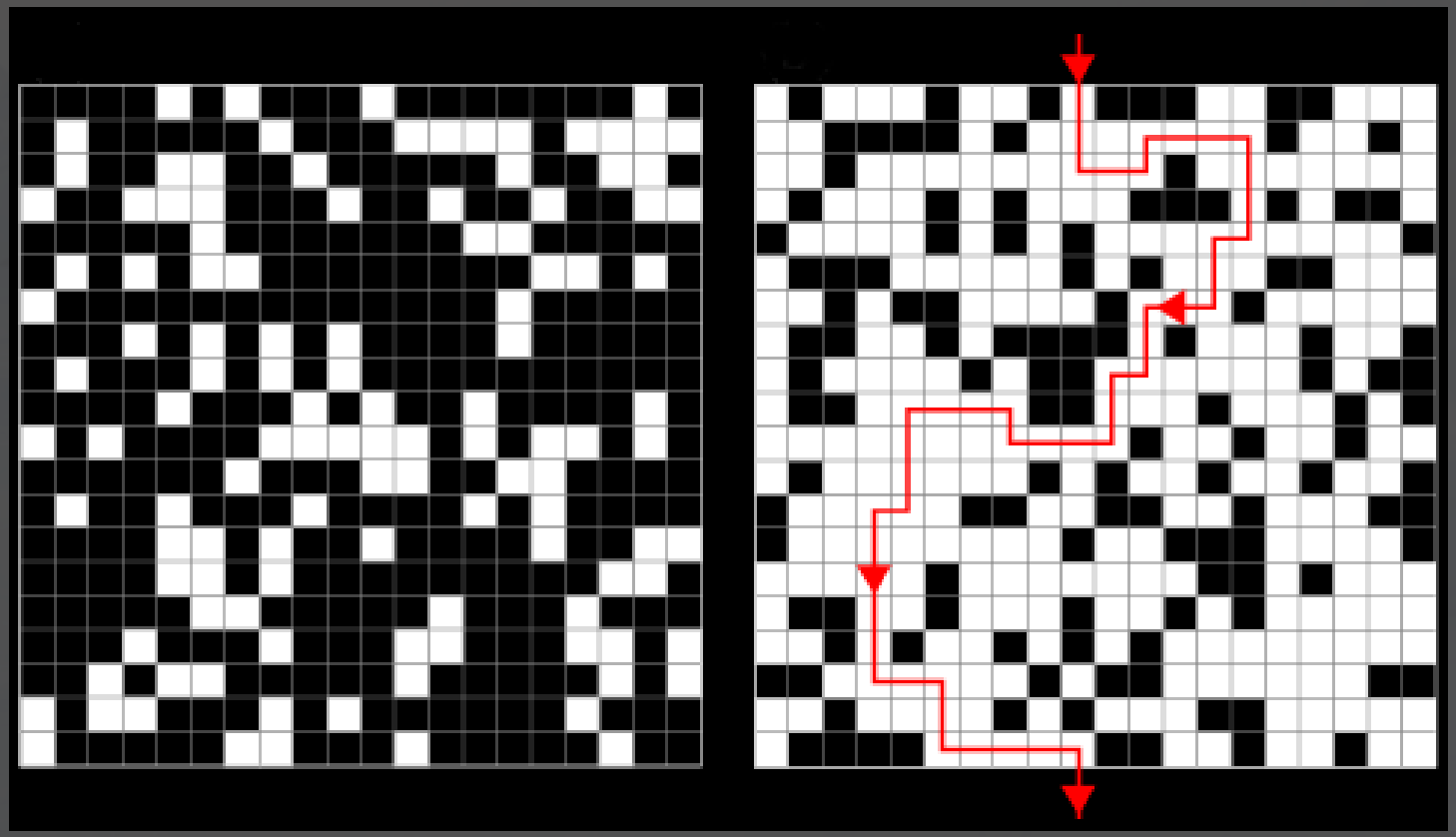
How does this network respond to changes in temperature and what is the impact on fluid permeability?





Brine Channel Morphology

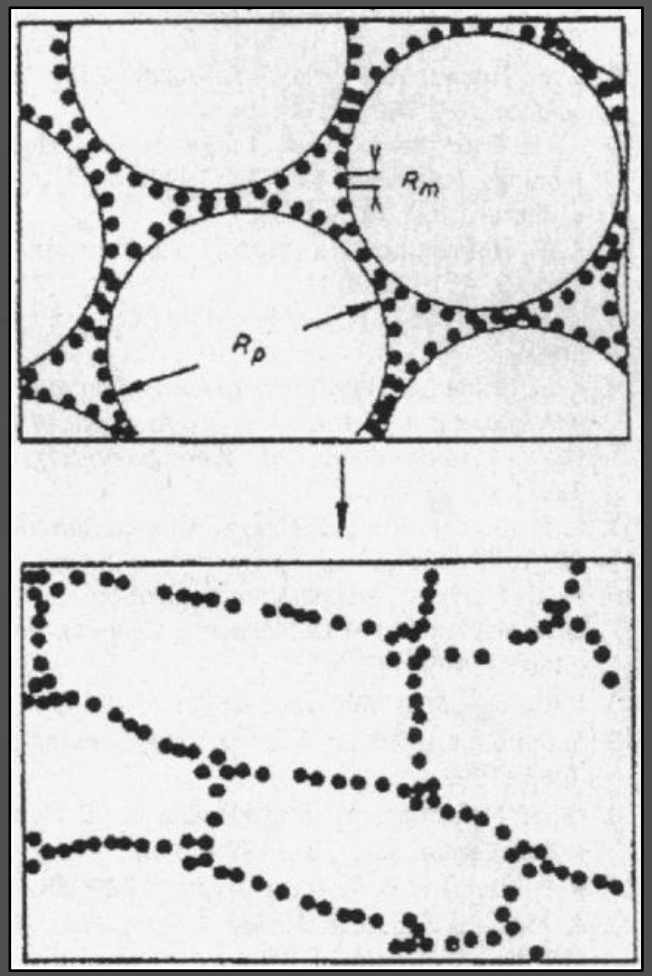
Percolation Theory and The “Rule of Fives”



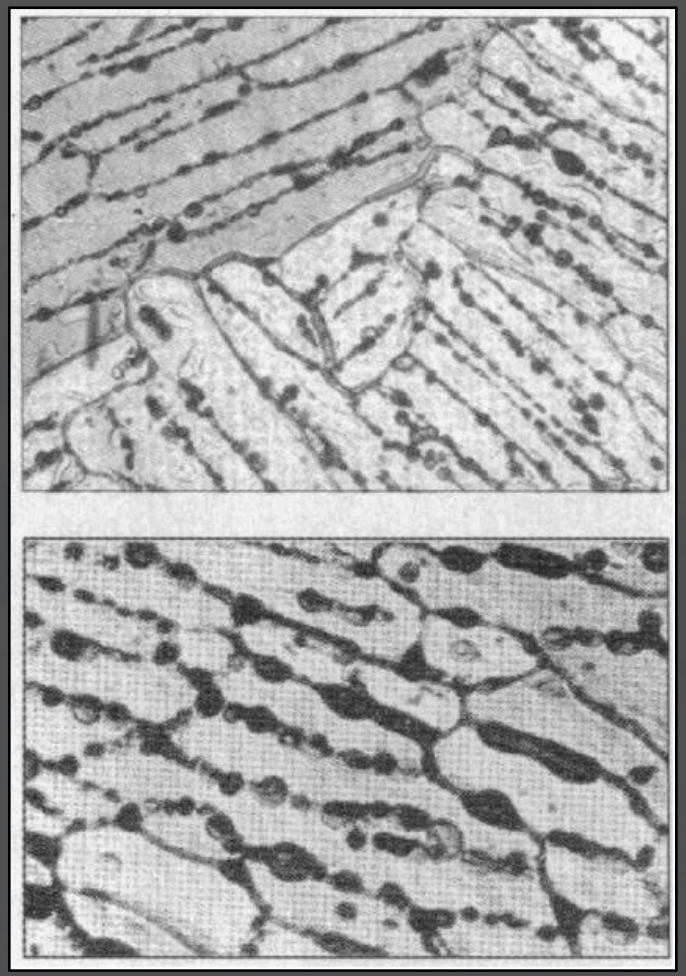
For sea ice, percolation occurs for a brine volume fraction above 5%.
Coincidentally, this occurs at a temperature of -5 °C and a salinty of 5 ppt!

Brine Channel Morphology

Compressed Powder



Sea Ice



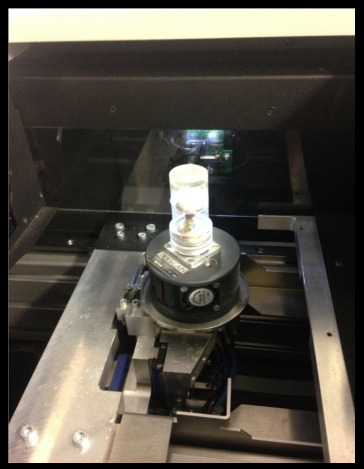
$\varepsilon = R_p/R_m \approx 24$ produces $\phi_c \approx 5\%$ and similar microstructure

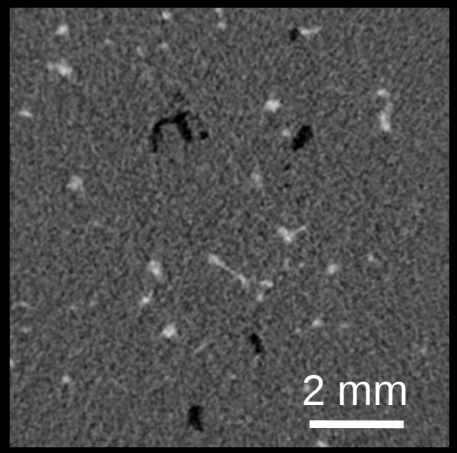
Golden et al. The Percolation Phase Transition in Sea Ice, Science,282, 2238–2241, 1998.

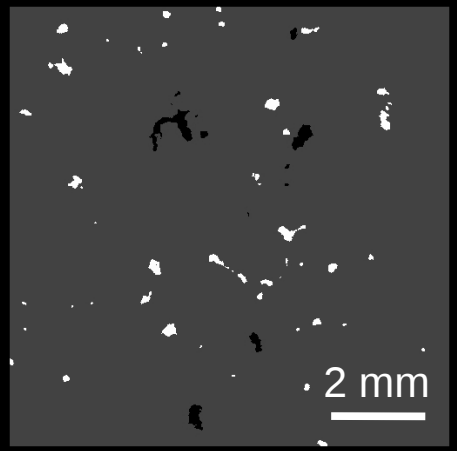
Brine Channel Morphology

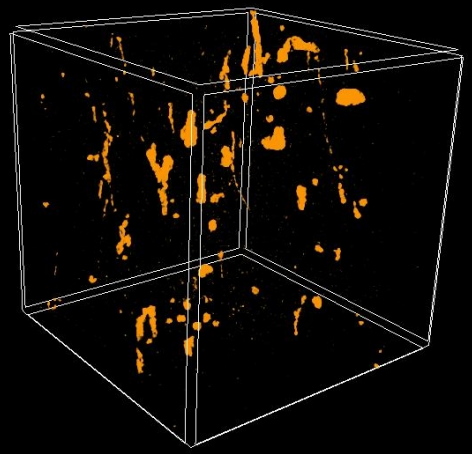
Analysis Phase

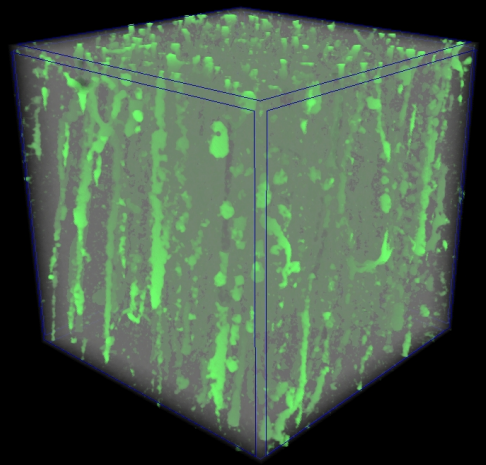
X-Ray Micro-Computed Tomography





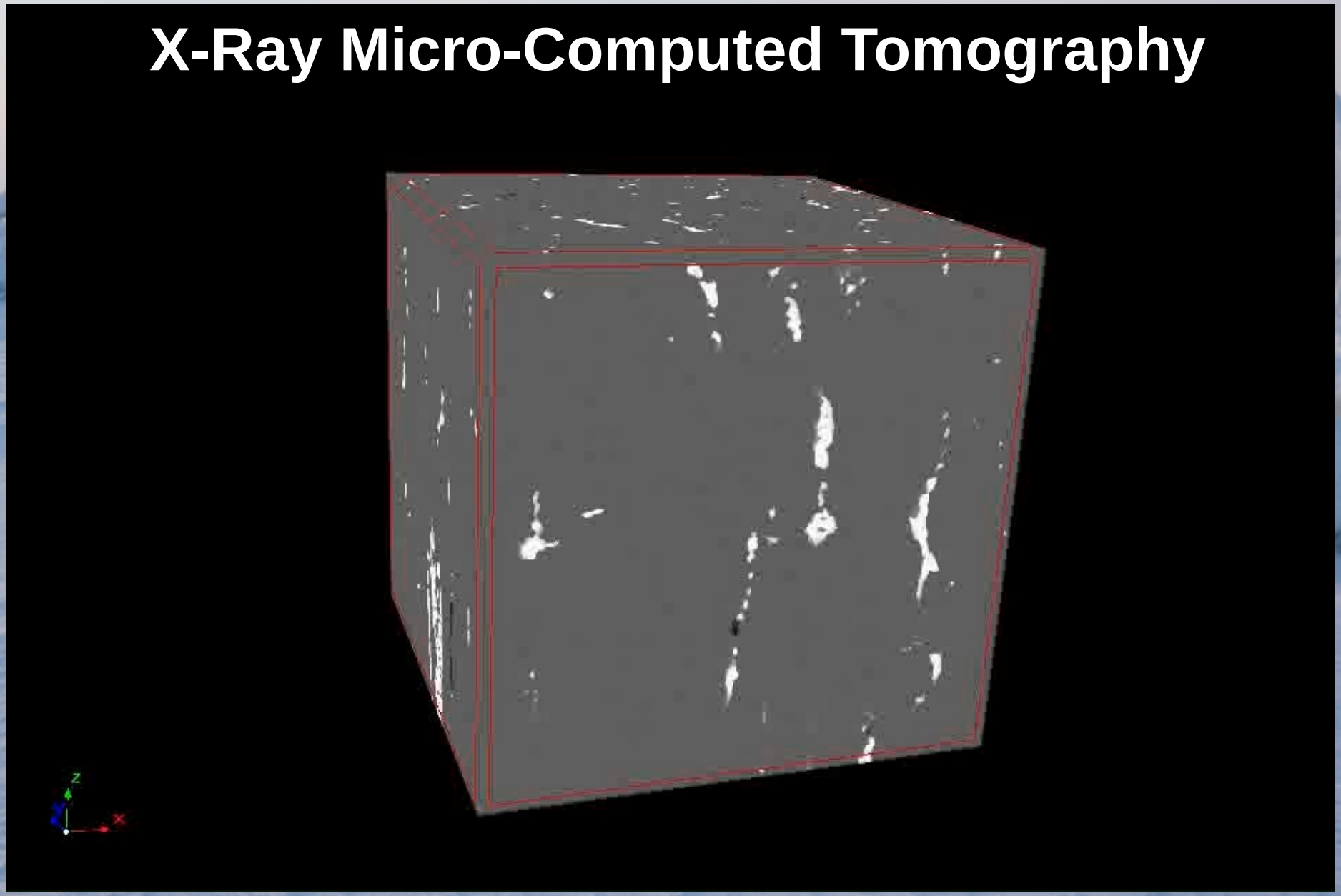






Brine Channel Morphology

X-Ray Micro-Computed Tomography

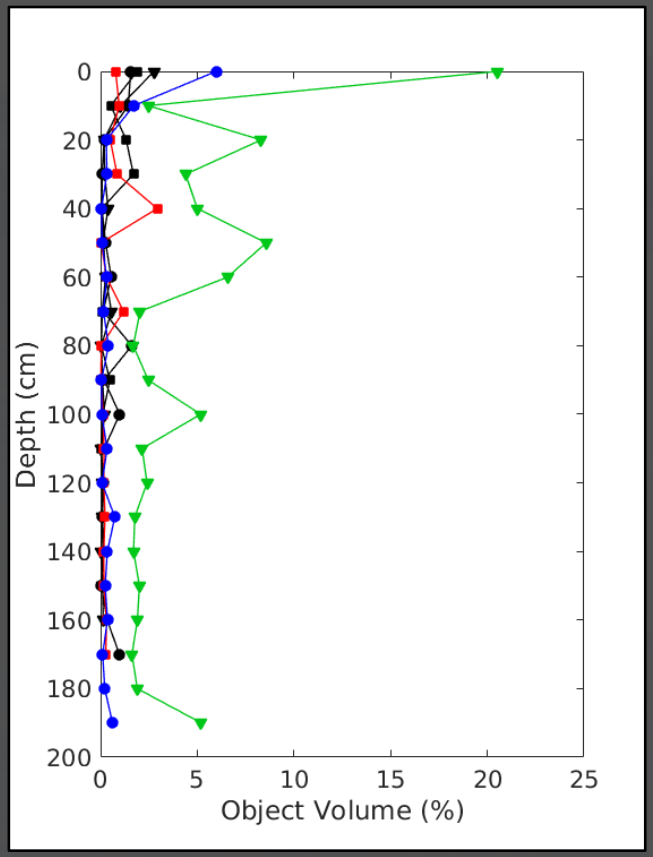


Brine Channel Morphology

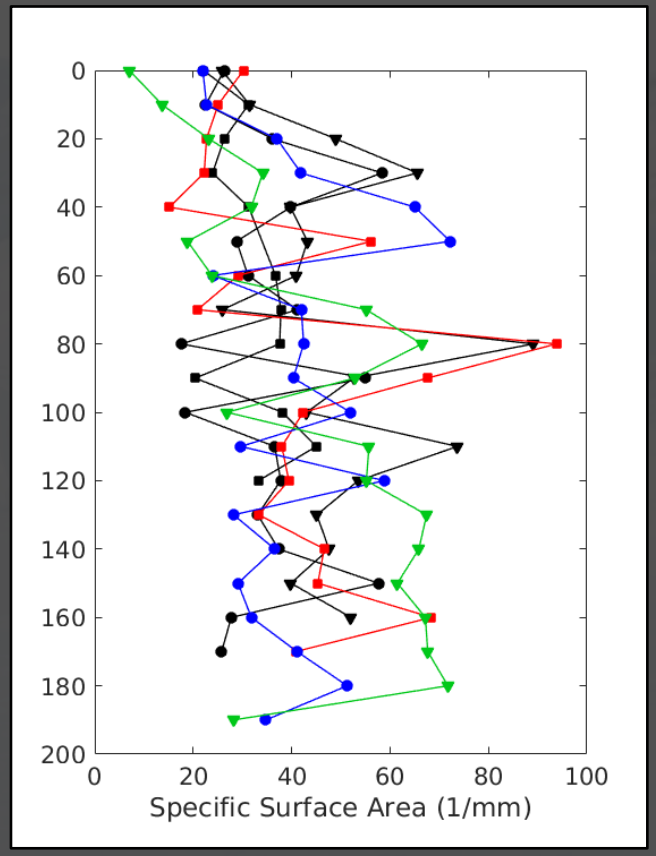
= Butter Pt
= Iceberg

Air Phase

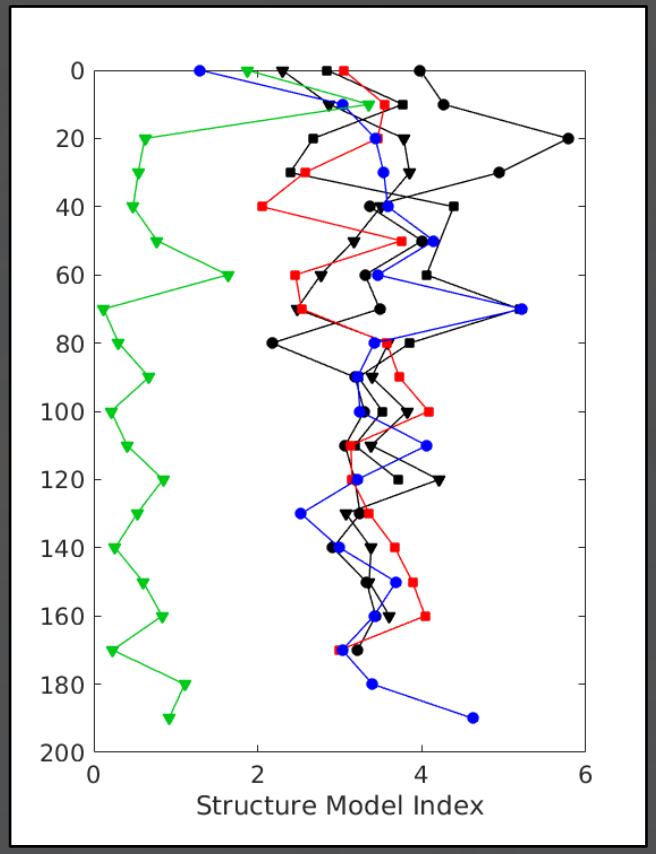
= Scott Base
= Transect



Not much air, except in multi-year ice



SSA of air pockets increases with depth



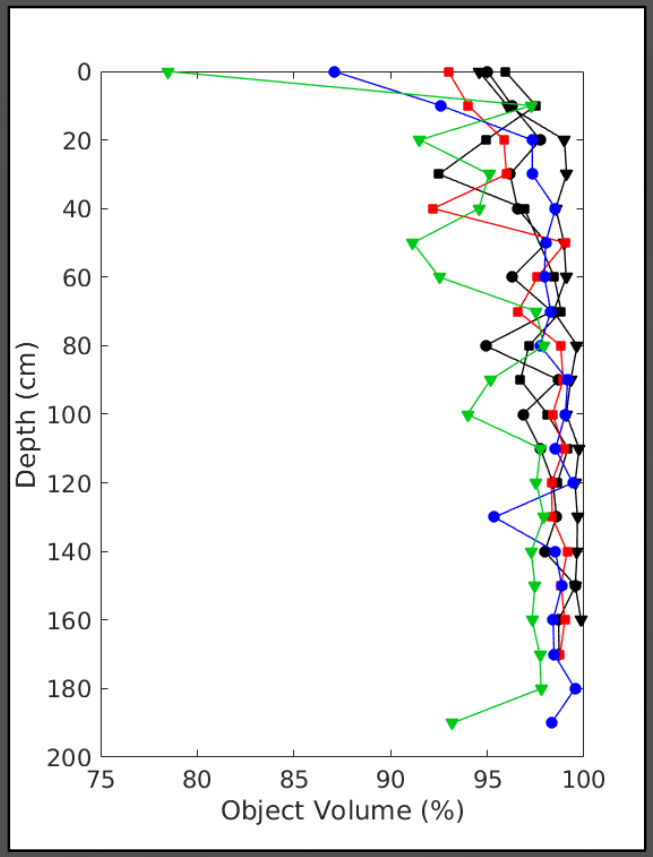
FYI air pockets are spherical, while MYI pockets are elongated

Brine Channel Morphology

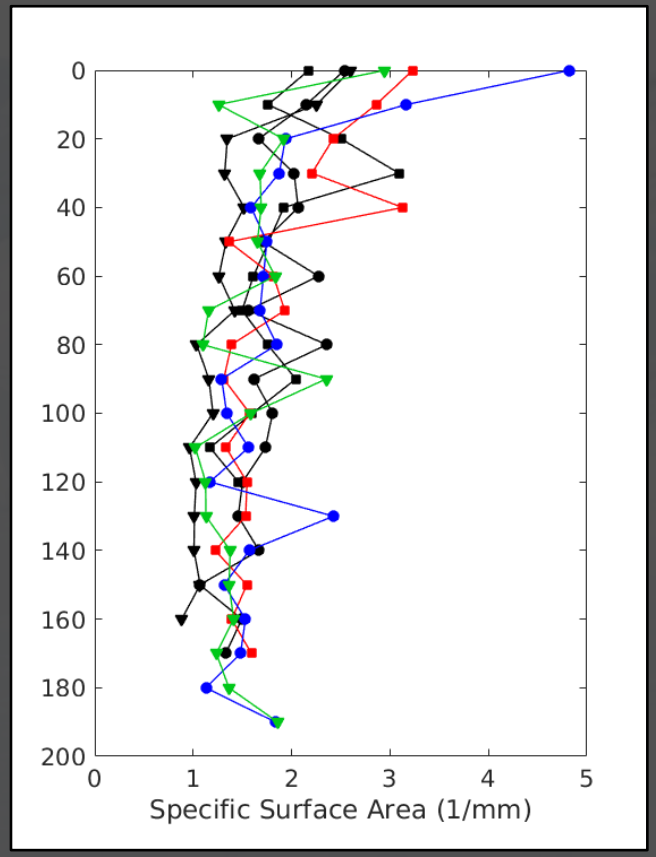
= Butter Pt
= Iceberg

Ice Phase

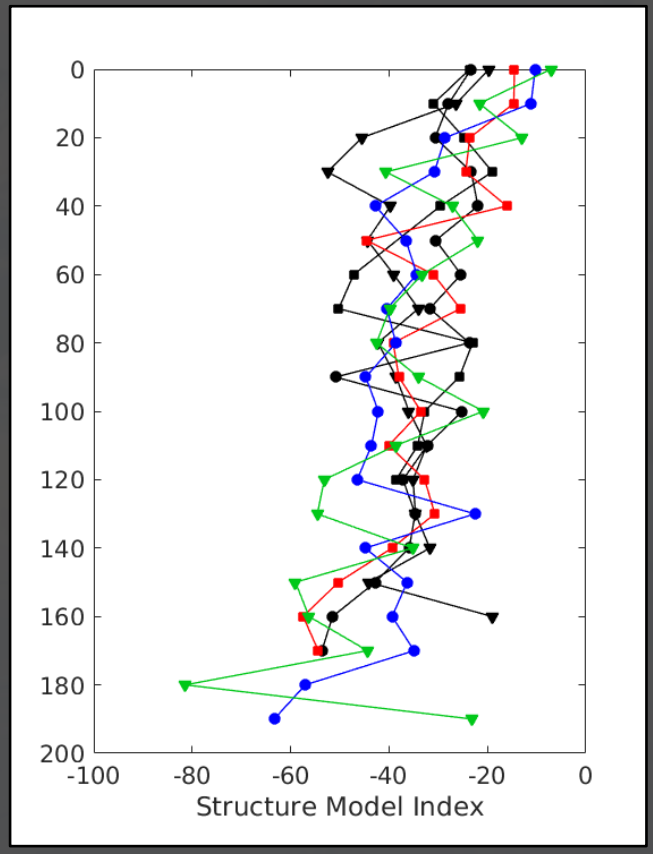
= Scott Base
= Transect



Perhaps a C-shape, majority of sample



SSA of ice phase decreases with depth



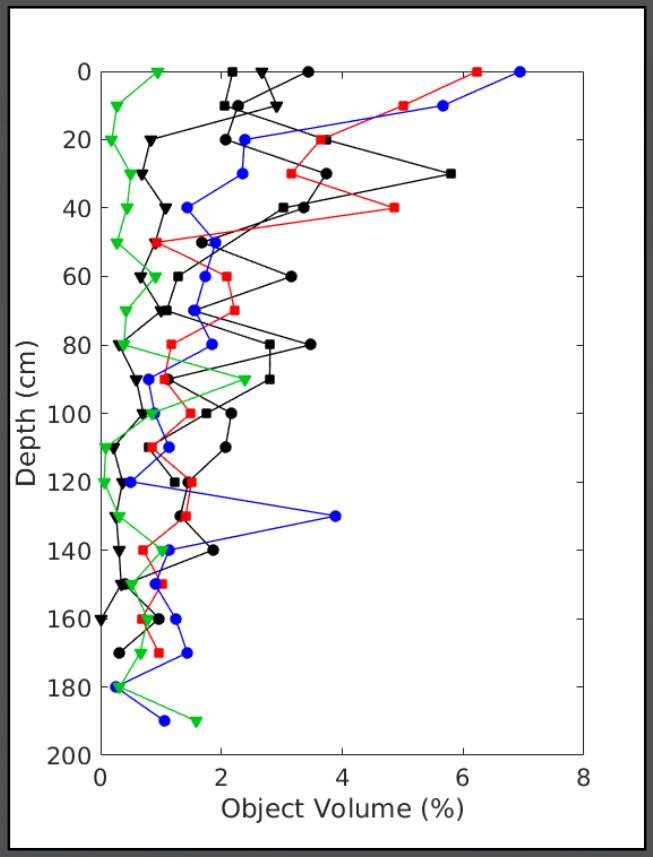
More concavities with depth

Brine Channel Morphology

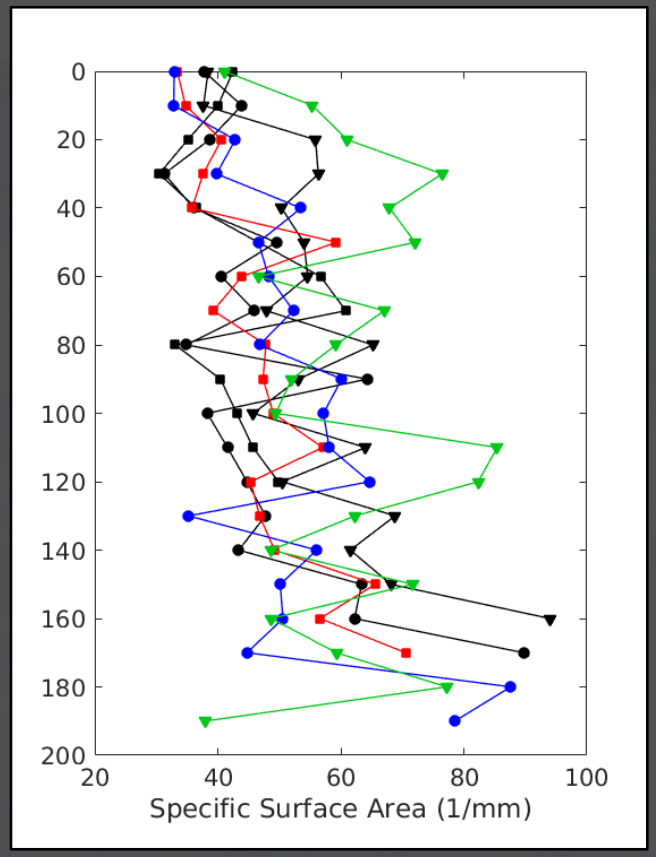
= Butter Pt
= Iceberg

Brine Phase

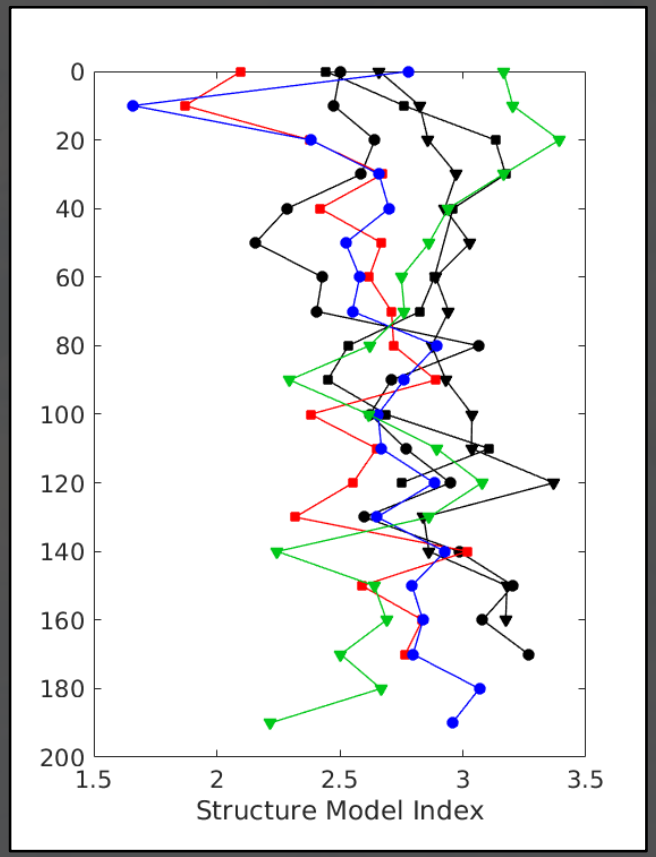
= Scott Base
= Transect



More brine pockets near top of FYI cores



SSA of brine increases with depth



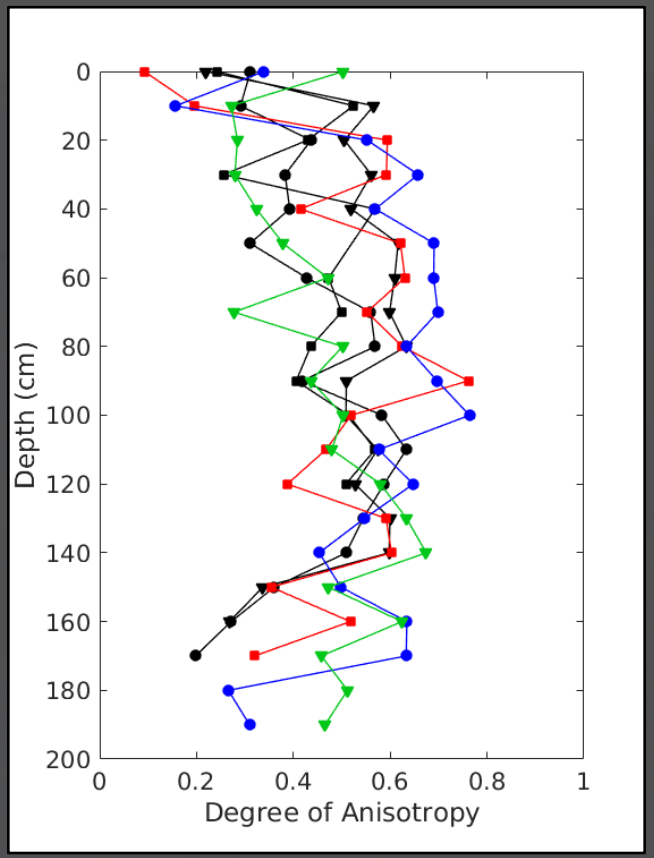
Brine channels are mainly cylindrical

Brine Channel Morphology

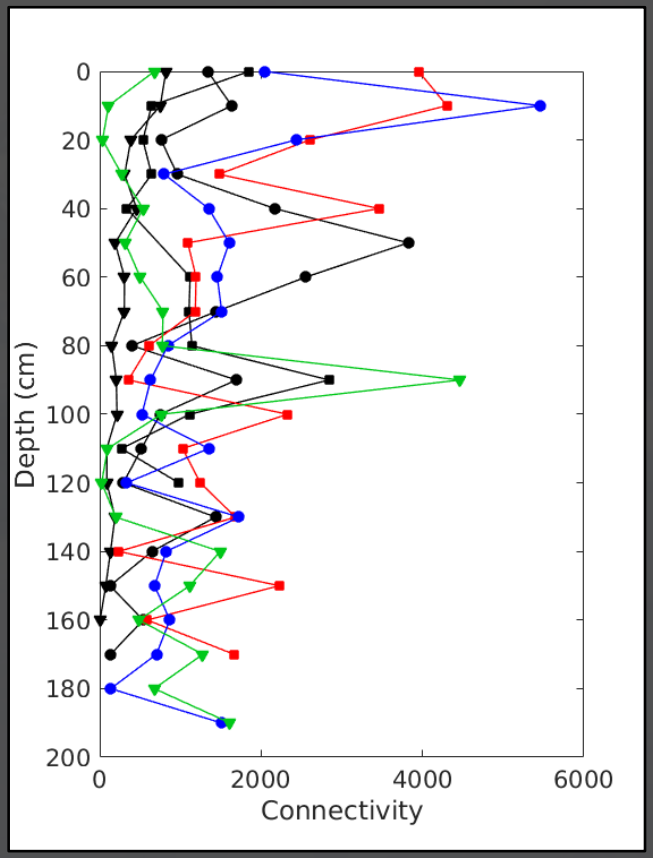
= Butter Pt
= Iceberg

Brine Phase

= Scott Base
= Transect



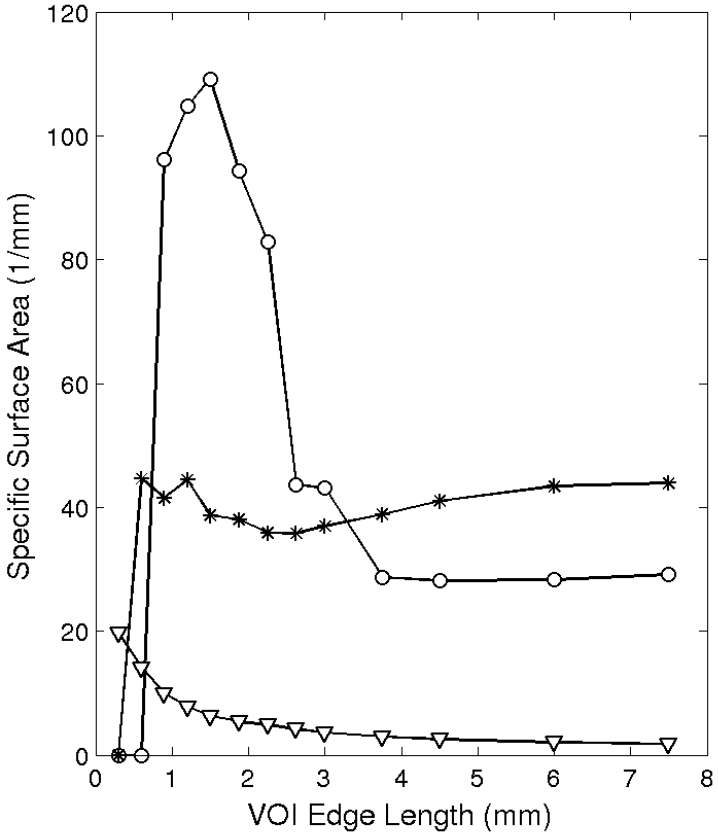
More vertical channels through middle of core

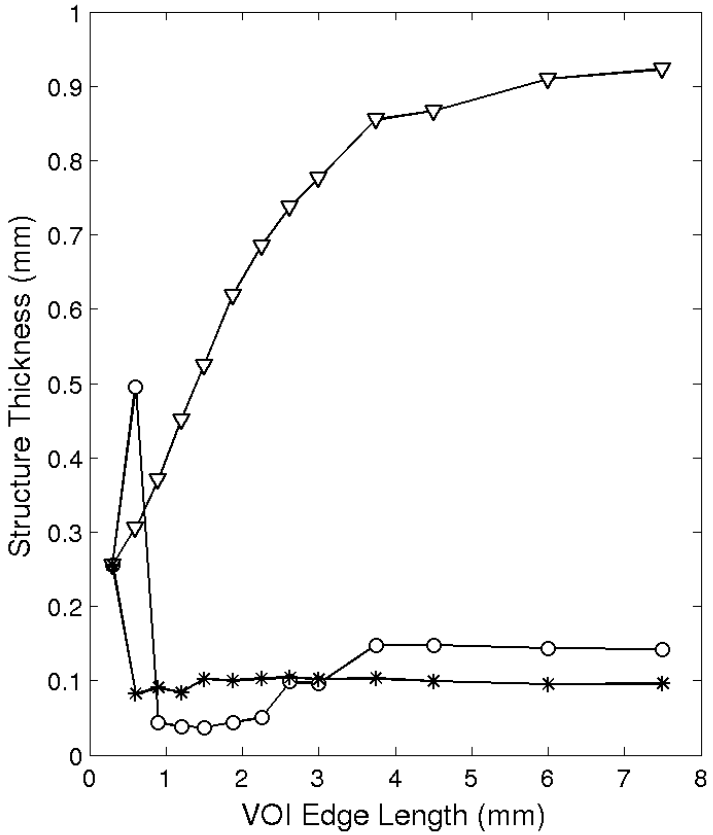


Highly variable connectivity, slight increase near top

Brine Channel Morphology

Representative Elementary Volume





Citation: Lieb-Lappen, R. M., Golden, E. J., and Obbard, R. W. Metrics for interpreting the microstructure of sea ice using x-ray micro-computed tomography. Cold Reg. Sci. Technol. *In Review.*

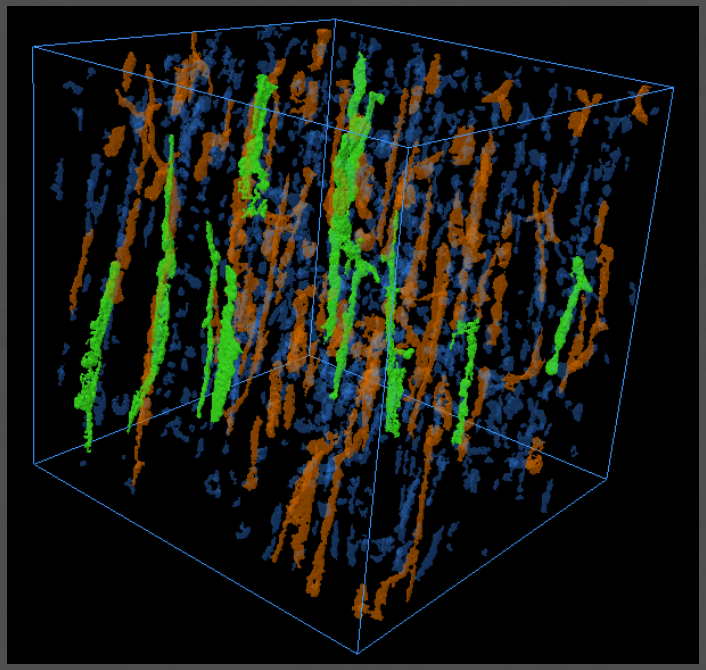
Brine Network Model

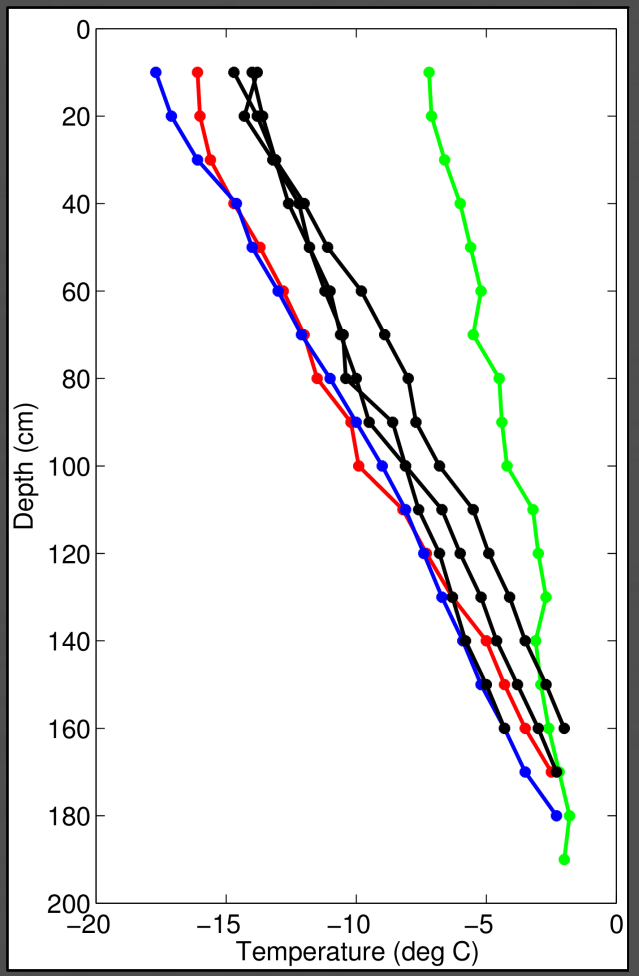
Brine Network Model

Let's Build a Model

Assumptions

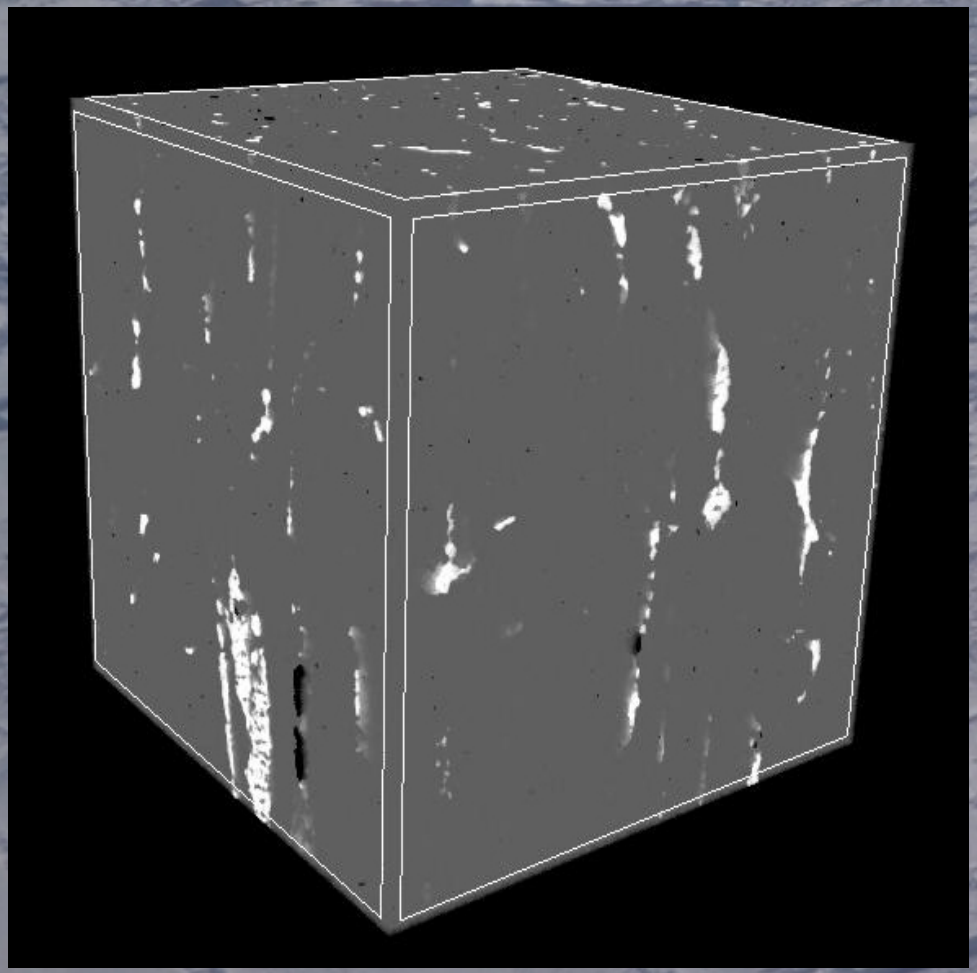
- Core collection was complete (no drainage)
- Temperature varies linearly with depth
- No hysteresis effects

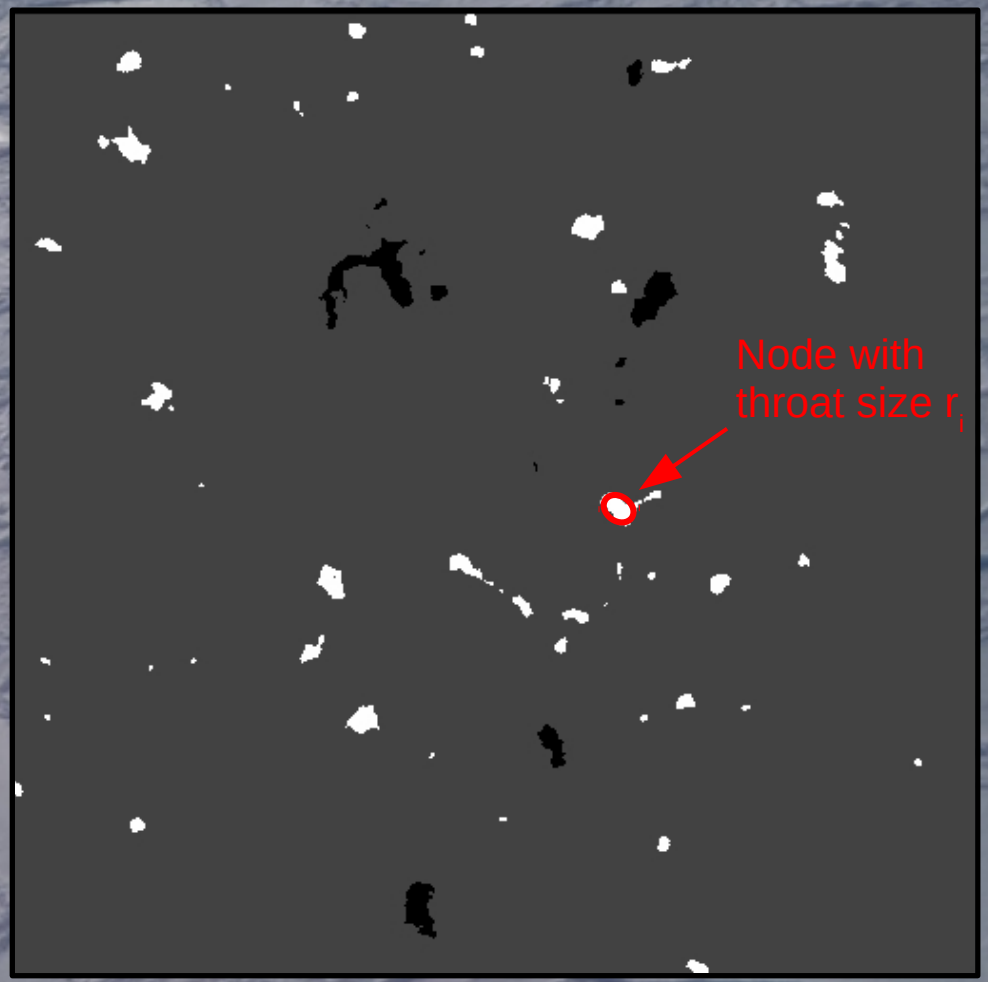




Brine Network Model

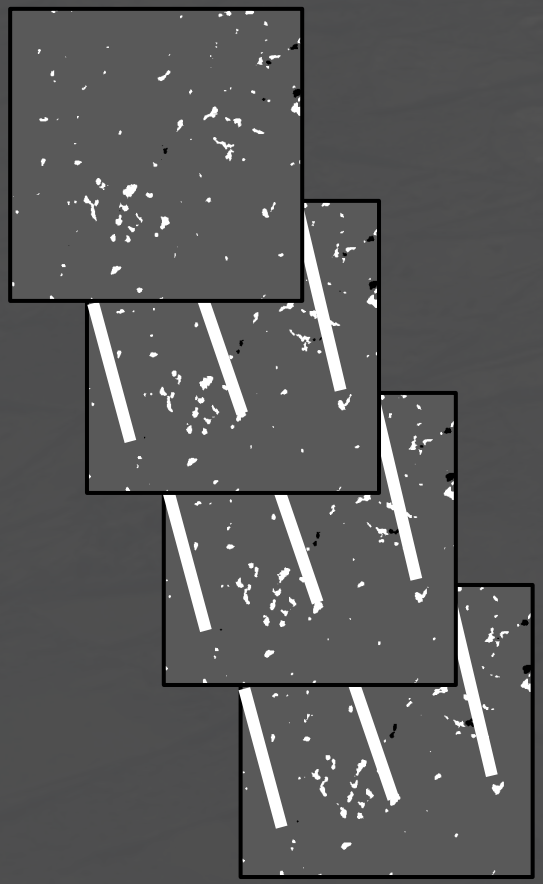
Defining Nodes





Brine Network Model

Defining Edges



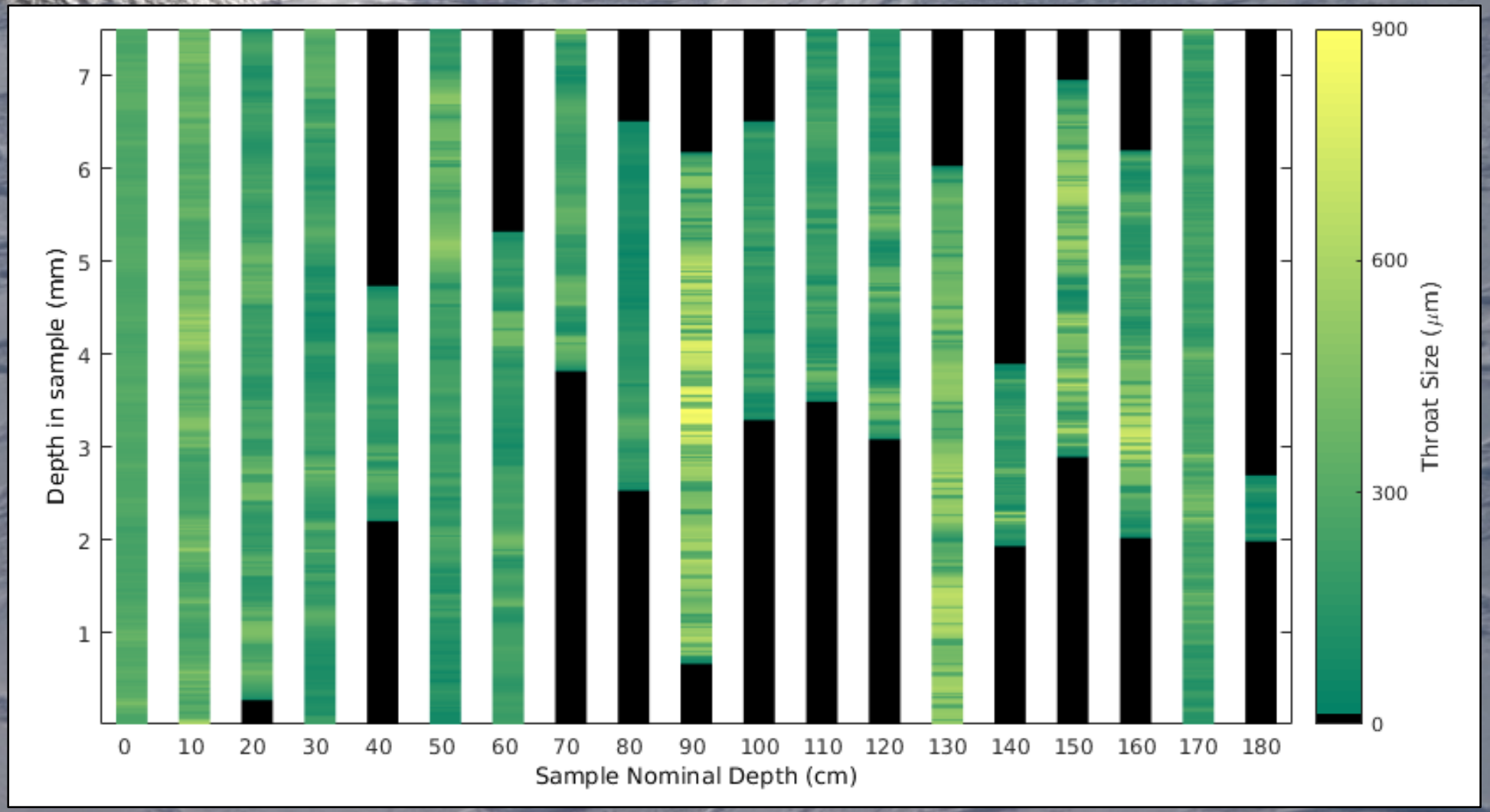
Record edges in an adjacency matrix

Track each node and its corresponding throat size

Calculate statistics on average throat size, network branching, particular paths, topological complexity, minimal and maximal throats, etc.

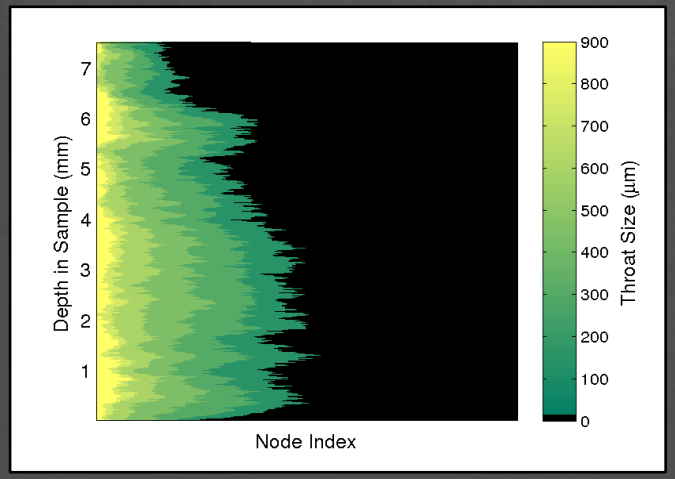
Brine Network Model

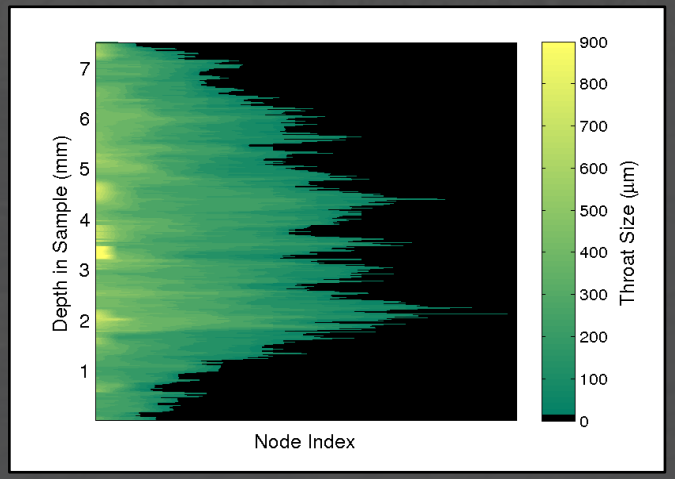
Average Throat Sizes

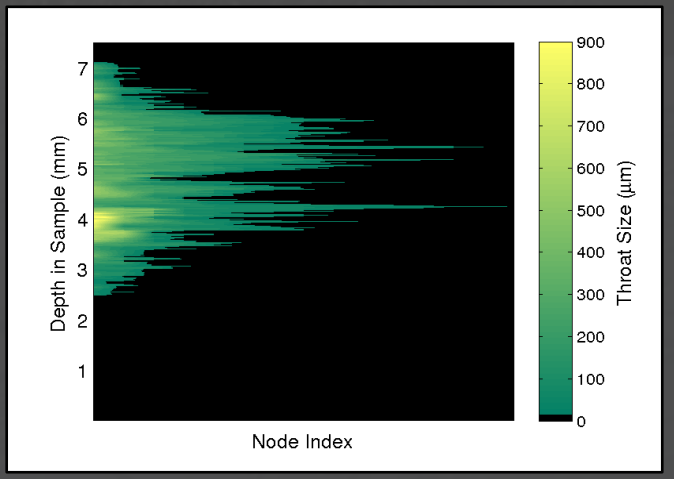


Brine Network Model

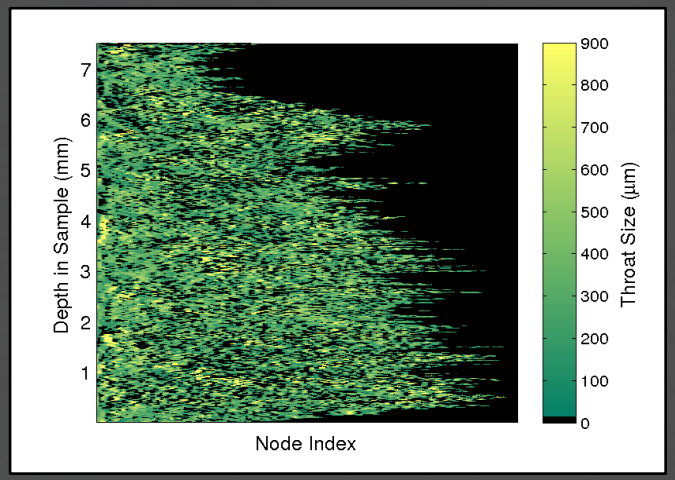
Throat Size Distribution (Sorted)

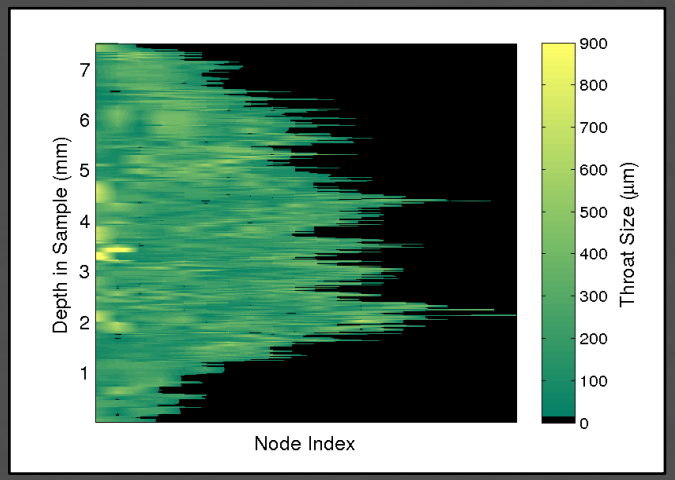


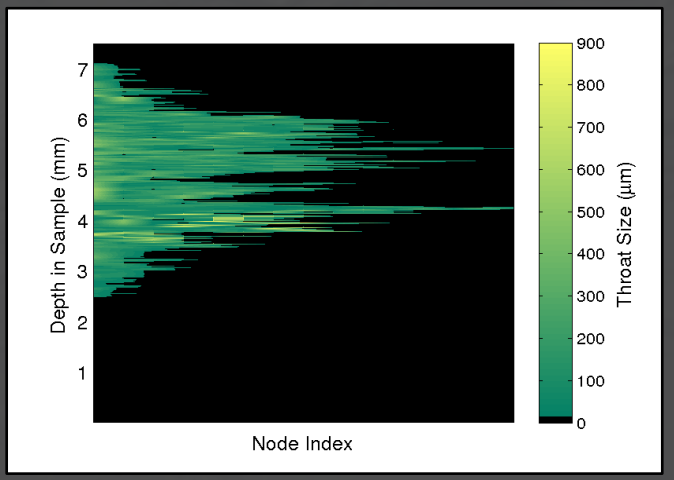




Throat Size Distribution (Unsorted)



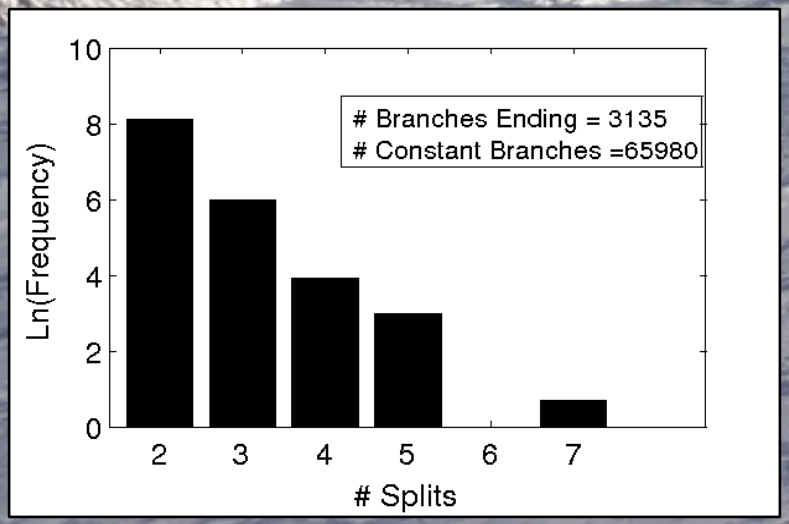


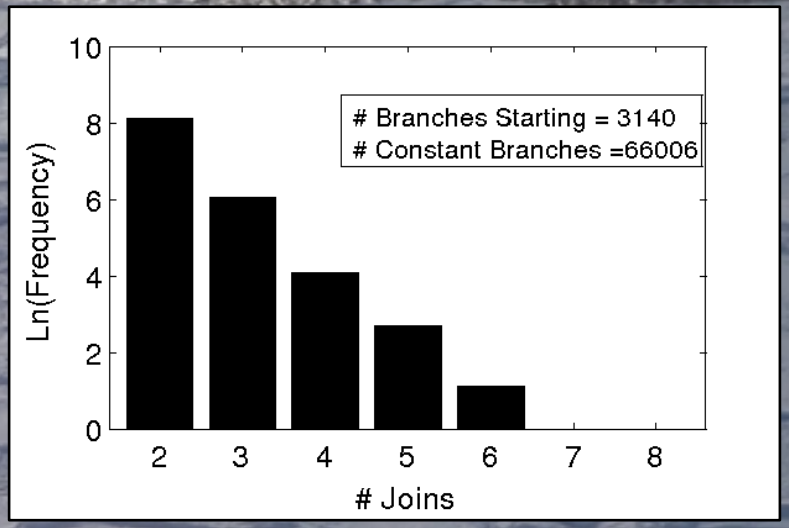


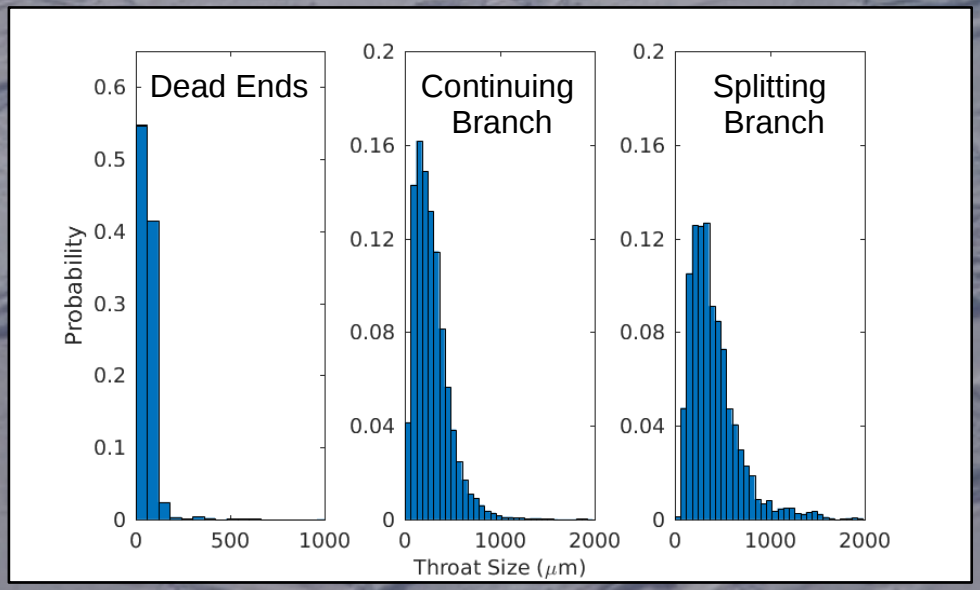
0 cm **70 cm** **170 cm**

Brine Network Model

Branching

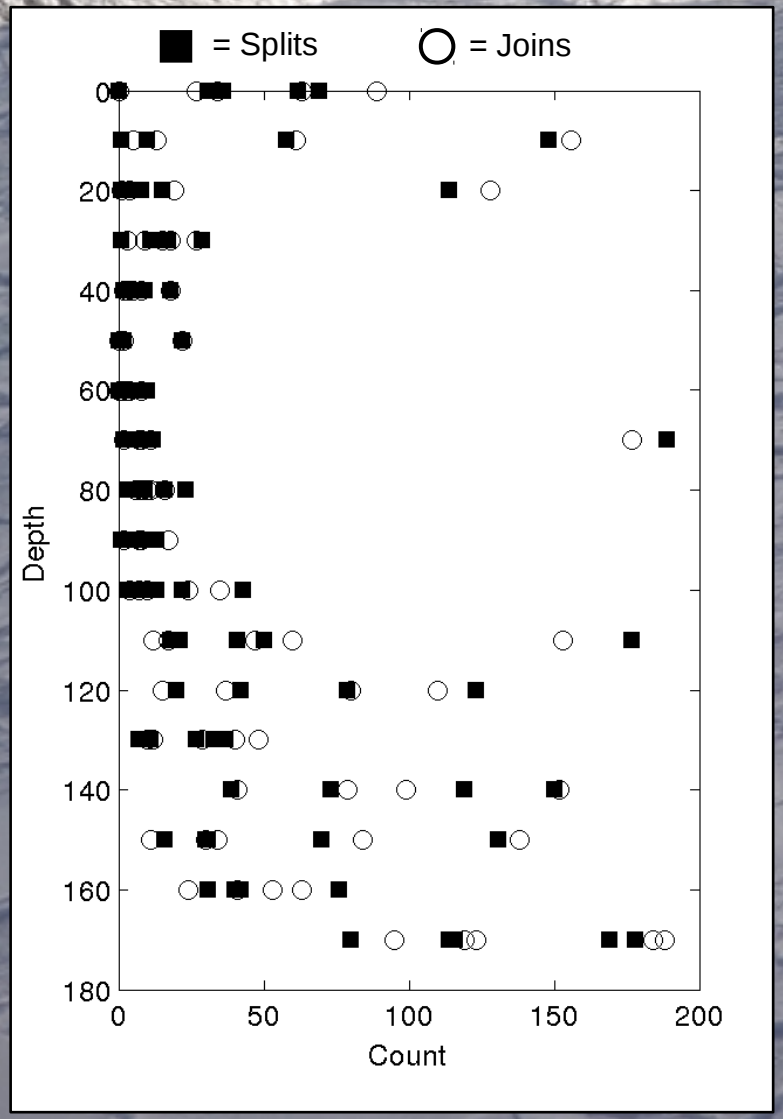


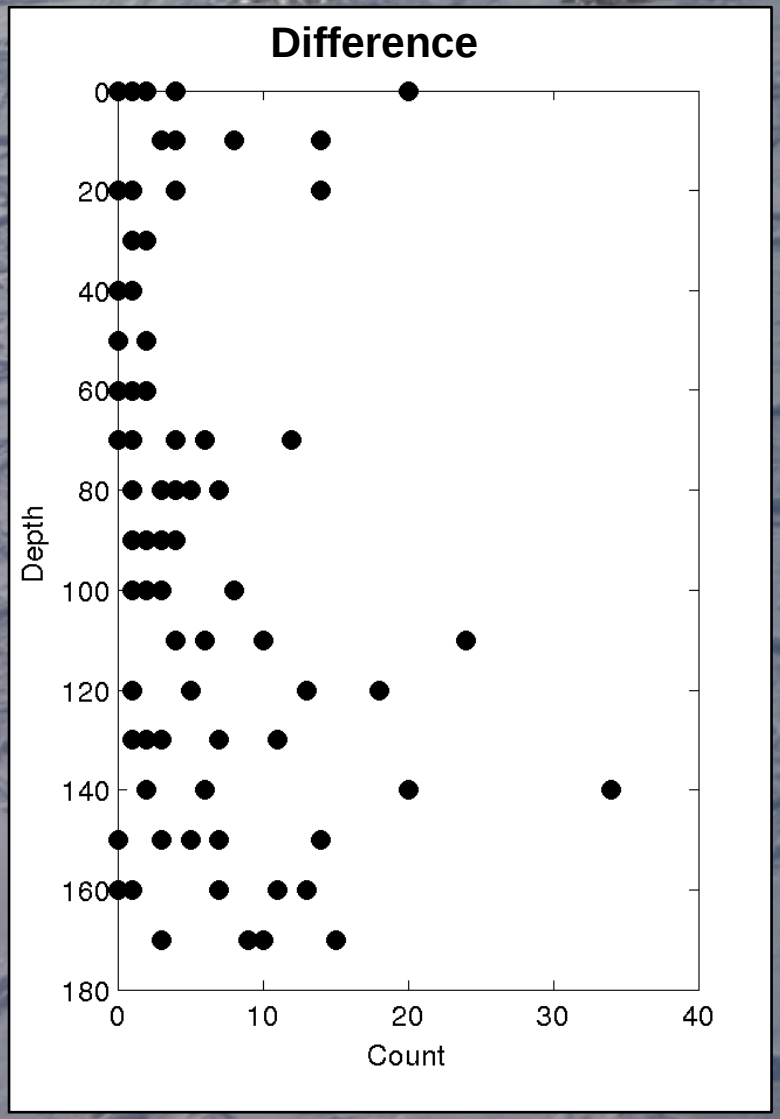




Brine Network Model

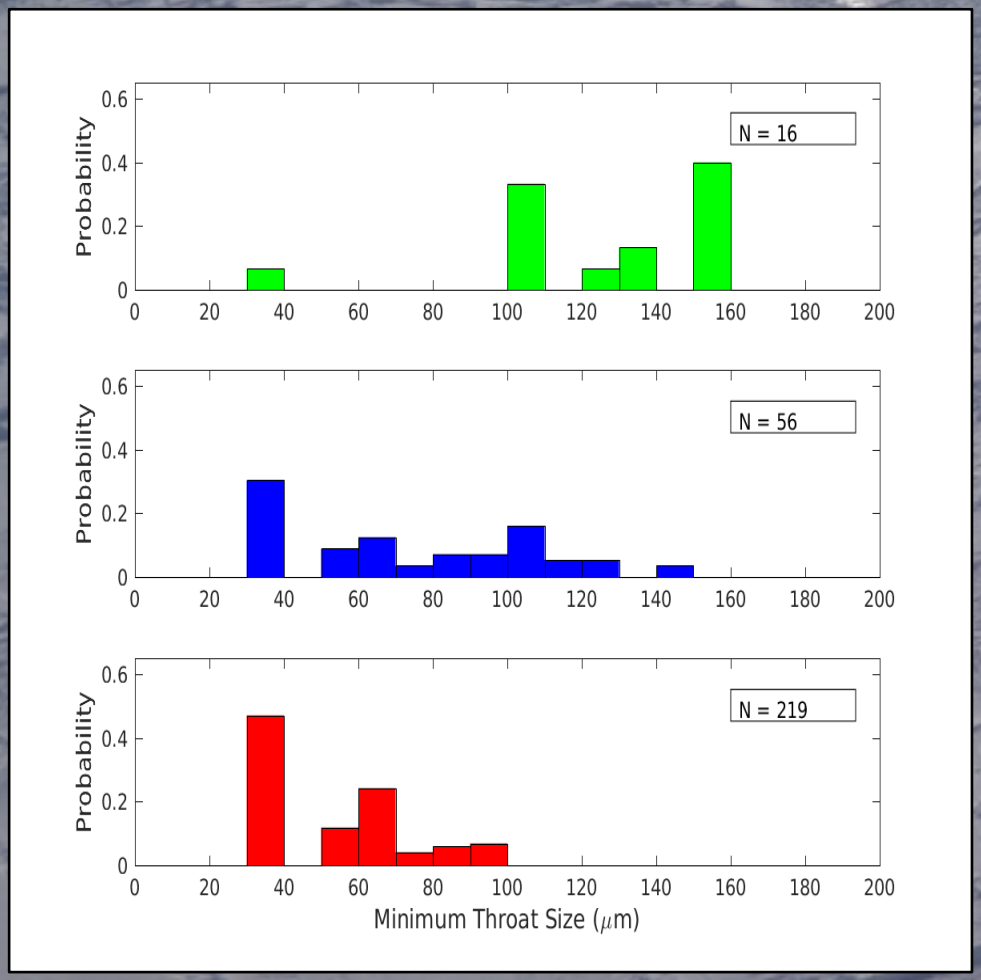
Topological Complexity

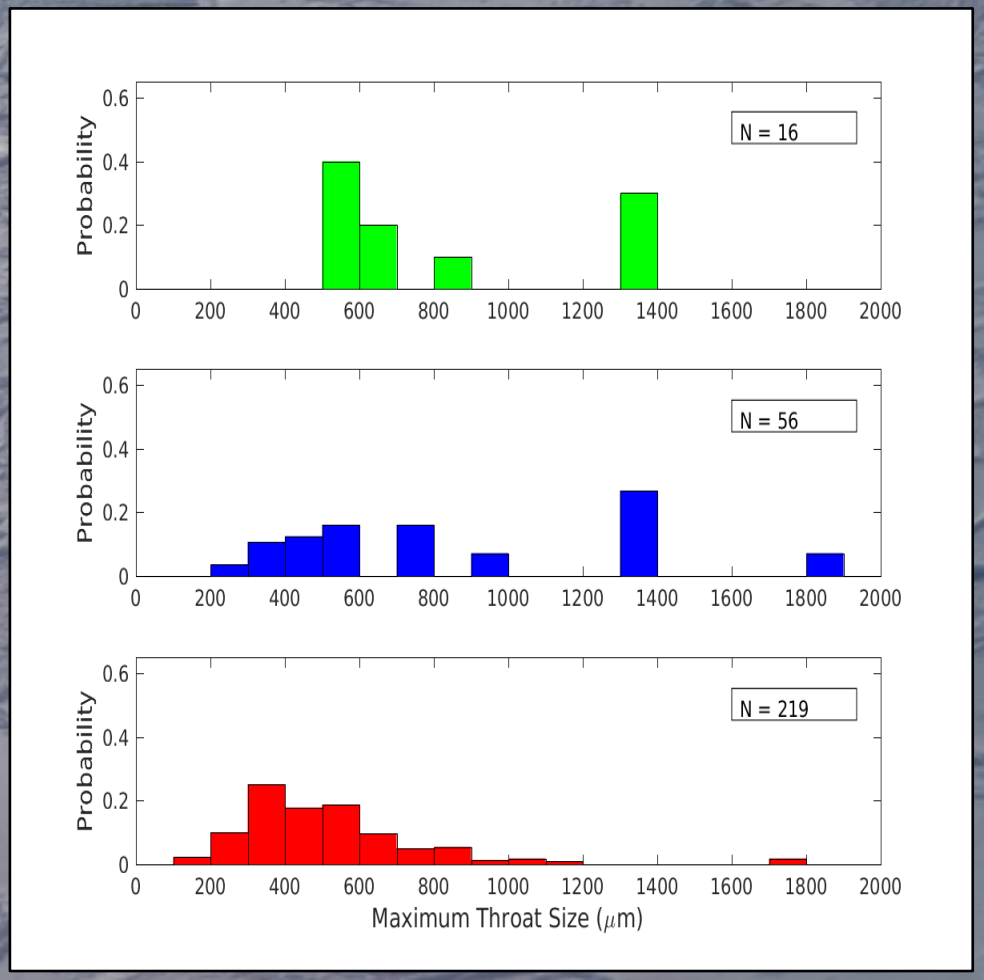




Brine Network Model

Throat Size Probability Distribution



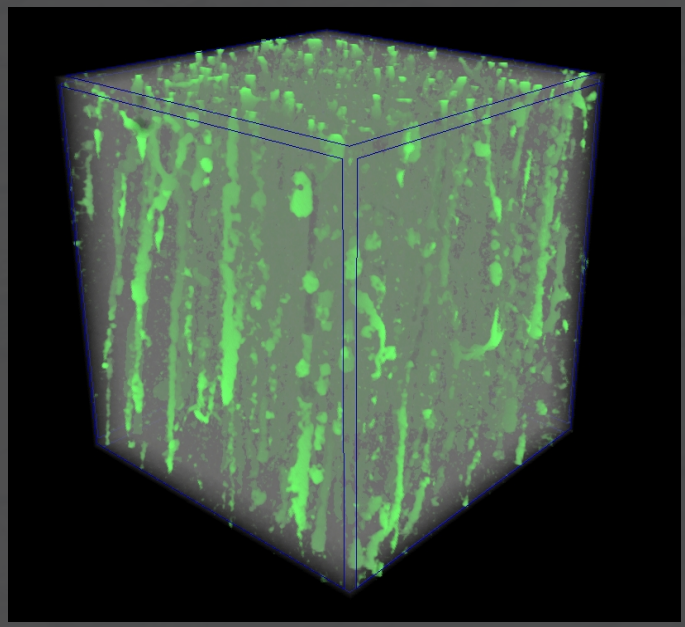


= Small Initial Throat = Medium Initial Throat = Large Initial Throat

Conclusions & Future Work

Conclusions

- Brine channels can transport salts (e.g. Br) to the sea ice surface, where they can be a catalyst for ozone depletion events
- 3D imaging of the brine phase using μCT enables visualization and quantification of the brine channel network morphology, topology, and connectivity
- Network theory can be used to calculate the topological complexity of the brine channels, which can later be used to create a statistical model of brine channels



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NSF Award #1304134

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Gunnar Pope

Natalie Afonina

Anna Miller
George Boateng
Dave Ferris
ENGS 21
ENGS 89/90 team

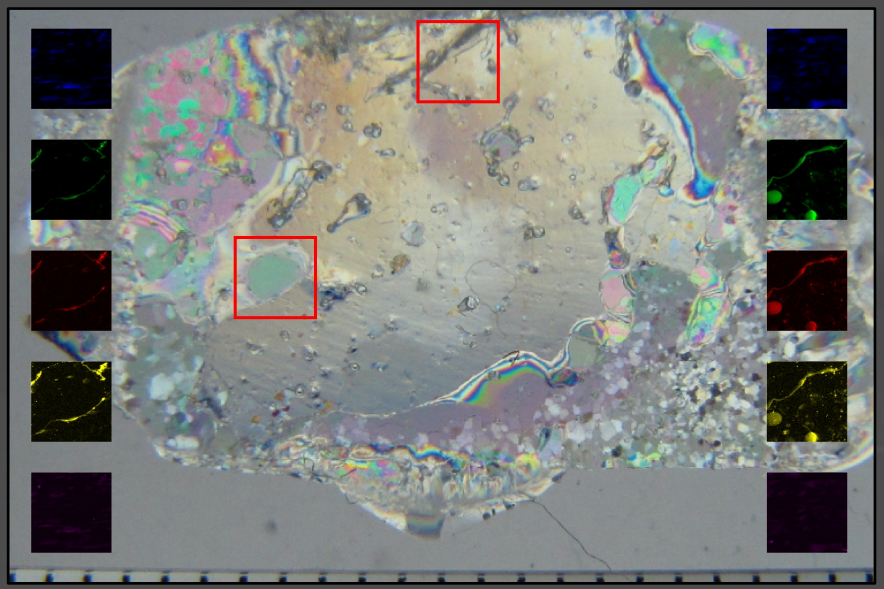
Questions?

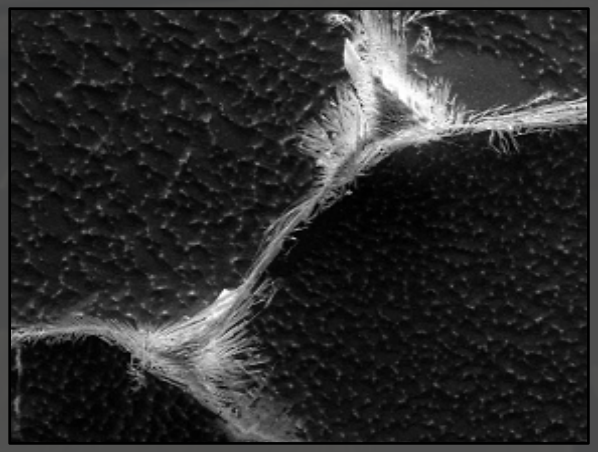
Microstructural Location of Salts

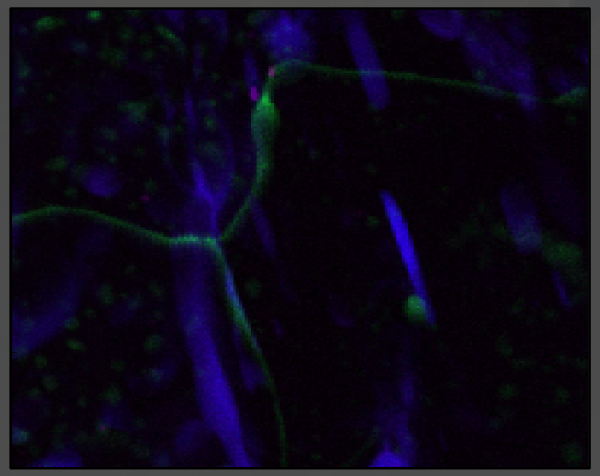
Research Question #2

Where exactly are the salts located microstructurally?

Specifically, are salts located solely in brine channels/inclusions and at grain boundaries?



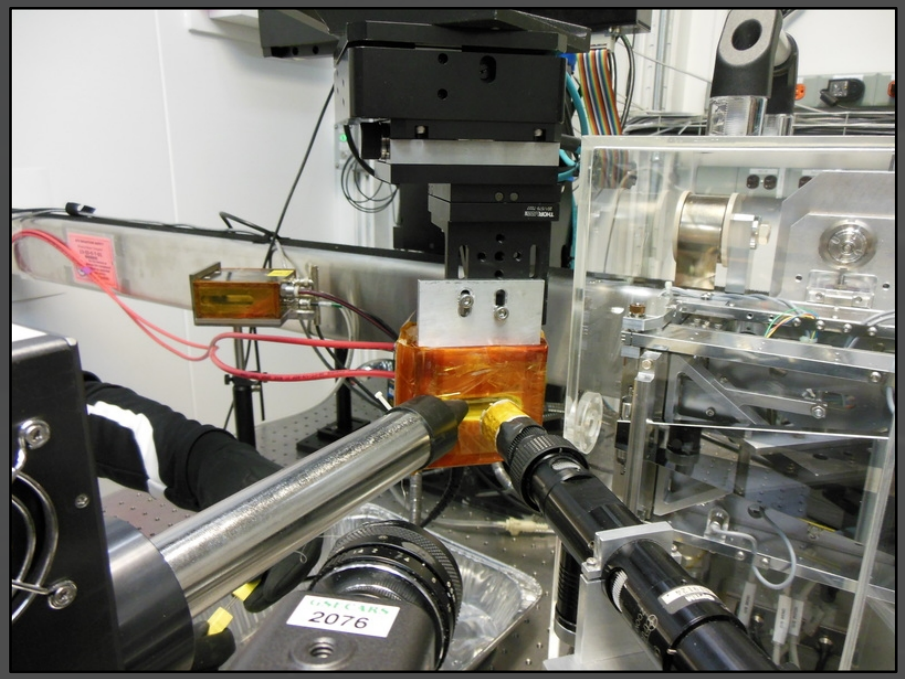


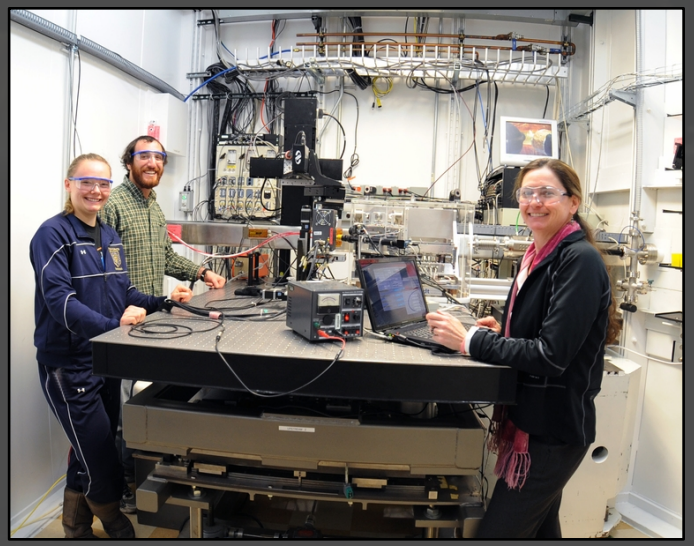


Microstructural Location of Salts

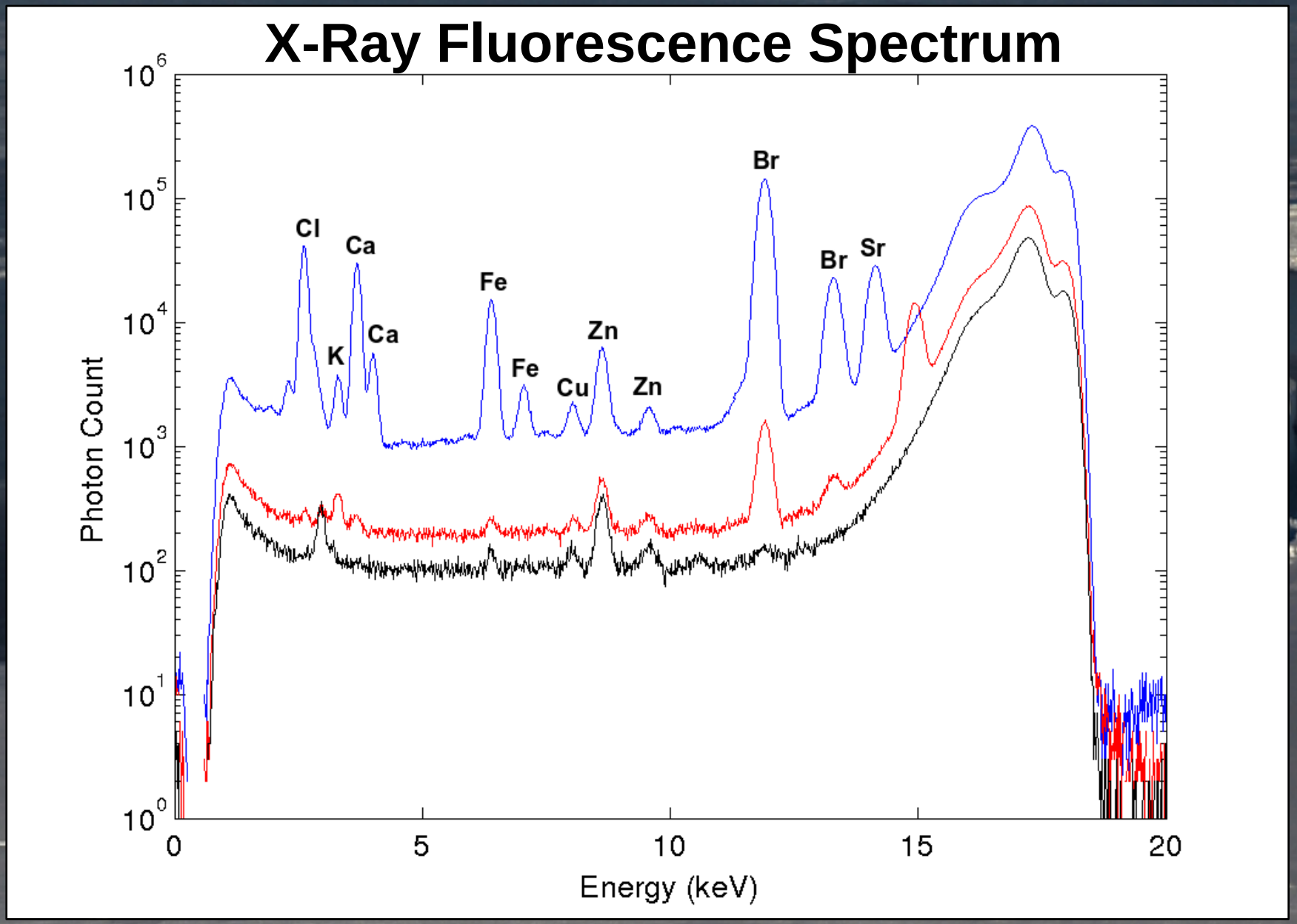
Argonne National Laboratory's Advanced Photon Source (APS)

Provides brightest X-rays in western hemisphere
Electrons circle ring 270,000 times per second!



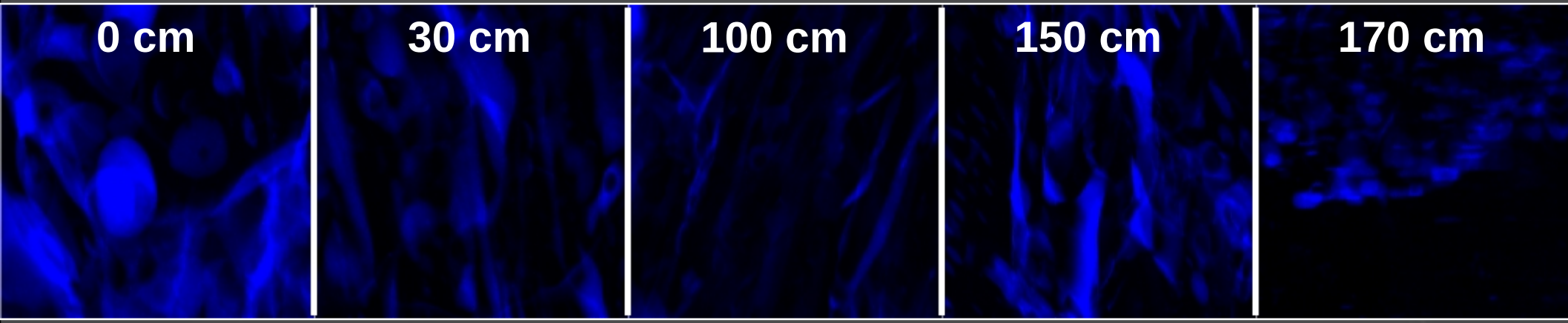


Microstructural Location of Salts

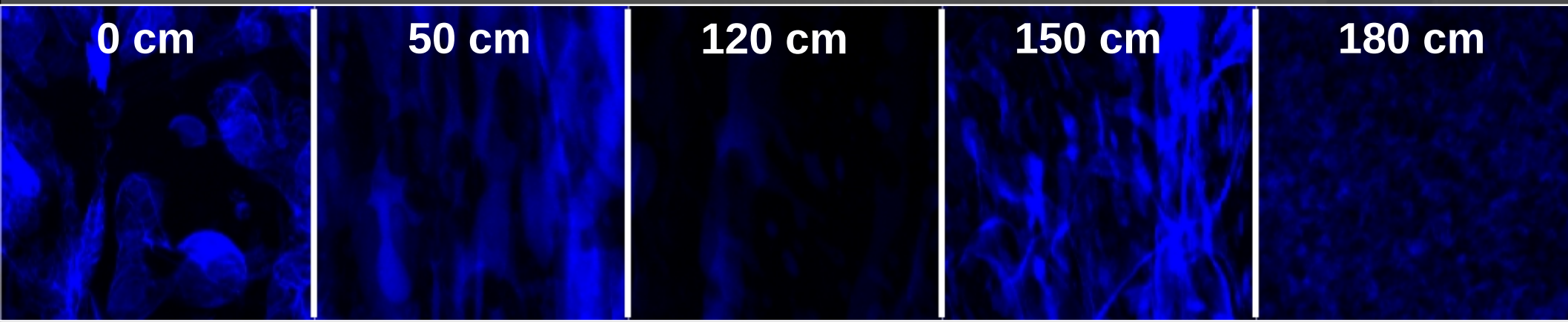


Microstructural Location of Salts

Butter Point Site - Bromide

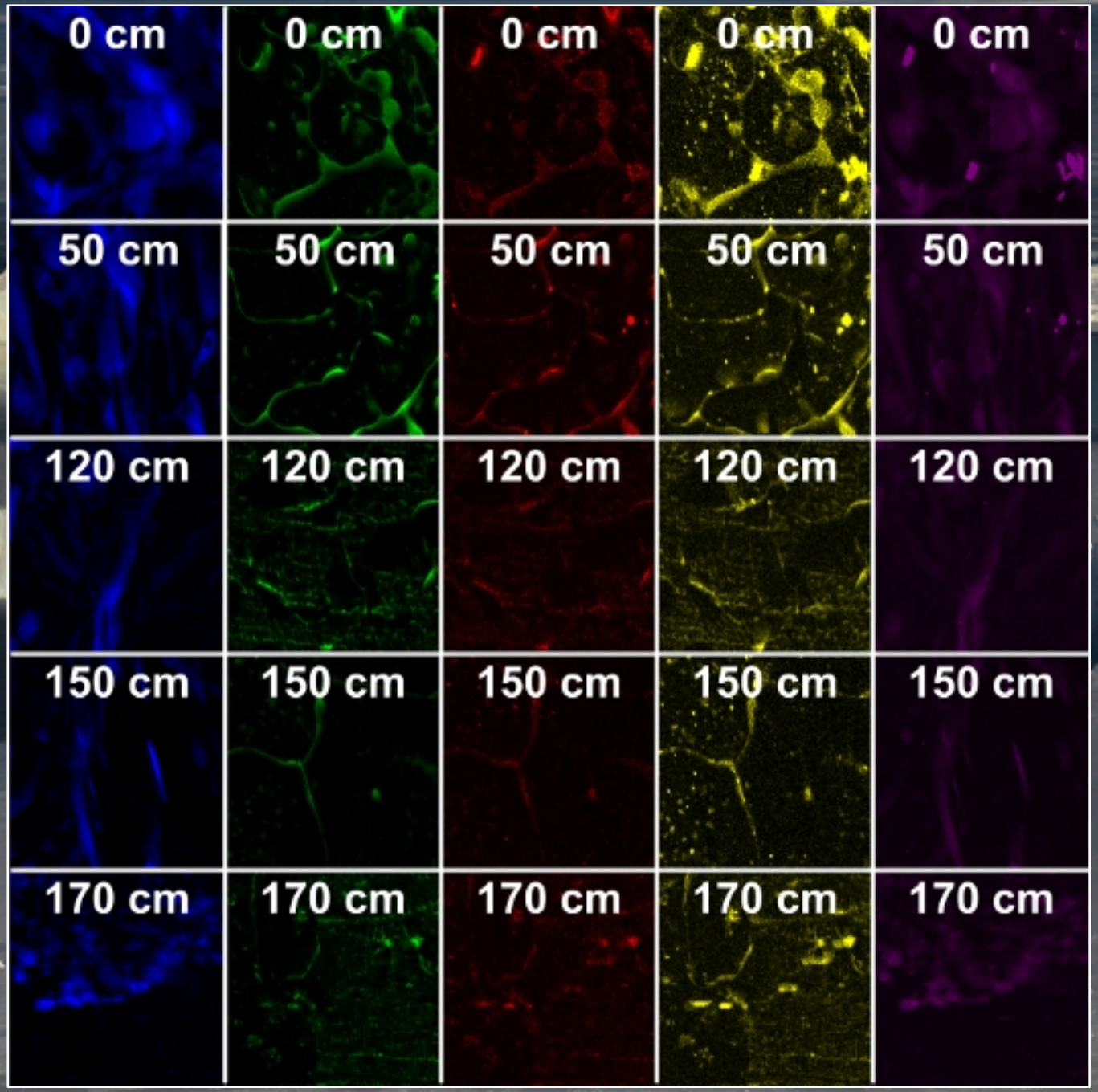


Iceberg Site - Bromide



2 mm x 2 mm elemental maps, 10 μm spatial resolution

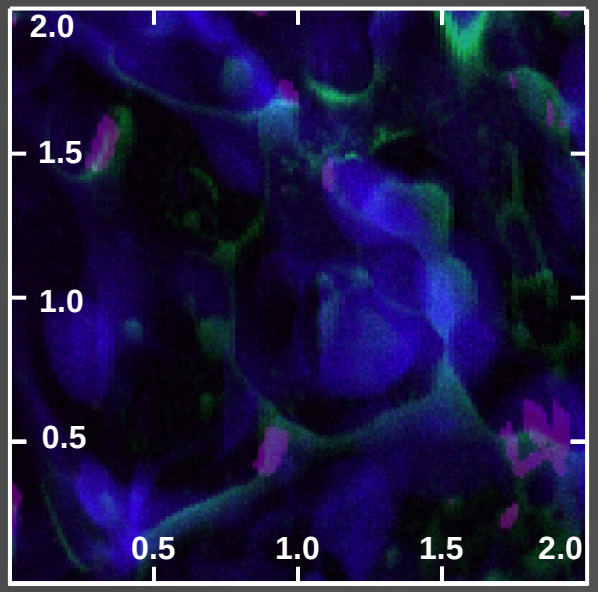
Microstructural Location of Salts

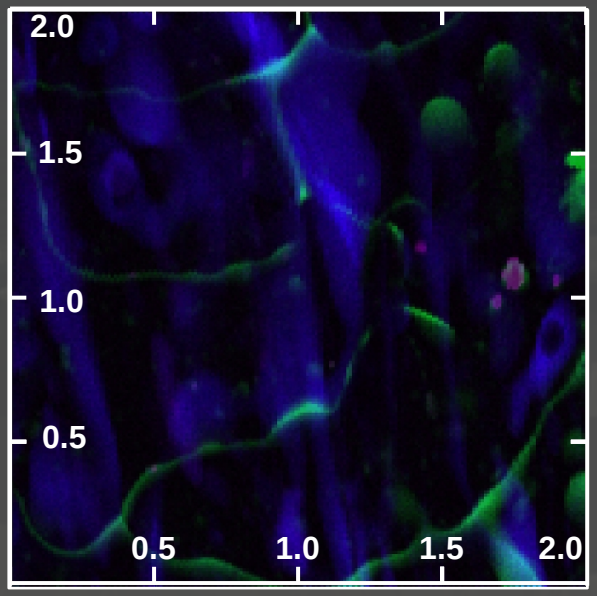


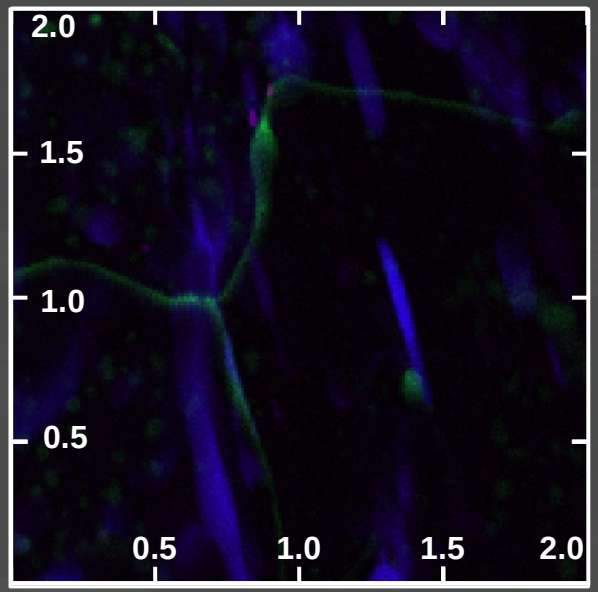
= Bromide
= Chloride
= Potassium
= Calcium
= Strontium

Microstructural Location of Salts

Correlation of Salts



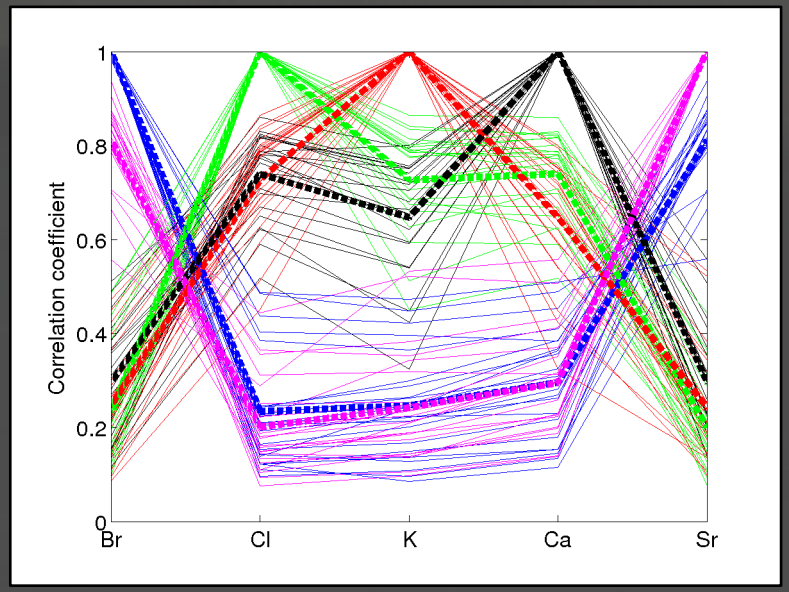




= Bromide

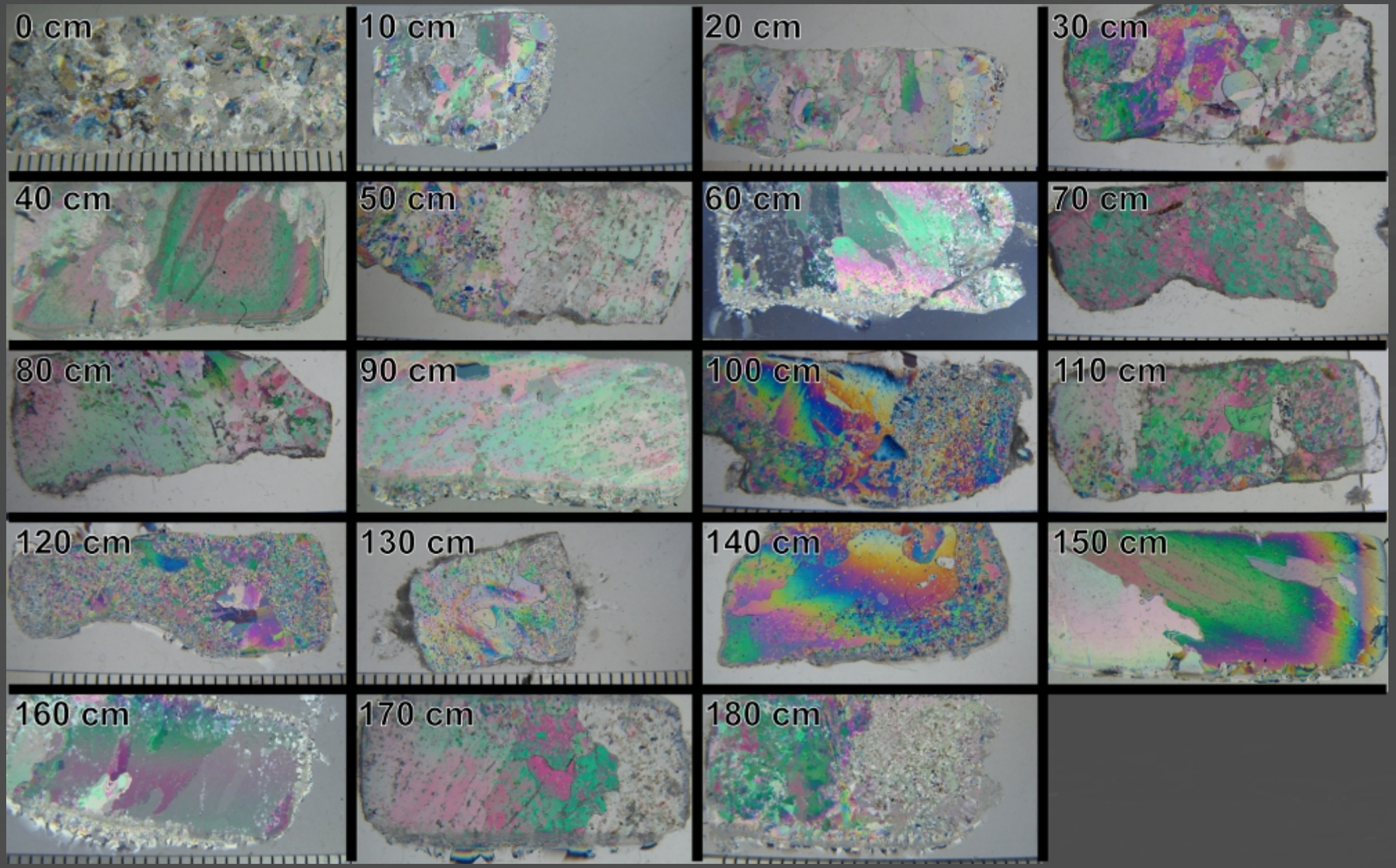
= Chloride

= Strontium



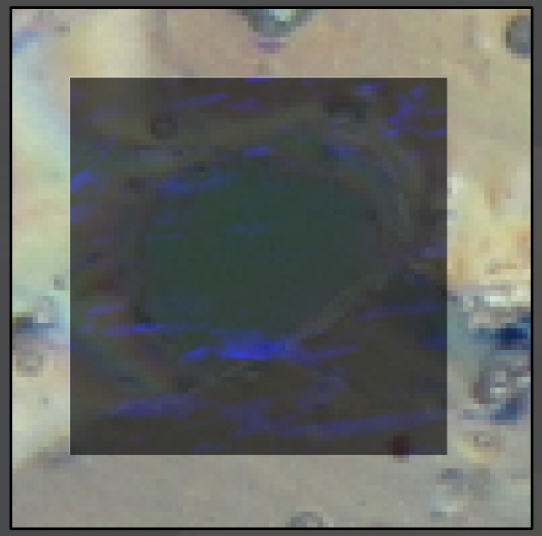
Microstructural Location of Salts

Horizontal Thin Sections

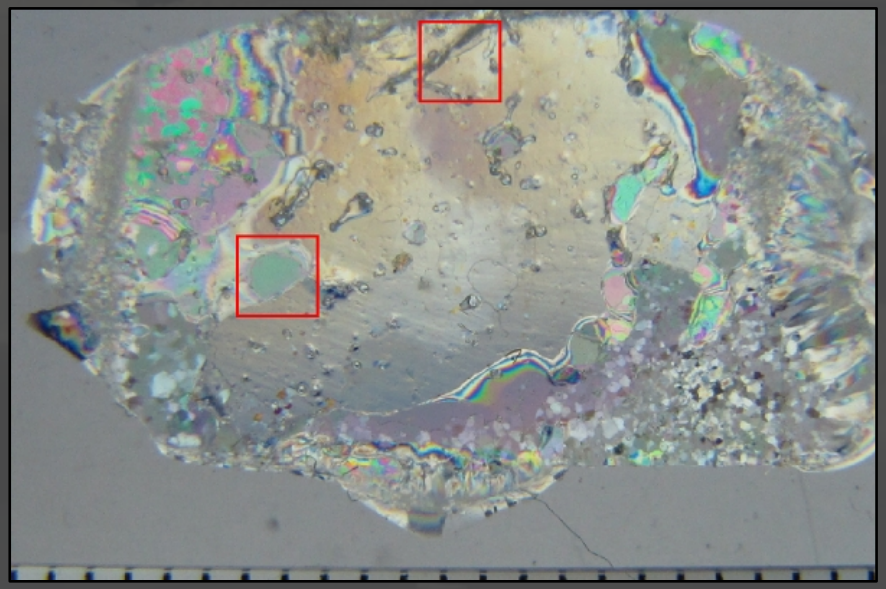


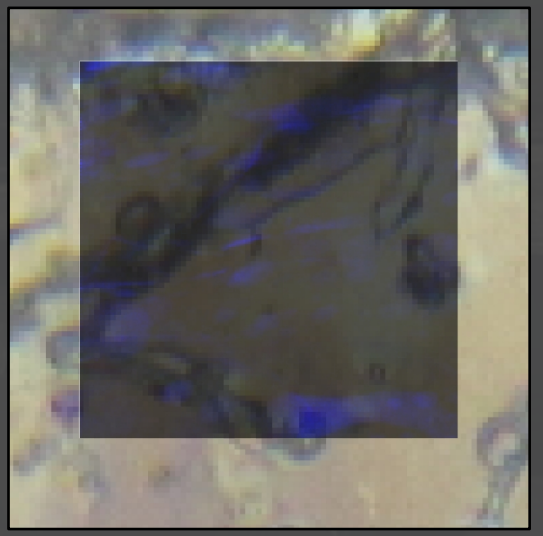
Microstructural Location of Salts

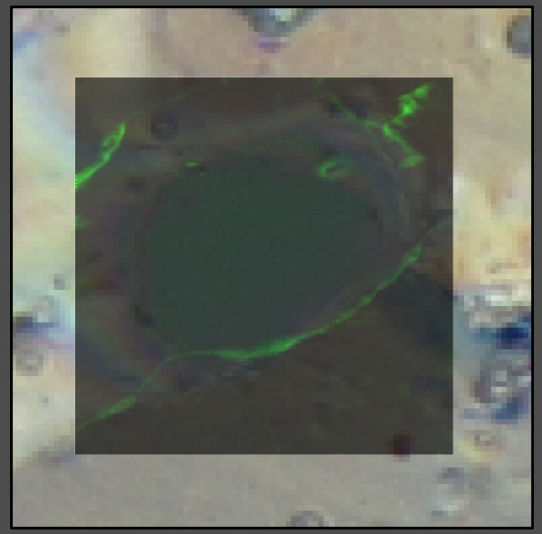
Matching XRF Maps to Thin Sections



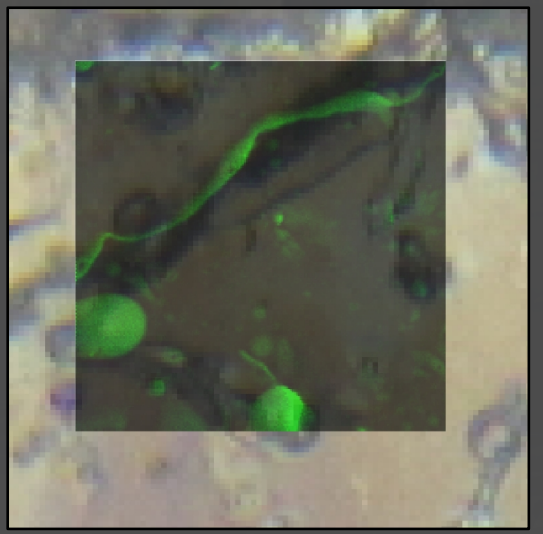
= Bromide





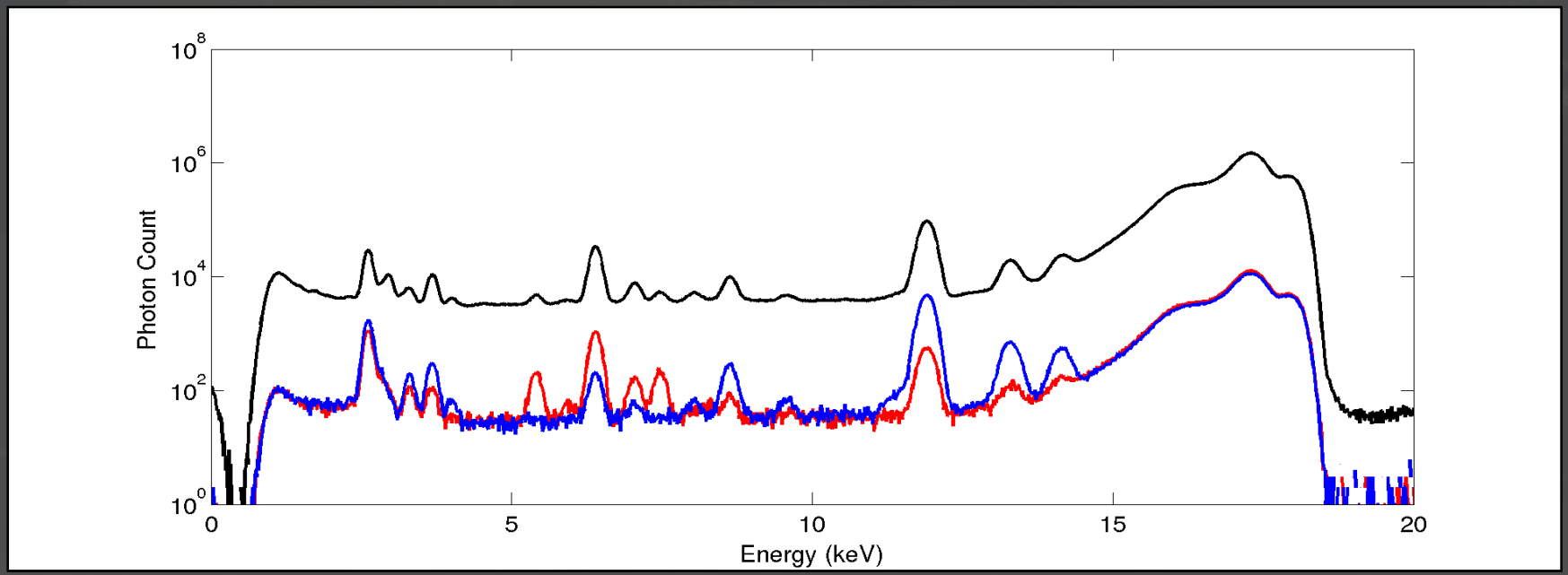


= Chloride



Microstructural Location of Salts

Identifying Particular Features

= Grain Boundary
(Increased Br & Sr)

= Round Speck
(Increased Cr, Fe & Ni)