

# The Role of Refreezing Meltwater Beneath Antarctic and Greenland Ice Sheets

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WAIS 2014 Camp Cedar Grove, Julian CA



# Overview

- Refreezing Basics
- Gem & Black Refrozen Ice
- Major Modes
  - Large Lake
  - Refreezing From Well Defined Water Networks
  - Refreezing and Deformation
  - Surface Meltwater Refreezing in Ablation Zone
- Mechanisms
- Implications & Conclusions

# Refreezing -Overview

- Why does it matter
  - Changes stratigraphy thermal structure and rheology of ice sheet
  - More more in a warming world – more water more refreezing
- What water refreezes?
  - Basal Melt, Surface Melt, Subglacial Aquifers

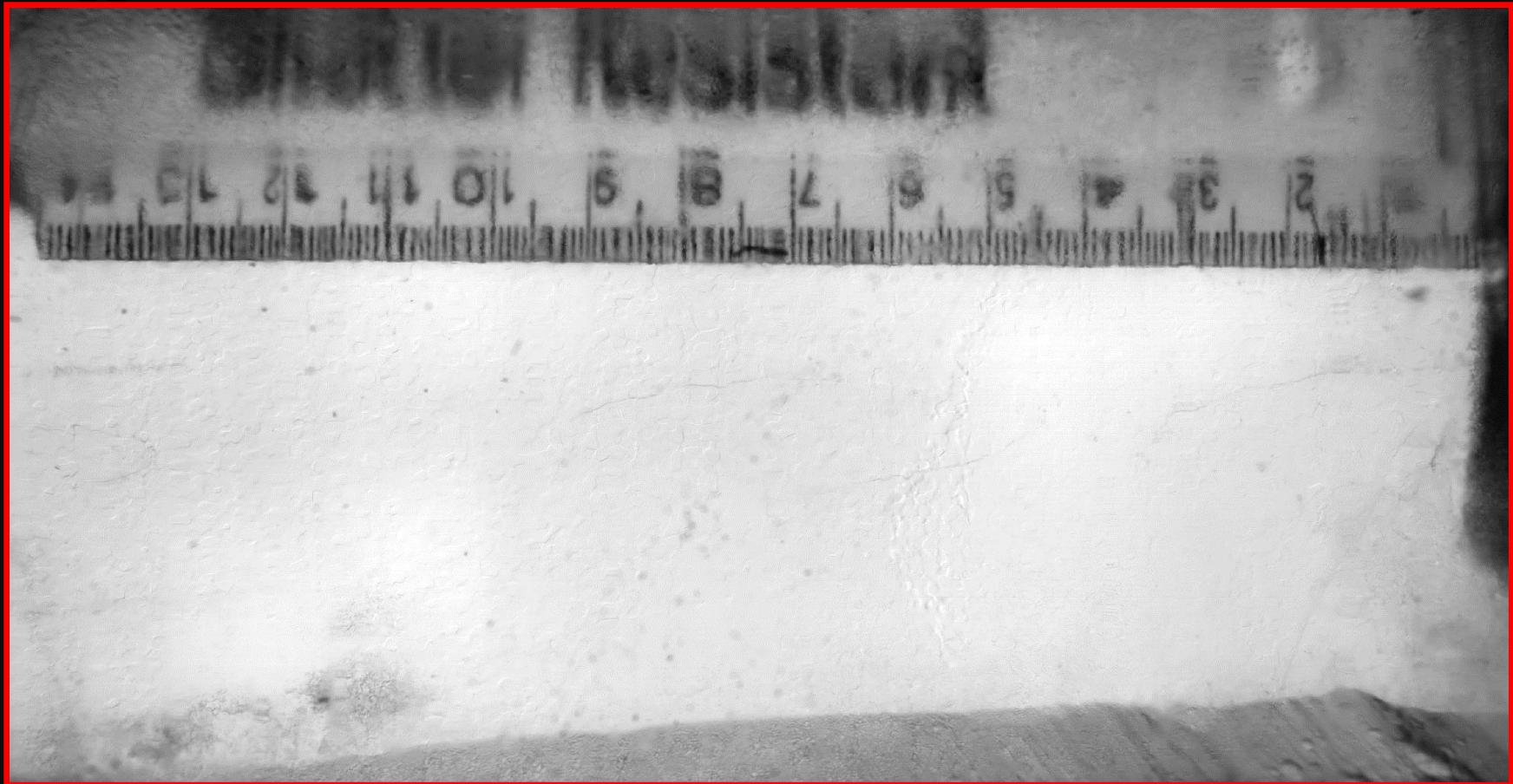
What Does it Look Like:

Gem & Black Refrozen Ice

# Vostok Gem Ice

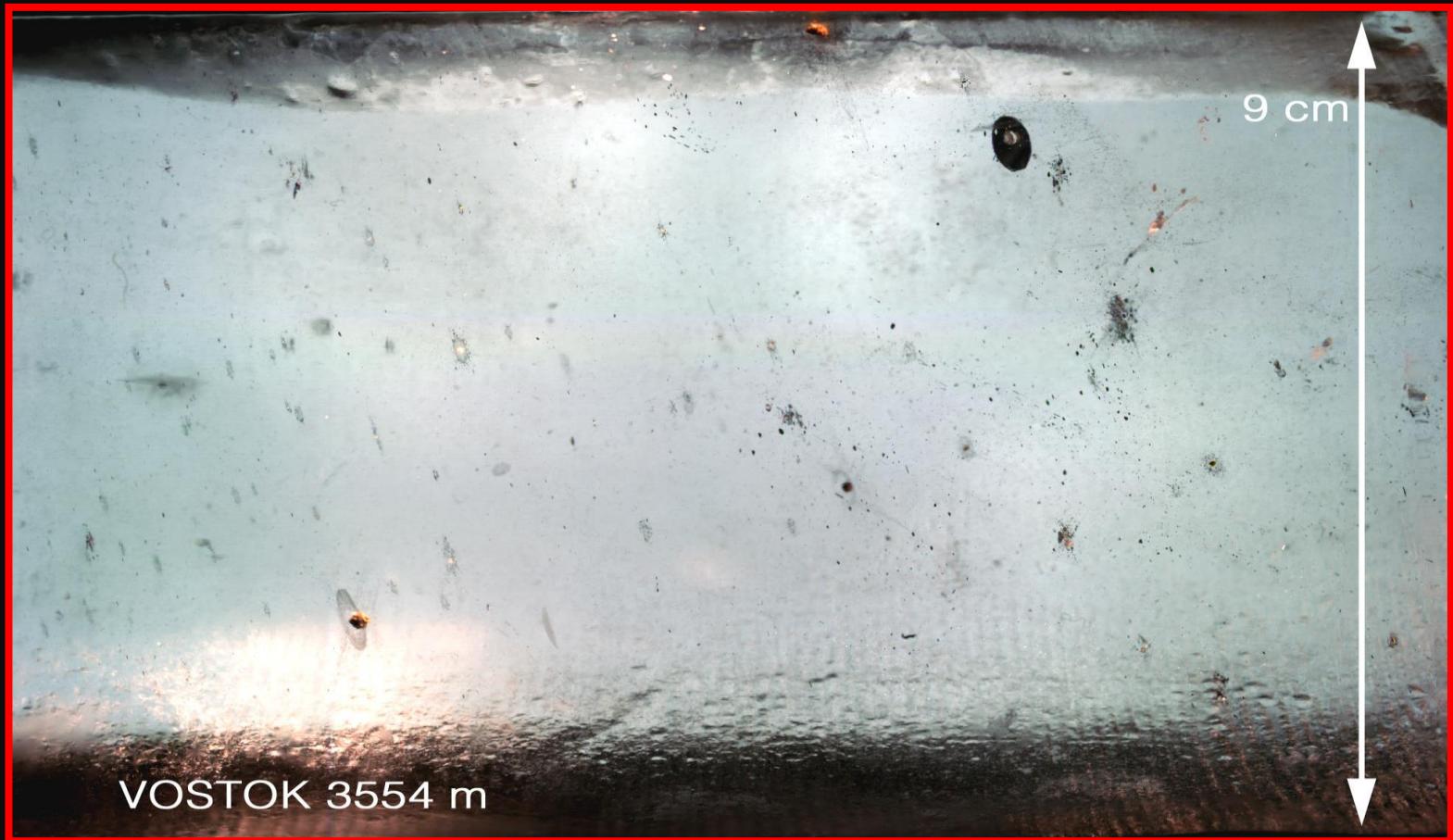
## Bubble Free, Distinct Chemistry, Large Crystals

- SS



# Vostok Swamp Ice

## Bubble Free, Distinct Chemistry, Large Crystals Debris



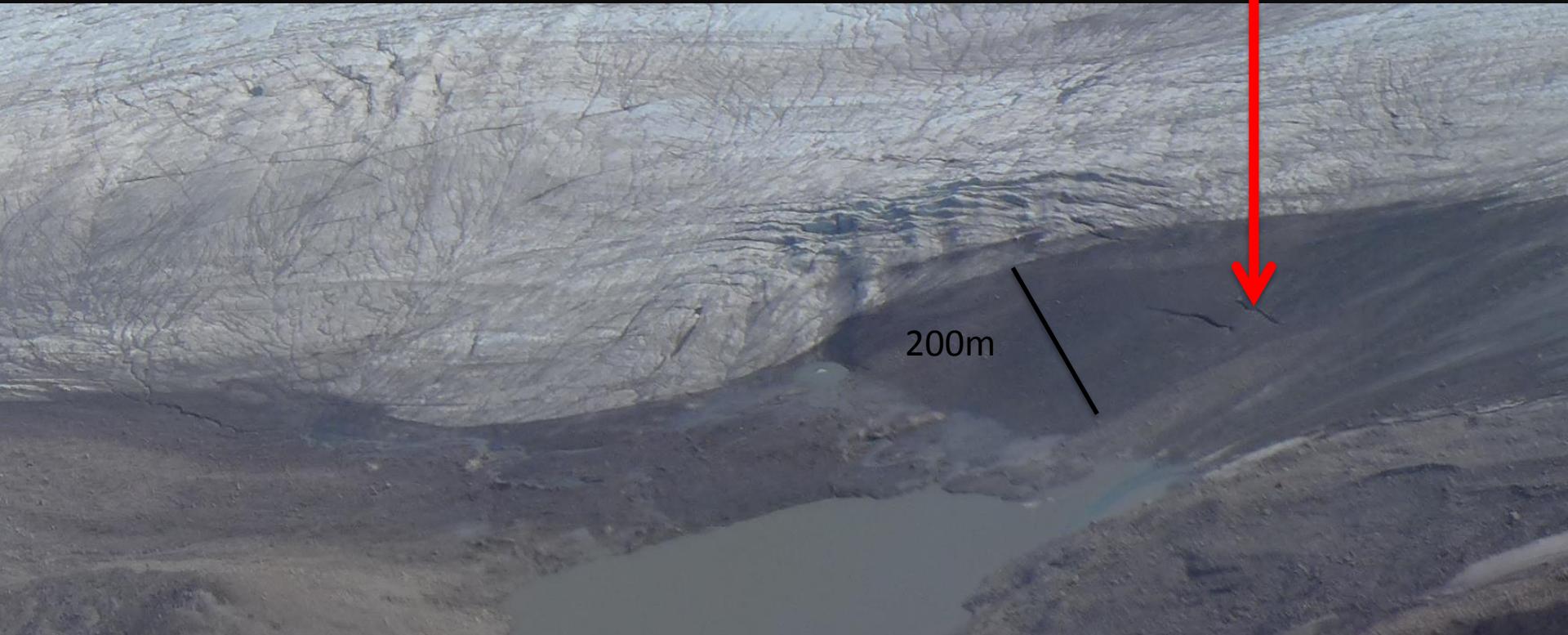
# Greenland Black Ice (Debris Rich)

Often Rocks accumulate on top

(Ask Jeff Sevrinhaus)

Pakitsoq see Reeh et al 1997

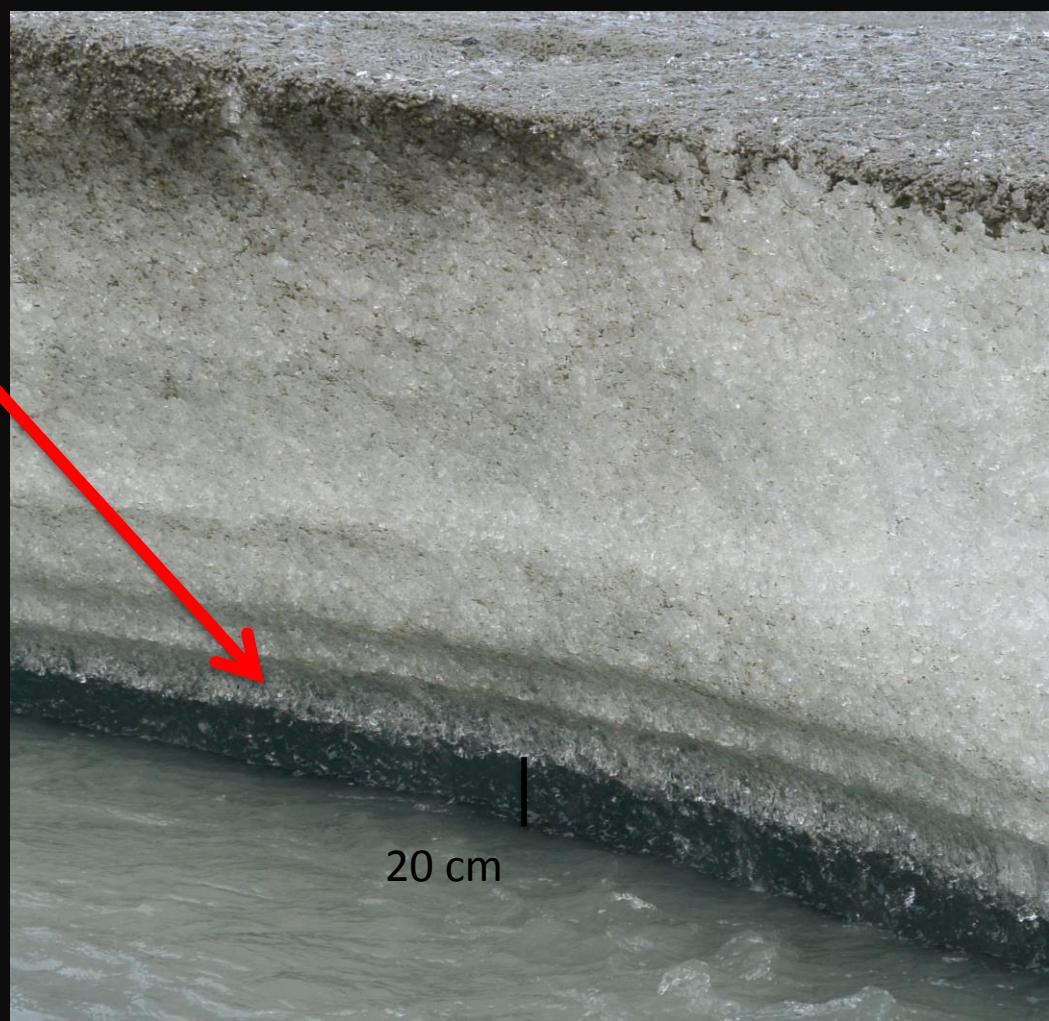
Image From IcePod Flight 2014



# Russell Glacier @ the Road

## Sugden et al Nature 1987

Black  
Bubble Free  
Distinct Oxygen 18



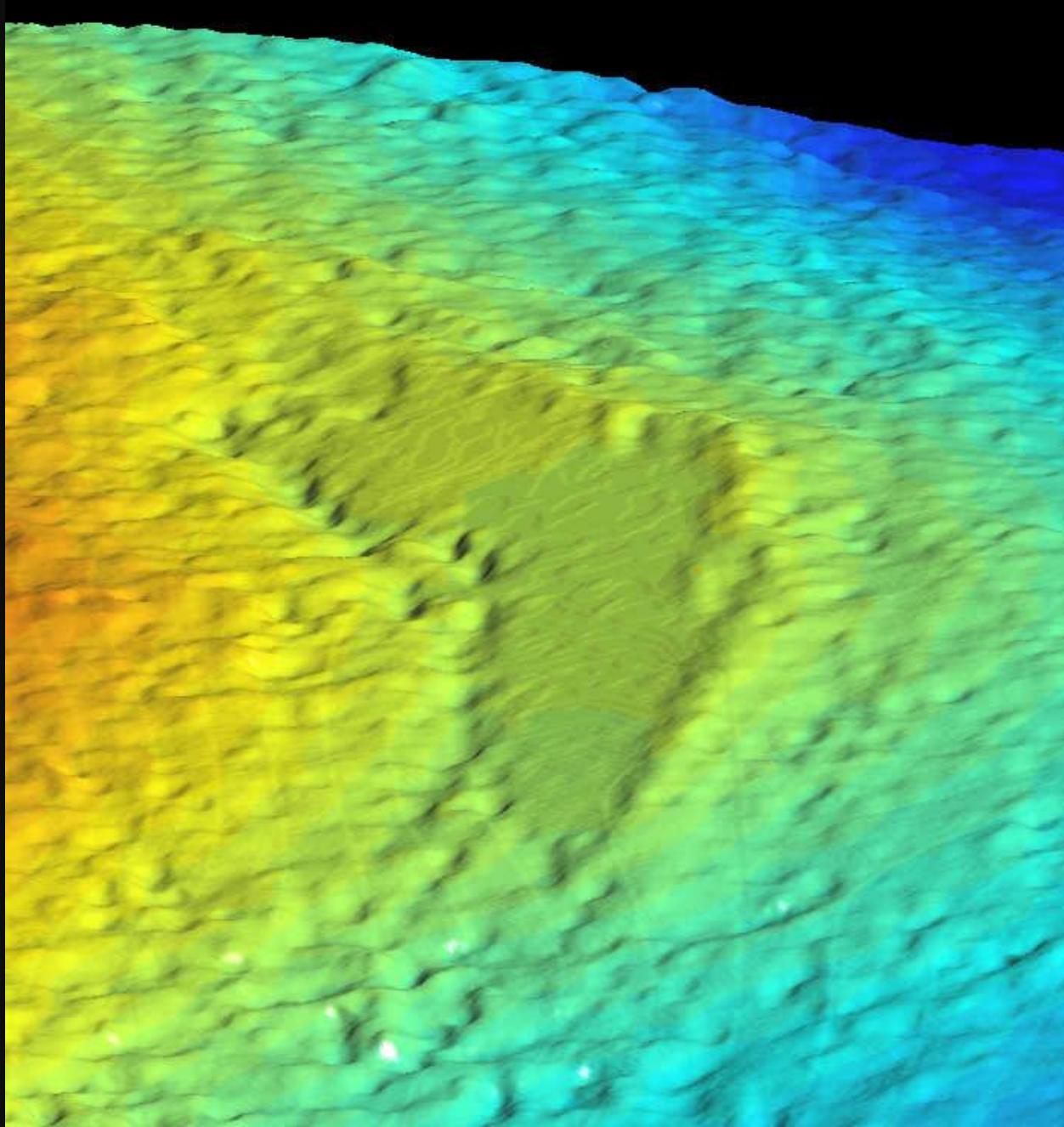
# Refreezing Occurs in Multiple Places

## Large Lakes

Refreezing From Well Defined Water Networks

Refreezing and Deformation

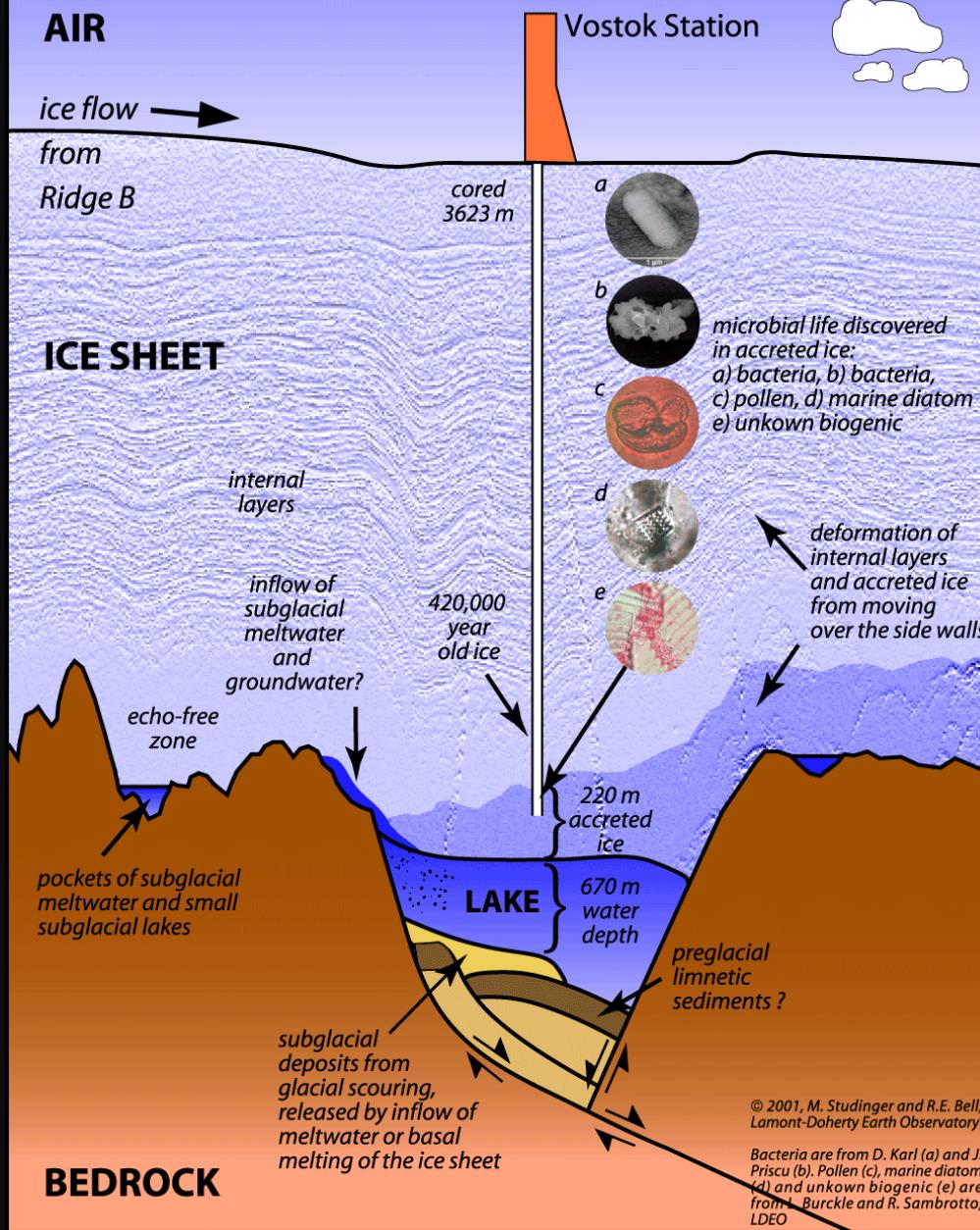
Surface Meltwater Refreezing in Ablation Zone

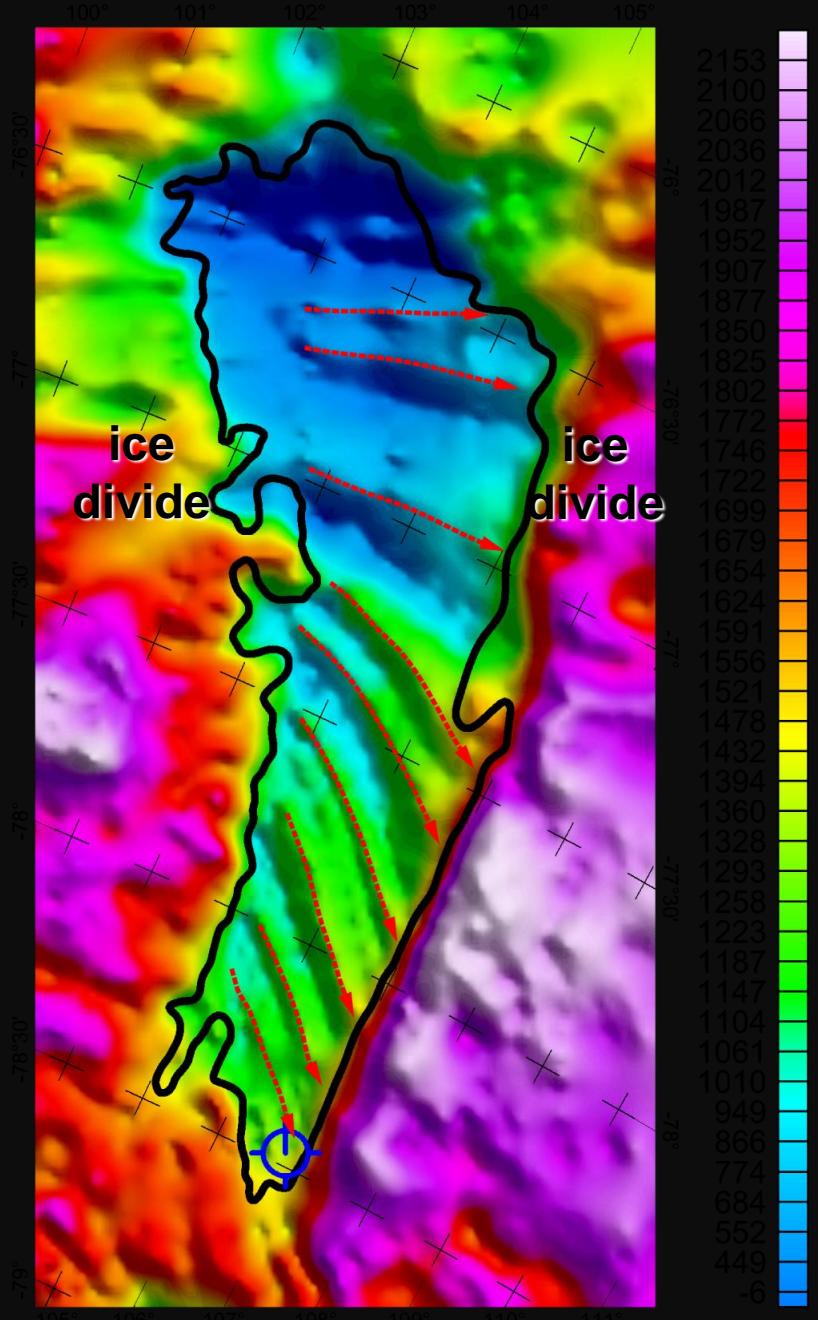


Lake  
Vostok  
  
Ice Surface  
Elevation



# The Subglacial Lake Vostok System



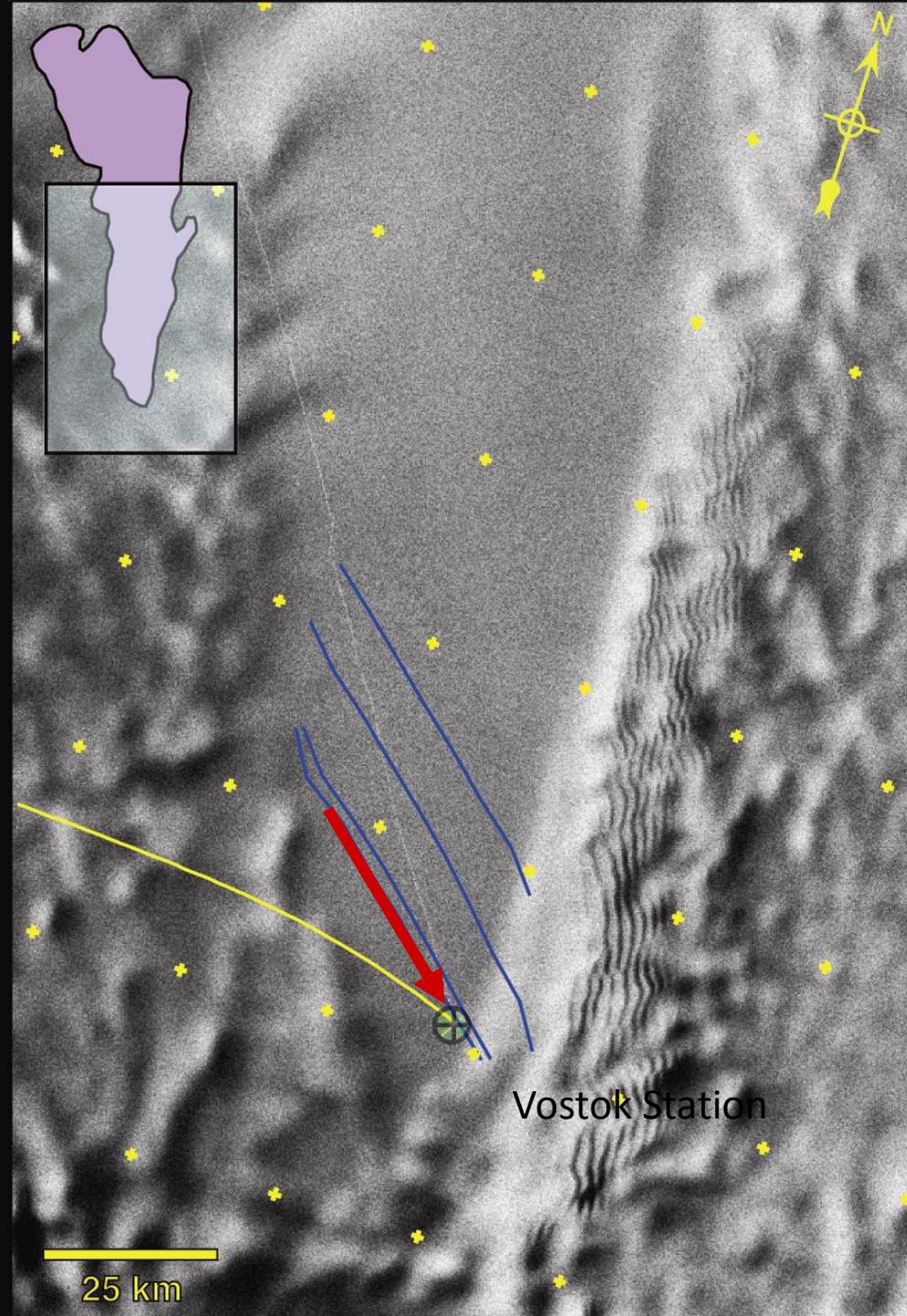


Elevation of Internal Layer A [m asl]

Ice Sheet Flows  
Across the Lake

Here Flow Direction Preserved in  
Internal Layers

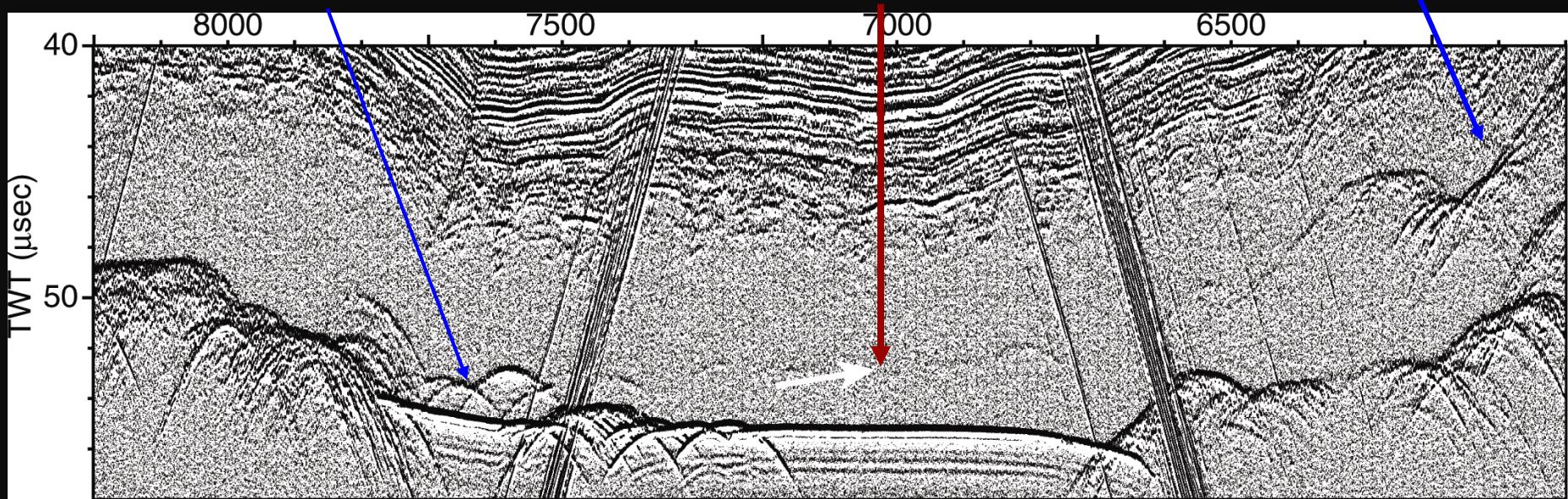
# Refreezing Along Flow Produces Deformation and Gem Ice



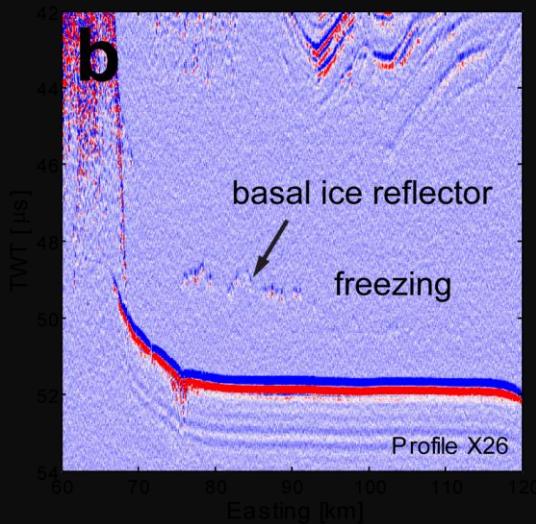
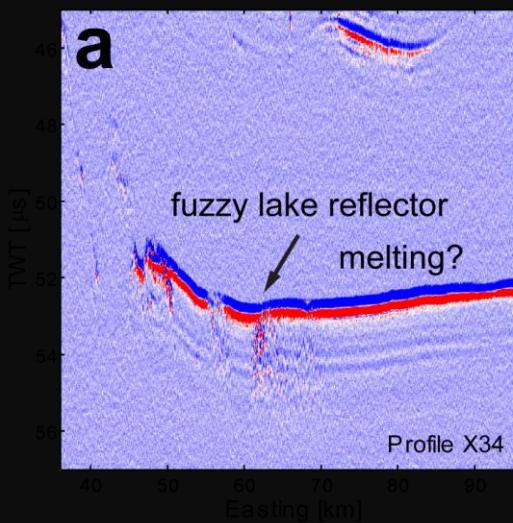
Refrozen Ice  
Leaving Lake

Refrozen Ice

Vostok Core



## Melt in North



## Freeze in South

Keeps Water in Lake Vostok “Young”  
Sort of ~ 55-110,000 yr residence time



# What are Major Modes

Large Lake

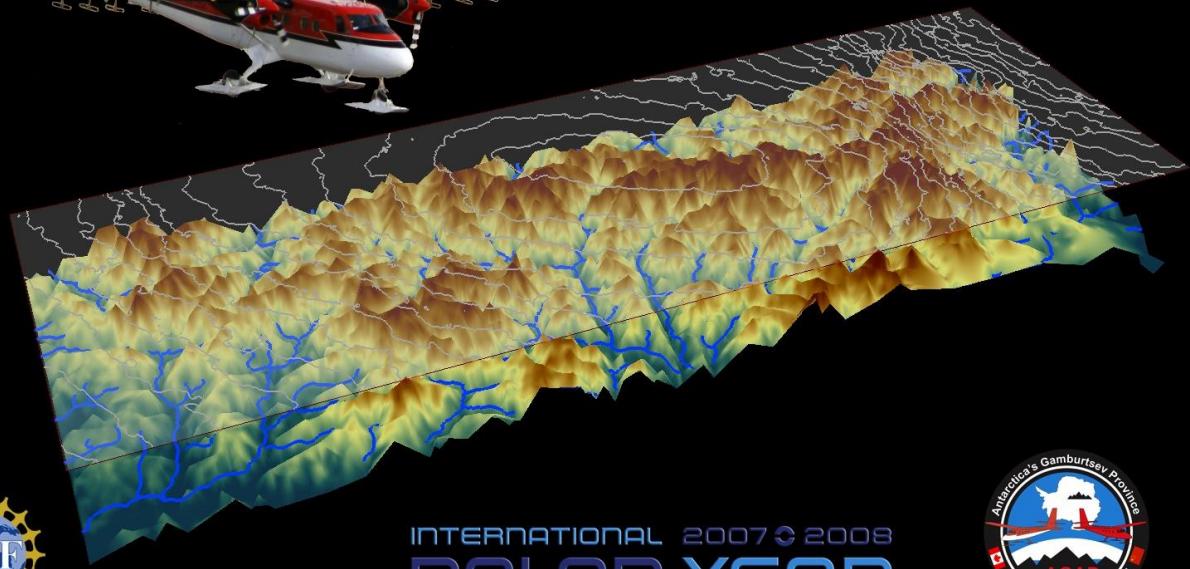
**Refreezing From Well Defined Water Networks**

Refreezing and Deformation

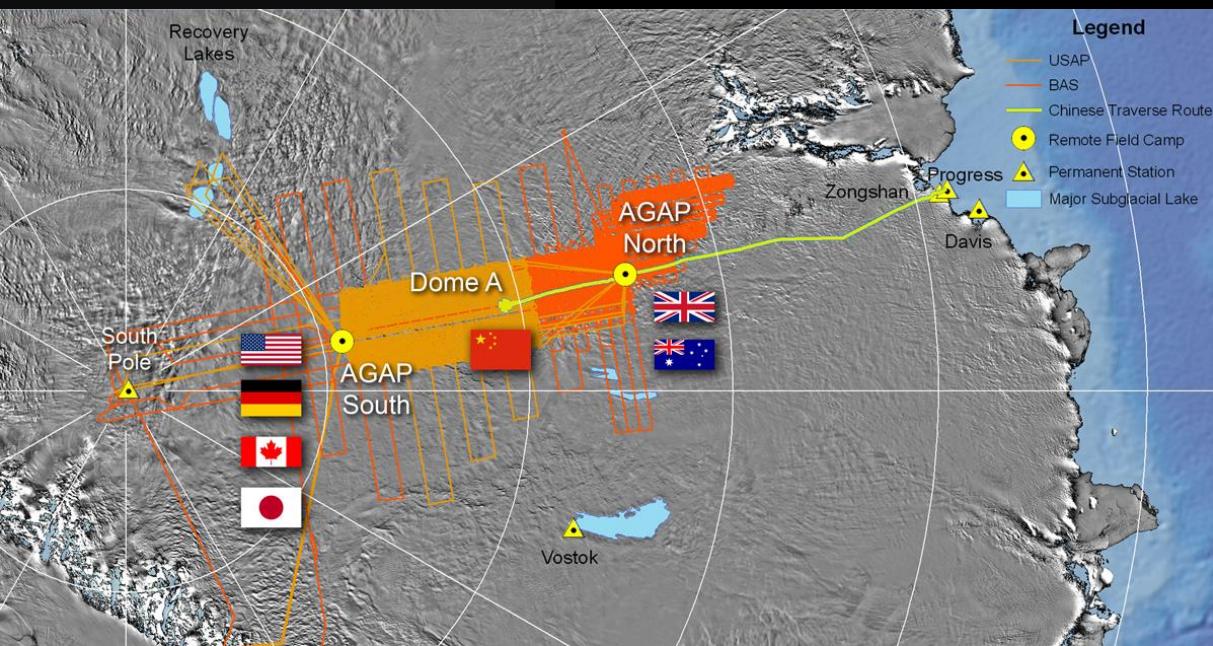
Surface Meltwater Refreezing in Ablation Zone



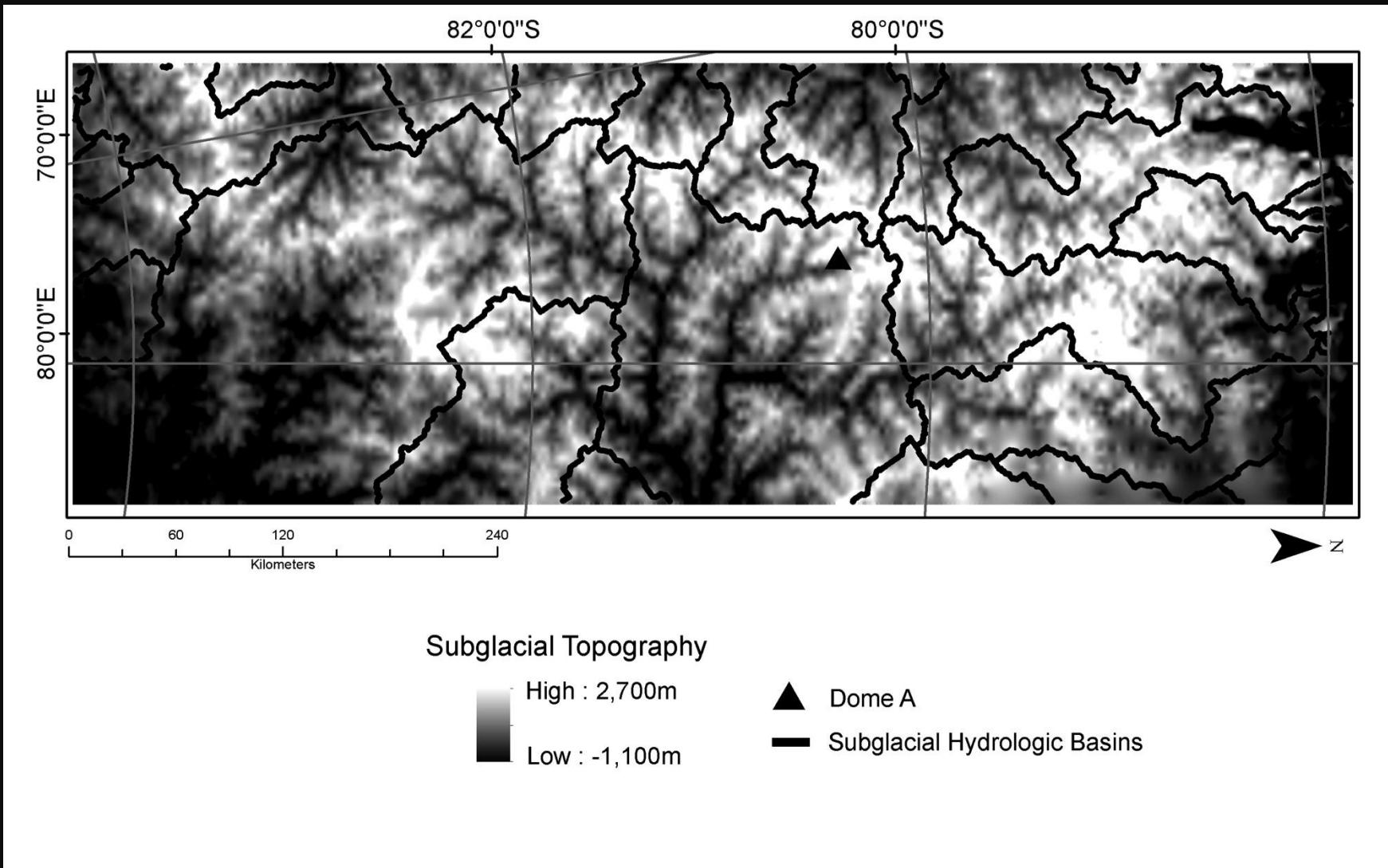
Lamont-Doherty Earth Observatory  
COLUMBIA UNIVERSITY | EARTH INSTITUTE

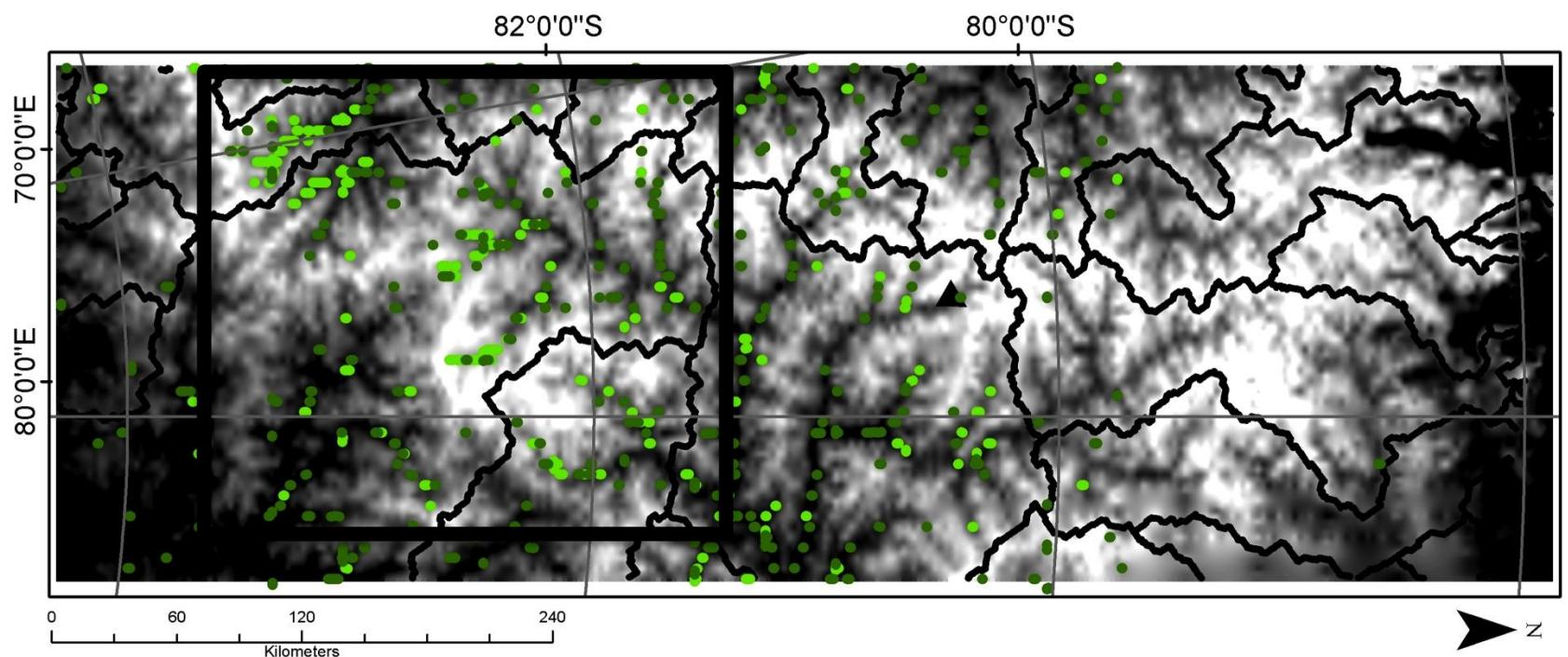


INTERNATIONAL 2007-2008  
**POLAR YEAR**



# Water in the Valleys



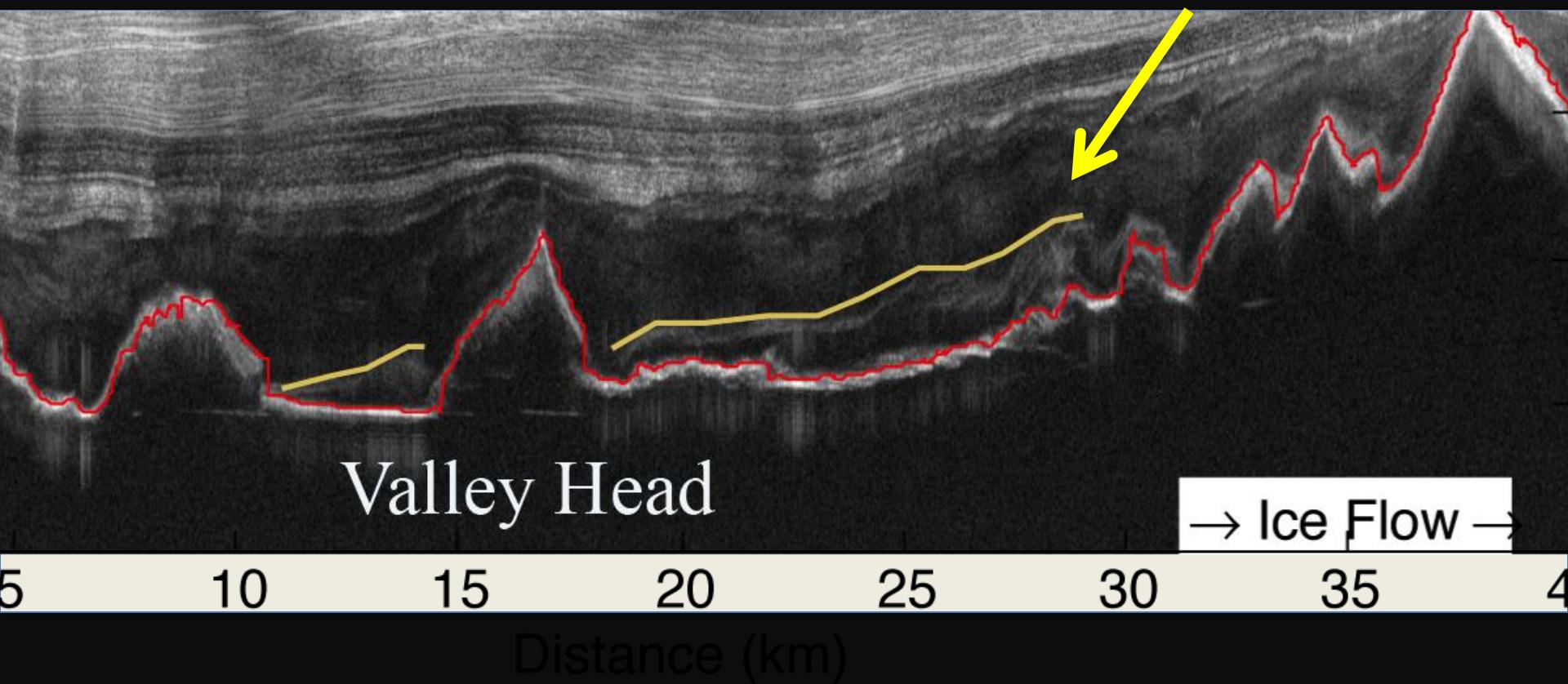


### Subglacial Topography

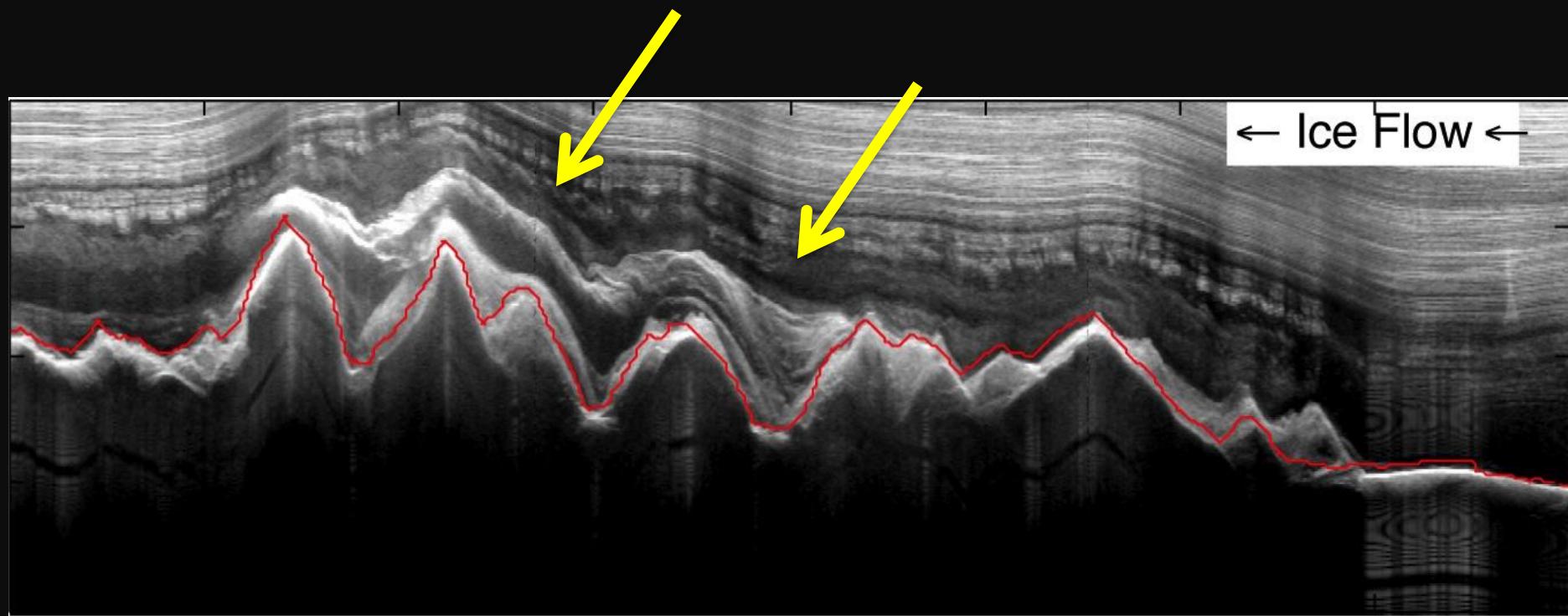
High : 2,700m  
Low : -1,100m

▲ Dome A  
— Subglacial Hydrologic Basins

# Reflectors Similar Vostok Emerging from Basal Water Networks



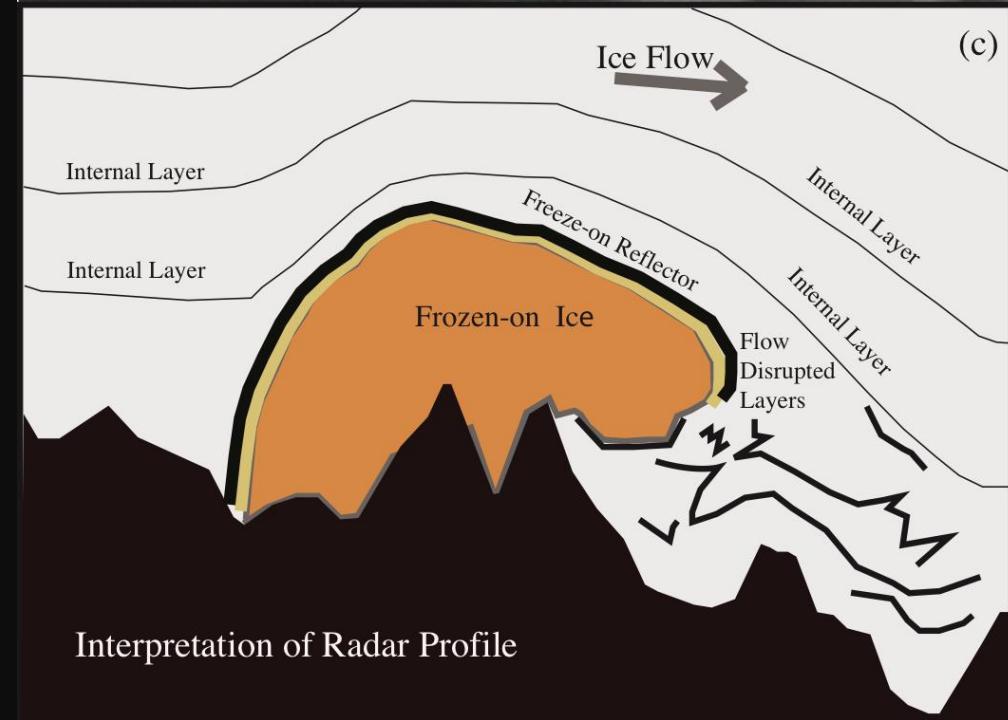
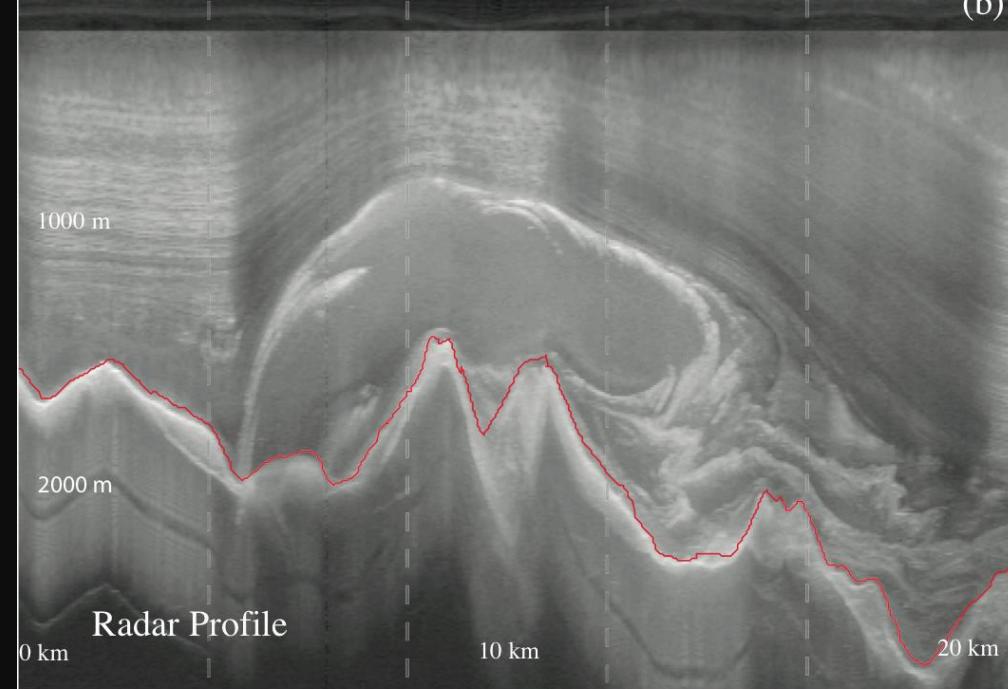
# On Both Sides of Dome A



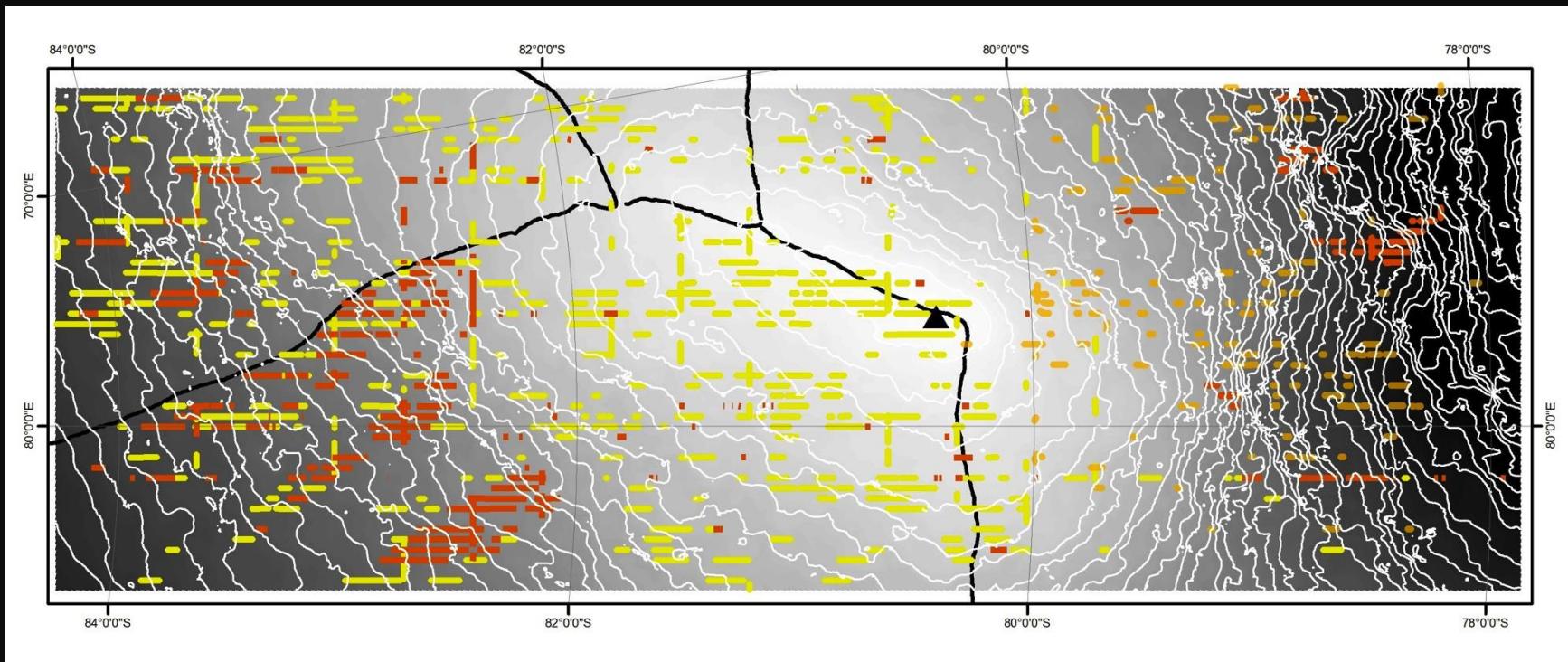
Up to 1000m  
Thick----50%  
of the Ice  
Sheet

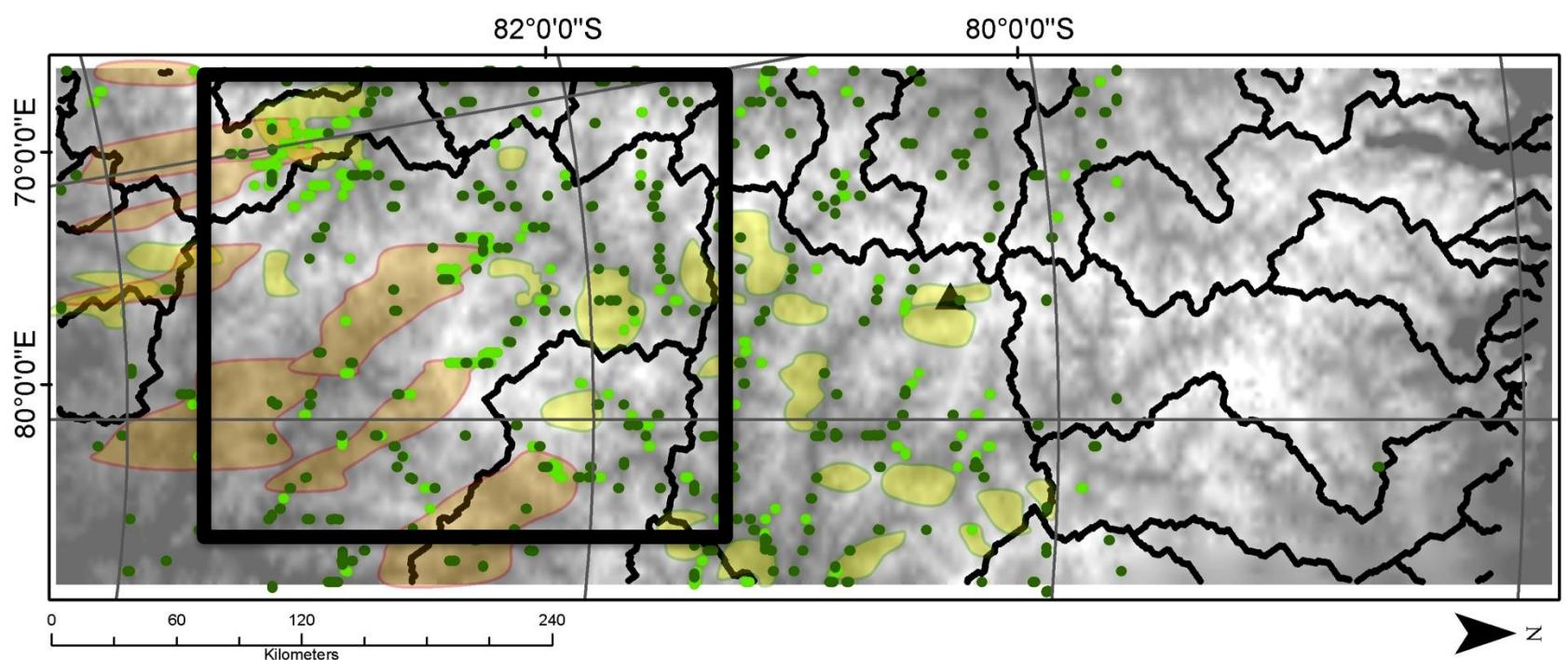
Also from  
Basal Water  
Network

Deformation  
in Front of  
over  
Freeze-on



# Orange - Distribution of Well Defined Bright Reflector Ice Surface Contours Coherent Features



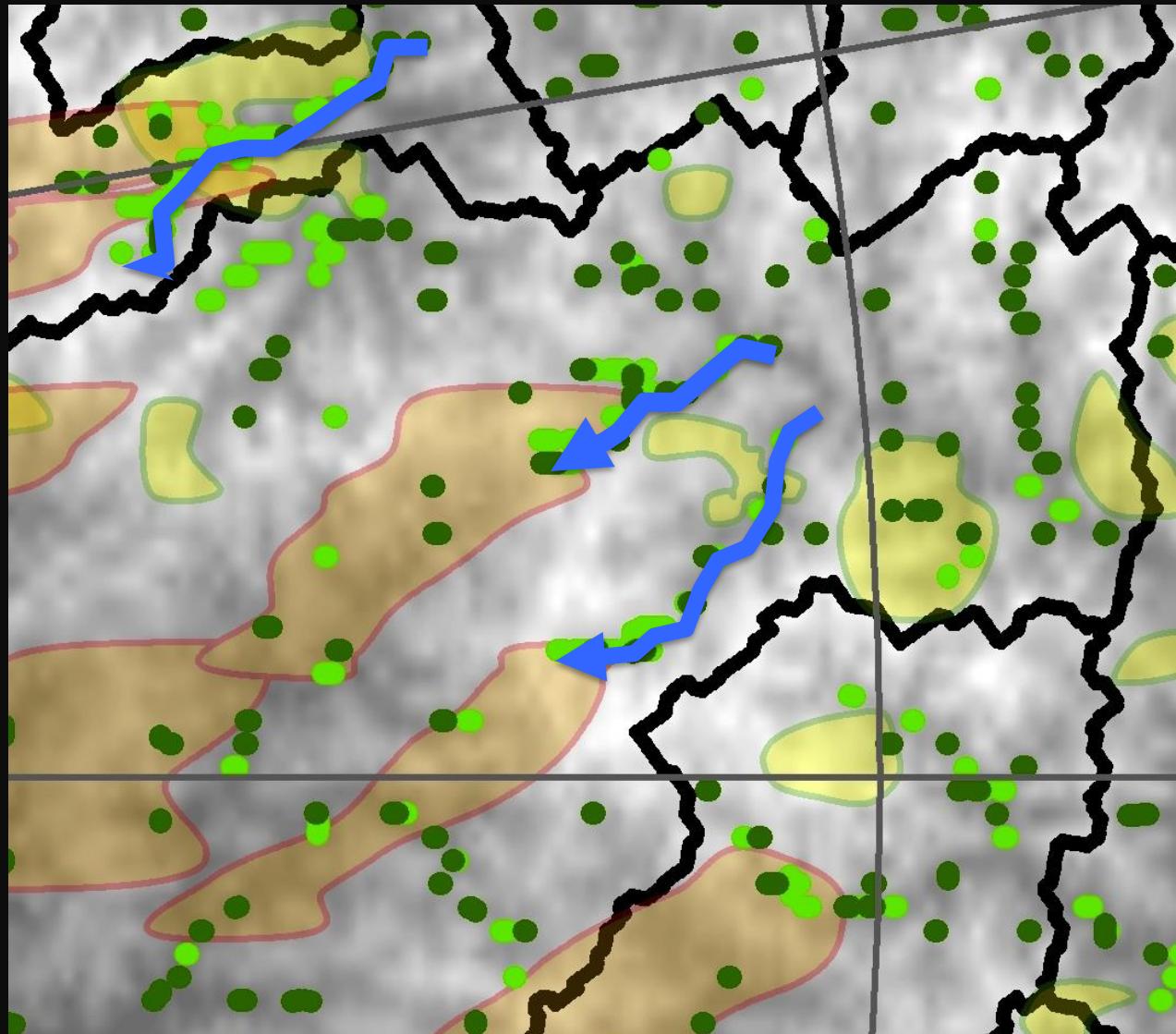


### Subglacial Topography

High : 2,700m  
Low : -1,100m

- ▲ Dome A
- Subglacial Hydrologic Basins
- Basal Brightness Reflectors (Unclear)
- Basal Brightness Reflectors (Clear)
- Frozen-on Ice Package: Valley Wall
- Frozen-on Ice Package: Valley Head

# Basal Ice At the End of the Water Networks Refreezing Occurs at Ridgelines



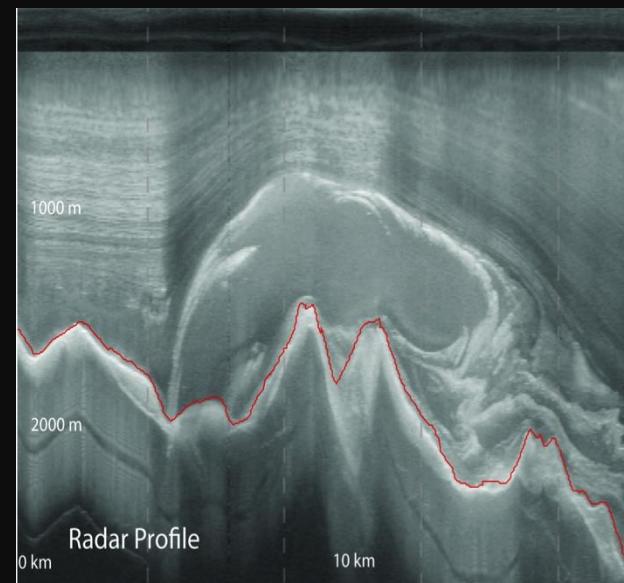
# What are Major Modes

Large Lake

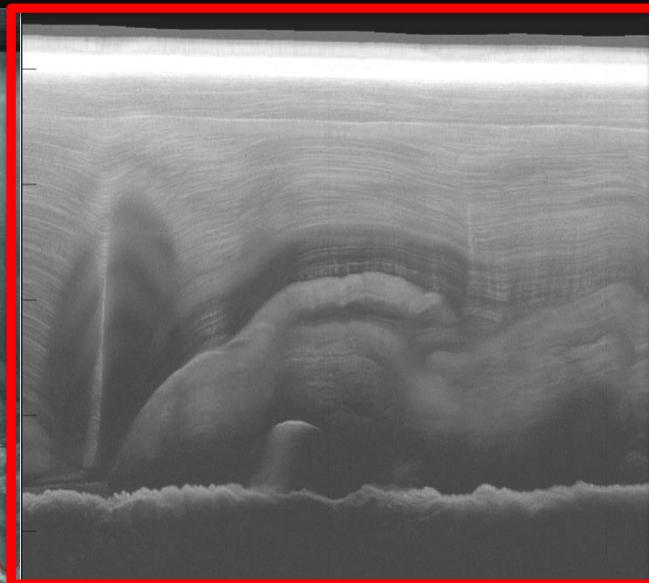
Refreezing From Well Defined Water Networks

**Refreezing and Deformation**

Surface Meltwater Refreezing in Ablation Zone

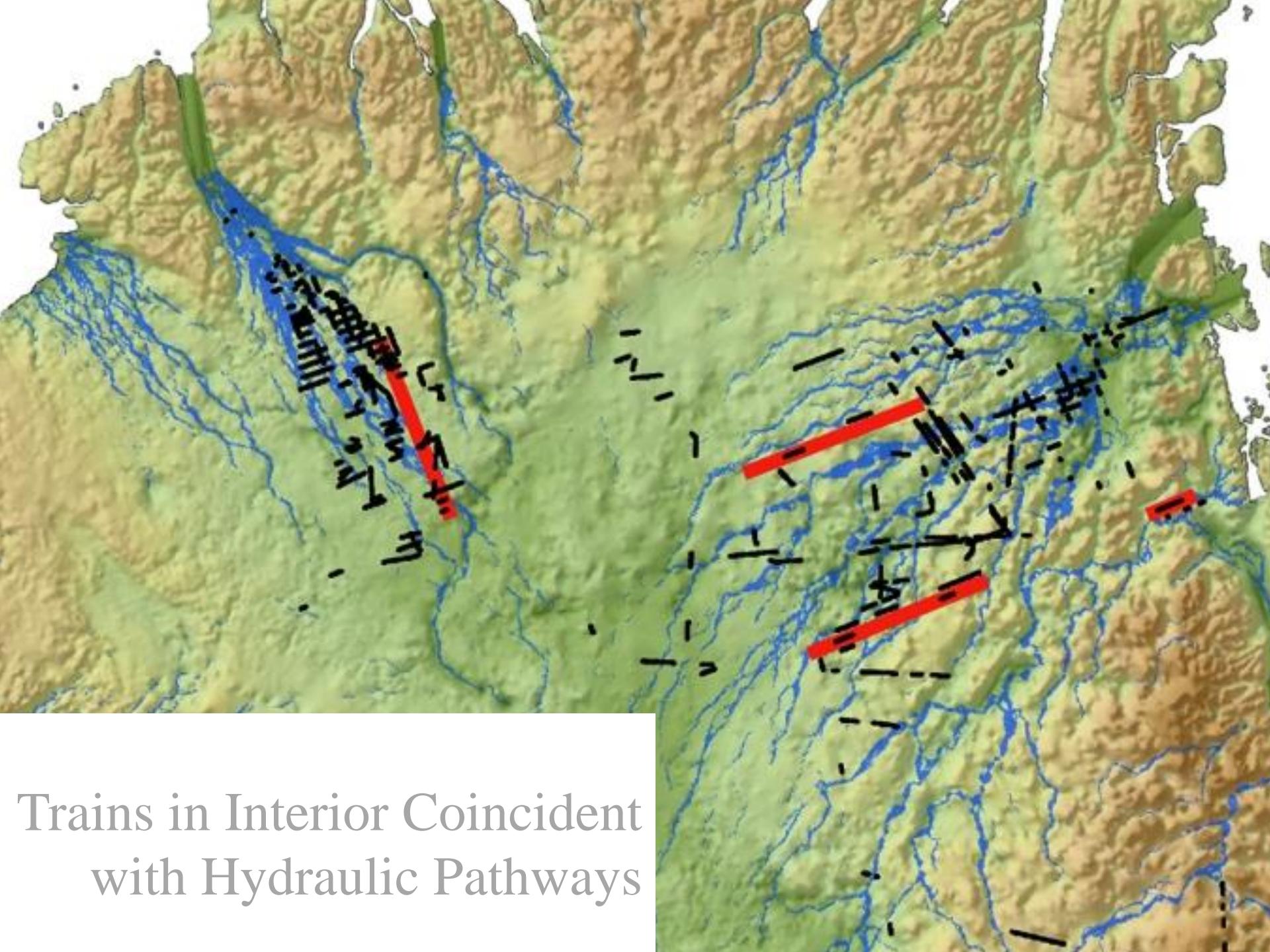


Antarctica  
Dome A



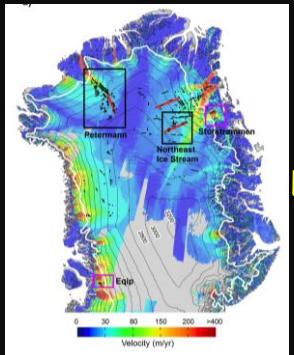
Greenland  
Petermann





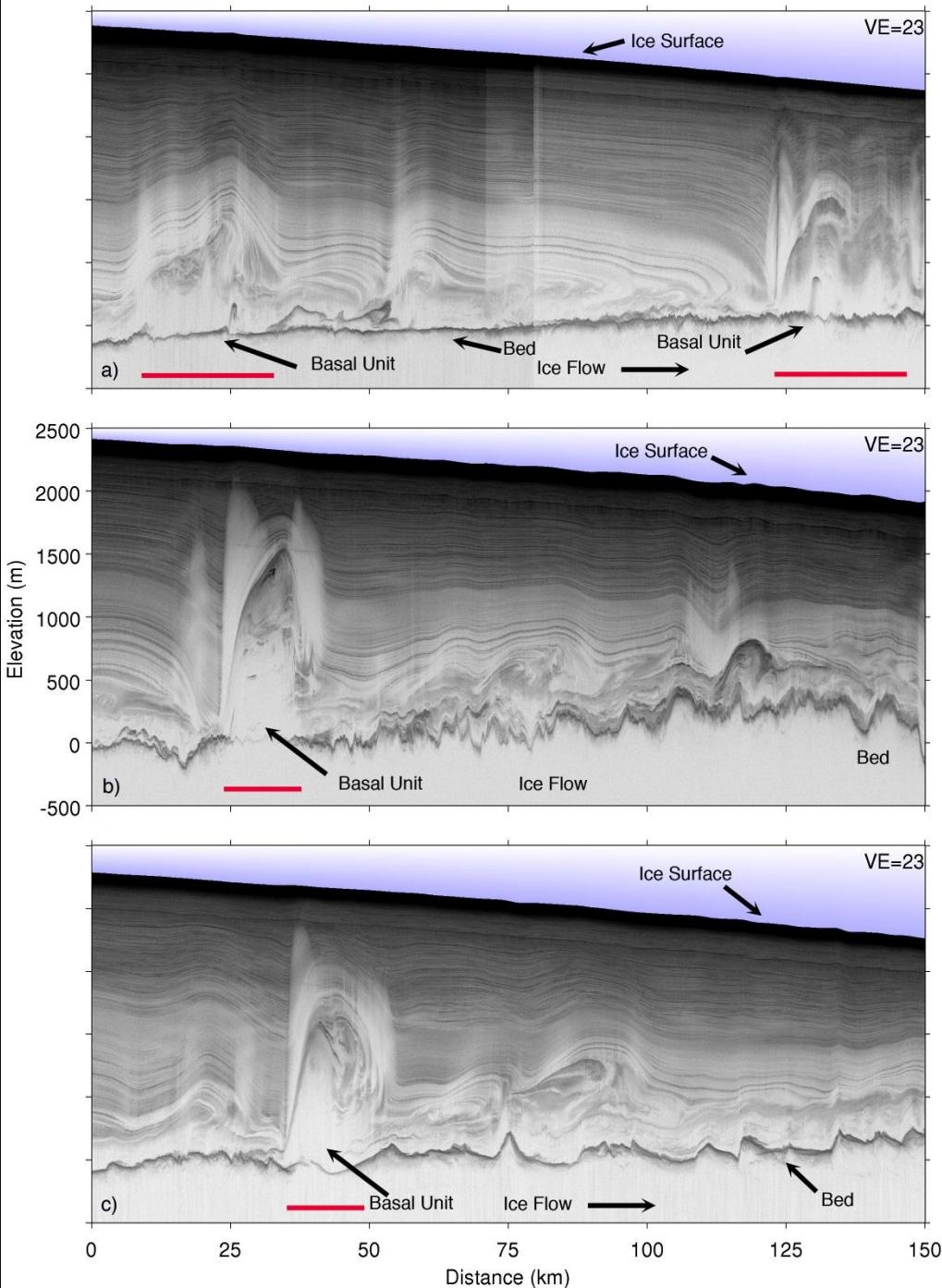
Trains in Interior Coincident  
with Hydraulic Pathways

# PETERMANN

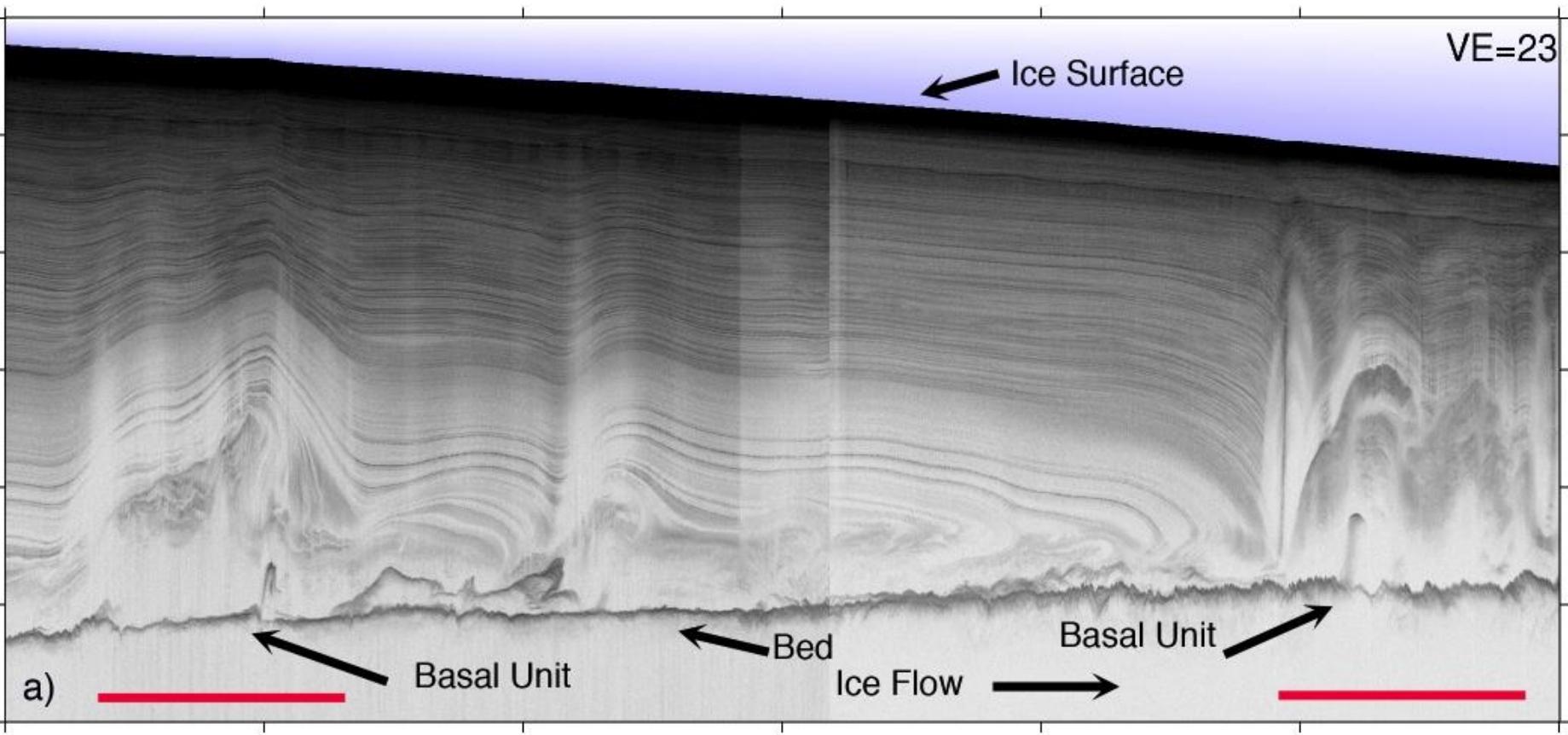


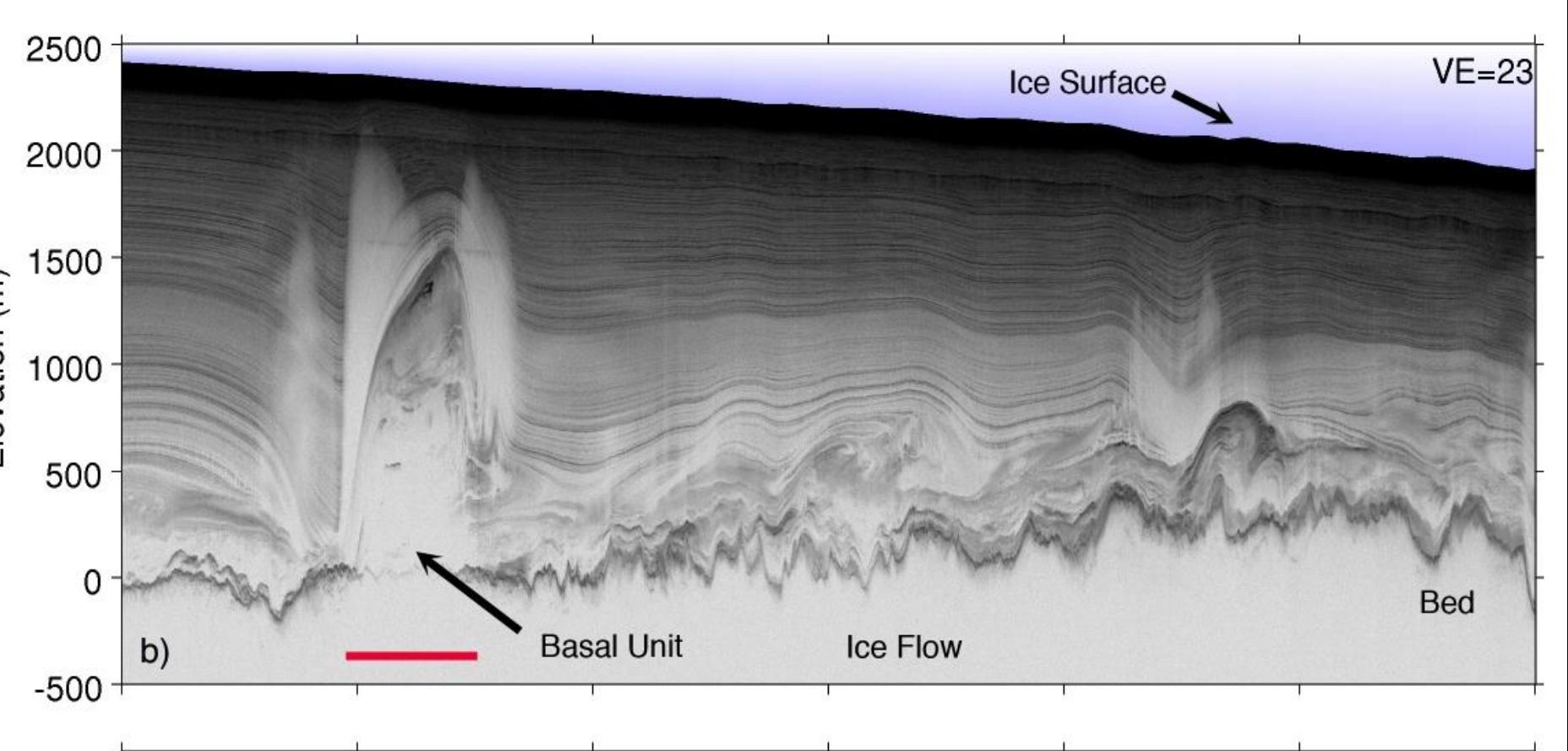
NORTHEAST ICE STREAM (NEGIS)

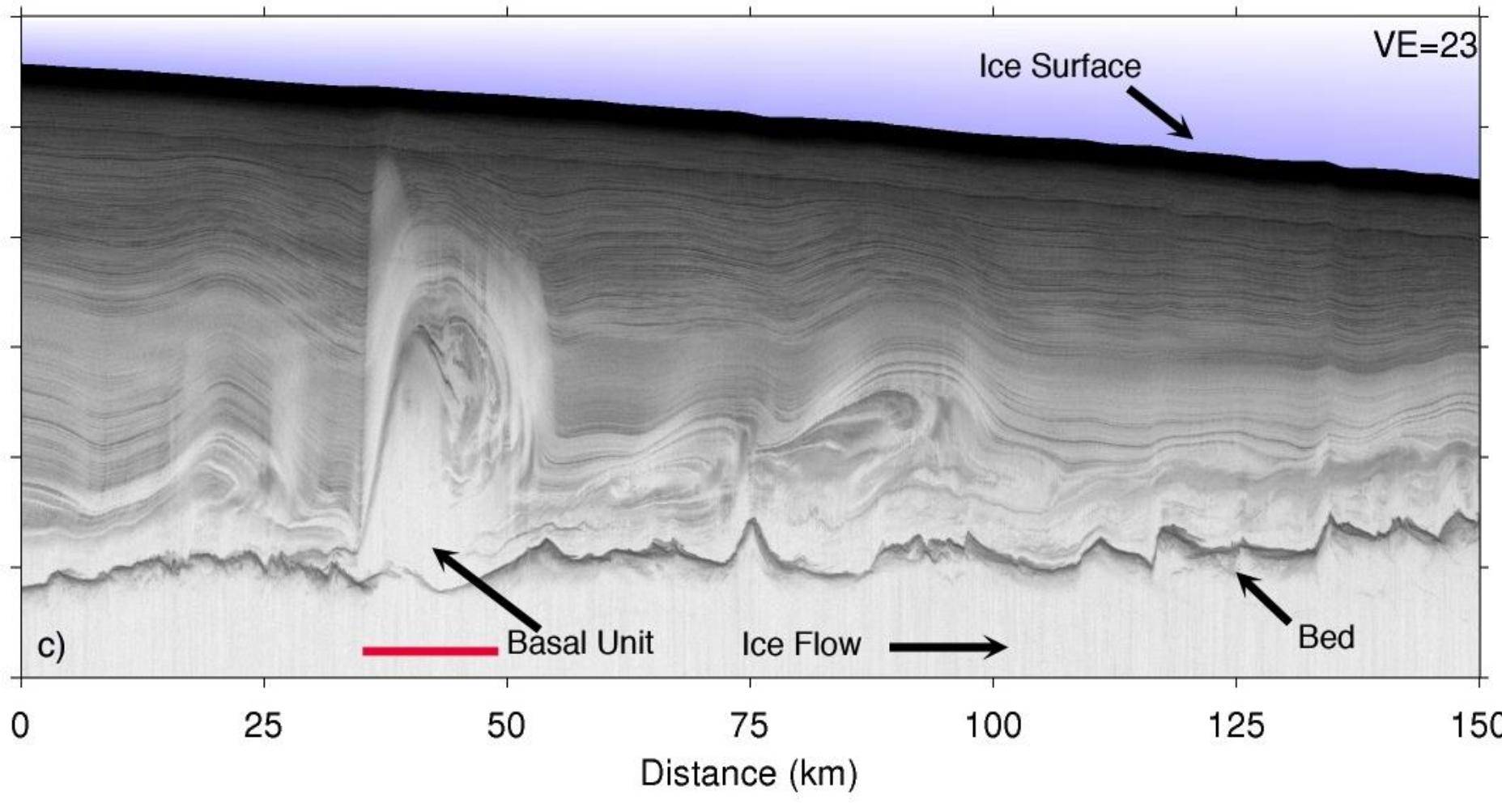
NORTHEAST ICE STREAM (NEGIS)



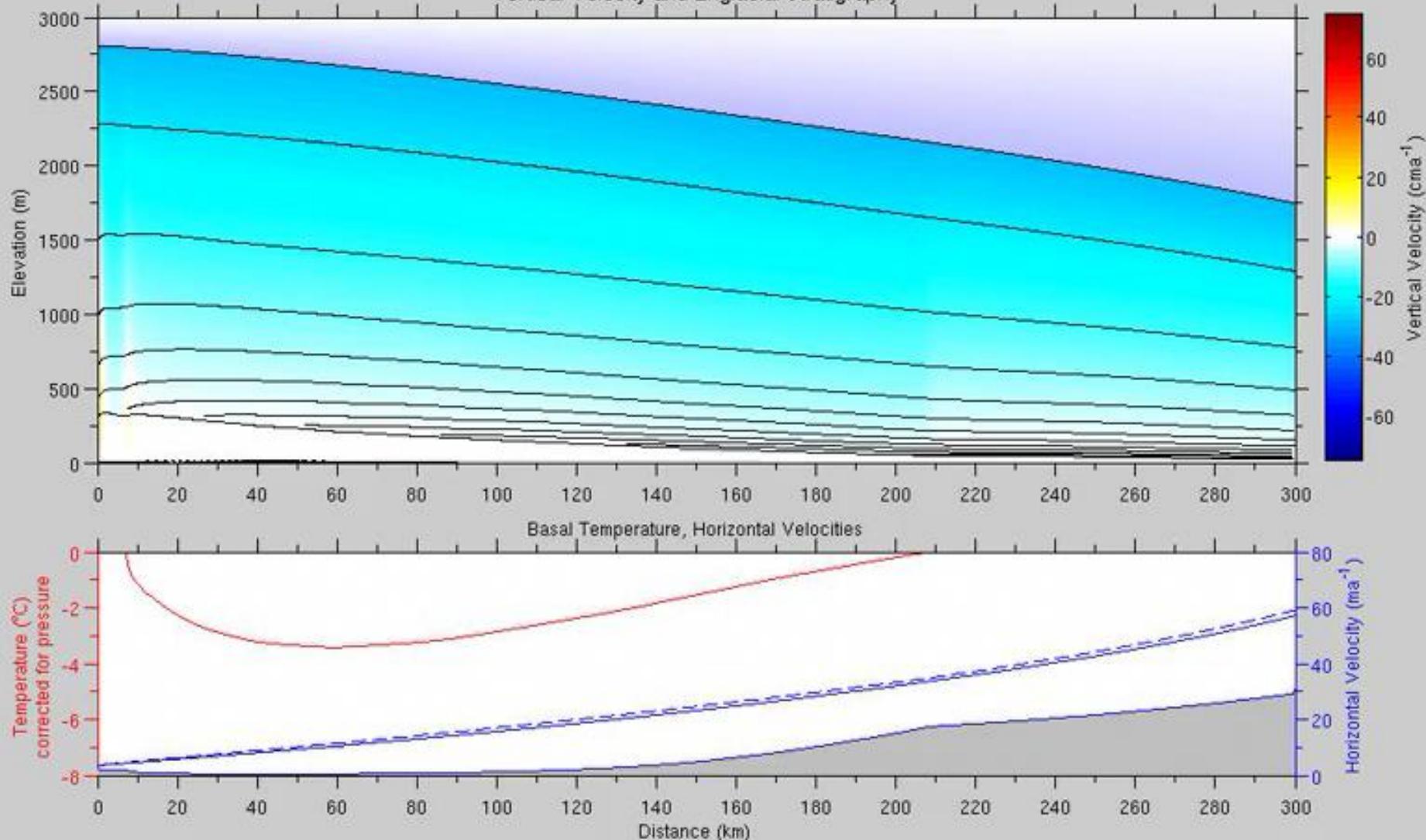
VE=23







Gaussian Water Forcing, time= -9990 yr  
Vertical Velocity and Englacial Stratigraphy



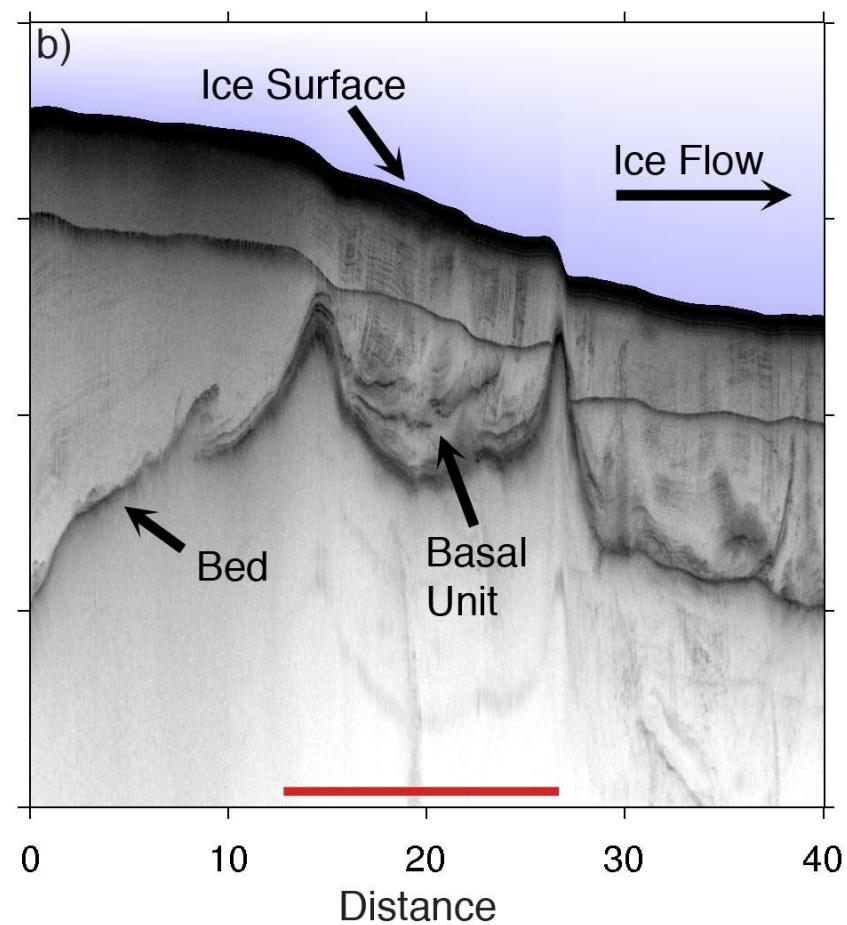
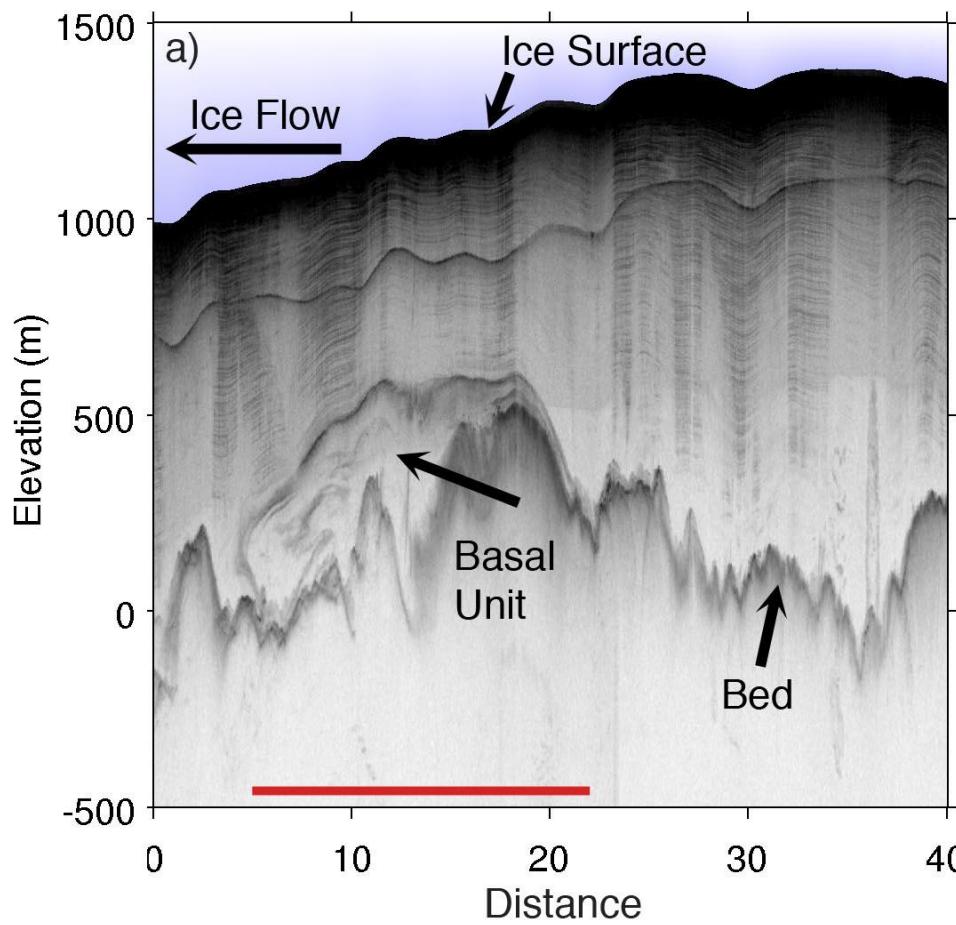
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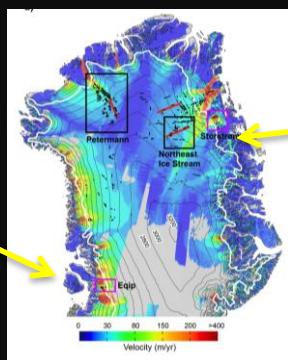
Refreezing From Well Defined Water Networks

Refreezing and Deformation

**Surface Meltwater Refreezing in Ablation Zone**

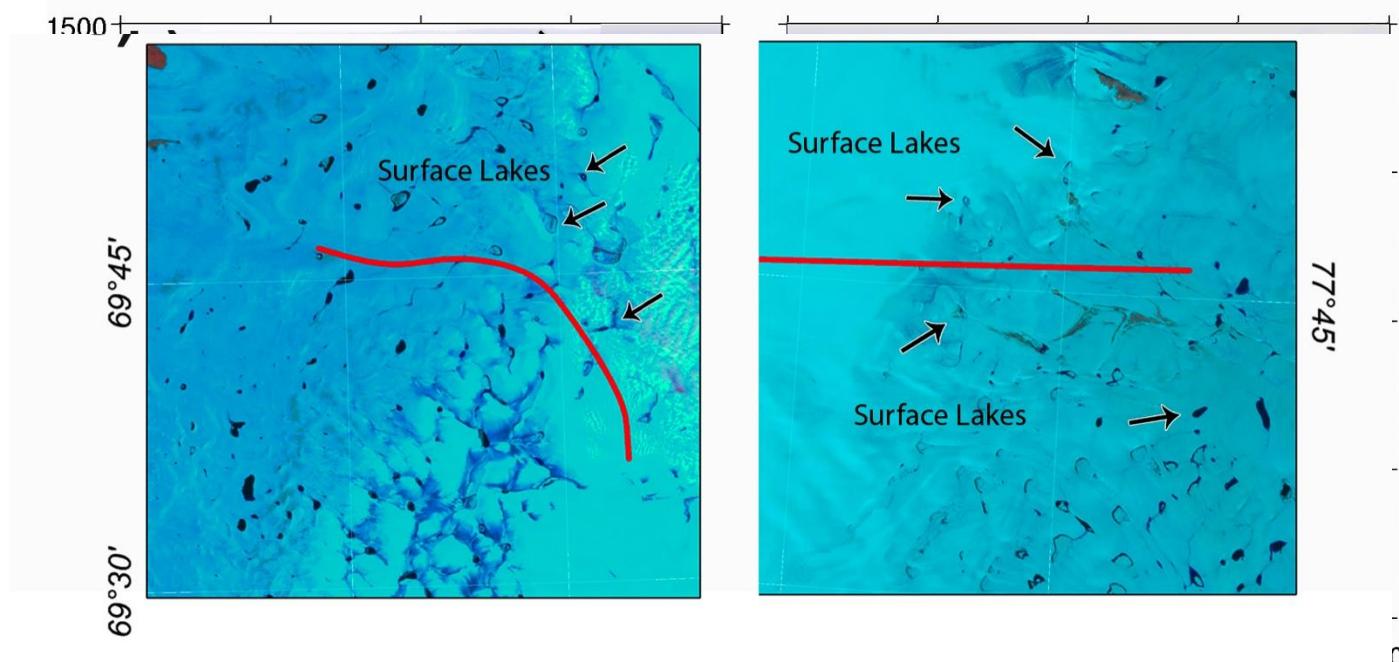
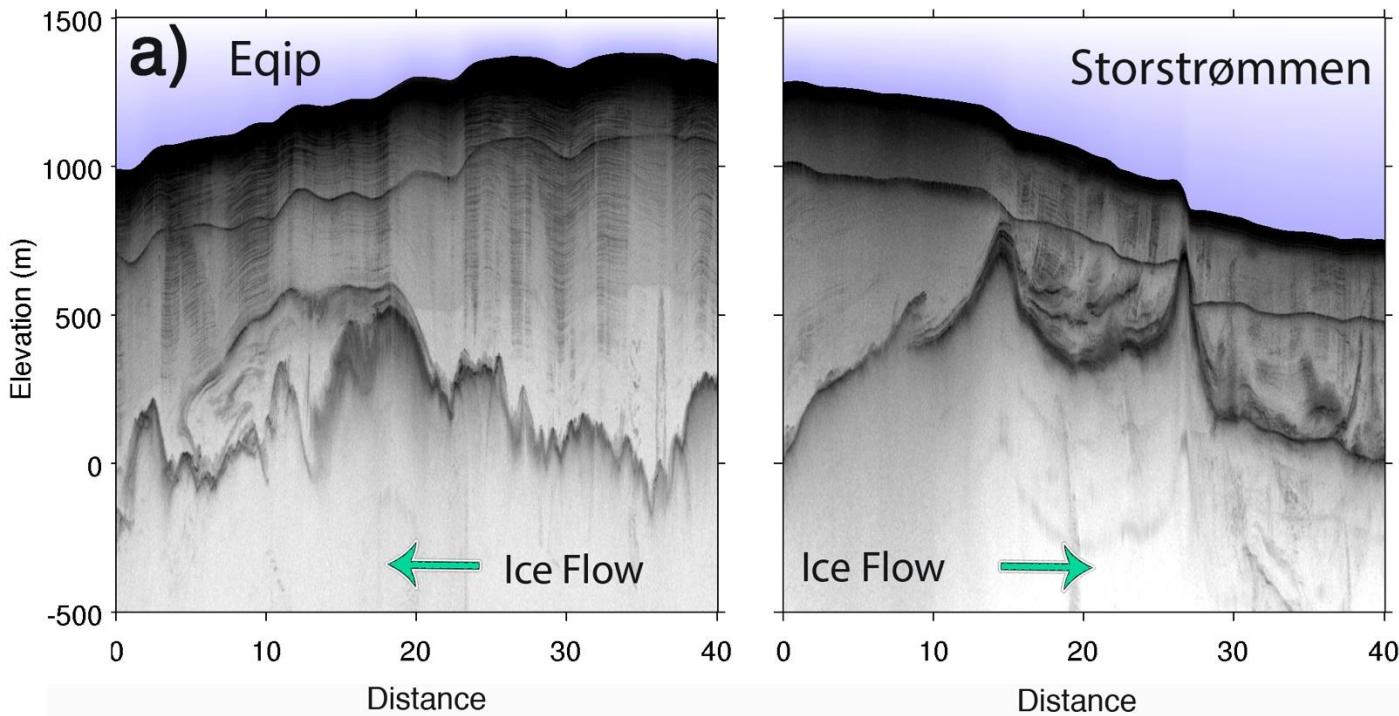


EQIP



STORSTOMMEN

Isolated  
Marginal  
Units Not  
Coincident  
With  
Hydraulic  
Pathways

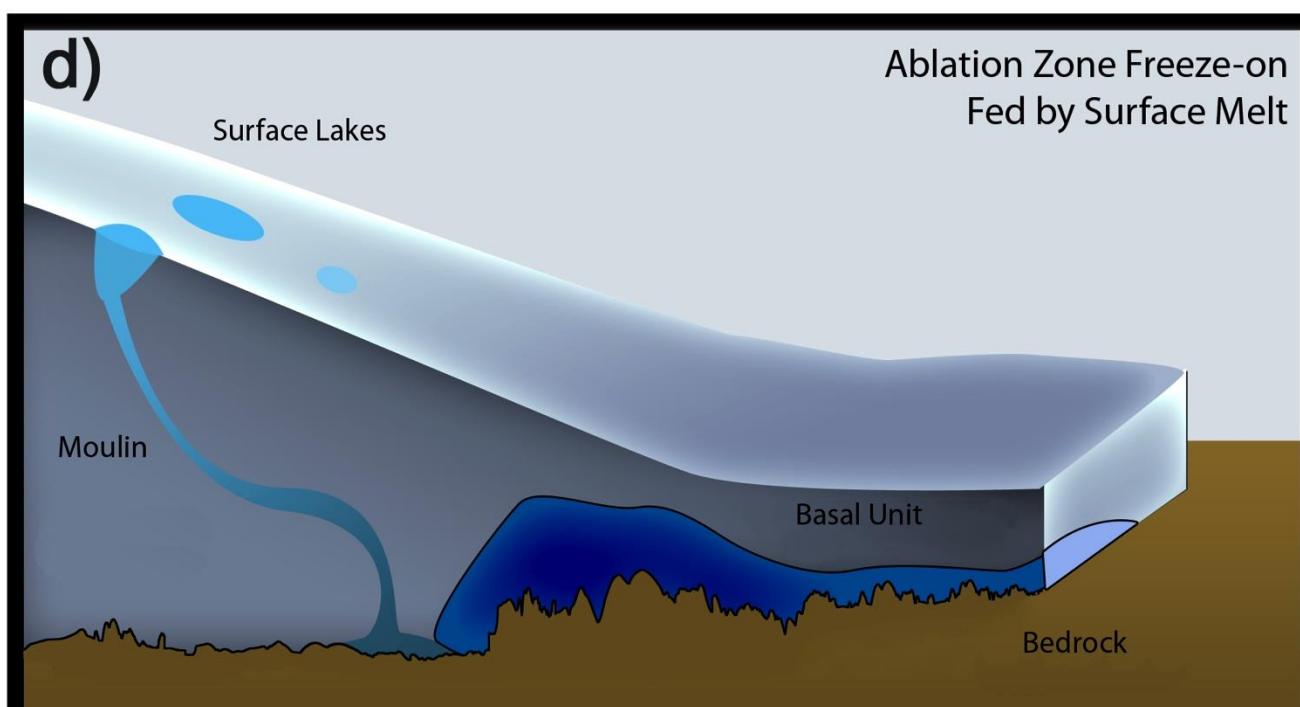
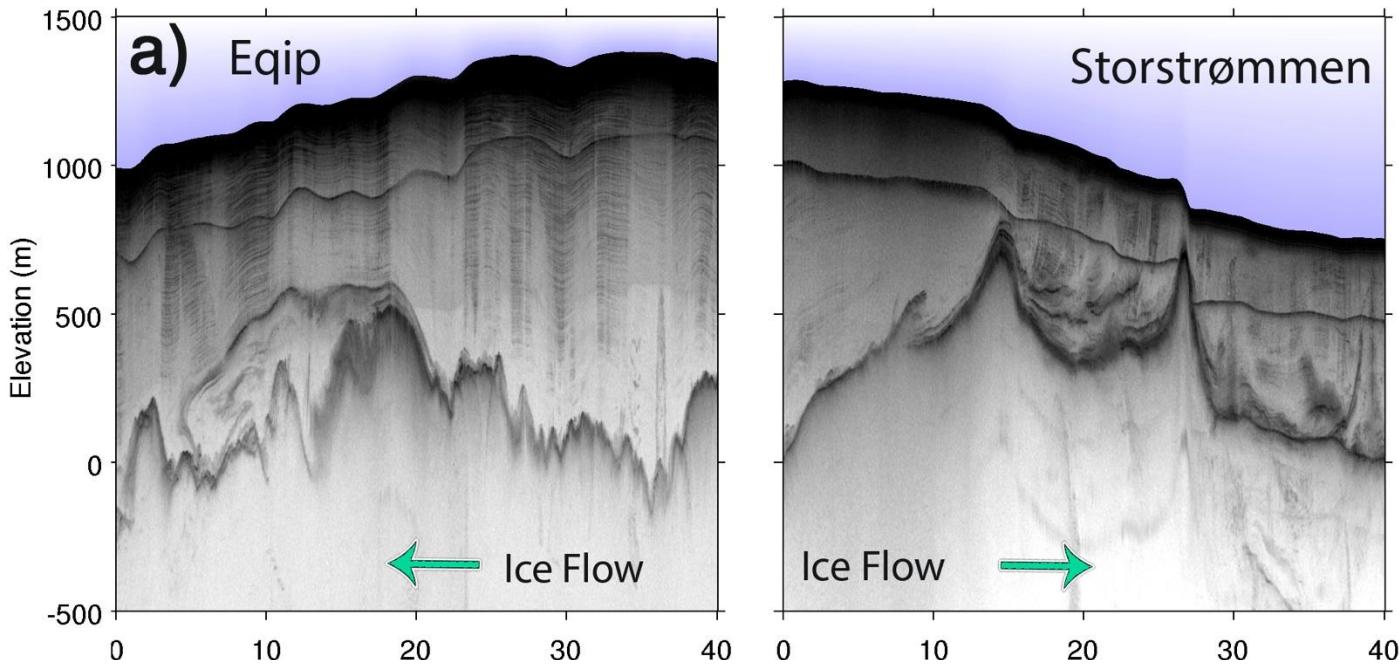


Beneath  
Surface  
Lakes and  
Crevasses

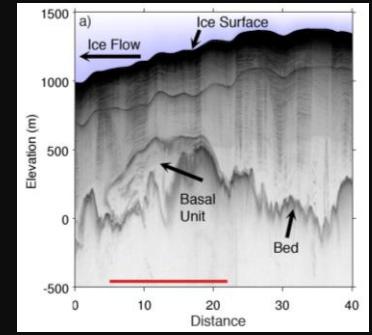
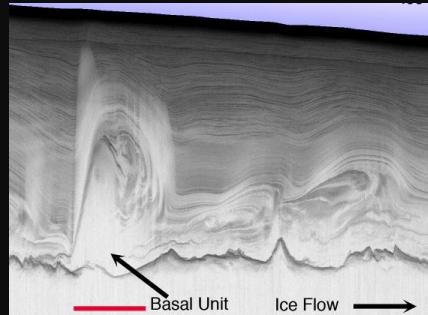
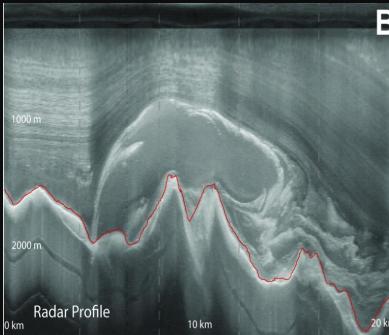
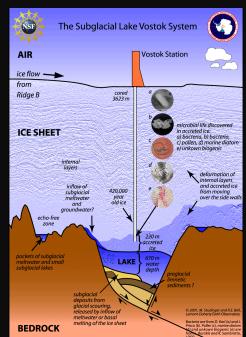
# SURFACE MELTWATER AS WATER SOURCE

Isolated  
Ablation Zone  
Units Not  
Coincident  
With  
Hydraulic  
Pathways

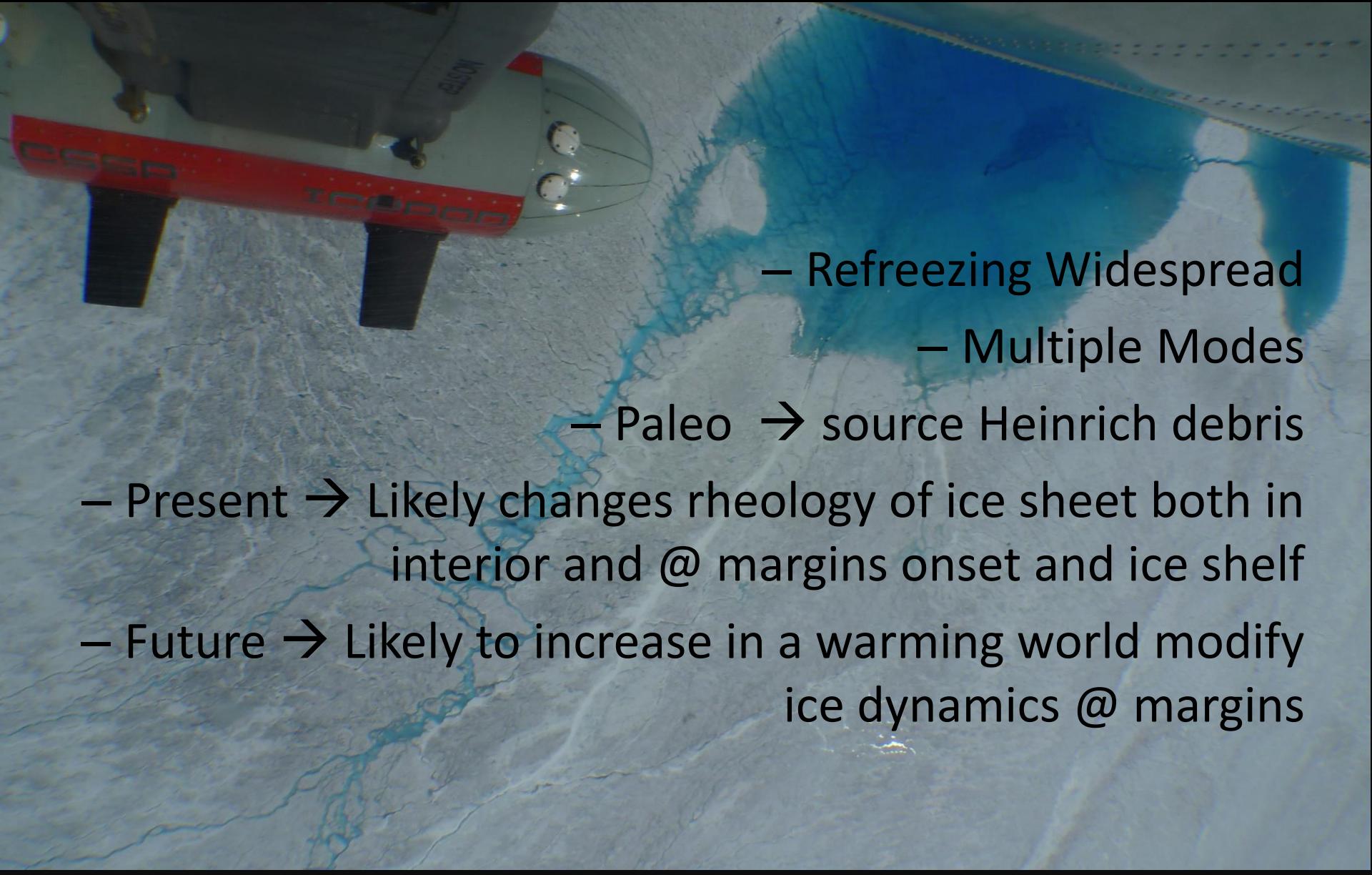
Beneath  
Surface Lakes  
and Crevasses



- Mechanisms
  - Refreezing both supercooling and conductive cooling
  - Often associated or even dominated deformation



# Implications & Conclusions

- 
- Refreezing Widespread
  - Multiple Modes
  - Paleo → source Heinrich debris
  - Present → Likely changes rheology of ice sheet both in interior and @ margins onset and ice shelf
  - Future → Likely to increase in a warming world modify ice dynamics @ margins





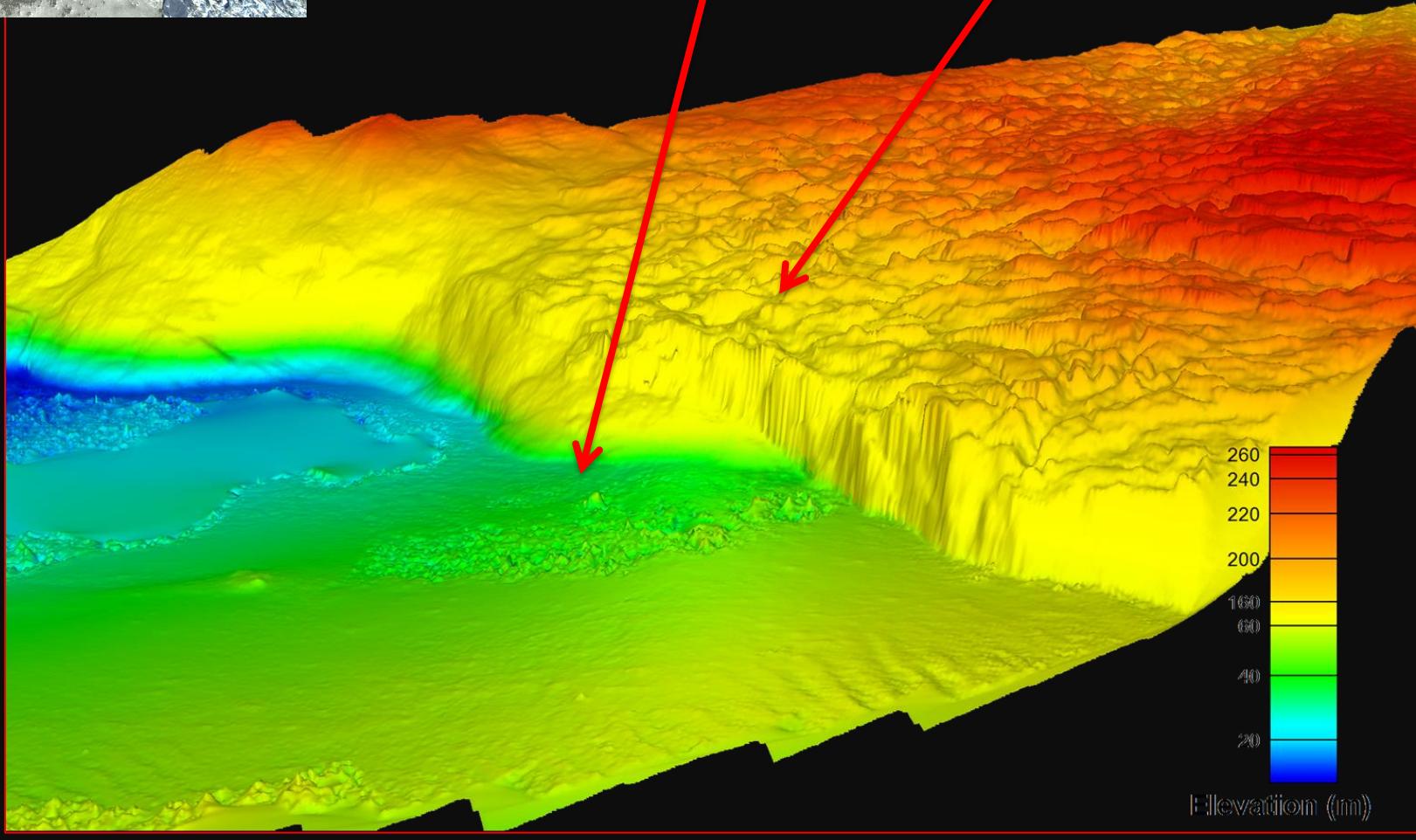
IcePod



Digital Elevation Model  
From Images

Eqip  
Calving Front

Meltwater Plume

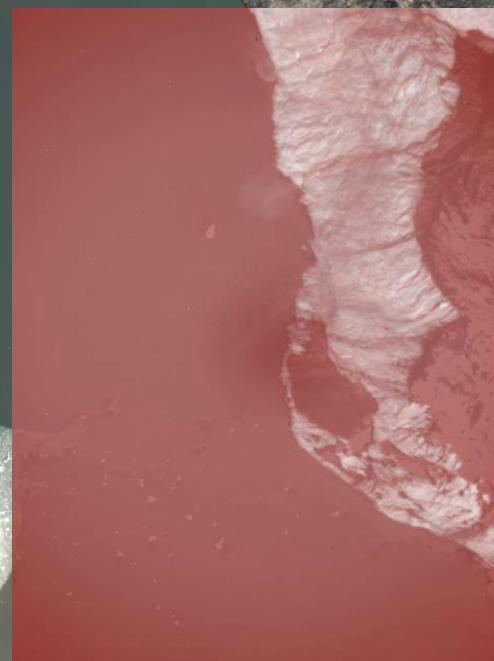


Elevation (m)

Scale – 1 km Vertical 20 cm pixel

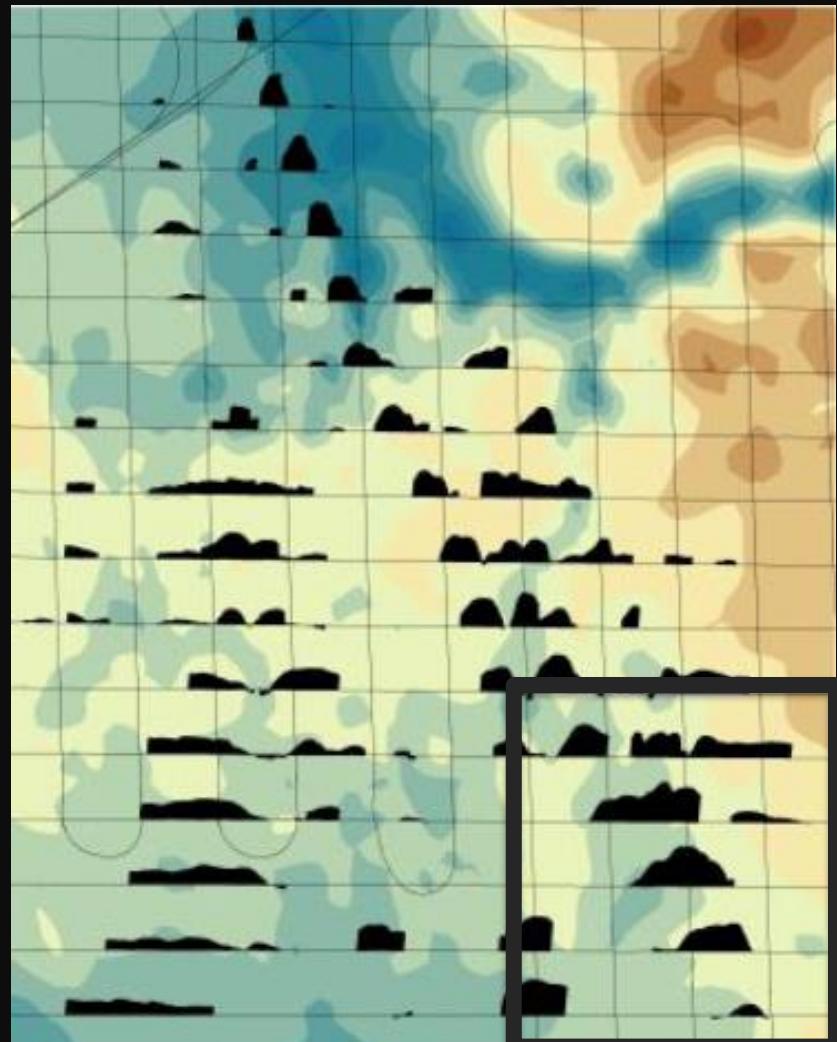
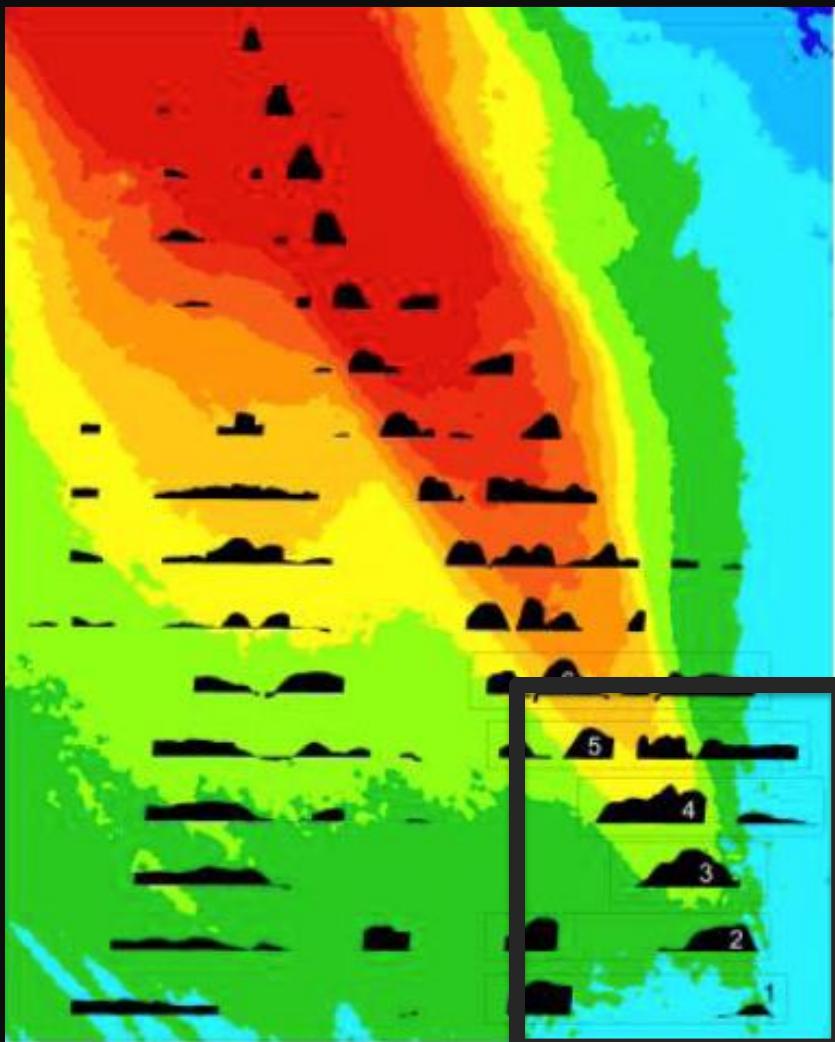
Calving Front

Meltwater Plume



# Associated with Onset of Fast Flow

## Velocity Bed Topography



0 —

-500 —

Relative Elevation, m

-1000 —

-1500 —

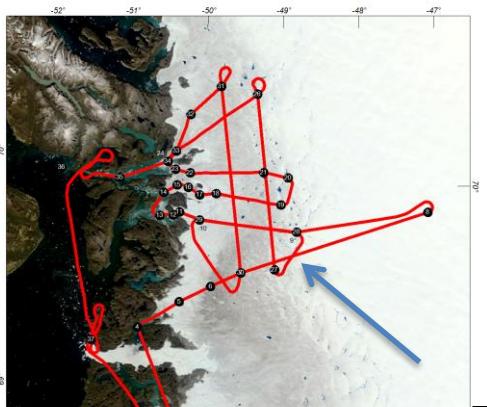
-2000 —

**Ice Surface**

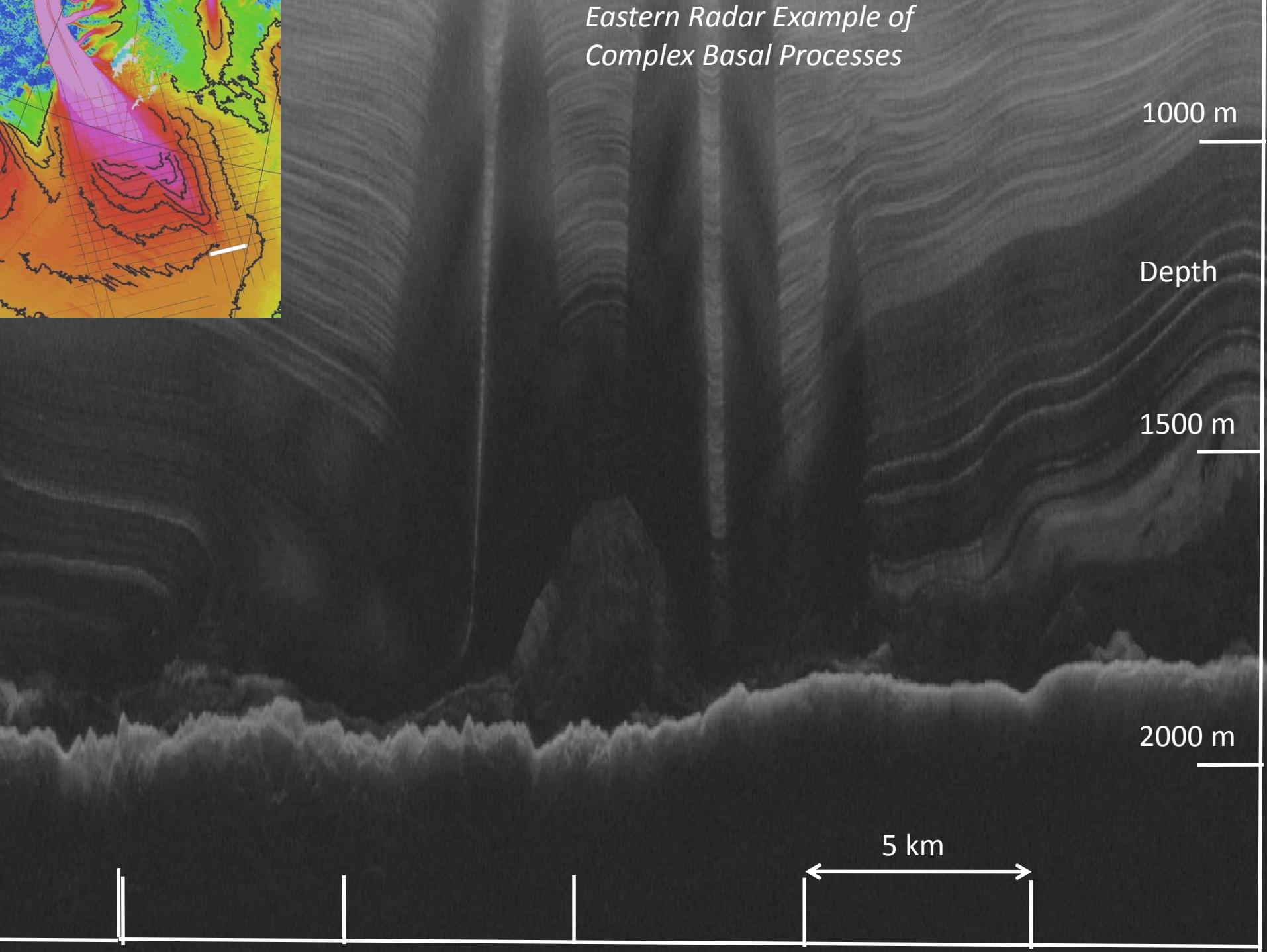
**Surface Multiple**

**Accreted Ice Structure**

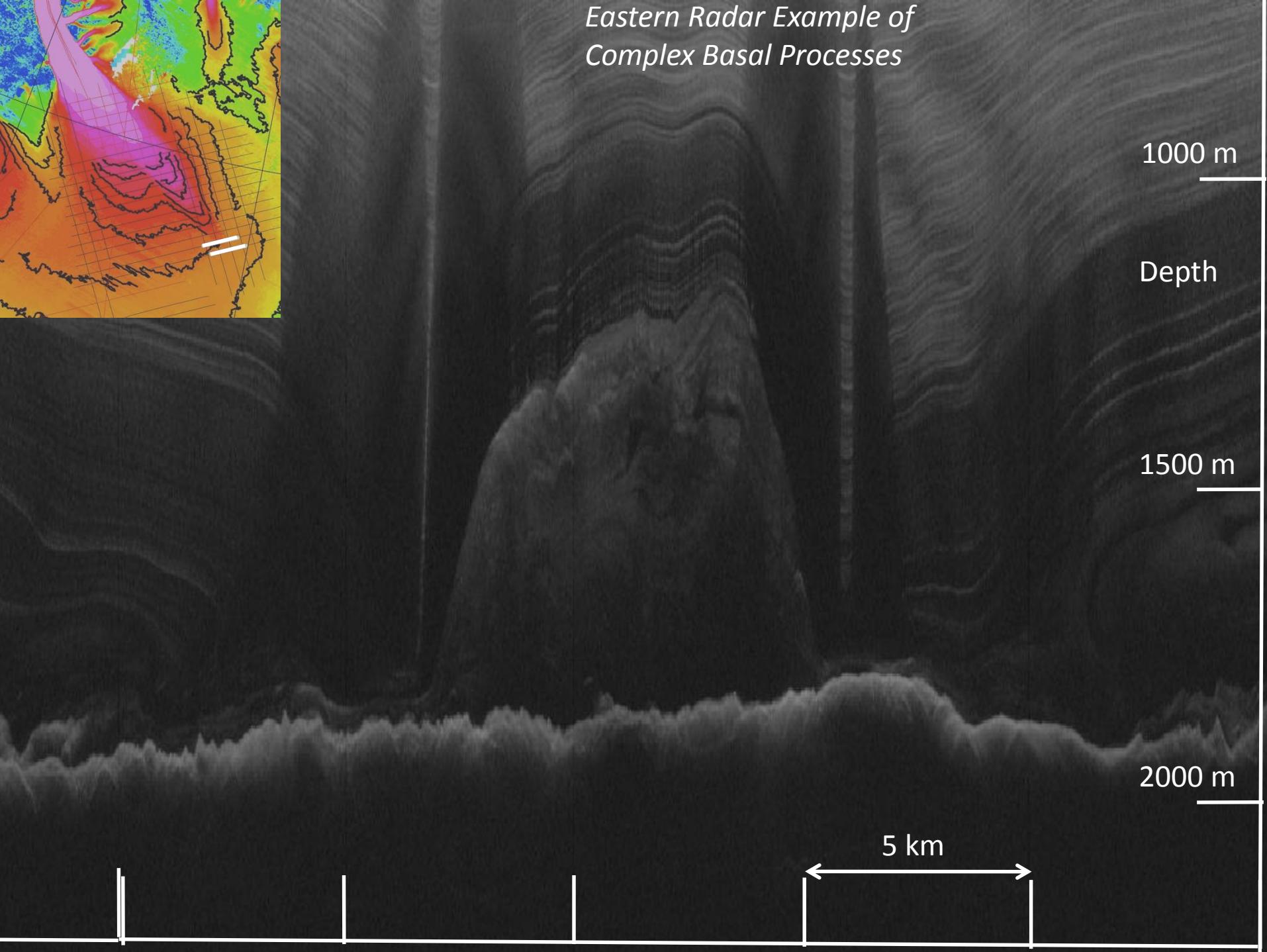
**Ice Sheet Bed**



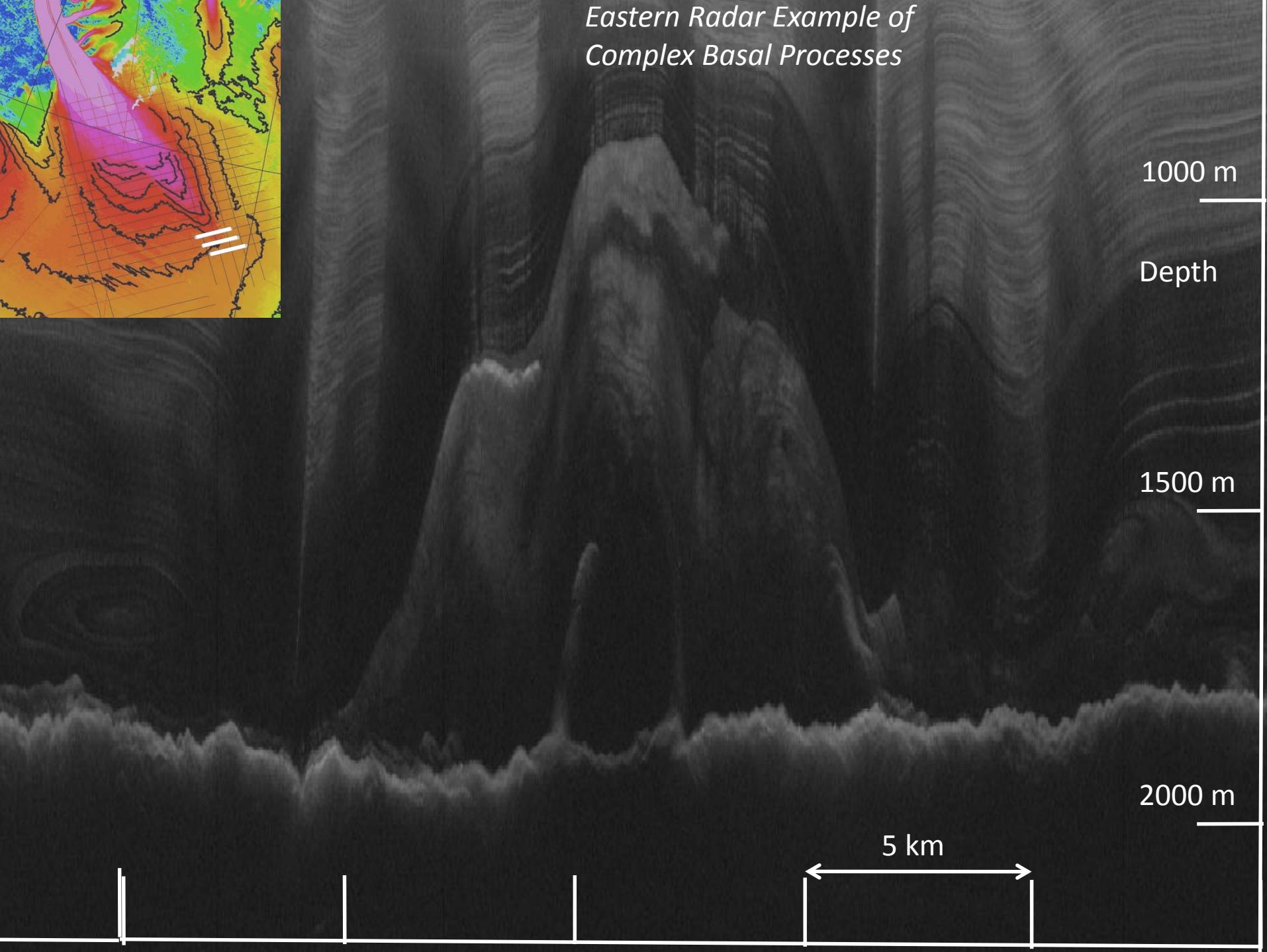
*Eastern Radar Example of  
Complex Basal Processes*



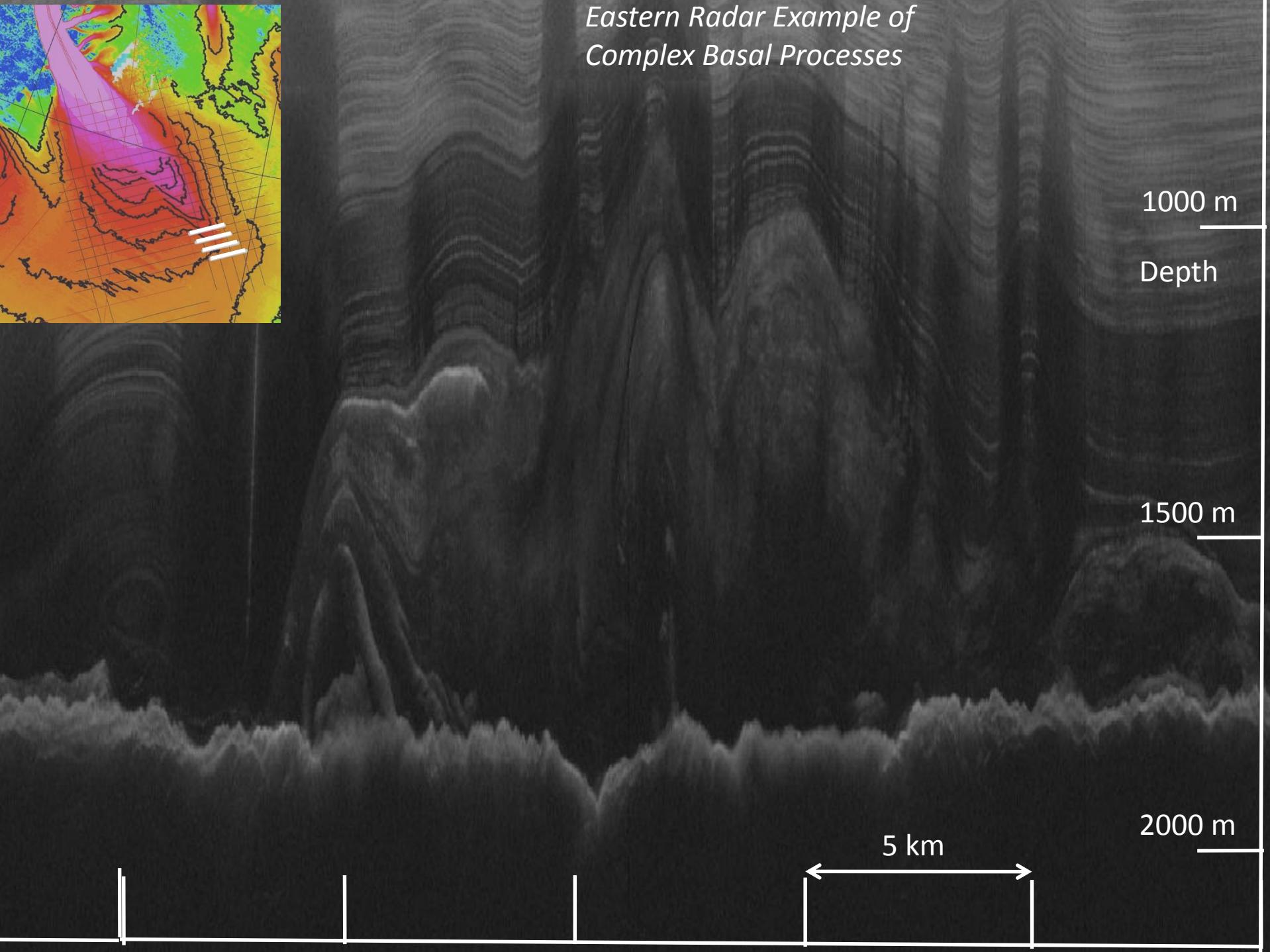
*Eastern Radar Example of  
Complex Basal Processes*



*Eastern Radar Example of  
Complex Basal Processes*



*Eastern Radar Example of  
Complex Basal Processes*



# Overview

- Refreezing -Overview–
  - Why does it matter
    - Changes stratigraphy thermal structure and rheology of ice sheet
    - If more water in a warming world --. More refreezing key process
  - What water can refreeze??
    - Any water at the ice sheet base → Lakes, sub glacial water networks “rivers”
  - Where Does the subglacial Water Come From?
    - Basal Melt, Surface Melt, Subglacial Aquifers
- What Does Refrozen Ice Look like?
  - Vostok - Gem Ice
  - Pakitsoq (Greenland) - Black Ice
- Vostok – Slow Freeze-on as ice sheet passes over lake
- Gamburtsev Mountains – Valley Water Networks Feeds Ridgeline Refreezing
- Interior of Greenland – Refreezing and Deformation in flat interior
- Margin of Greenland – Surface Water Feeds Refreezing Along Steep Topography
- Mechanisms
  - Refreezing both supercooling and conductive cooling
  - Often associate or even dominated deformation
- Implication & Conclusions
  - Widespread
  - Paleo Implications → source Heinrich debris
  - Present implications → Likely change rheology of ice sheet both in interior and @ margins Onset and Ice Shelf
  - Future Implications → Likely to increase in a warming world modify ice dynamics @ margins