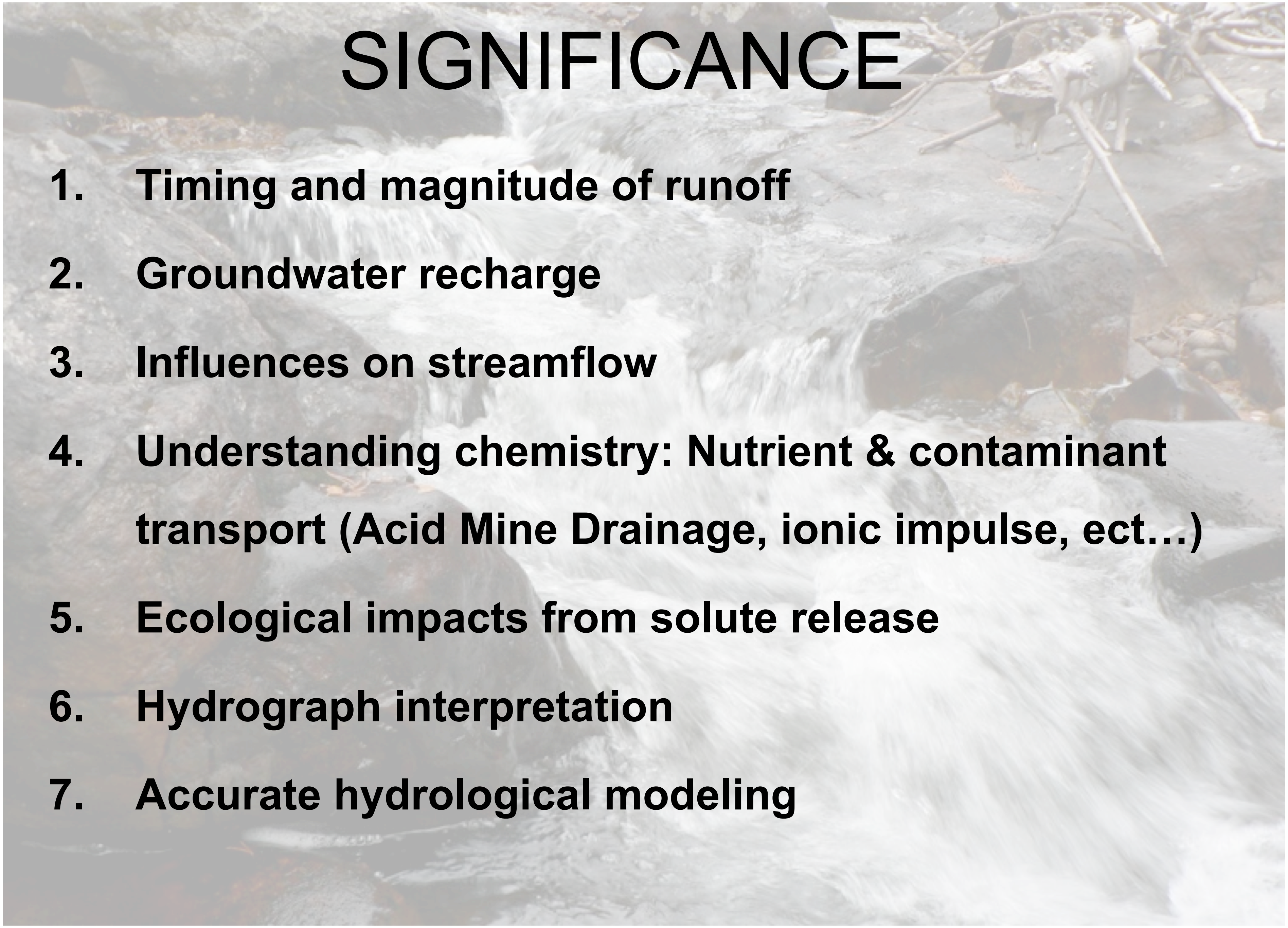
Theories and Methods for Meltwater Flow through a Snowpack

By: Jennifer Petrzelka

OUTLINE

- Background
- Theories
- Methods
- Studies
- Snow guillotine!



SIGNIFICANCE

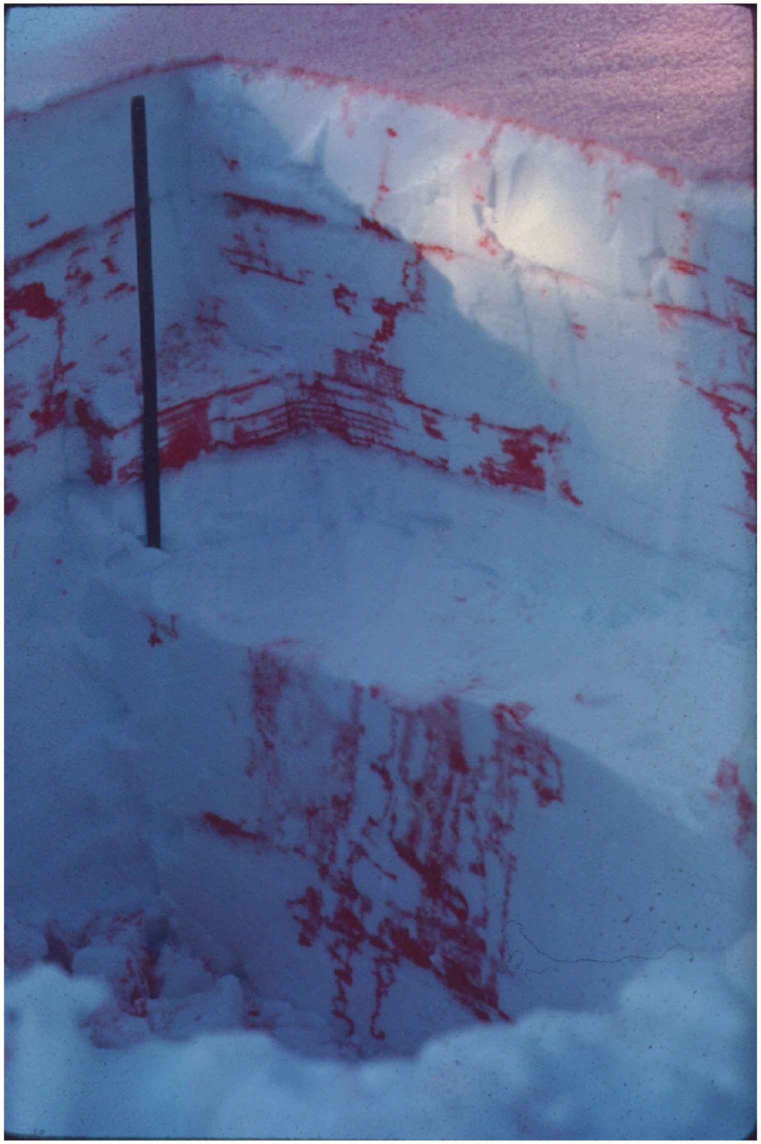
1. **Timing and magnitude of runoff**
2. **Groundwater recharge**
3. **Influences on streamflow**
4. **Understanding chemistry: Nutrient & contaminant transport (Acid Mine Drainage, ionic impulse, ect…)**
5. **Ecological impacts from solute release**
6. **Hydrograph interpretation**
7. **Accurate hydrological modeling**

Background

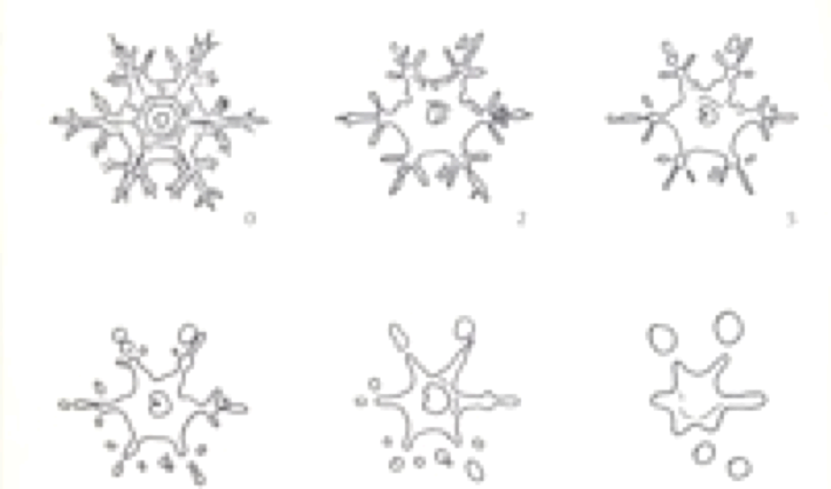
Least understood process in snow hydrology

Depends on:

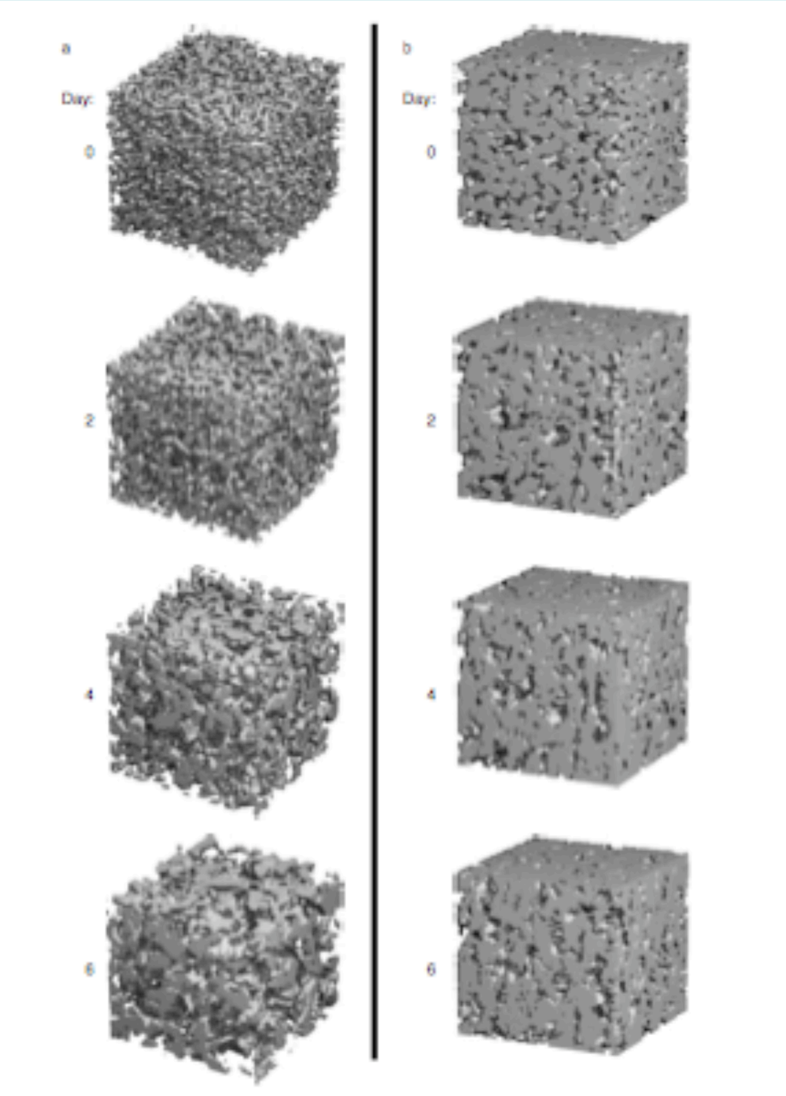
- snowpack structure (heterogeneous)
- condition of snowpack before liquid water is introduced
- amount of water available at the snow surface



Snow Metamorphism



LDS HDS



Microscale variations affect:

- density
- ice grain structure (porosity)
- macroscopic layering (permeability)

(LaChapelle, 1992, pg, 16; Schneebeli and Sokratov, 2004)

SUMMARY

- Constantly changing hydraulic and thermal properties

- Large spatial and temporal variability

- Once melt occurs at the snow surface, we lose track of it as liquid water infiltrates the snowpack.

- Movement of liquid water generally occurs as distinct flow paths rather than as uniform flow through a homogeneous medium

- Most current methods of measuring flowpaths involve sparse and invasive sampling techniques

- Studying scale and time-dependent processes, such as preferential flowpaths, is very difficult

Flow through heterogeneous snow

- at melting temperature, a thin film of water surrounds snow grains
- water can flow through this film and begins filling pore spaces

Field Capacity: max amount of liquid water a porous media holds before affected by gravity

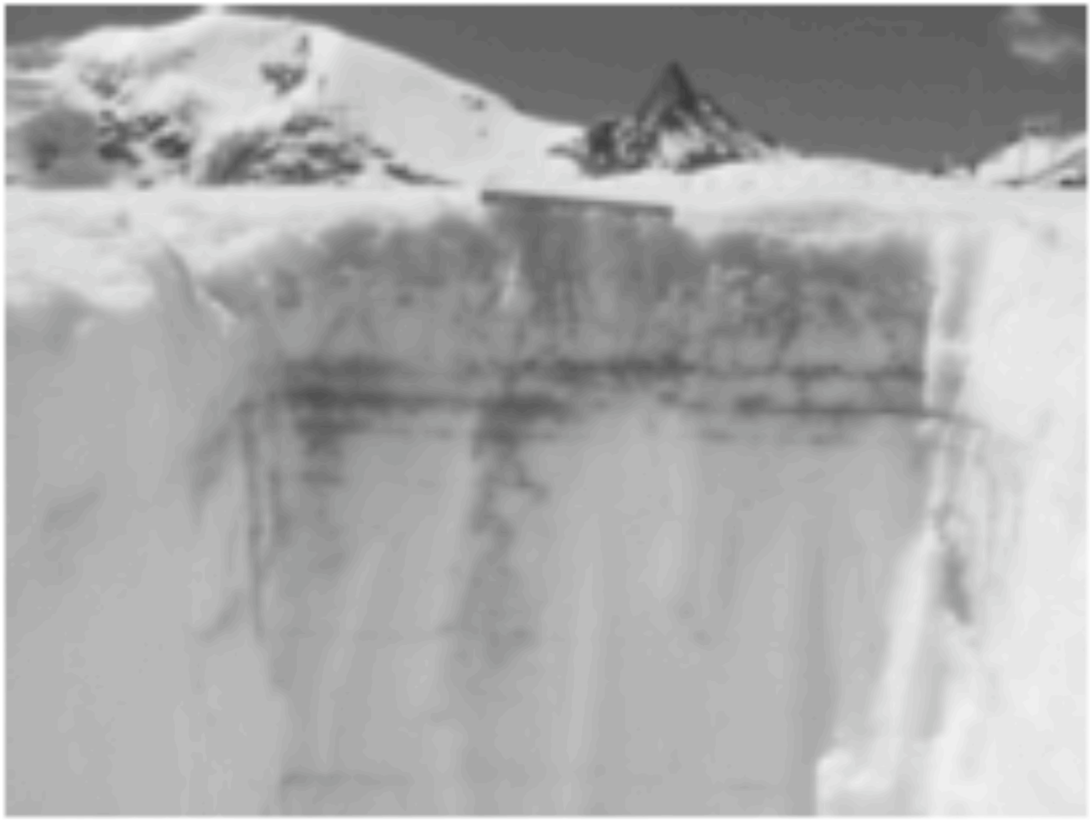
Laminar flow: very efficient mechanism for moving water through snowpack

Field capacity → gravity dominates → laminar flow

Four liquid water regimes:

1. **Capillary:** <1% free water. Water does NOT drain due to capillary tension
2. **Unsaturated (Pendicular):** 1-14% free water. Water drains by gravity, but air spaces are continuous
3. **Saturated (Funicular):** >14% free water. Water drains by gravity, but air spaces are discontinuous
4. **Melt/Freeze:** water melts and refreezes. May occur several times before water drains from the snowpack

Preferential Flow Paths



- ↑Grain growth
- ↑Permeability
- ↑Water Flux

- Positive feedback system!
- Saturated conditions and non-Darcy flow
- Fingers may carry 70% flow within 20% of the cross-sectional area
- Reduces lag between melt and runoff (important for solute release)

Melt/Freeze (Ice Layers)

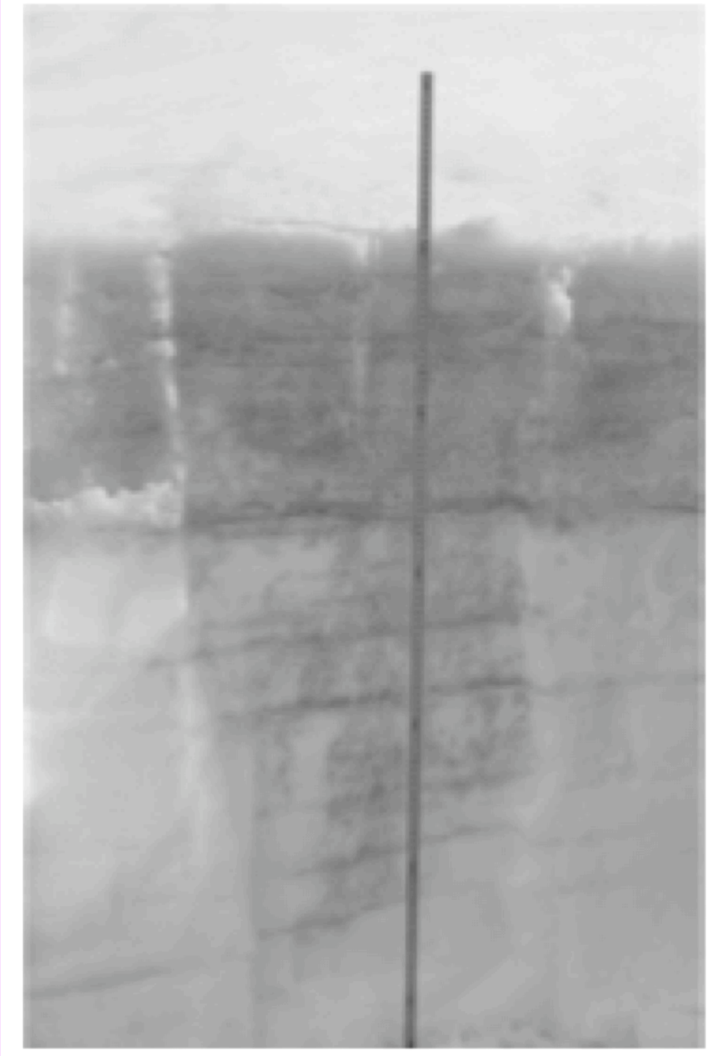
Impedes vertical flow

↓ Permeability

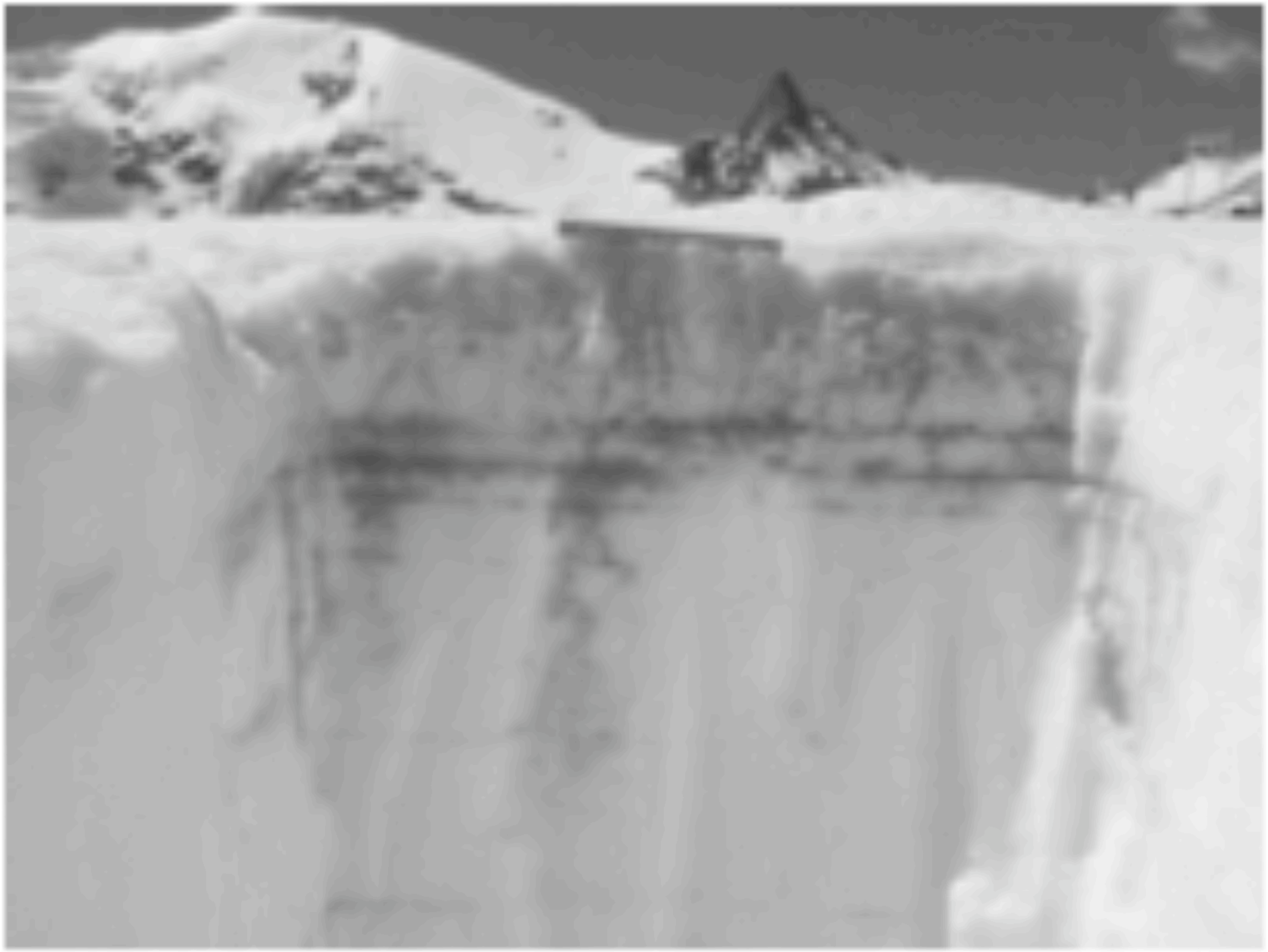
↑Water Content

LATERAL FLOW

Heat transfer: the total volume of water that refreezes is determined by the initial snow temperature and the soil heat flux



(Colbeck, 1978; Campbell et al., 2006)



(Campbell et al., 2006)

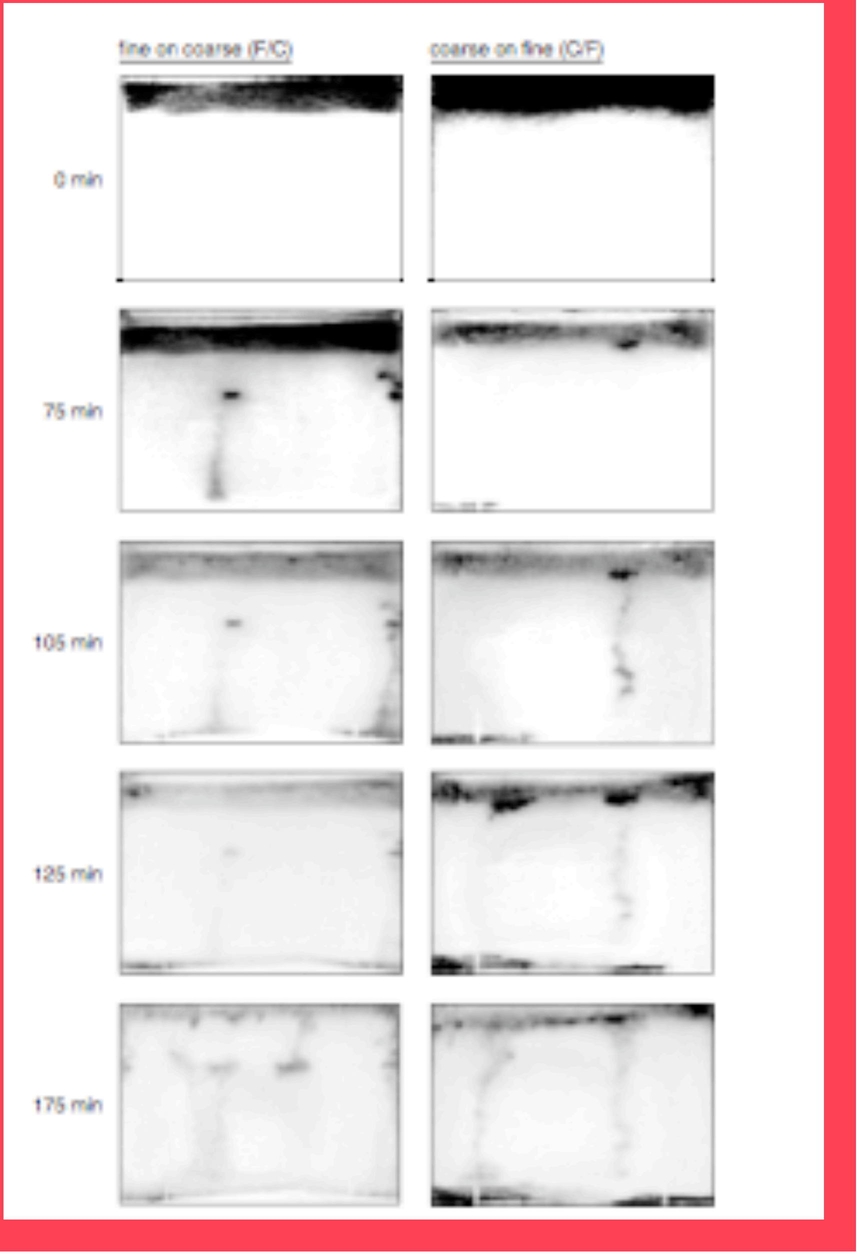
Texturally different horizons

F/C vs. C/F

Capillary forces

VS.

Gravitational forces



(Waldner et al., 2006)

Modeling the movement of water through snow

- Has generally followed the approach of Colbeck (1972), yielding the simplified form of Darcy's equation
- Approach has worked fairly well

DARCY'S FLOW

For movement through an unsaturated porous medium, the downward flux of water is balanced by an equal upward flux of air. It is a function of elevation above a datum and permeability (hydraulic conductivity)

Permeability (**k**) is related to ***hydraulic conductivity*****(K)** which describes the flow of water due to pressure gradients as it relates to the properties of the porous medium (not the fluid)

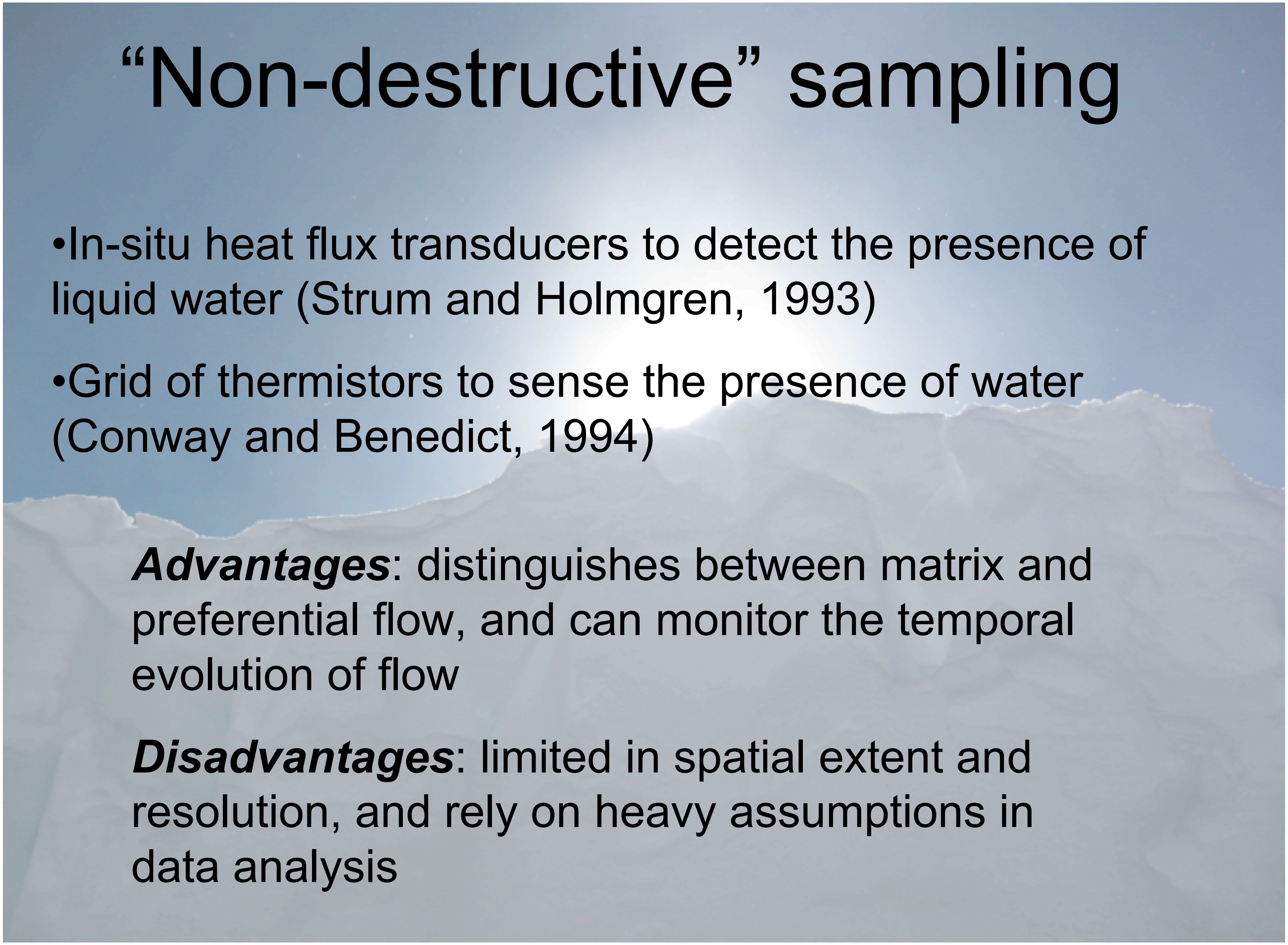
Problems

Results in current models of meltwater flow are limited by inadequate characterization of:

- water retention in snow under unsaturated conditions (capillary pressure effects)
- intrinsic permeability
- textural changes
- thermodynamics
- Ice lens and macropore formation
- Surface topography
- Air-entry pressure of saturated layers

METHODS

“Non-destructive” sampling

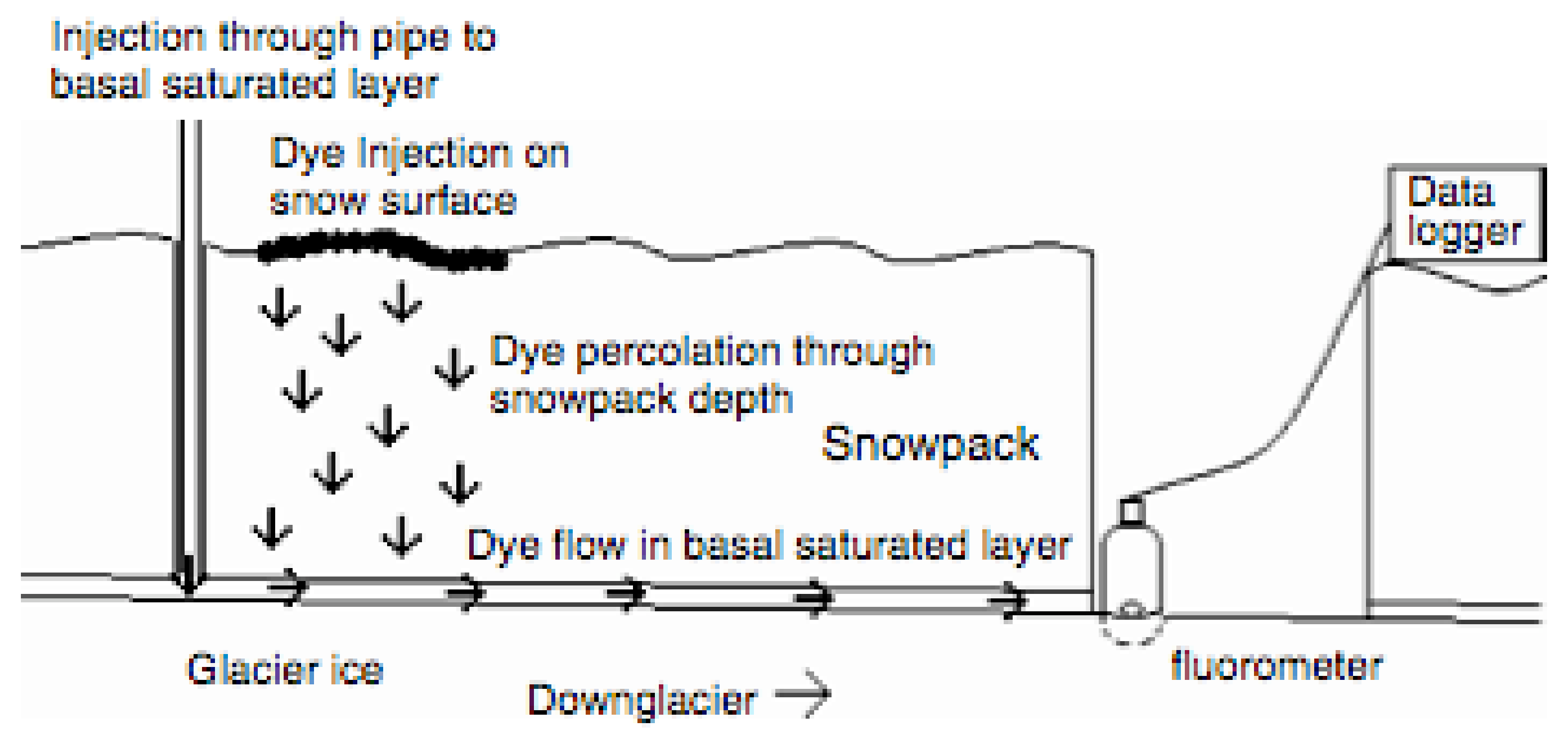


- In-situ heat flux transducers to detect the presence of liquid water (Strum and Holmgren, 1993)
- Grid of thermistors to sense the presence of water (Conway and Benedict, 1994)

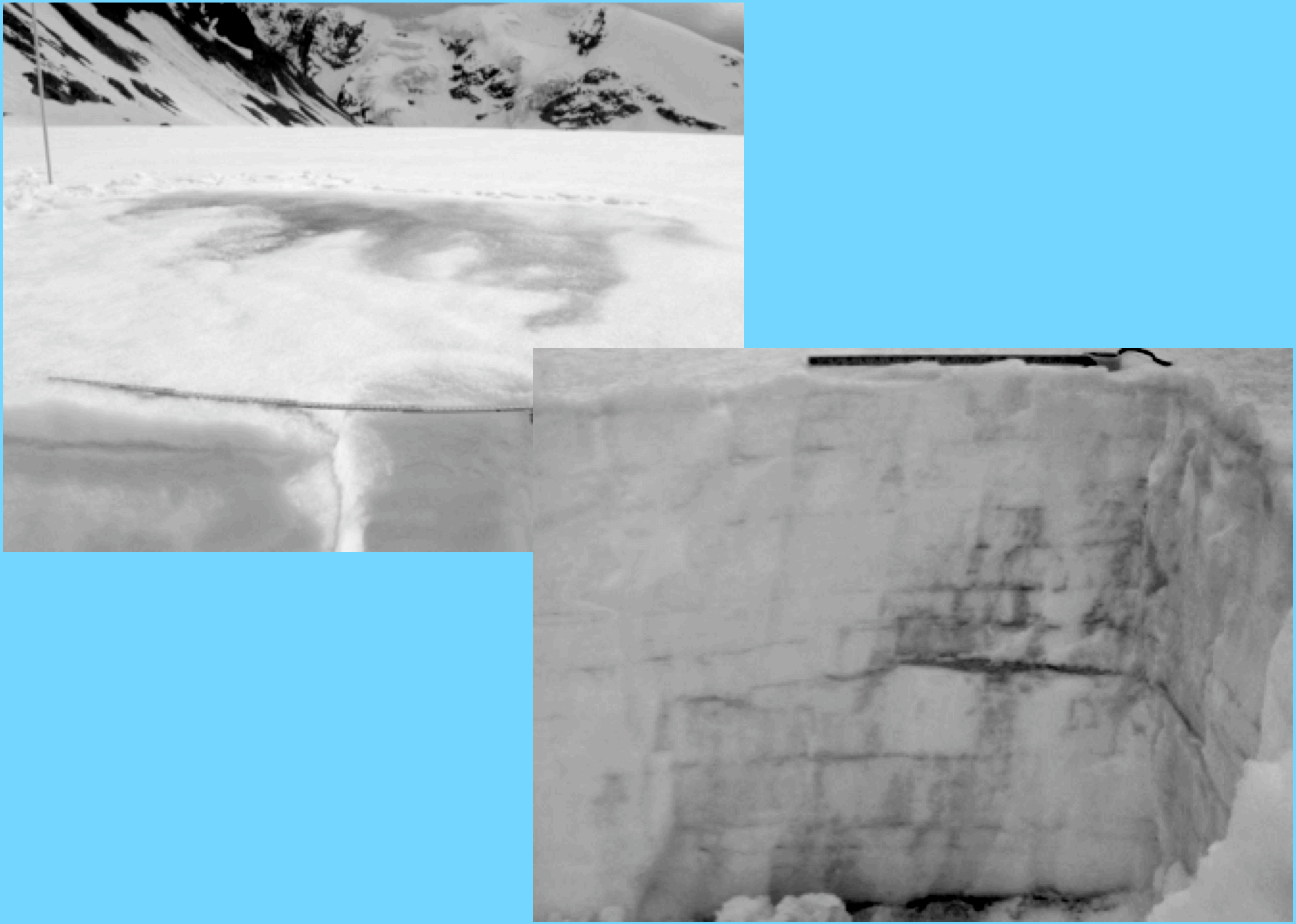
Advantages: distinguishes between matrix and preferential flow, and can monitor the temporal evolution of flow

Disadvantages: limited in spatial extent and resolution, and rely on heavy assumptions in data analysis

Dye Tracers

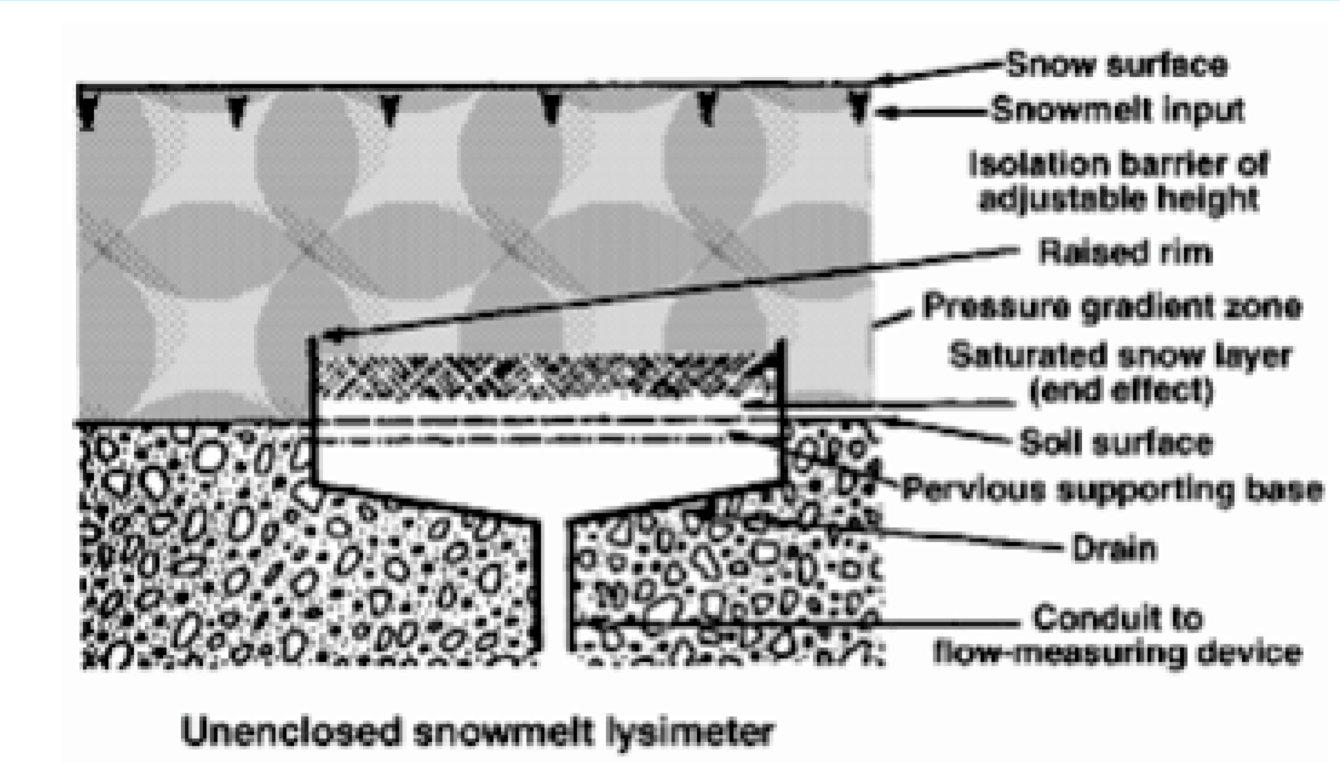


(Campbell et al., 2006)



(Campbell et al., 2006)

Snow Lysimeters



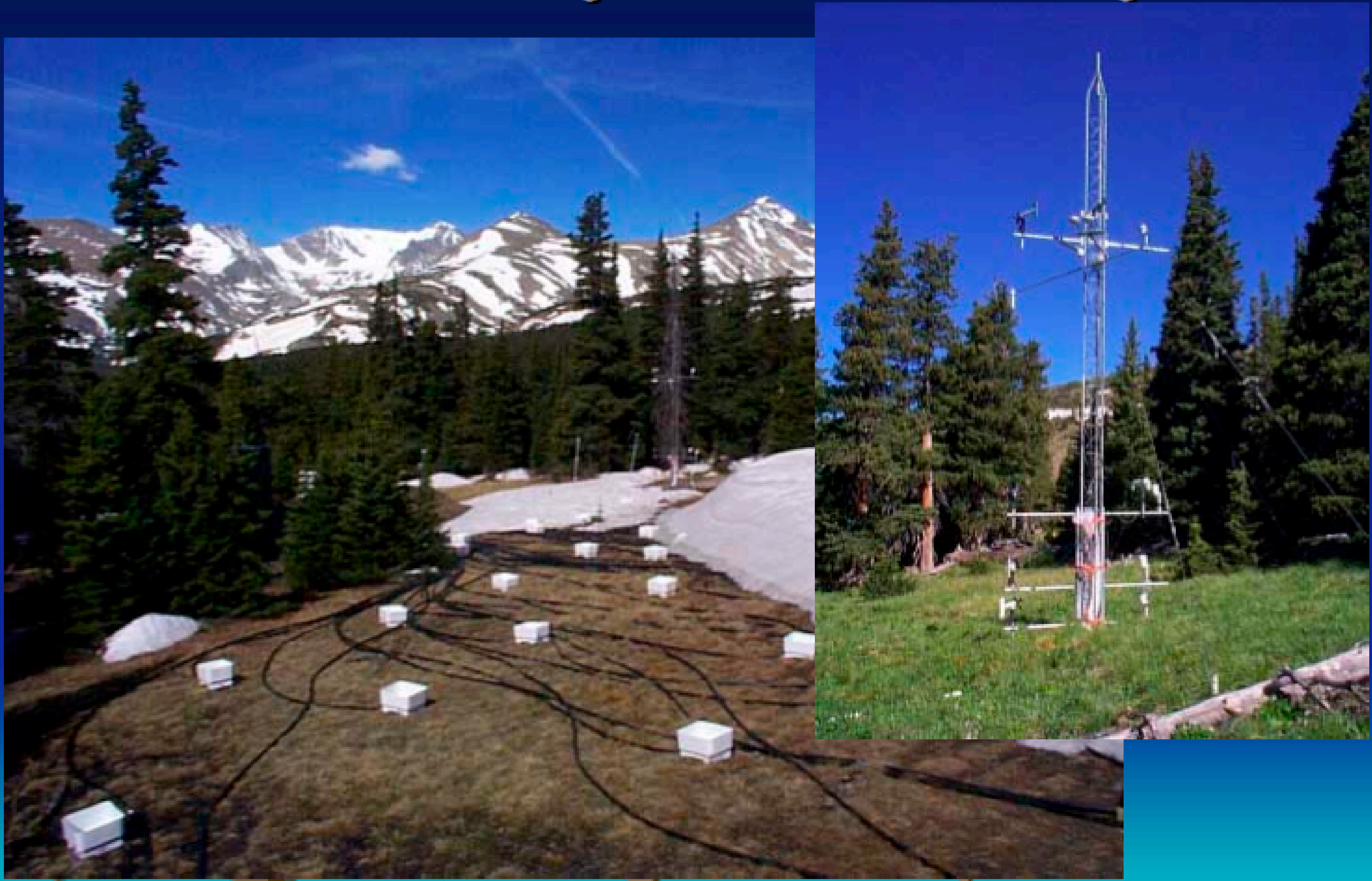
Unenclosed snowmelt lysimeter

Measures basal meltwater flow (discharge) in order to estimate surface melt rate

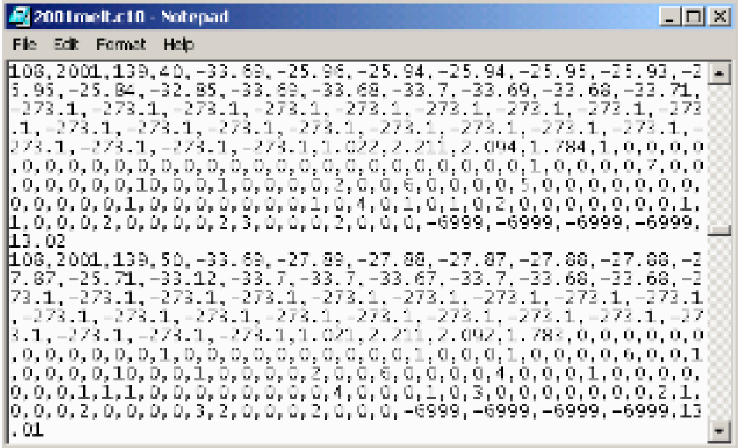
Flow ranged from 0-240% of the mean in individual lysimeters

Sampled area should be equal to the square of the snow depth

Soddie Lysimeter Array



Data Collection



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5.95,-25.84,-32.85,-33.69,-33.68,-33.7,-33.69,-33.68,-33.71,
-273.1,-273.1,-273.1,-273.1,-273.1,-273.1,-273.1,-273.1,-273
.1,-273.1,-273.1,-273.1,-273.1,-273.1,-273.1,-273.1,-273.1,-
273.1,-273.1,-273.1,-273.1,1.022,2.211,2.094,1.784,1,0,0,0,0
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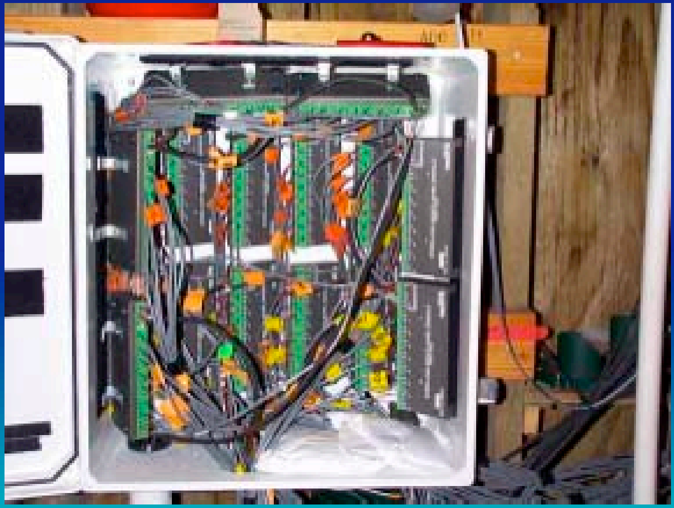
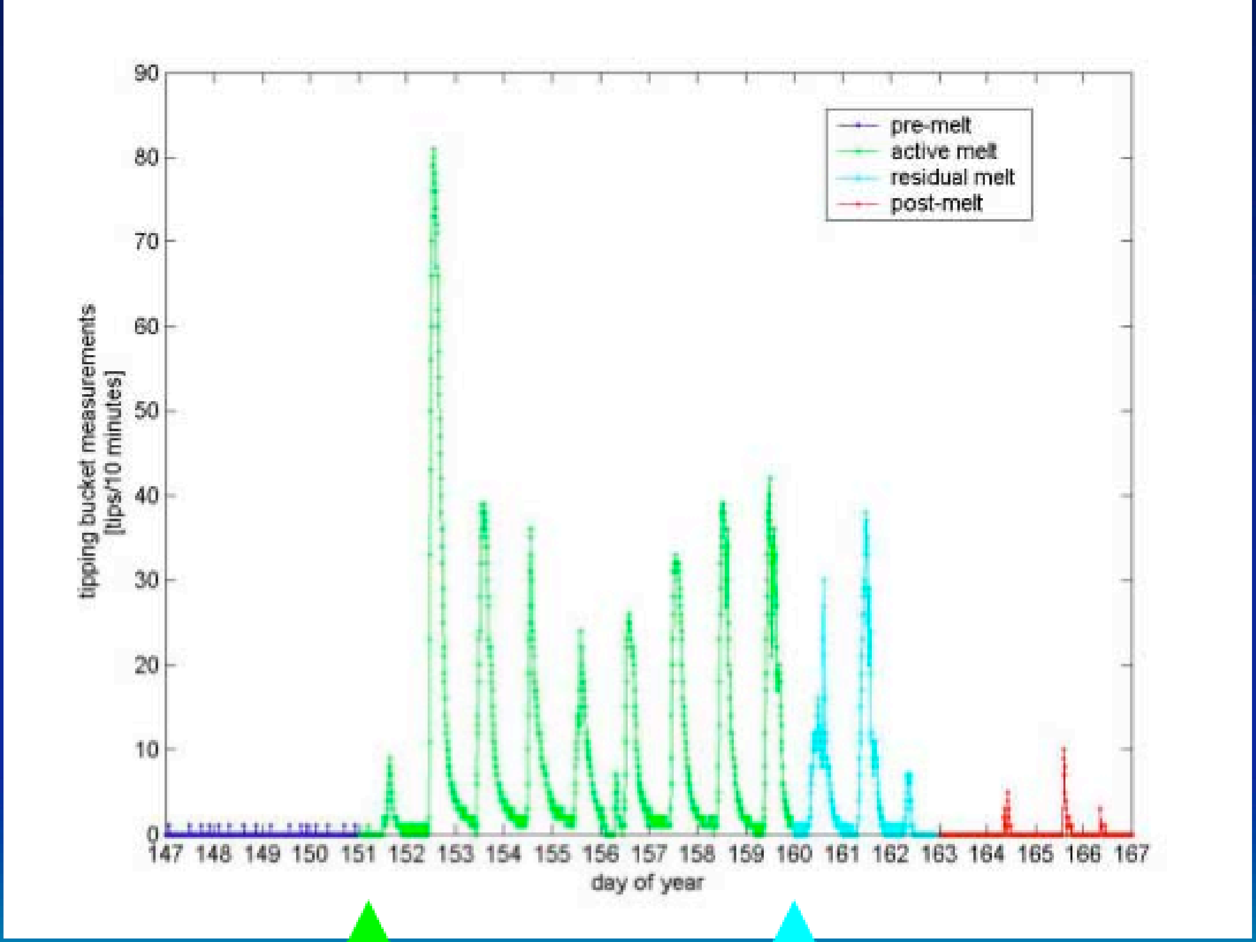
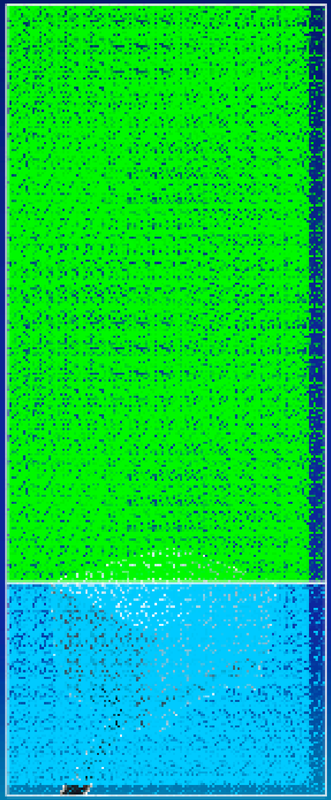
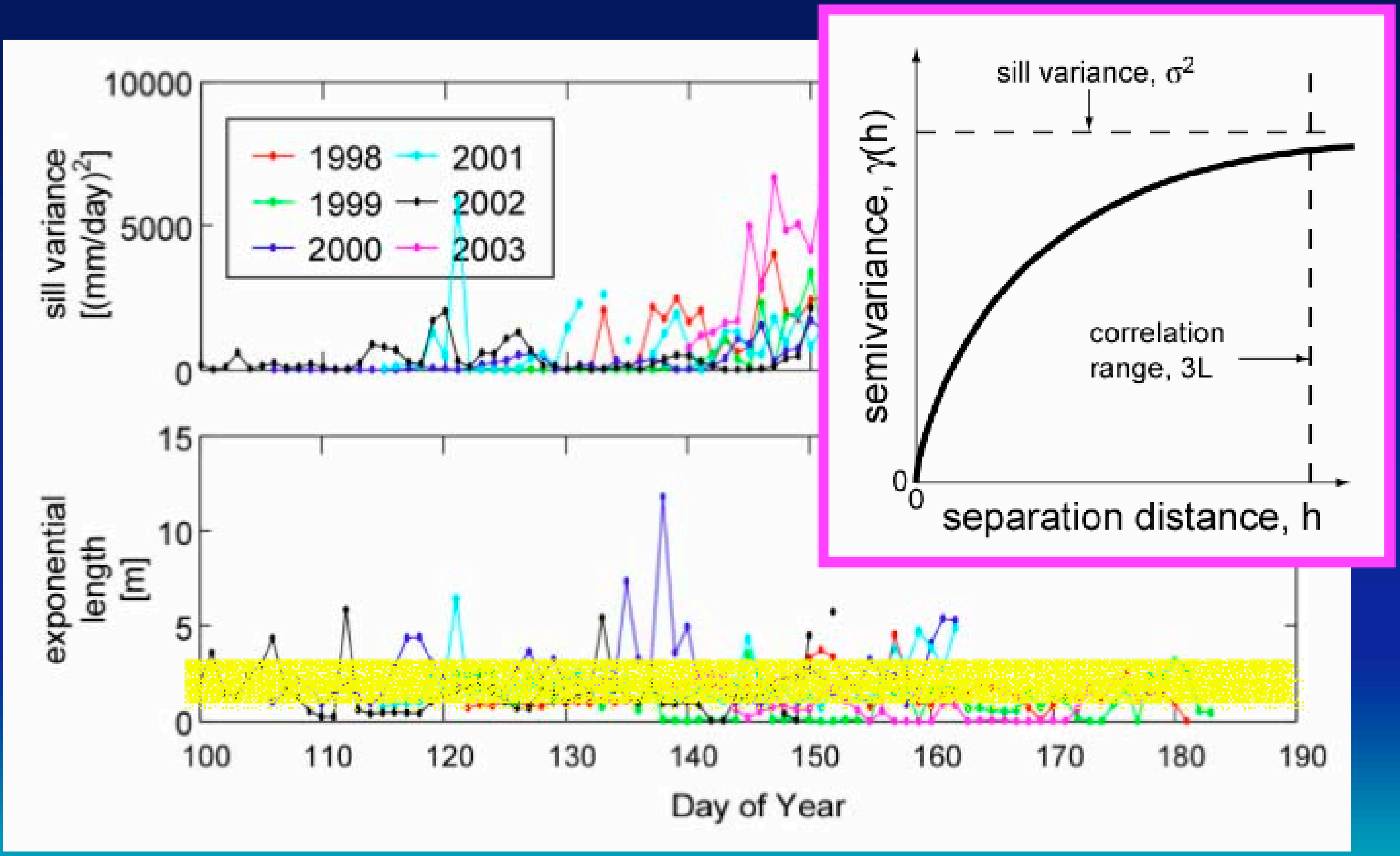


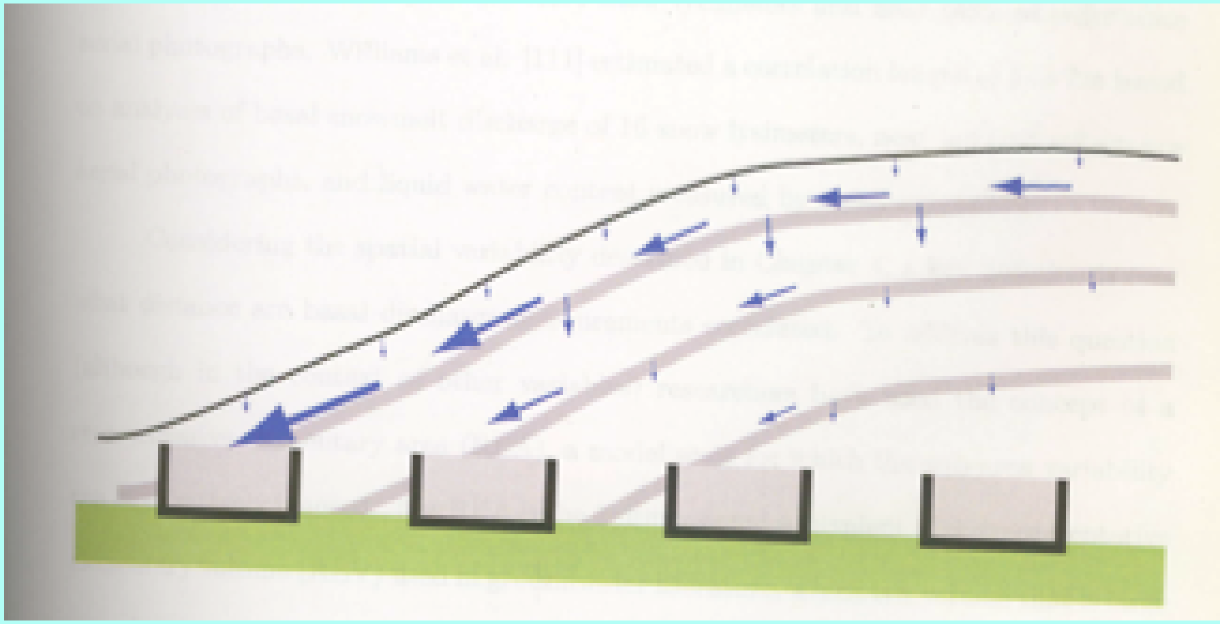
Meltwater Discharge Processing





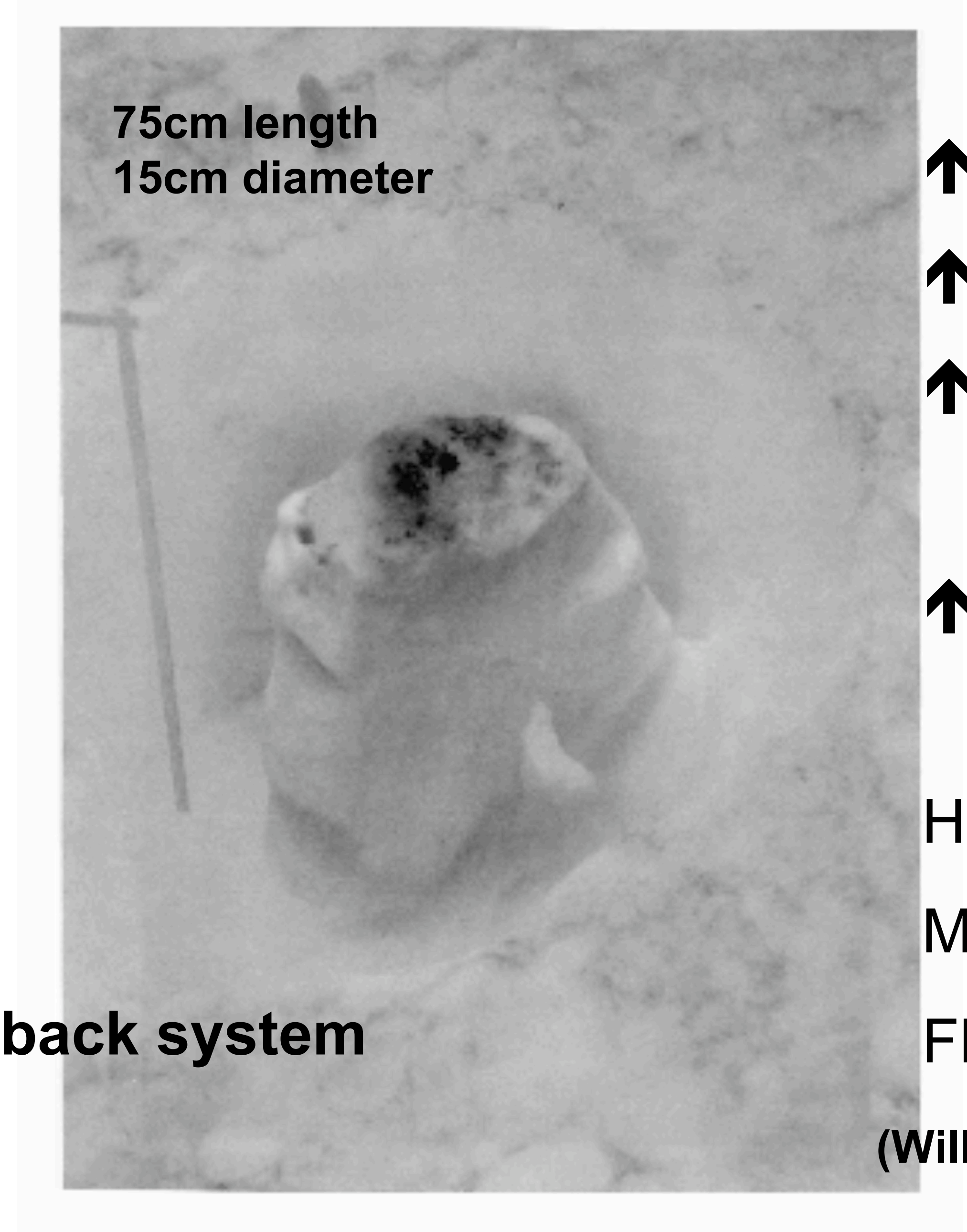
Discharge Variability vs. Time





- Lysimeters at low snow depths will collect more meltwater than those in deeper snow cover
- Larger discharges exhibit greater variability and require a larger number of lysimeters to estimate the true mean
- Low snow depths=higher variability
- Variability decreases throughout the season

Ice Columns



75cm length
15cm diameter

Surface rills

↓

Vertical flow

↓

Freezing

↓

Ice Columns

Positive feedback system

↑Water content

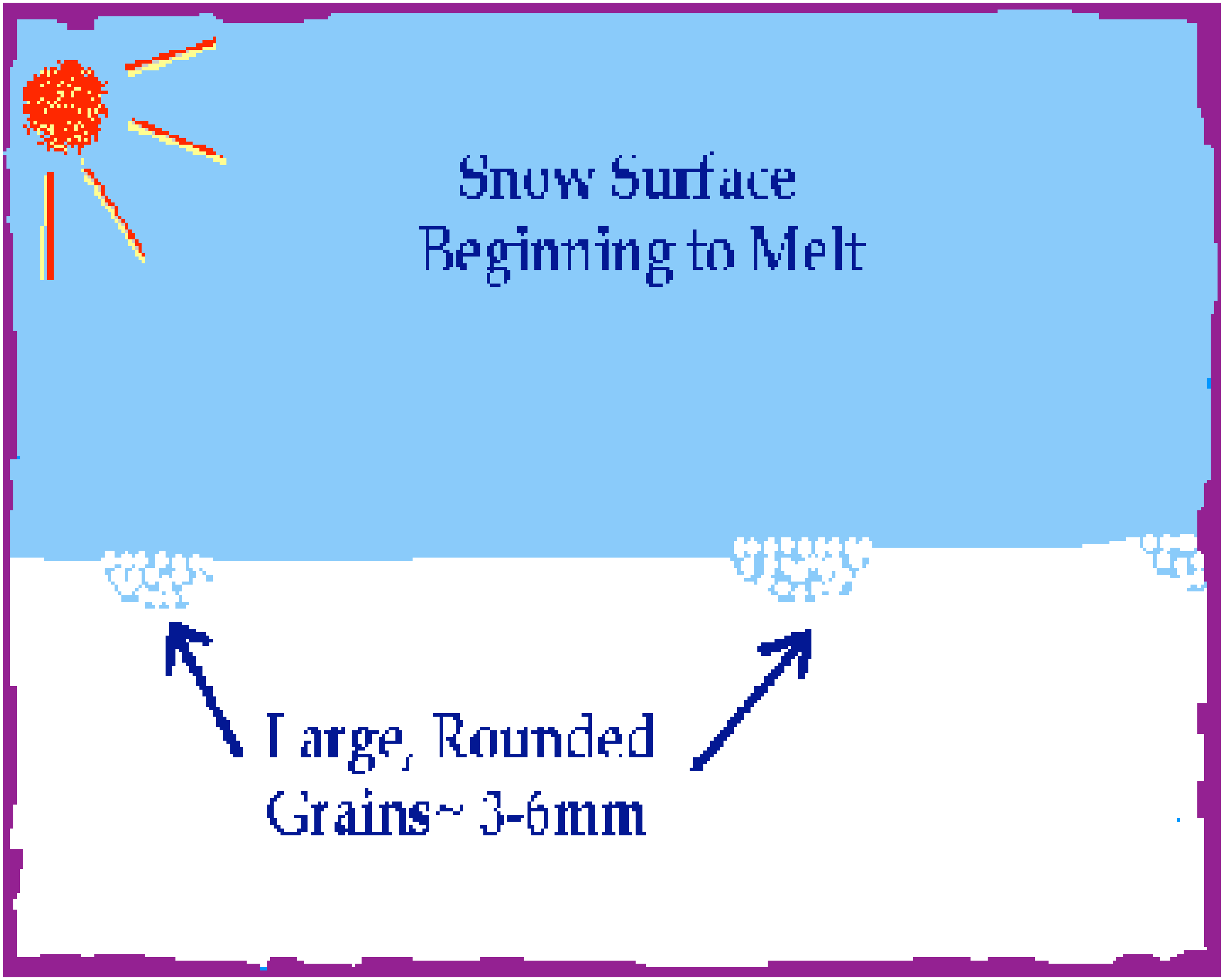
↑Grain growth

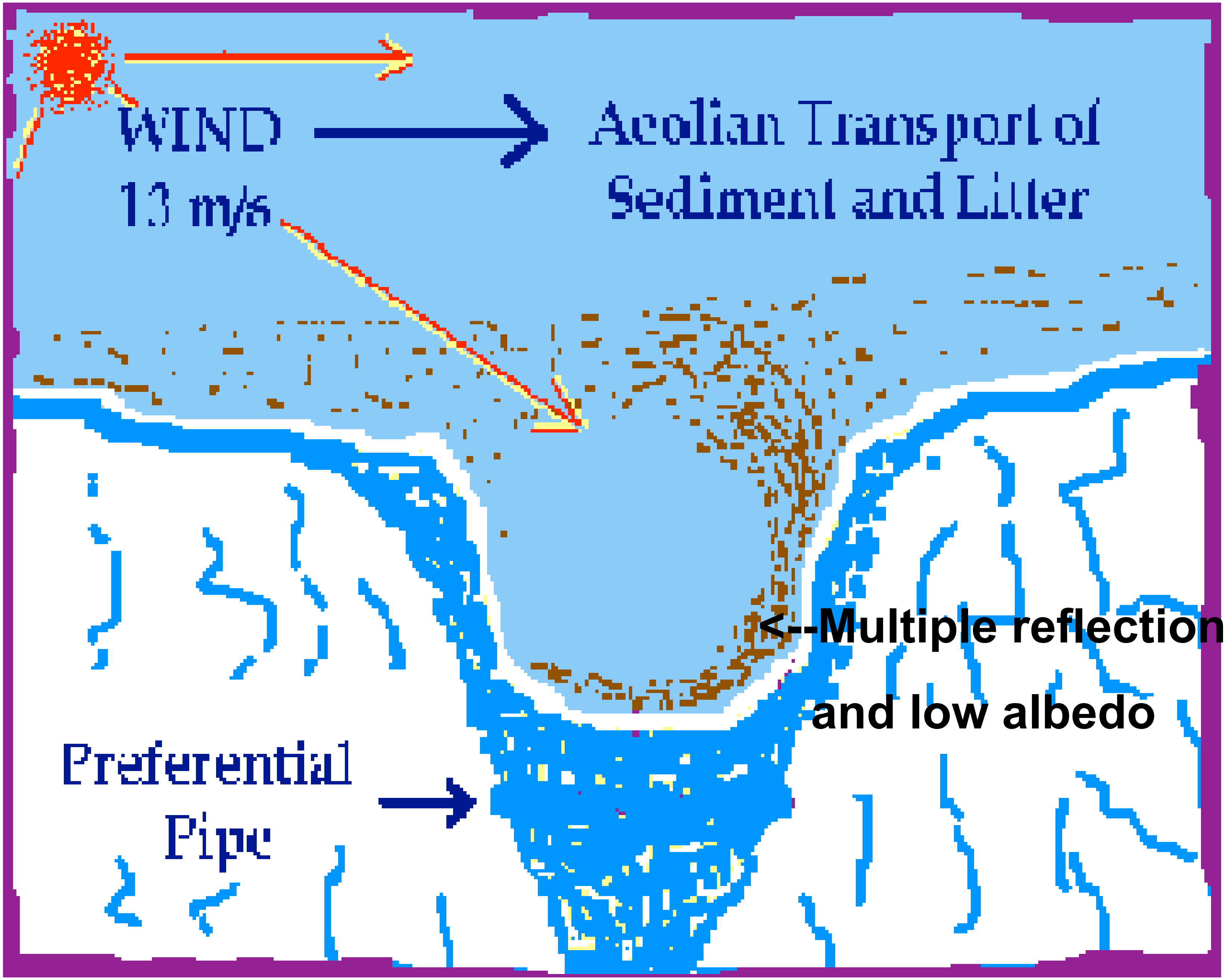
↑Hydraulic conductivity

↑Heat flux

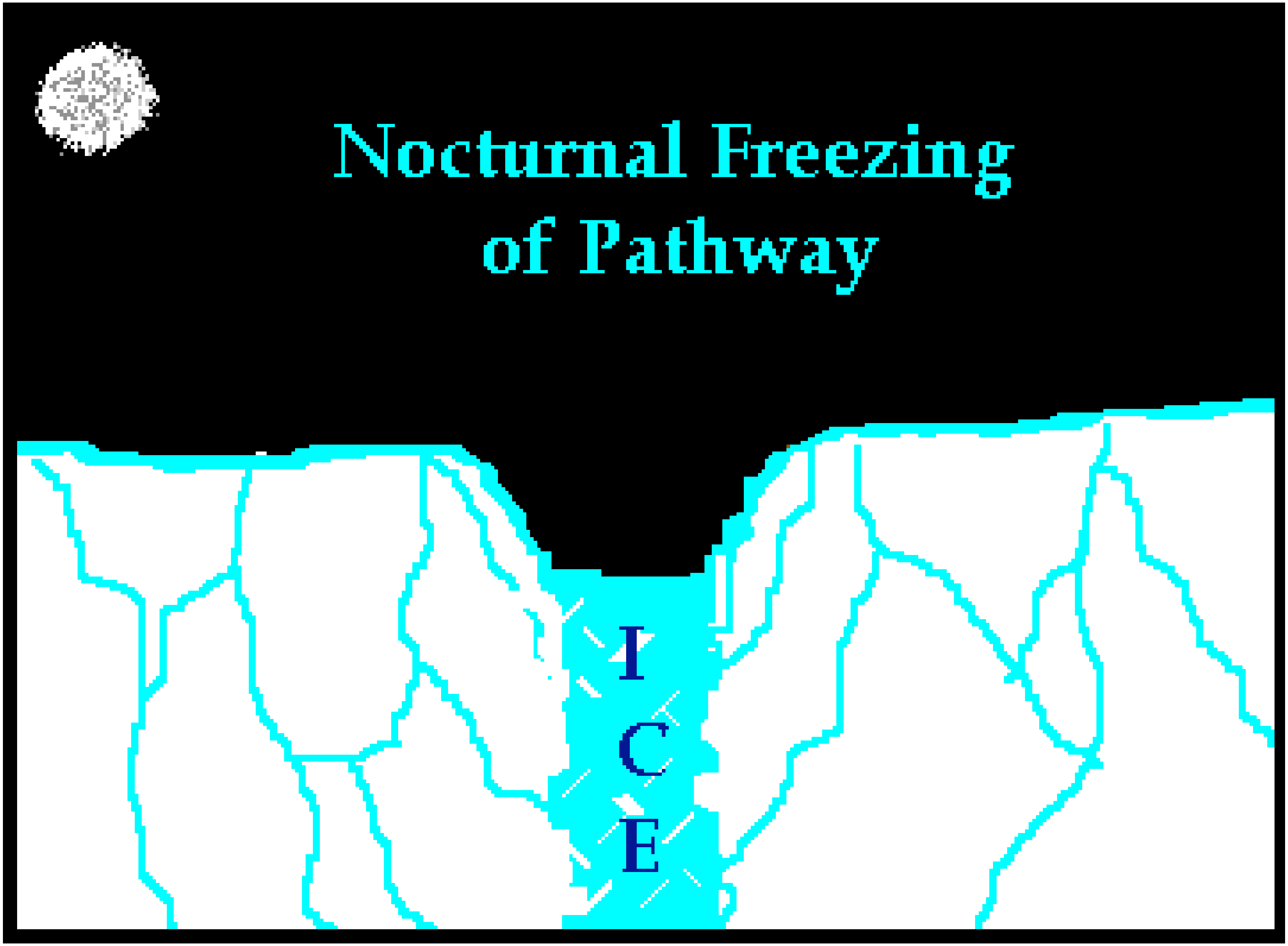
HIGH
MELTWATER
FLUX

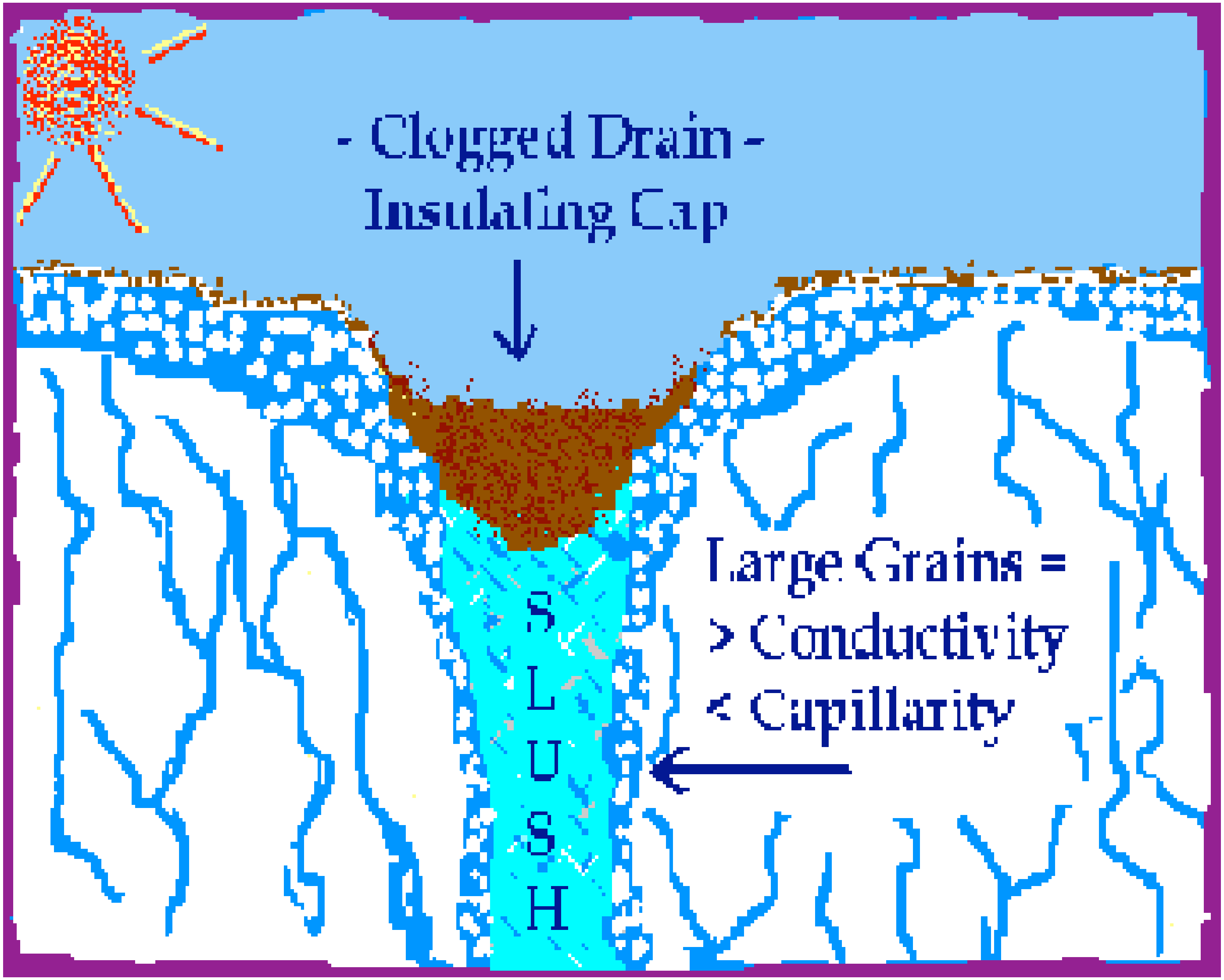
(Williams et al., 2000)

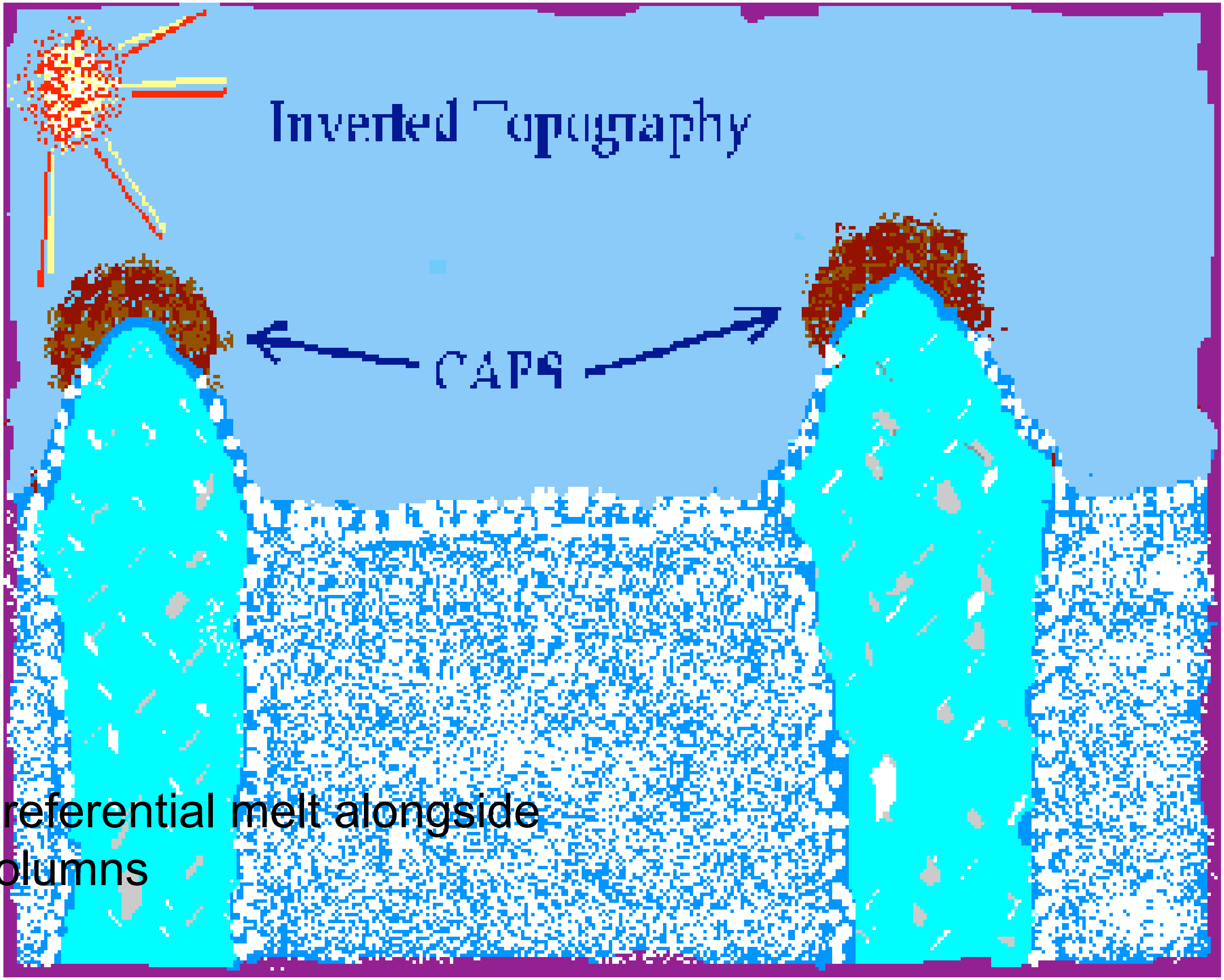

Snow Surface
Beginning to Melt
Large, Rounded
Grains~ 3-6mm


WIND
13 m/s
Aeolian Transport of
Sediment and Litter
<--Multiple reflection
and low albedo
Preferential
Pipe

Nocturnal Freezing of Pathway




- Clogged Drain -
Insulating Cap
S
L
U
S
H
Large Grains =
> Conductivity
< Capillarity



Preferential melt alongside columns

Frozen rills composed of vertical ice columns on Martinelli snow field. Rills are separated by 2.6 meters on average


'96 8 8

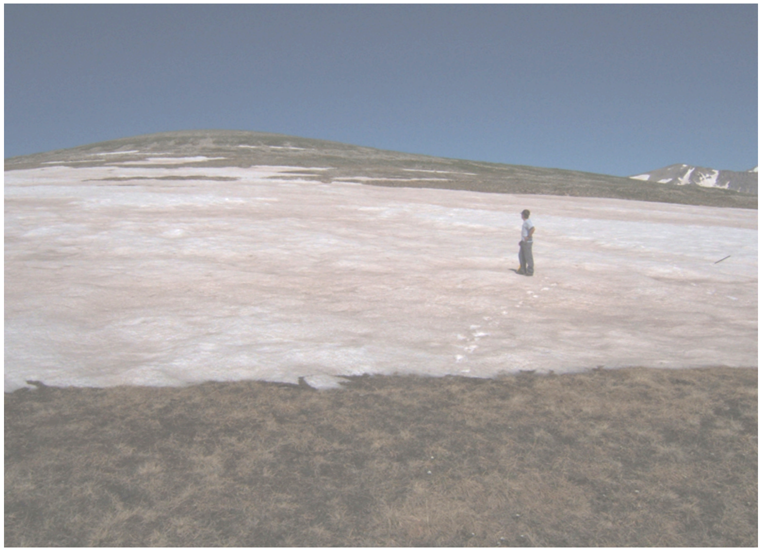
Summary

- 81 columns on South vs. 57 on north-facing slopes
- Higher liquid water content than surrounding snow
- Higher heat flux
- Columns correlated at a distance of 2.6 meters
- View of internal flow system
- Suggests the spacing of surface rills may be inversely proportional to the melt rate of the snow

Ice column excavation after “red snow” event

Red Snow Ice Columns were conical, with maximum width occurring in all cases close to the snow surface. Mean height of these columns was 16.7cm.

White Snow Ice Columns were consistent in shape, with nearly uniform size from surface to the bottom. Mean height of these columns was 60cm.


Saddle Grid Sampling location


Locating an Ice Column in red snow


Measuring surface diameter of a column


Isolating a column in red snow

Measuring the diameter and height

Ice columns isolated in snow pit

Measuring a column in white snow

Isolated column in white snow

“Correlation lengths of meltwater flow through ripe snowpacks, CO, USA”

- Near infrared aerial photos
- Geostatistics!
- 5-7 meters correlation
- Probability of finding this correlation increased throughout melt season
- Liquid water content measurements indicated 5-6m
- Not site specific

SNOW GUILLOTINE

- Meltwater flow is occurring at a much smaller scale than captured by lysimeters and other methods
- Lack of 3D data collection
- McGurk and Marsh (1995)

Questions

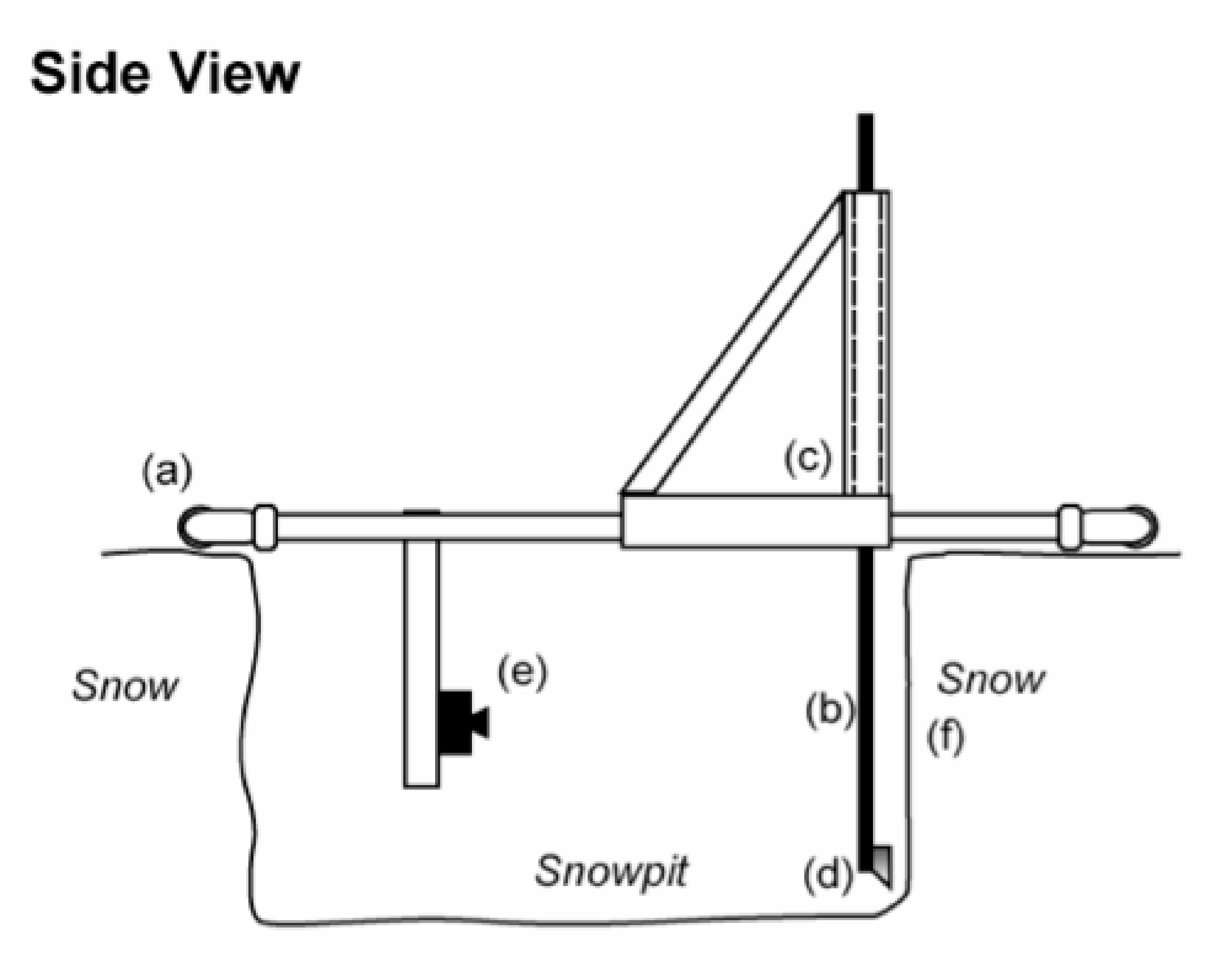
(1) What portion of the snowpack transmits meltwater?

(2) Under what conditions do vertical meltwater pathways occur?

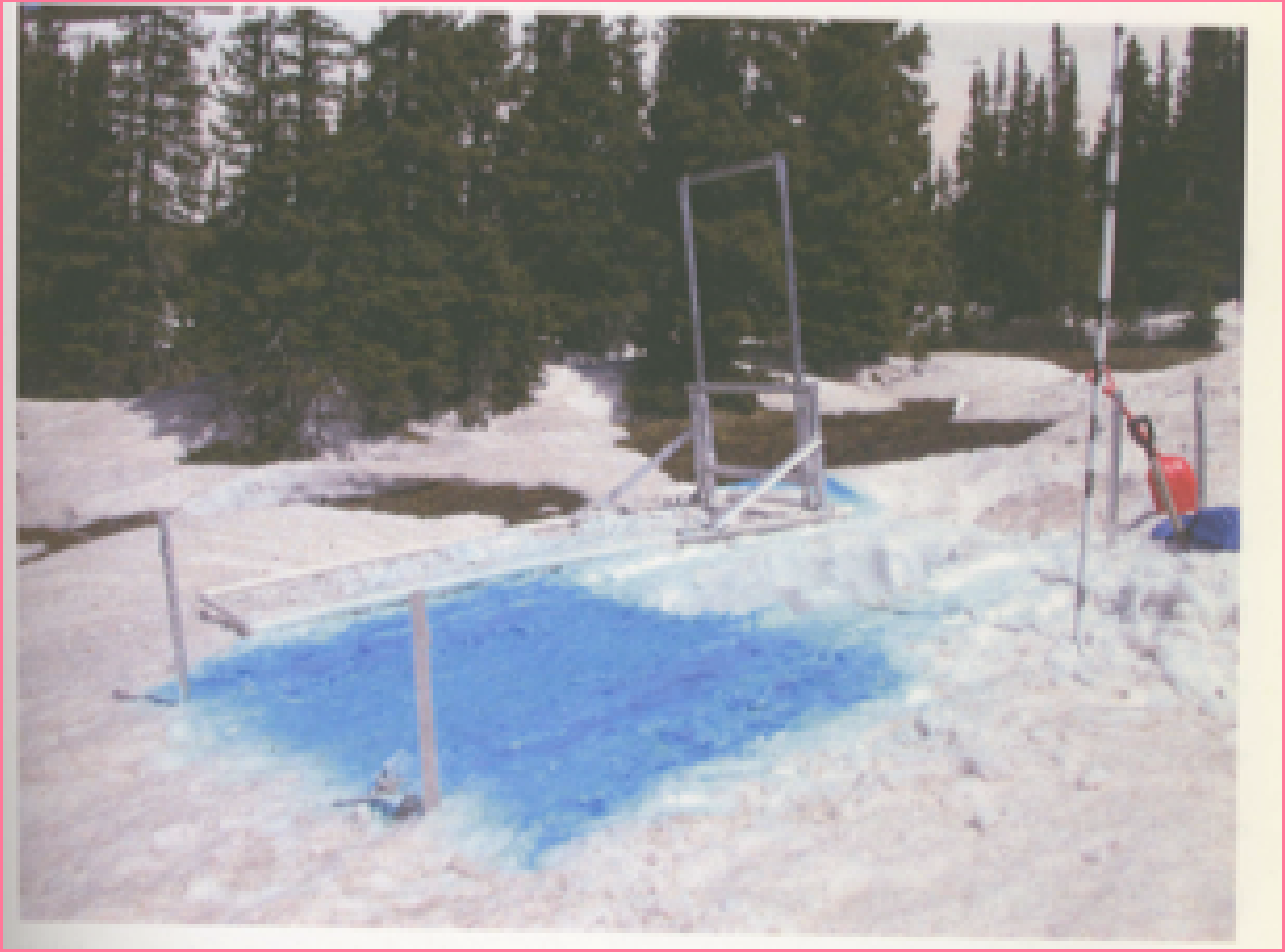
(3) Are vertical meltwater flowpaths continuous across layer boundaries?

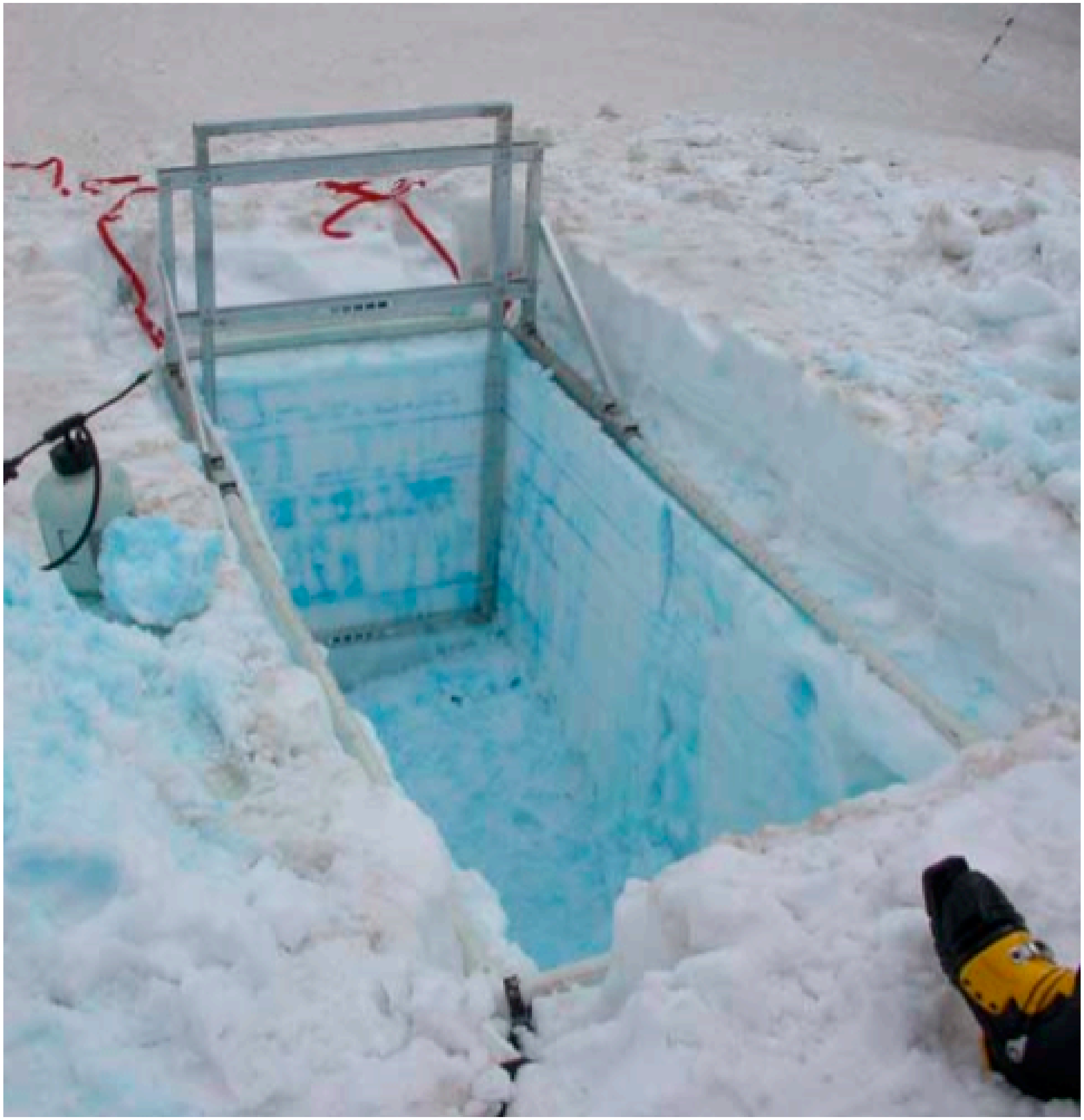
(4) Can dye tracer experiments be used to identify snowpack layer transitions that cannot be easily identified from snowpit sampling?

Snow Guillotine



(Erickson, 2004)



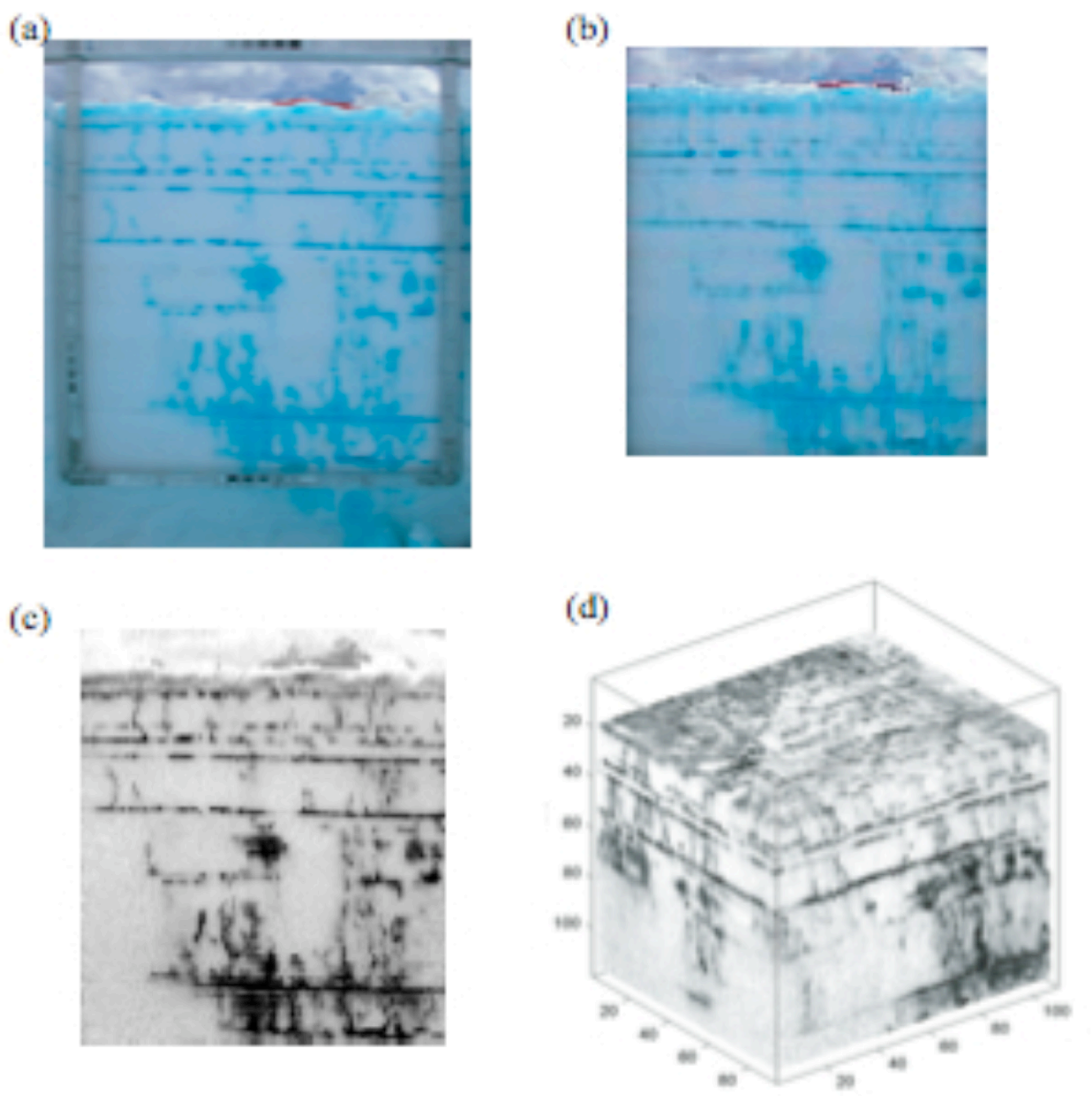


(a)Original image

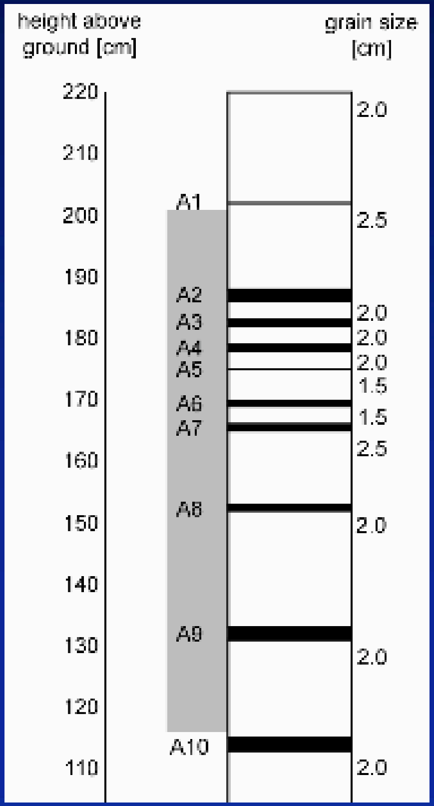
(b) Georectify

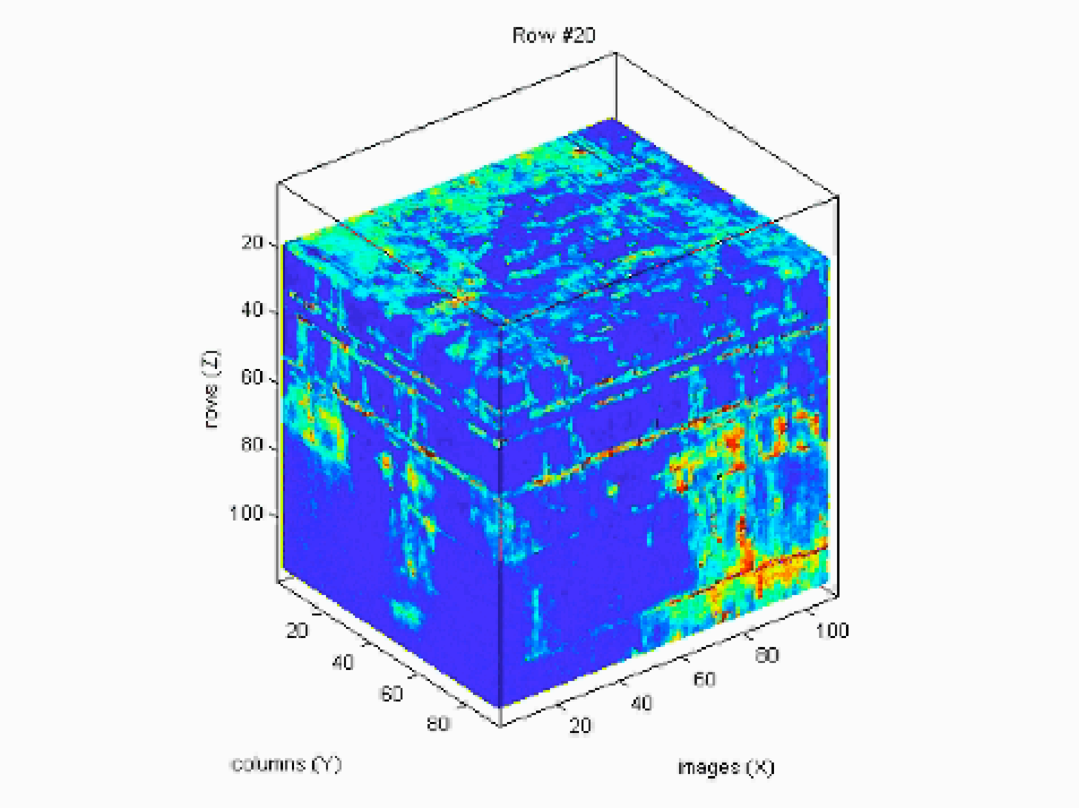
(c) Band Ratio

(d) Datacube

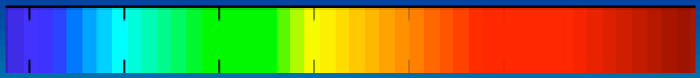


3-Dimensional Data

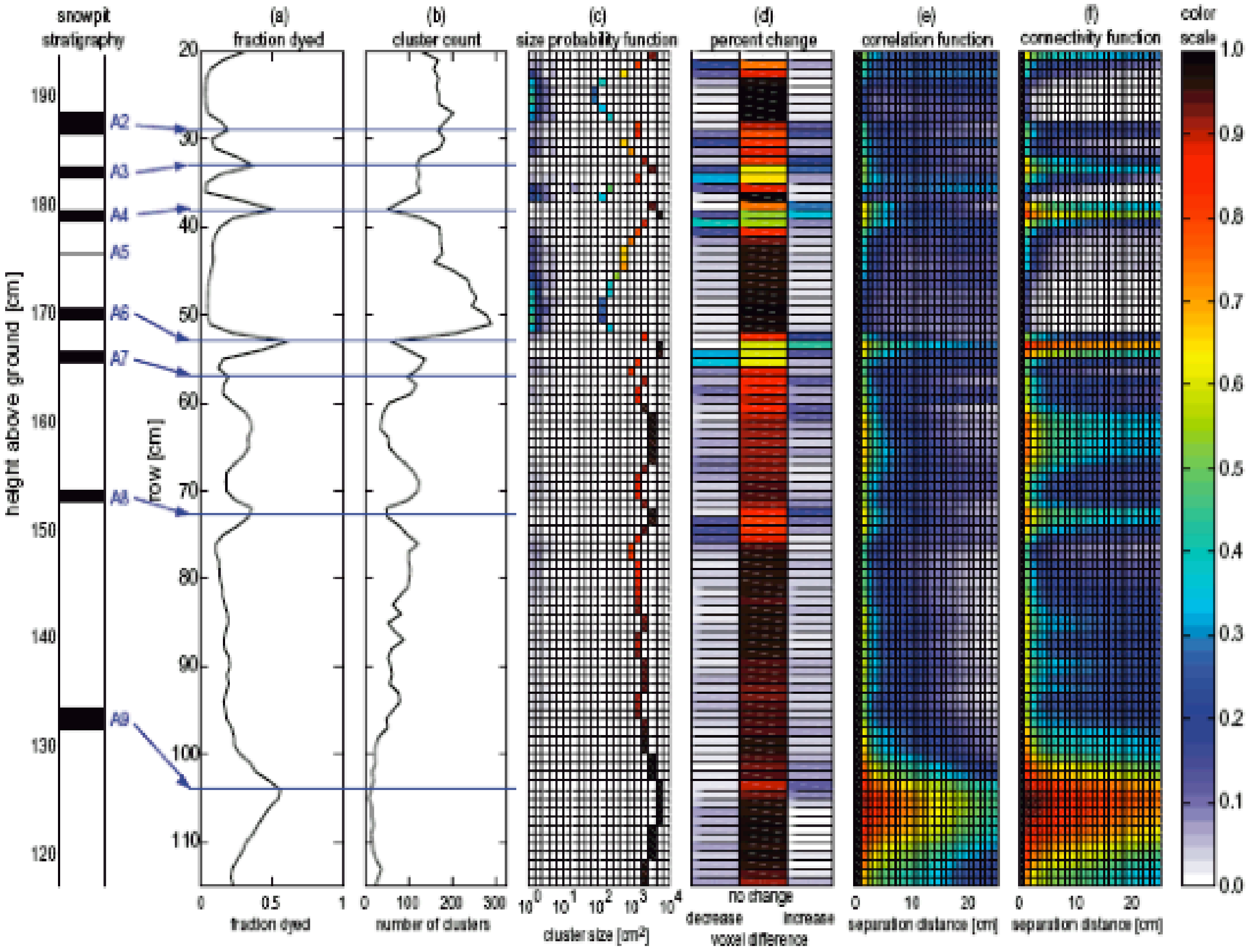


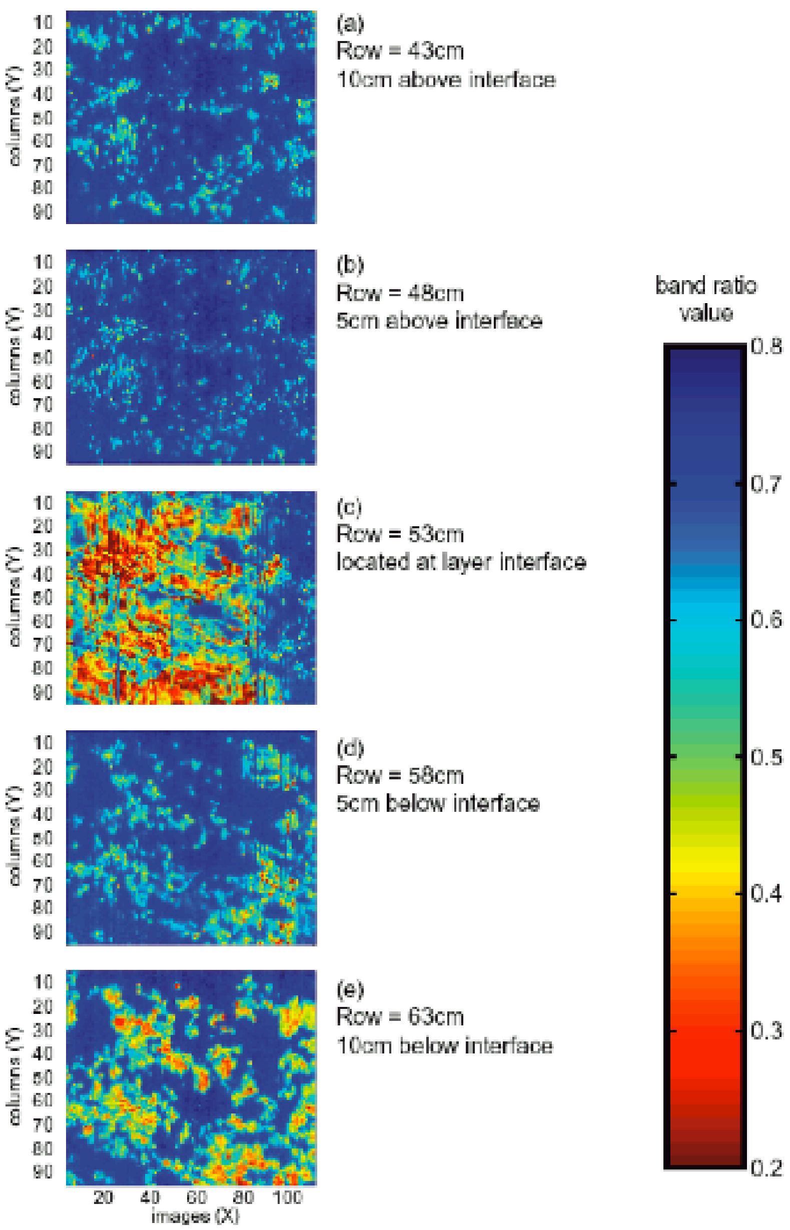


Relative dye concentration: low



high


snowpit stratigraphy
height above ground [cm]
190
180
170
160
150
140
130
120
A2
A3
A4
A5
A6
A7
A8
A9
(a) fraction dyed
row [cm]
20
30
40
50
60
70
80
90
100
110
0
0.5
1
fraction dyed
(b) cluster count
0
100
200
300
number of clusters
(c) size probability function
10^0
10^1
10^2
10^3
10^4
cluster size [cm^2]
(d) percent change
no change
decrease
increase
voxel difference
(e) correlation function
0
10
20
separation distance [cm]
(f) connectivity function
0
10
20
separation distance [cm]
color scale
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0


(a)
Row = 43cm
10cm above interface

(b)
Row = 48cm
5cm above interface

(c)
Row = 53cm
located at layer interface

(d)
Row = 58cm
5cm below interface

(e)
Row = 63cm
10cm below interface

RESULTS

- The fraction of the snowpack transferring liquid water was highly variable between experiments, as well as within individual experiments with respect to depth.
- All three experiments illustrated preferential flowpaths, with the majority of vertical flow occurring in the upper 20-55cm of the snowpack, and no preferential flowpaths apparent below 100cm.
- Layer interfaces were found to significantly affect the volume of dye, indicating dominance by lateral flow at these boundaries. These findings were supported by the decrease in probability with depth of finding vertical flow and an increase in the probability of finding lateral flow at layer interfaces.
- Preferential flowpaths decreased in distinctness with time after the snowpack reached isothermal conditions at 0 degrees C
- Layers not apparent in snowpit sampling were observed in guillotine experiments

Meltwater Summary (1m^3 scale)

- The snow guillotine enables the collection of high-resolution 3-D datasets of meltwater flowpath occurrence
- The horizontal distribution of meltwater flowpaths is strongly affected by stratigraphic interfaces in the snowpack
- Well-defined vertical pathways are more prominent near the surface