ESS 431 PRINCIPLES OF GLACIOLOGY
ESS 505 THE CRYOSPHERE

- SNOW -
DEPOSITION, WIND TRANSPORT, METAMORPHISM

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Homework

- Skating and the phase diagram
- See web page

Sources

D. McClung and P. Schaerer. 1993, 2010. ***The Avalanche Handbook***. The Mountaineers.

E. LaChapelle. 1969. ***Field Guide to Snow Crystals***. U. of Washington Press.

Lecture notes from C.F. Raymond and S.G.Warren.

Class Progress

Last week

- water drops and ice crystals in the atmosphere

Today

- Snow deposition
- Ice crystals in snowpack
- Ice crystals in slush

Air Flow over Ridges

Air moving over ridge moves faster than air over flat terrain because the same flux of air must be transported through a narrower "window" in elevation range

- Analogous to faster river flow where channel narrows

Avalanche Handbook

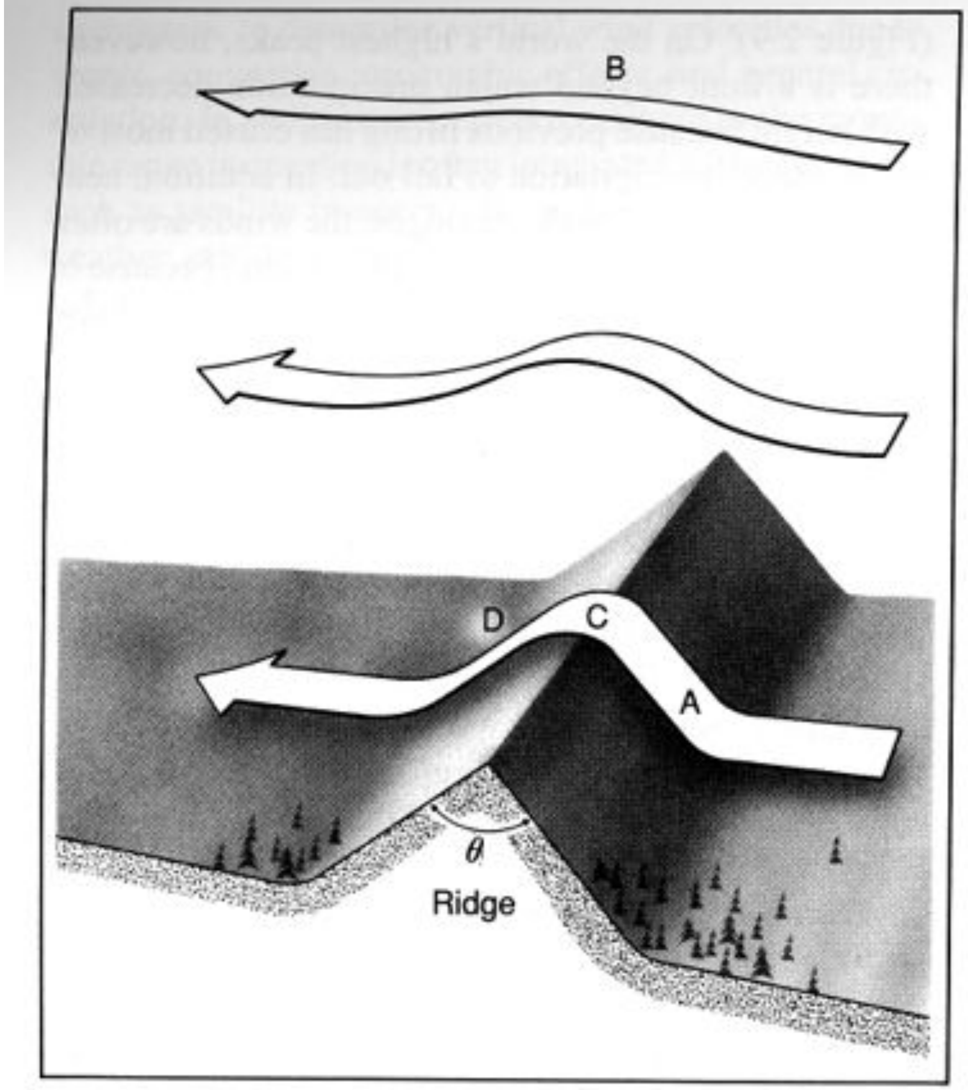


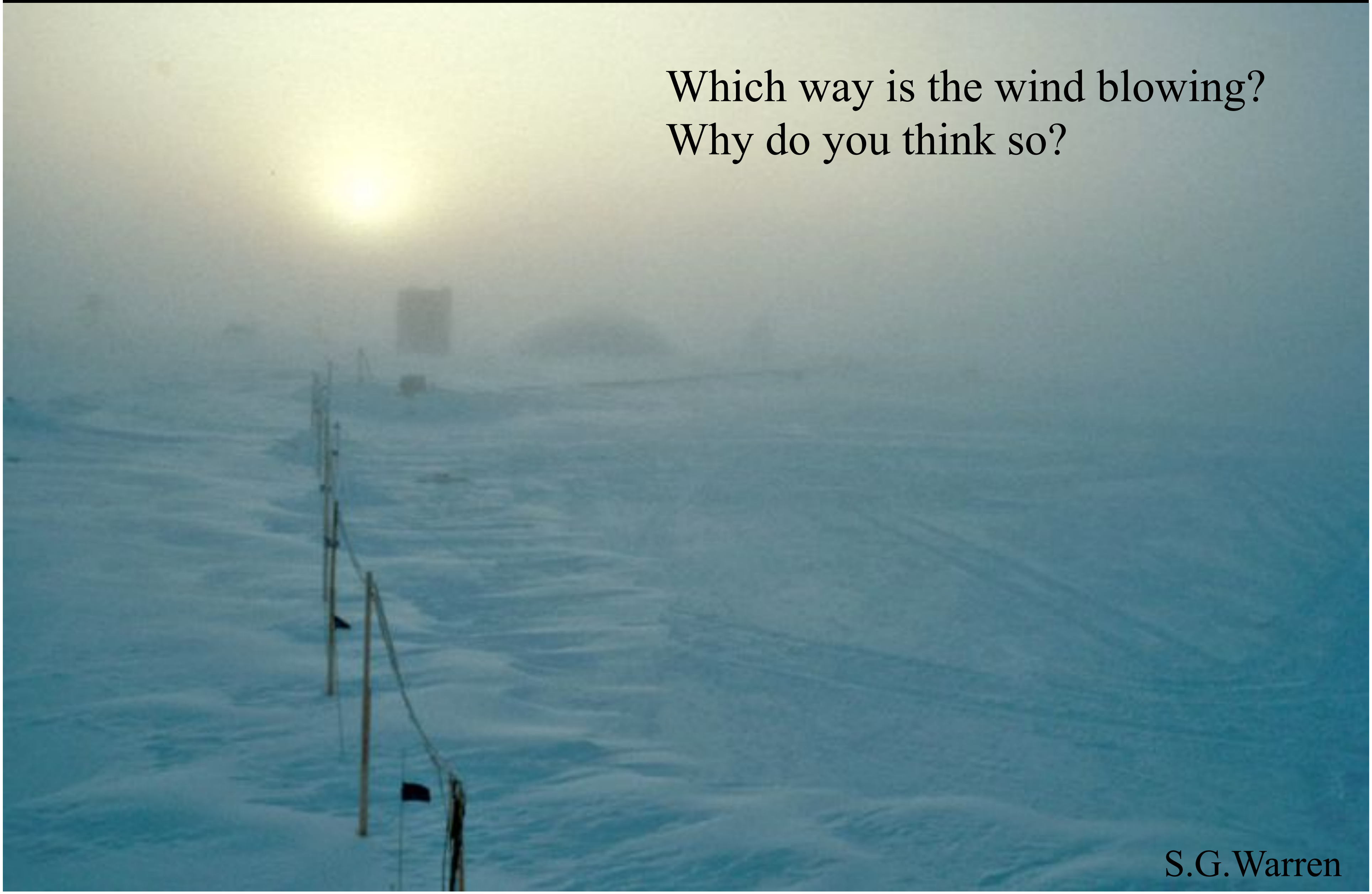
Figure 2.10. A: Airflow over a ridge; B: free-air motion; C: ridge crest; A, D: acceleration and deceleration zones.

Mountain Terrain and Snow

Snow transport depends on wind speed

- Accelerating air can pick up more snow
- Decelerating air drops some transported snow

South Pole Station in blizzard, 8 March 1992



Which way is the wind blowing?
Why do you think so?

S.G.Warren

Clean Air Facility at South Pole Station, March 1992

Why is the building up on stilts?

Sastrugi

- Dunes can sinter and stabilize when wind drops
- Saltating snow can be agent of erosion
- Subsequent wind can erode sintered dunes

Fig. 73. SASTRUGI.

Traverse from Dome C to Dumont dʼ Urville, February 2004

Traverse from Dome C to Dumont d’Urville, February 2004

Why is the surface so rough?

Physical properties of snow

1. **Density** (water is 1000 kg m^{-3} or 1 tonne m^{-3})

Type of Snow	Density (kg m^{-3})
Dry new snow	50 – 70
Damp new snow	100 – 200
Settled snow	200 – 300
"Depth hoar"	100 – 300
Cold wind-packed snow	300 – 400
Melting snow	300 – 550
"Firn" (survived 1 year)	550 – 830
Glacier ice (bubbles occluded)	830 – 917

Heat Flow and Temperature in Snow

2. Thermal conductivity

- Snow is a mixture of air and ice
- Which has higher thermal conductivity?

  $K_{ice} \sim 2$ W m^{-1} deg^{-1}

  $K_{air} \sim 0.024$ W m^{-1} deg^{-1}
- How does heat move through snowpack?

  Fourier's Law: $$Q = -K_{eff} \frac{\mathrm{d}T}{\mathrm{d}z}$$

  What is K_{eff}?

- Snow is supported by forces between touching grains. How does the structure of contacts affect heat flow?

Snow Physics

The Big Picture

- Wind and gravity can move snow after it falls
- Physical properties of deposited snow can change over time

Wind Transport

Wind must exceed a threshold speed w_c to move snow.

w_c depends on snow characteristics

- Warmer snow → larger w_c
- Higher humidity → larger w_c
- Older snow → larger w_c

What's going on?

Threshold Wind Speed

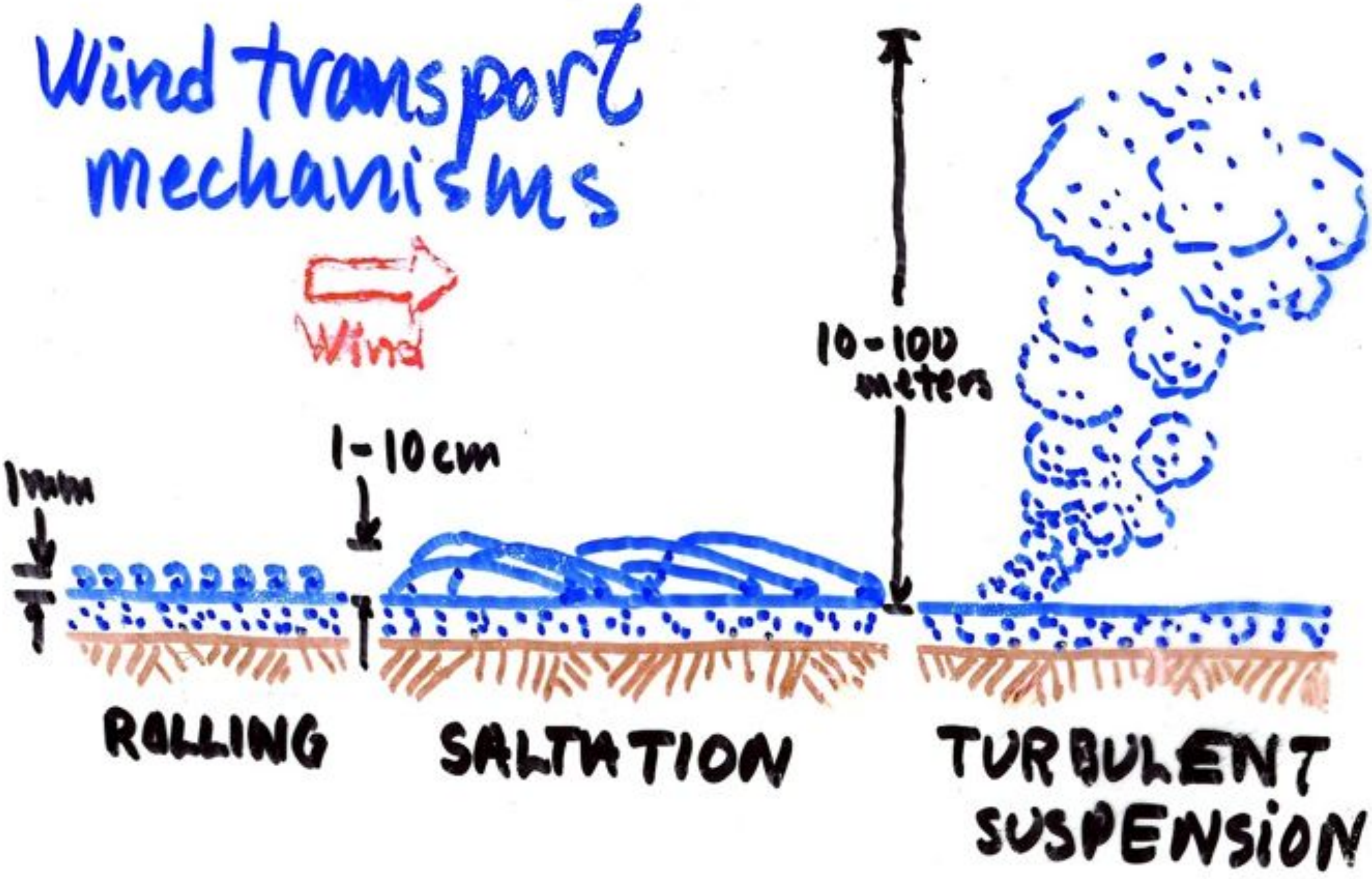
- Warmer snow → stickier snow
- Higher humidity → stickier snow
- Older snow → larger, heavier, better-bonded grains

Wind speed varies with height.

Standard to measure w_c at 10 m above surface:

- Loose unbonded snow $w_c \sim 5\ \mathrm{m\ s^{-1}}$ (~10 kt)
- Dense bonded snow $w_c \sim 25\ \mathrm{m\ s^{-1}}$

Modes of Snow Transport



Rolling Snow

Grains move along the surface in a layer ~ 1mm thick.

- Rolling crystals can account for 10% of mass transport when both rolling and saltation are active.

Saltating Snow

(Latin *saltare*, to jump)

Grains are kicked into the air when bombarded by other crystals

- Need some airborne particles to get started (e.g. dust, precipitating snow)
- Can get started at $w \sim 5$ m s^{-1} in cold loose snow
- Saltating grains concentrated in ~0.1 m above surface.

Suspended Snow

Horizontal wind over rough surface can cause eddies.

- Turbulent eddies can pick up snow.
- Snow crystals typically fall at 0.2 –2.0 m s^{-1}
- Upward eddy speed must exceed rate of fall.
- Saltation → suspension when w >15 m s^{-1}
- Most mass is transported within ~1 m of snow surface
- “blowing snow” vs. “drifting snow”
- What’s the difference?

Eddy Velocities and Wind Speed

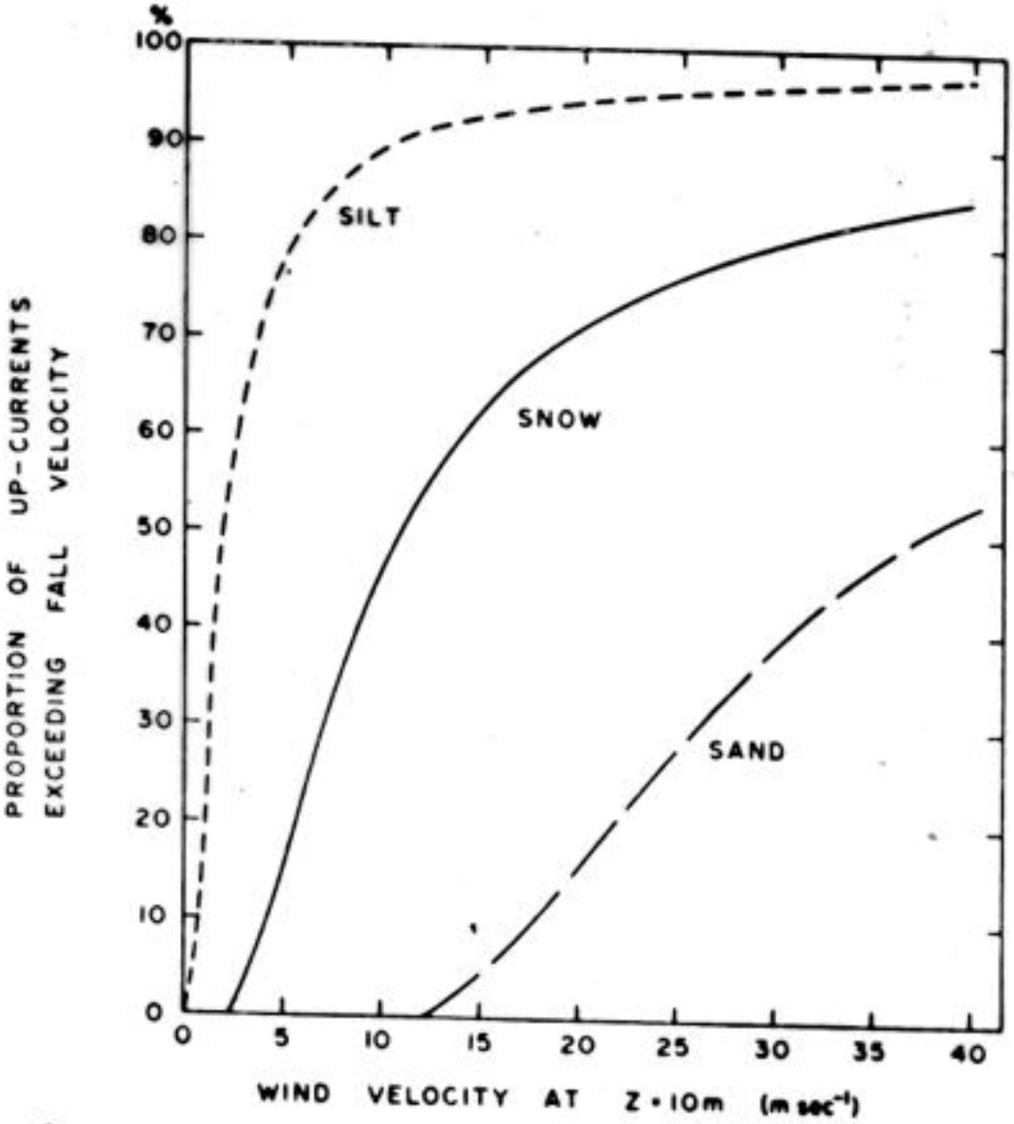


Fig. 17. Cumulative frequency of upward eddy velocities capable of supporting suspended particles of silt, snow and sand. [From Radok (1968)].

Horizontal Mass-Flux Profiles

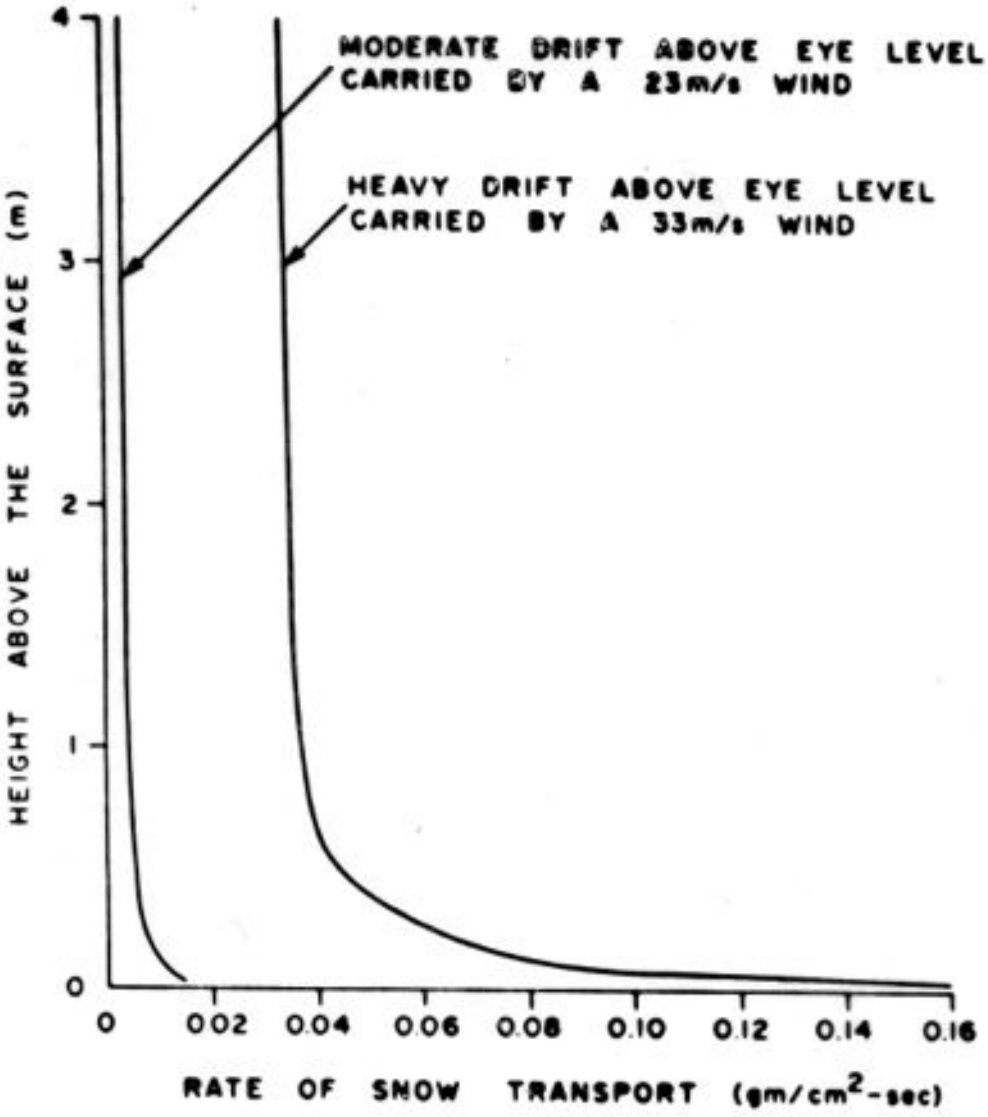


Fig. 13. Typical profiles of the horizontal mass flux [from Mellor (1965)].

More suspended snow at higher elevation in stronger wind

Air Flow over Ridges

Air moving over ridge moves faster than air over flat terrain because the same flux of air must be transported through a narrower "window" in elevation range

- Analogous to faster river flow where channel narrows

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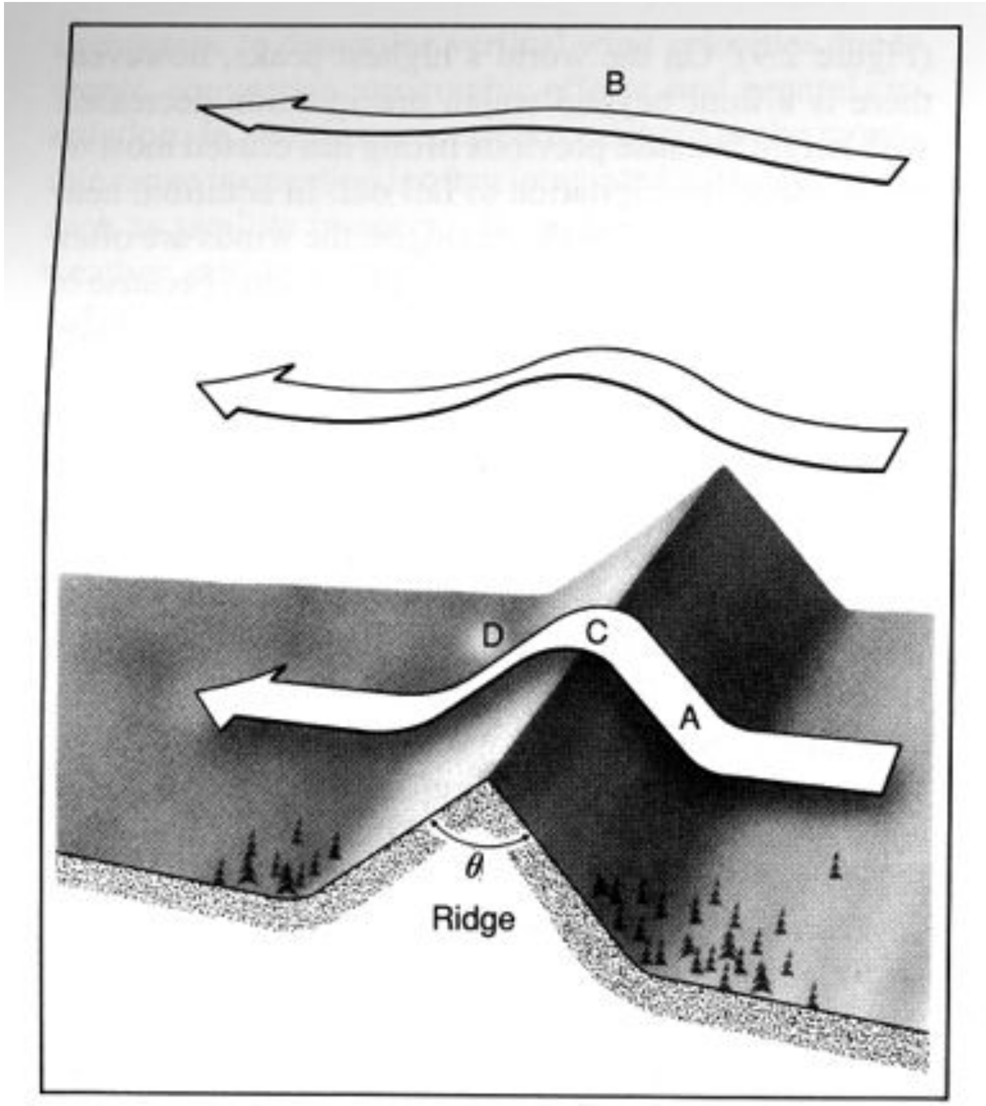

Figure 2.10. A: Airflow over a ridge; B: free-air motion; C: ridge crest; A, D: acceleration and deceleration zones.

Mountain Wind and Snow

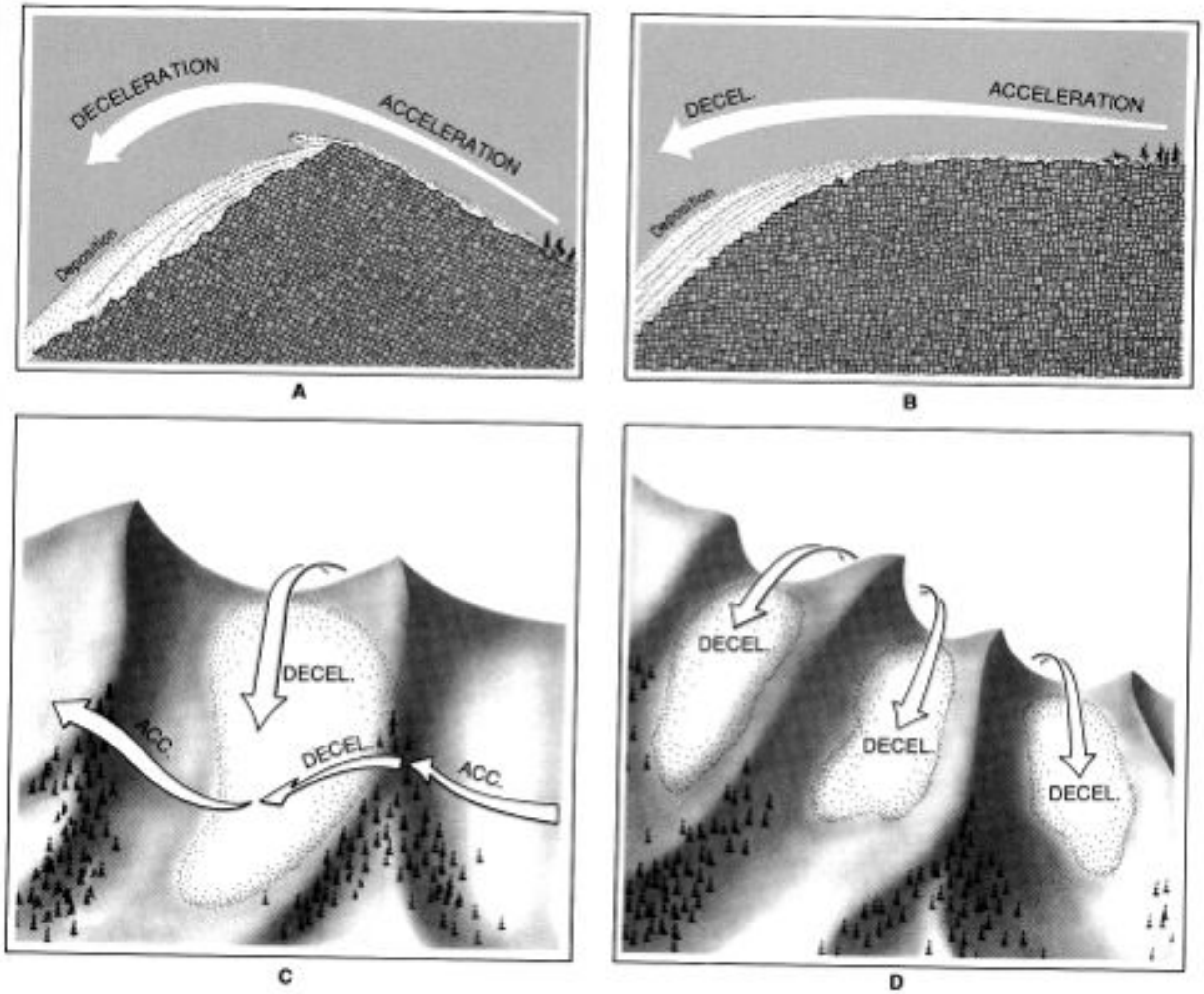

Figure 2.15. Snow is picked up in acceleration regions and deposited in deceleration regions (A, B). This produces lee zone deposition, cross-loading, and deposition in gullies and notches (C, D).

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Cornice Structure

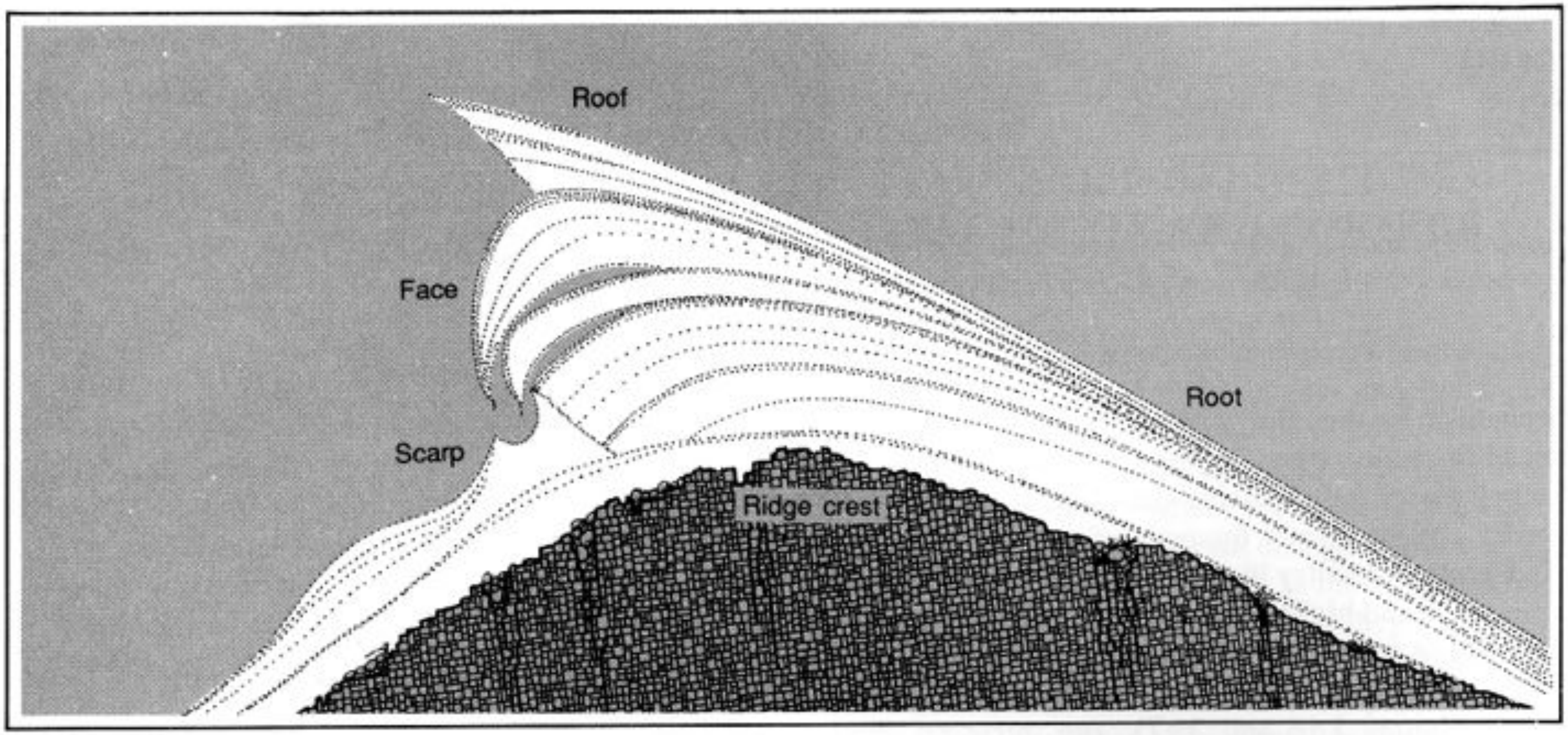

Figure 2.17. Cornice structure and nomenclature. Prevailing wind direction is from right to left.

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Cornice on a ridge crest

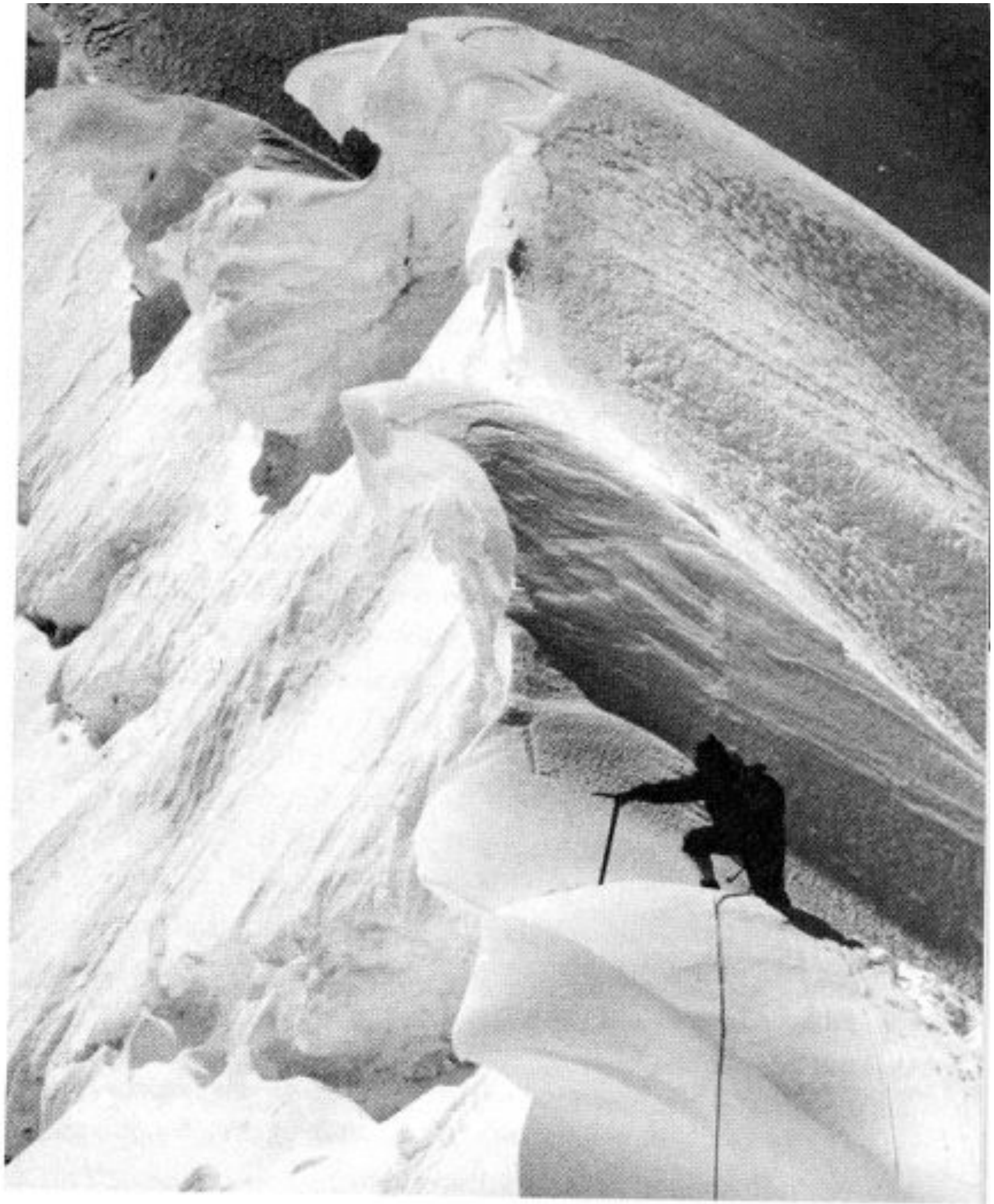

Figure 2.19. Cornice on a ridge crest. (Photo by A. Roch)

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Ridge Turbulence

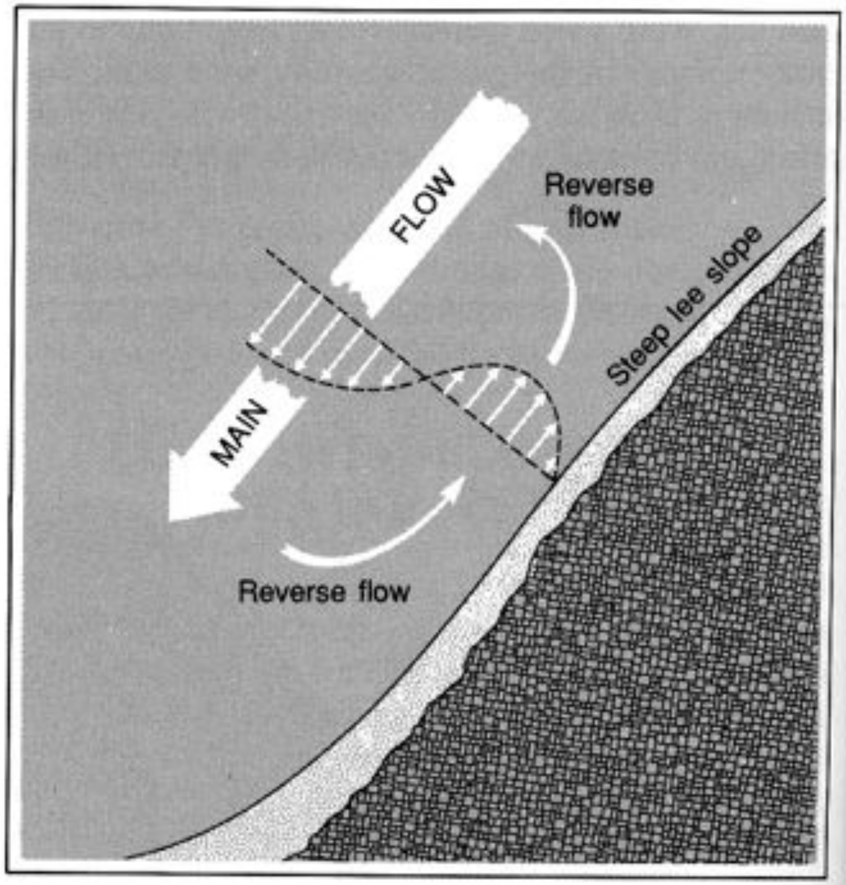


Figure 2.11. Reversal of flow on steep lee slopes. This pattern allows cornice and avalanche formation.

Flow separation over sharp ridges

- Reverse flow or eddy on lee slope
- Saltating and suspended snow drops from air moving up-slope

Avalanche Handbook

Dunes

Saltating snow forms moving dunes

Video:

Migrating dunes Niwot Ridge CO

Snow dunes - Ny Alesund, Svalbard

http://www.icehouse.net/john_benham/black&white-11.htm

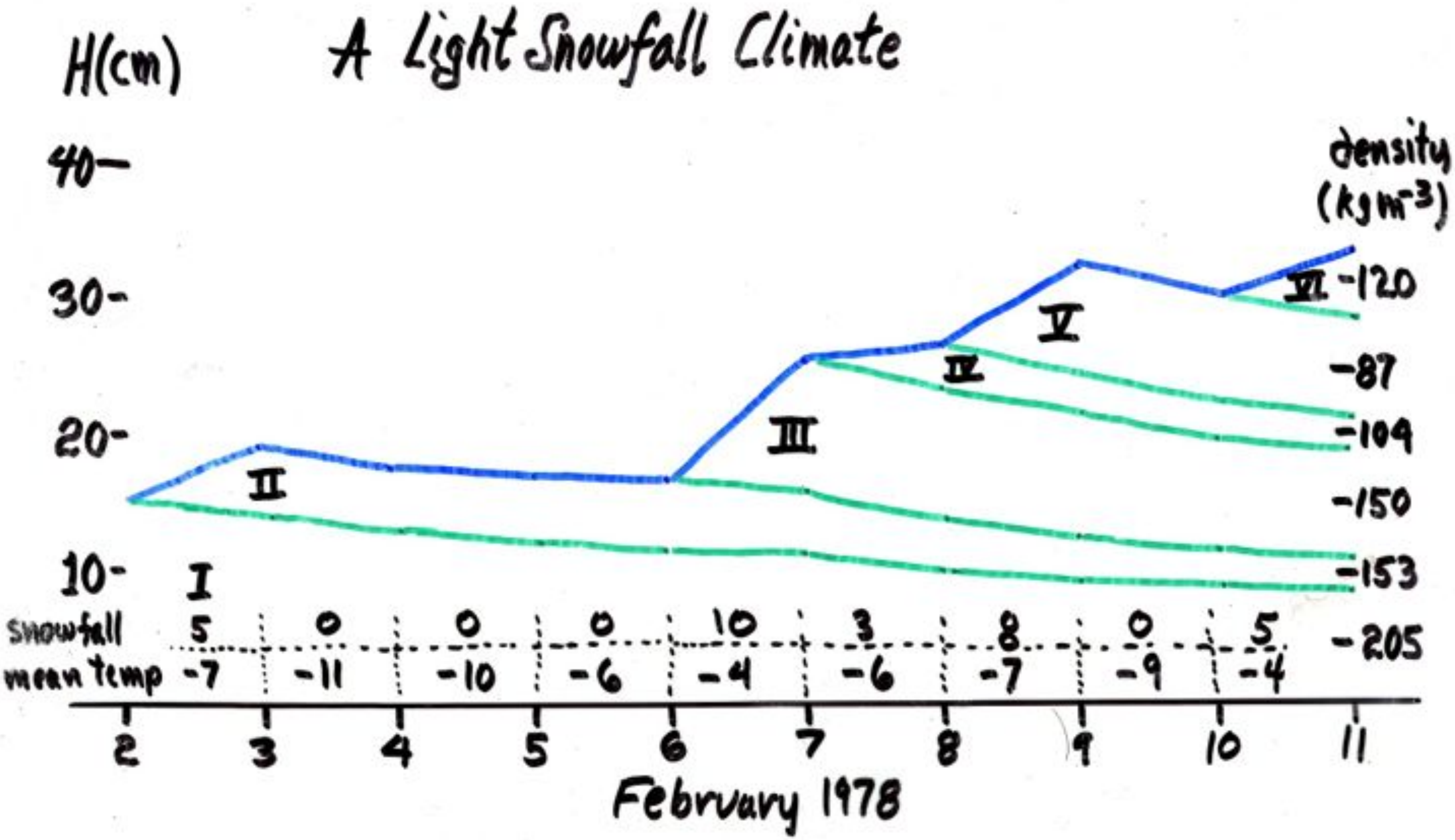
Consequences of Snow Transport

Snow can be redistributed on the ground.

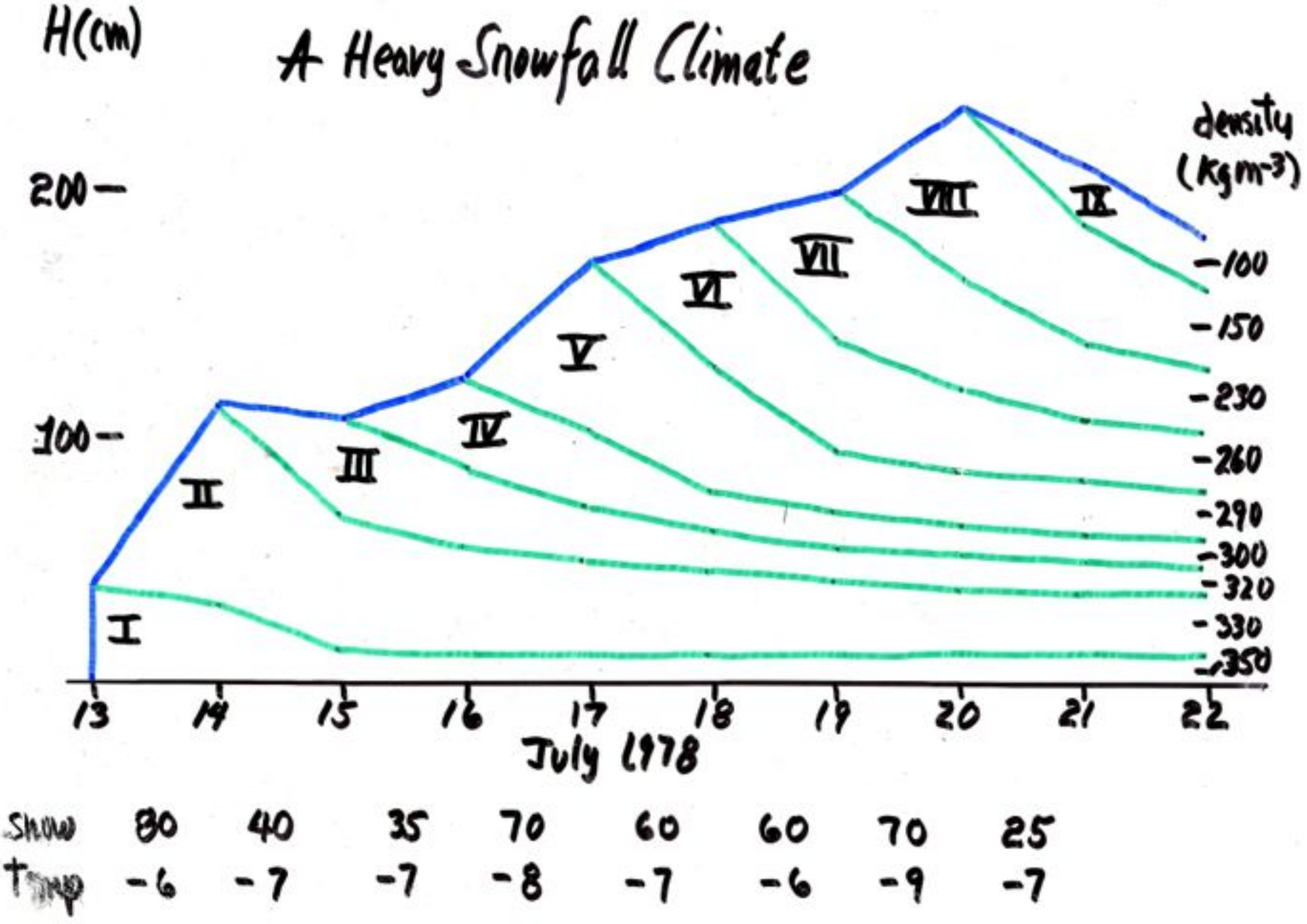
Surface morphology can be altered
- Dunes
- Sastrugi
- Wind crust, wind packing

Implications
- Hard to measure precipitation
- Sublimation losses can be severe during transport

Snowpack Evolution I



Snowpack Evolution II



Deposited Snow

Snow Stratigaphy

- Layers with differing density and texture (grain size, shape, bonding)
- Interfaces between layers

Causes of Stratigaphy

- Variations in snowfall
- Wind action
- Metamorphic processes acting on surface and interior of snow pack

Consequences of Stratigraphy

Mechanical

- avalanches

Hydrological

- water penetration

Energy

- solar radiation
- snow temperature

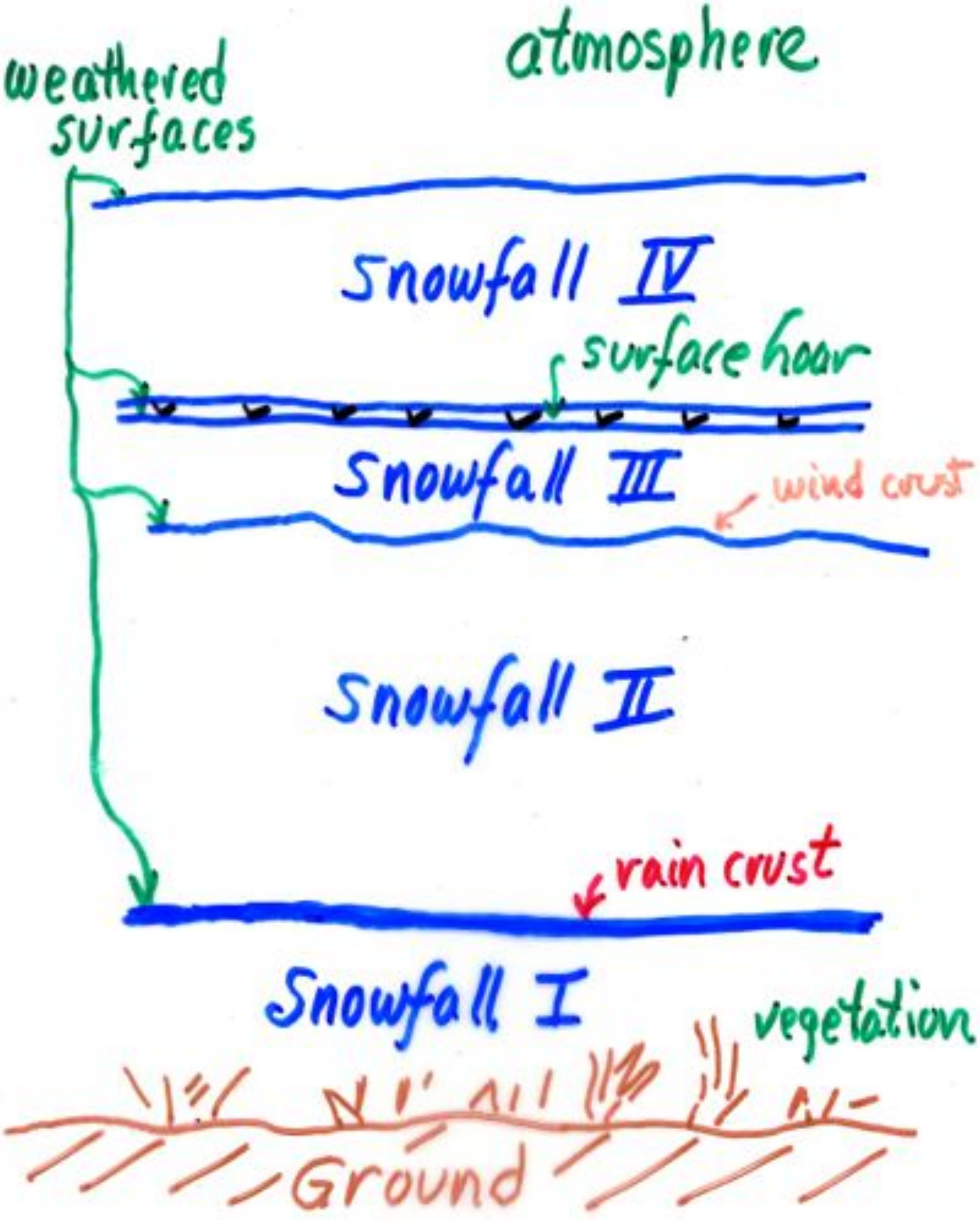
Important Properties of Snowpack

- layered structure
- state of stress
- distribution of temperature

Factors affecting these Properties

- weather (precipitation and air temperature)
- snow metamorphism
- terrain

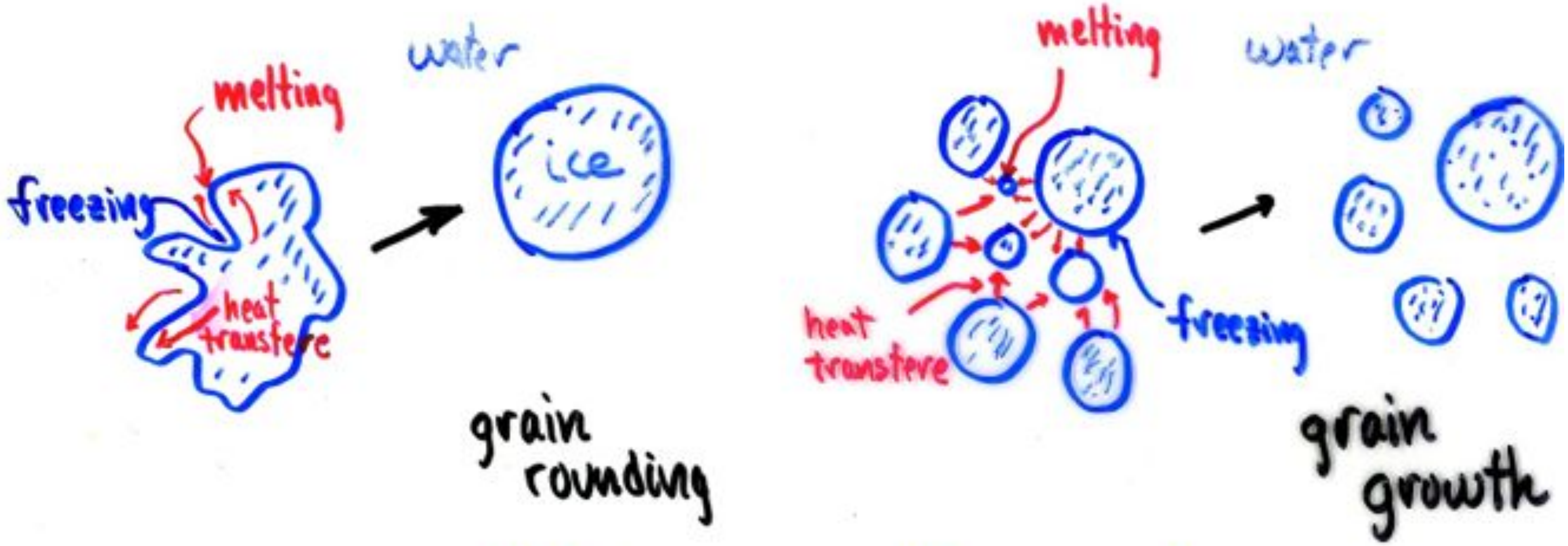
Snowpack Layered Structure



C.F. Raymond

Wet Snow

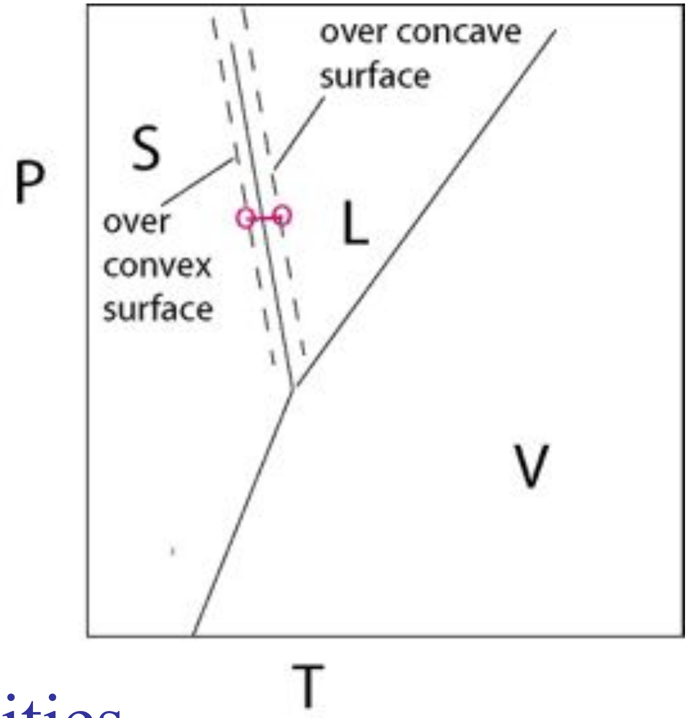
- Temperature gradients and freezing-point differences are created by curvature differences.
- Heat flows from concave to convex surfaces
- Heat is used for phase changes.



Metamorphism of very wet snow

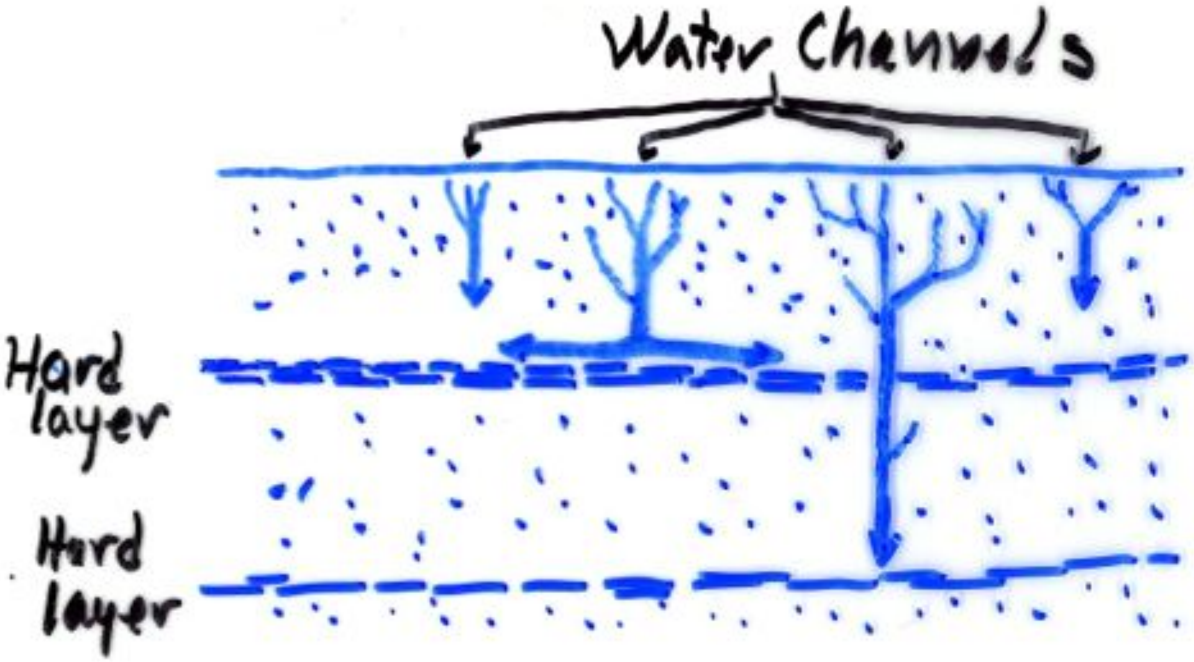
Wet Snow

- Temperature is pinned at local melting point everywhere on the ice-water interface
- Melting temperature is reduced over convex regions, and raised over concave regions
- Heat flows through the ice from “hot” concavities to cold convexities
- Concavities cannot cool; heat must be obtained by freezing liquid (to release latent heat)
- Convexities cannot get warmer; heat must be absorbed by melting



Water Motion in Wet Snow

- Water tends to form pipes
- It can pond and freeze on low-permeability layers, making ice lenses



Relict Pipe

Class 8ic and 8il, vertical and horizontal ice bodies. Photo P. Marsh.

P. Marsh

Crusts

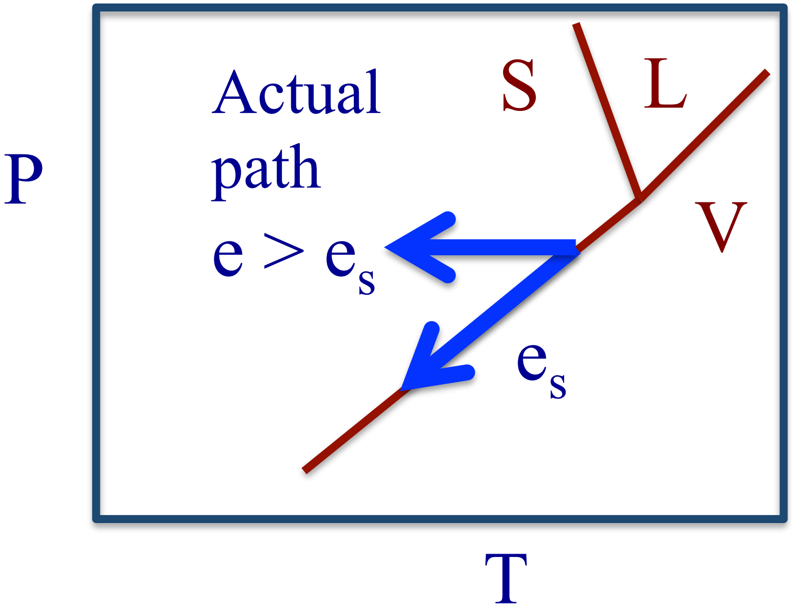
- Saltation can break crystals into fine fragments
- Surface snow is porous and permeable
- Wind drives fragments into holes between grains
- Often denser and less permeable than snow below.
- Result is called "wind slab"

https://www.flickr.com/photos/somenice/3404055374/

Crusts

When surface snow is cold, and snow at depth is warm …

- Crusts can form when vapor from within the snowpack deposits in surface snow.
- May be associated with depth hoar forming below.



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Surface Hoar

Surface hoar can form when air cools rapidly but surface snow is still warm.

Vapor leaving warm snow is supersaturated in cold air

https://en.wikipedia.org/wiki/Types_of_snow#/media/File:Skiing_Christmas_%2705_034.jpg

Temperatures in Snow

- air is cold, ground is warm

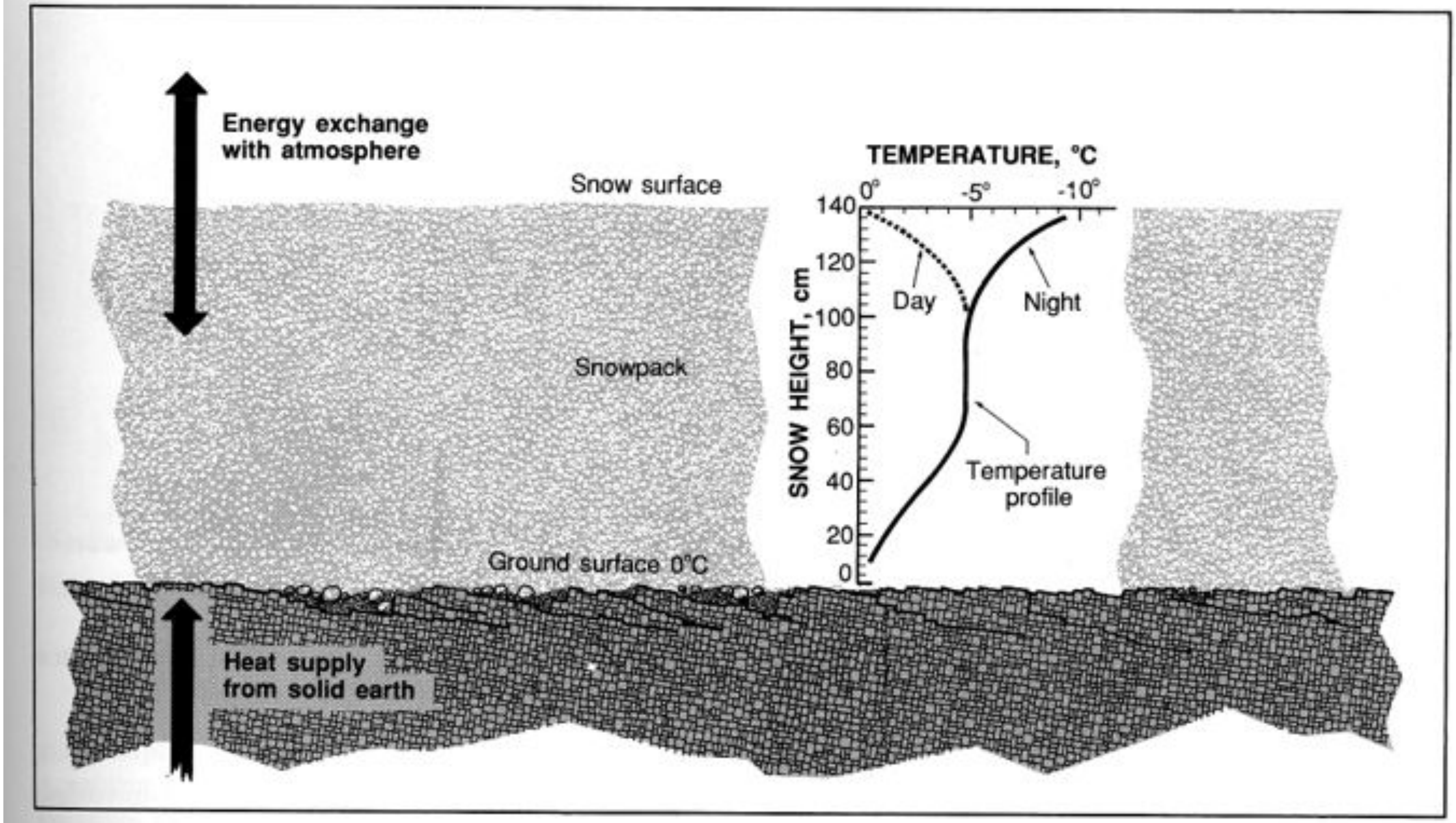
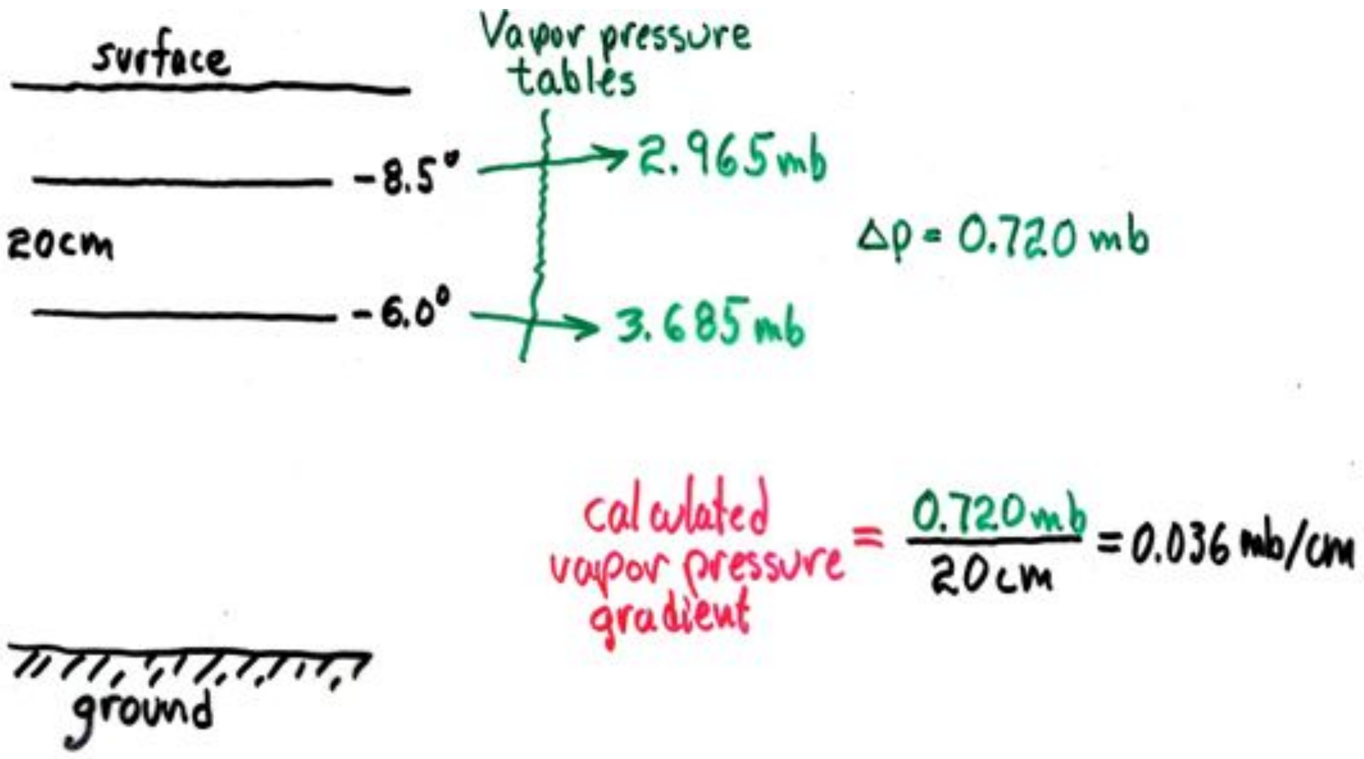


Figure 3.9. Illustration of the temperature variations in a snowpack. Diurnal variations occur in the upper portion. A temperature gradient of 10°C/m is strong enough to produce facets in the snowpack.

Vapor-Pressure Gradients

- Vapor-pressure gradients created by temperature gradients
- Vapor diffuses from higher to lower pressure
- Refreezes in faceted forms and hoar



Equilibrium-form Metamorphism (“Destructive” Metamorphism)

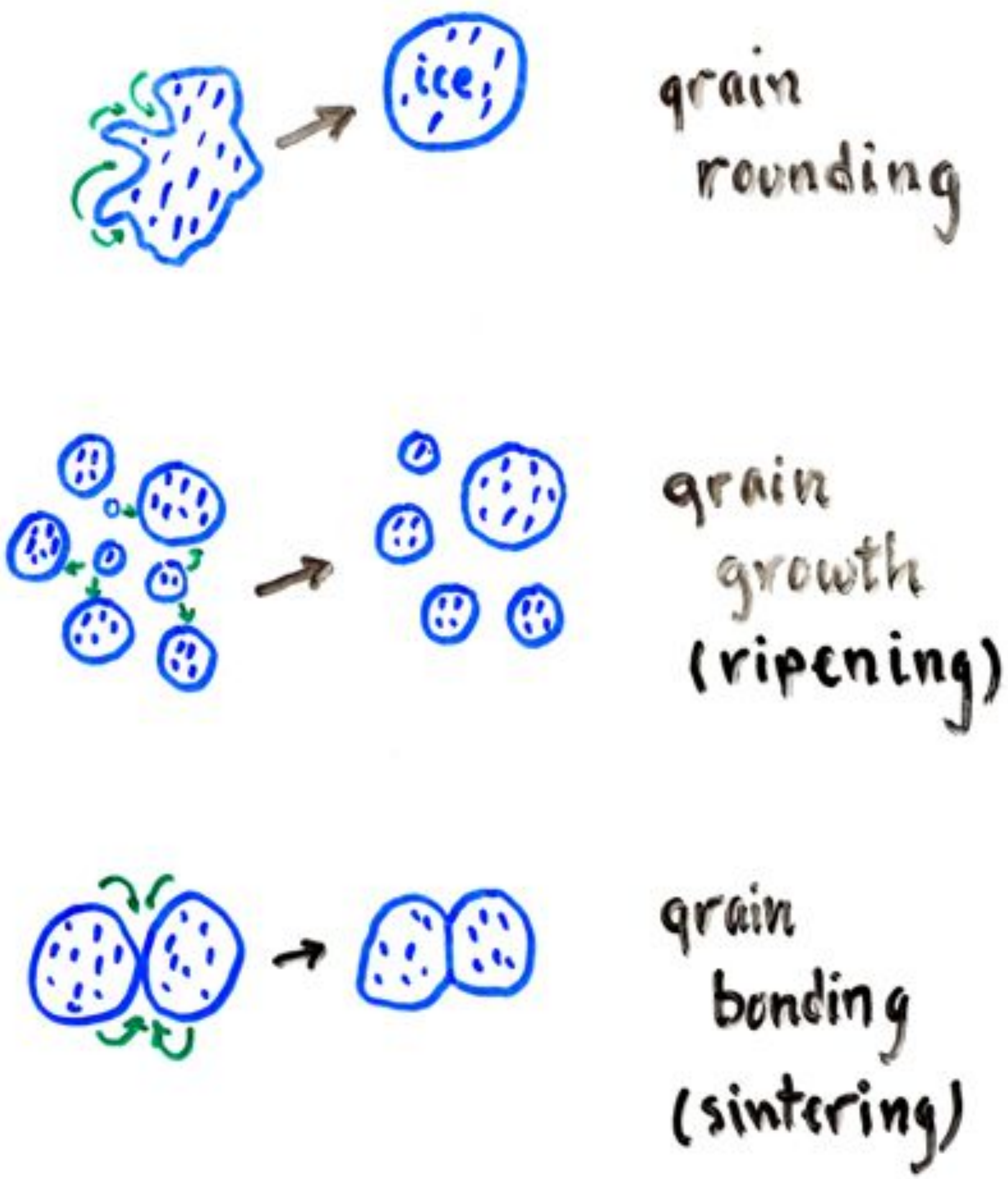
- Ice-air surface area represents stored energy (broken bonds)
- New snow has high surface-to-volume ratio (small grains, complex shapes)
- Old snow with large rounded grains represents a lower-energy state

Processes in snow act to:

- Increase mean grain size (larger grains grow, smaller grains shrink and vanish)
- Make grains round
- Fill in cracks between grains (bond growth)

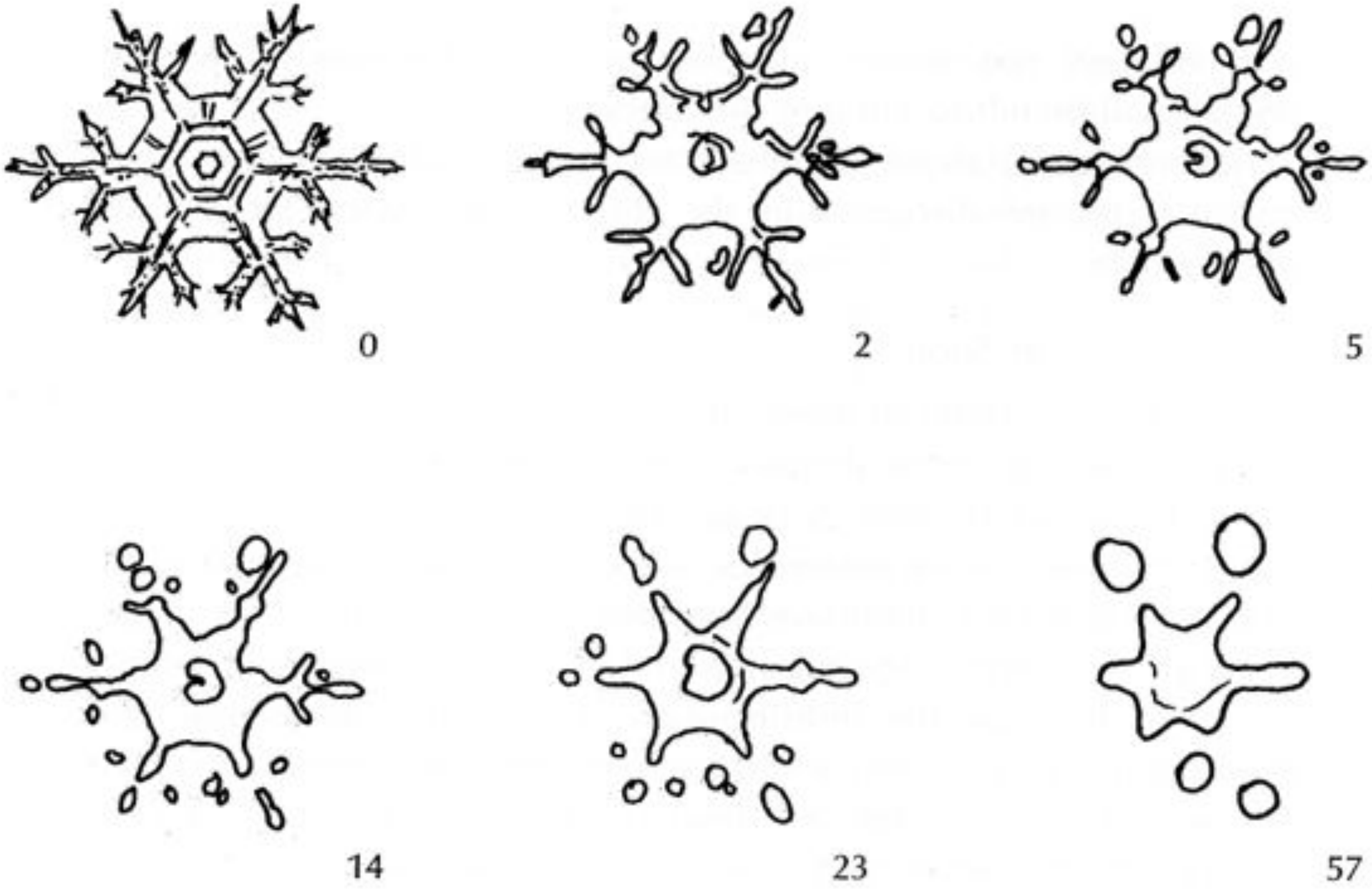
Mass Transfer Reduces Surface Area

Result is equilibrium forms



C.F. Raymond

Destructive Metamorphism of a Snow Crystal



6. The destructive metamorphism of a stellar snow crystal. The numerals give the age of the snow crystal in days.

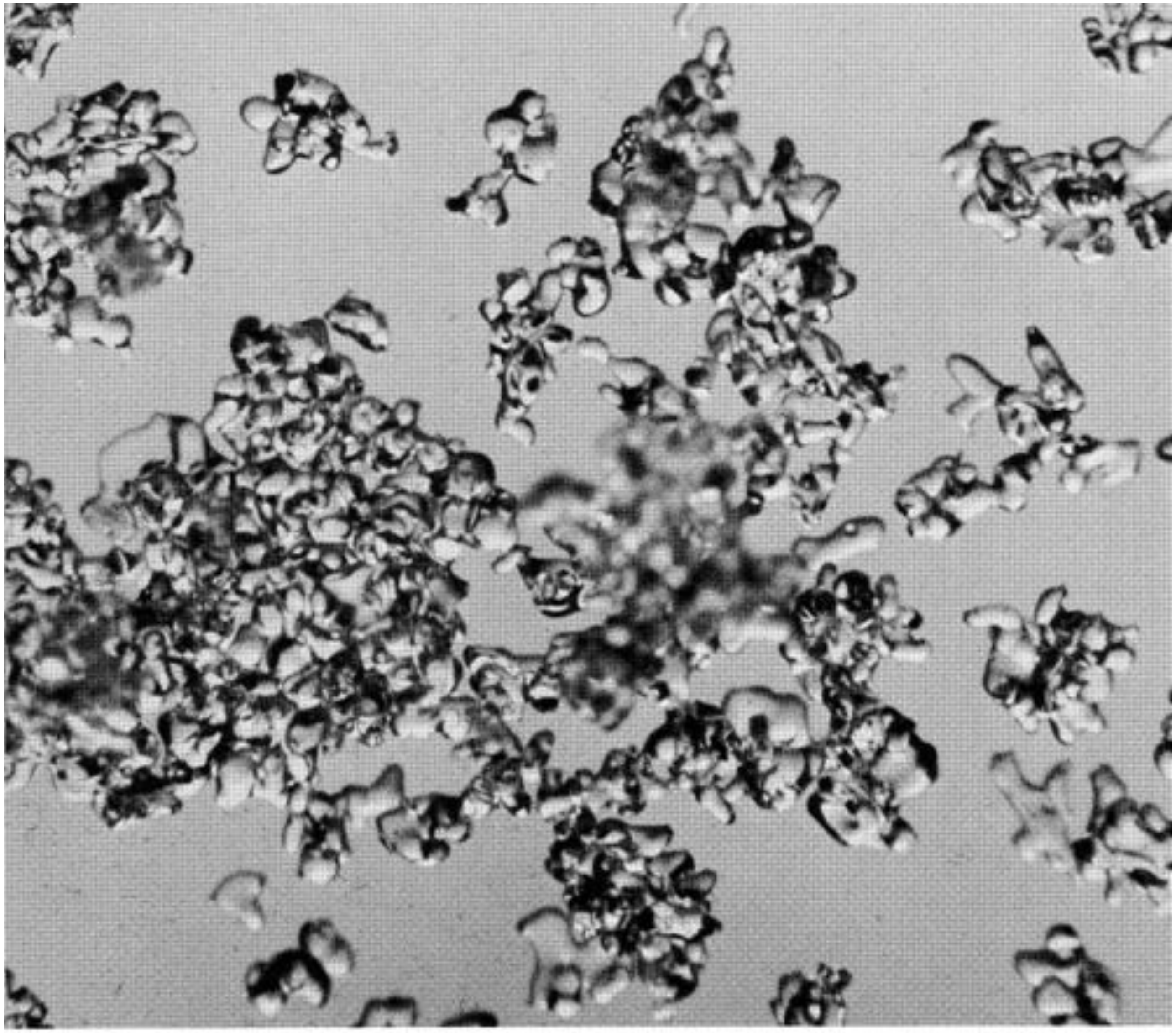
E. LaChapelle, ***Field Guide to Snow Crystals***

Early Destructive Metamorphism

35. Stellar crystals in the first stages of equitemperature metamorphism. 26X

LaChapelle, *Field Guide to Snow Crystals*

Ongoing Destructive Metamorphism

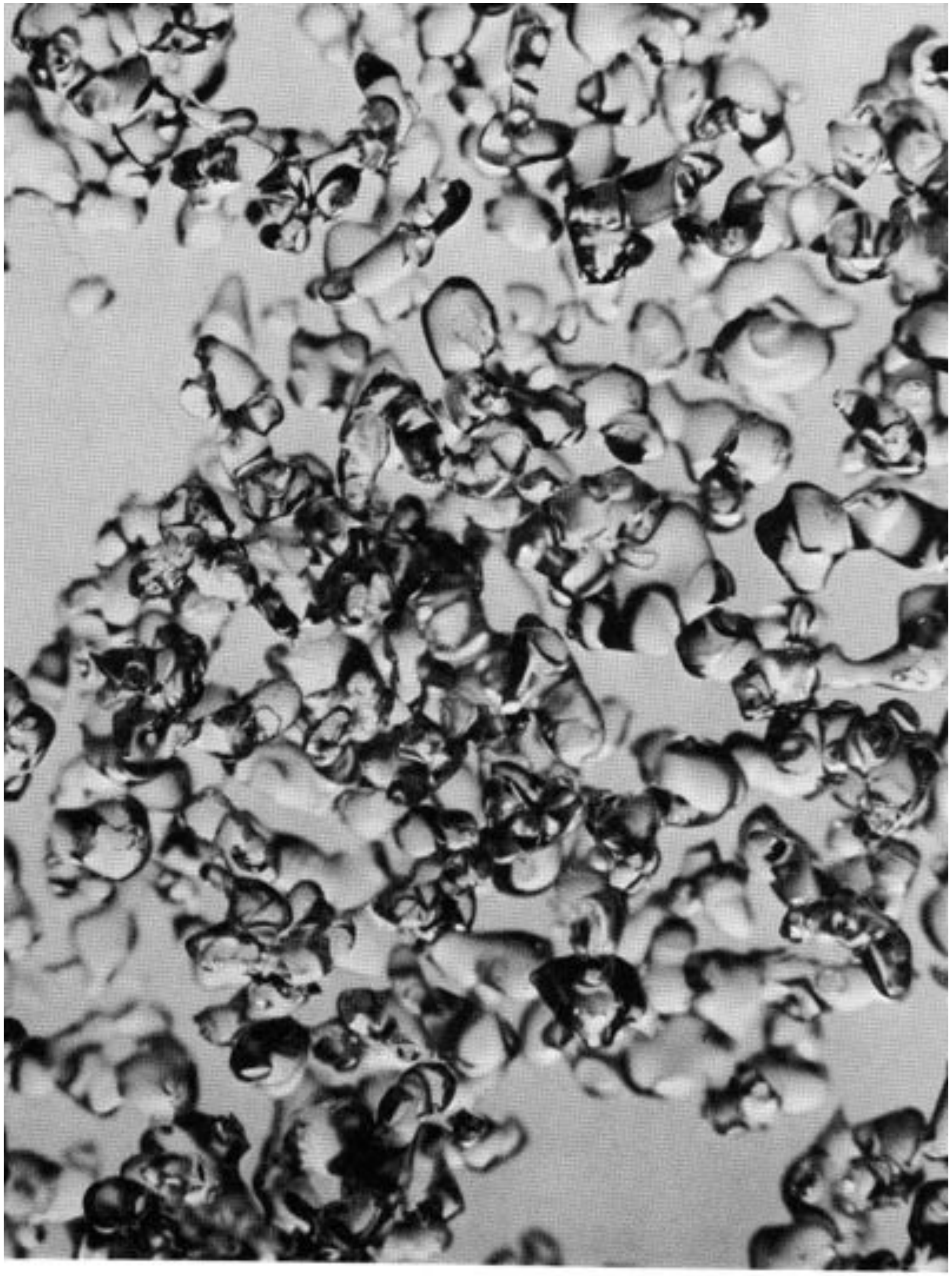


38. Stellar crystals which have lost almost all their identity through equitemperature metamorphism. 26X

LaChapelle, ***Field Guide to Snow Crystals***

"Old Snow": the equilibrium form.

The end result of destructive metamorphism.



44. Fine-grained old snow, 6 weeks old. 26X

LaChapelle,
Field Guide to Snow Crystals

Destructive Metamorphism

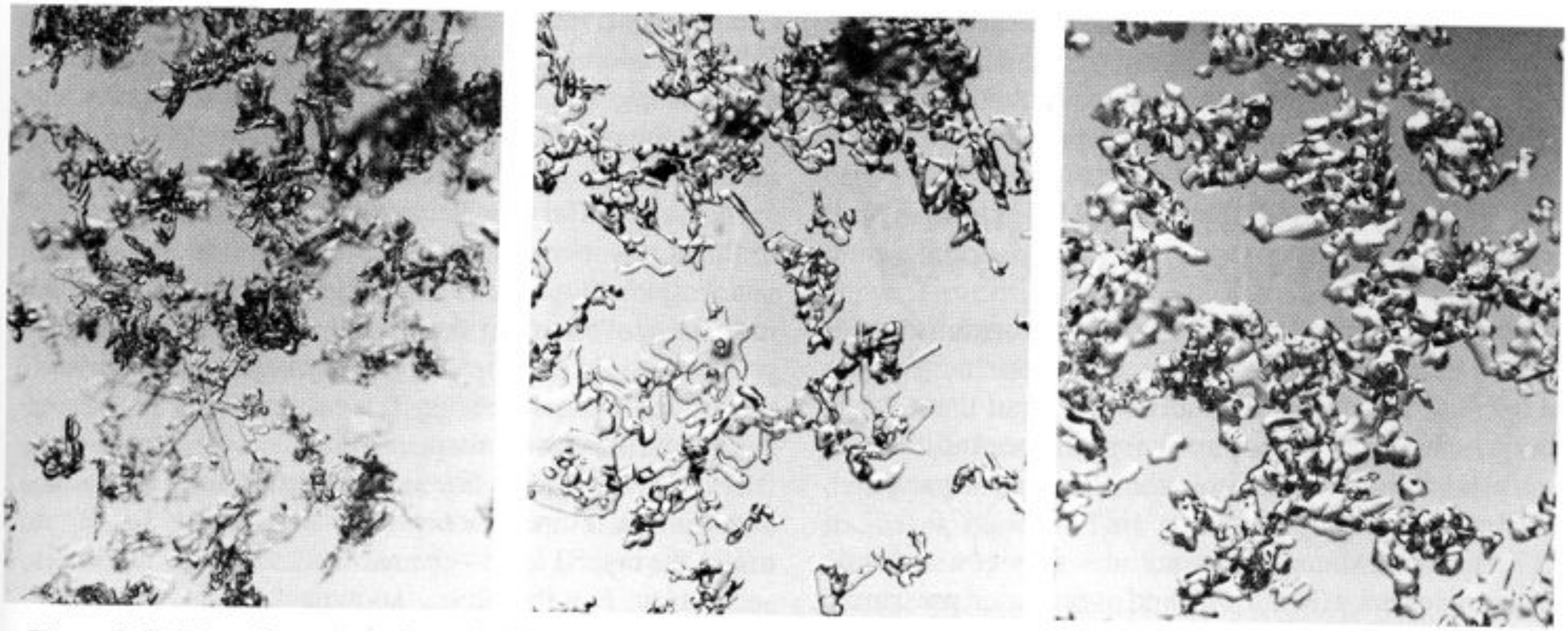


Figure 3.11. Transformation of newly fallen snow to rounded forms in three stages. (Photos by E. LaChapelle)

McClung and Schaerer, ***Avalanche Handbook***

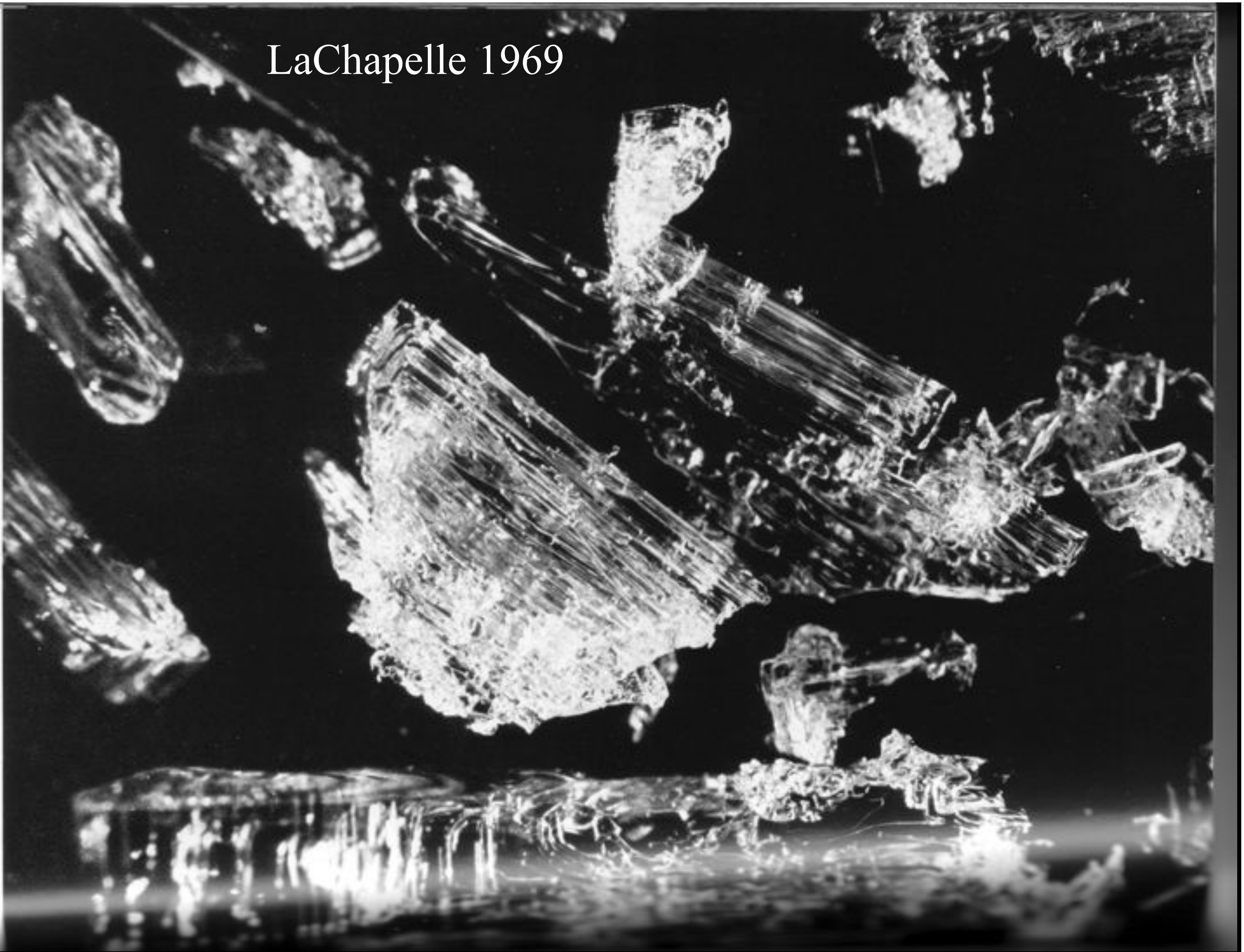
Kinetic-Growth Metamorphism
[“Constructive” Metamorphism]

- Formation of frost and hoar
- Complex shapes ***increase*** surface area
- vapor-pressure gradients created by
  temperature gradients
  are more important than vapor-pressure

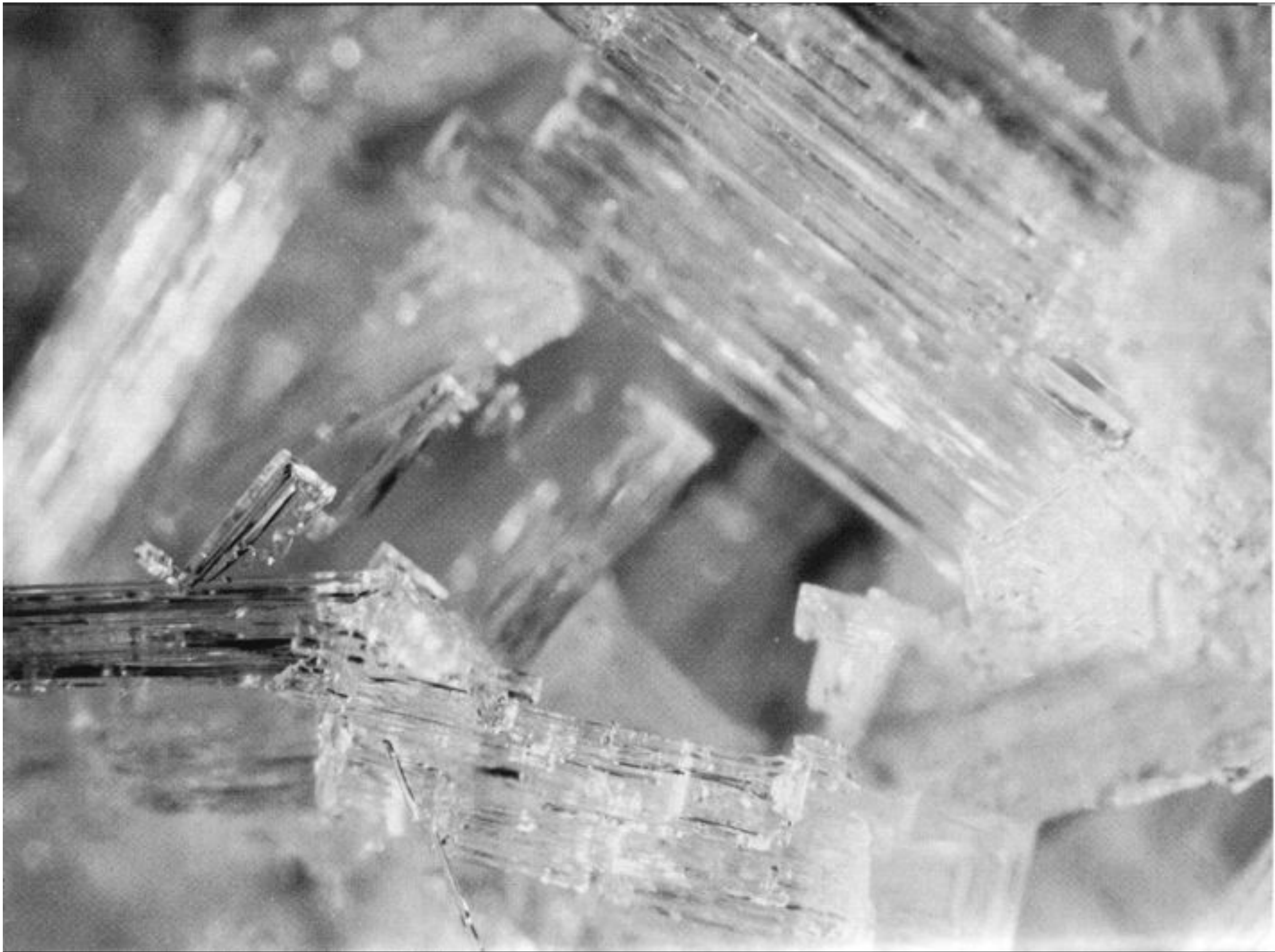
gradients from grain curvature

when $dT/dz > 10$ deg m^{-1}

LaChapelle 1969



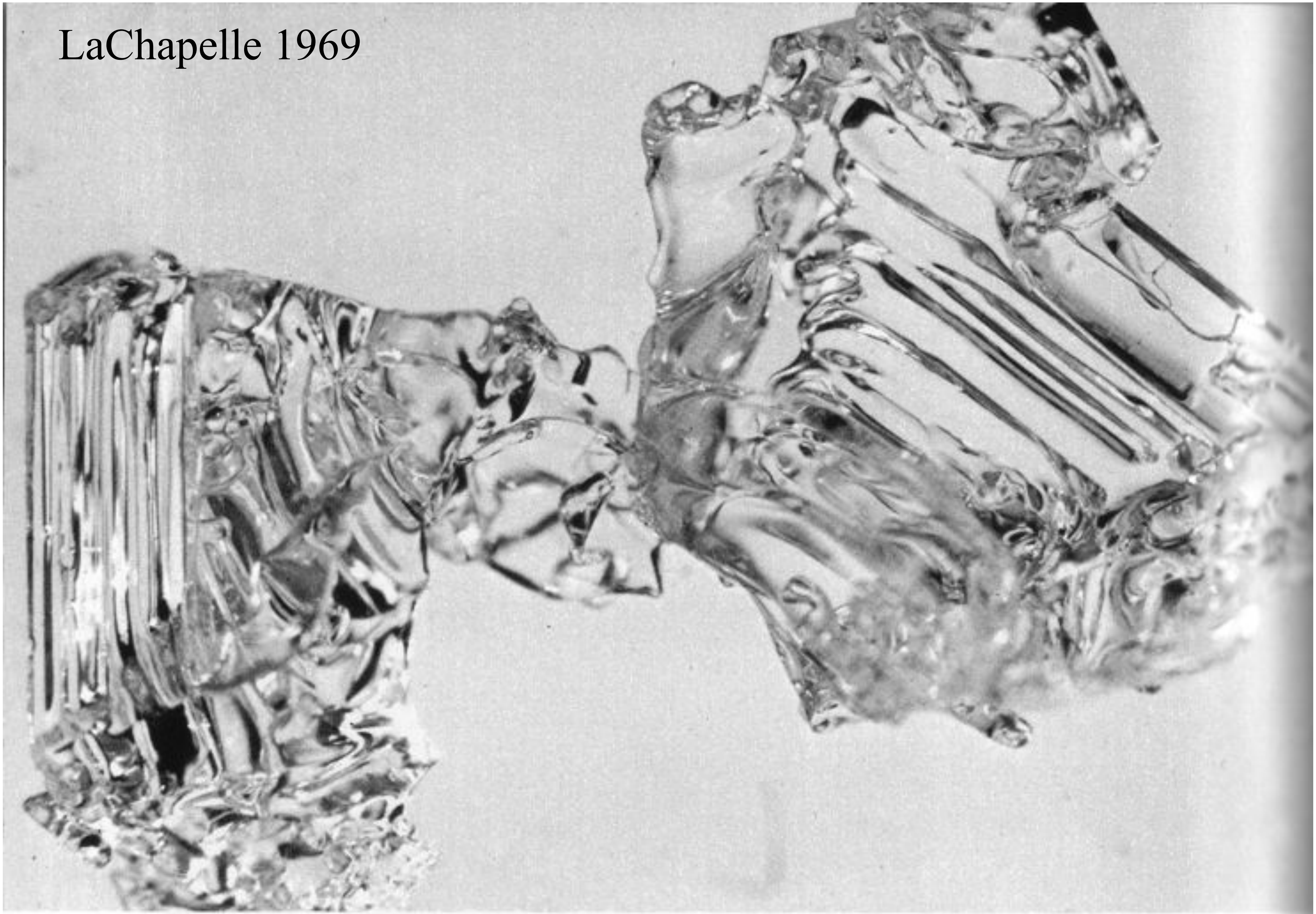
48. Typical crystals of mature depth hoar. 24X



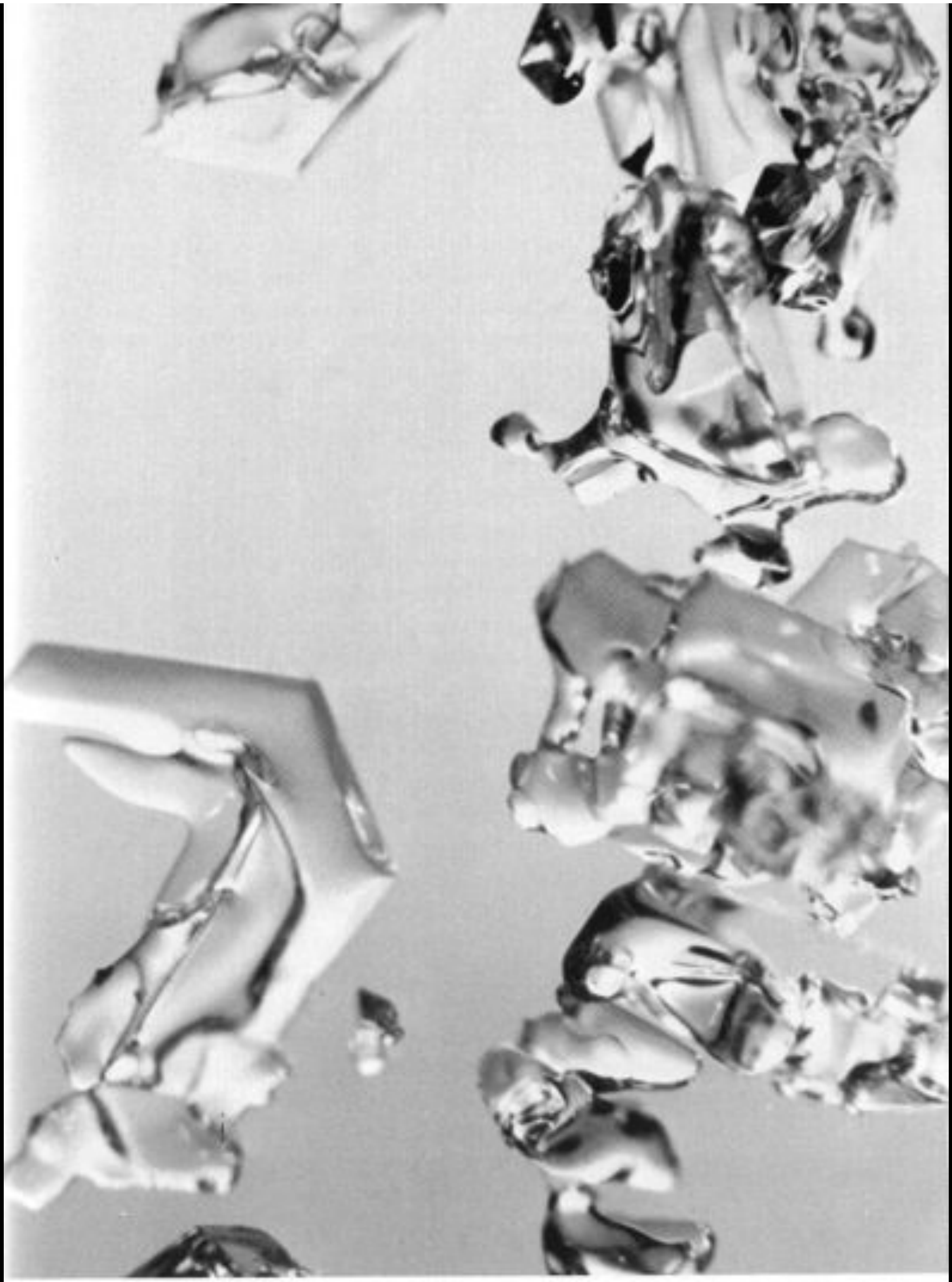
49. *Undisturbed sample of depth hoar showing natural arrangement of crystals. 24X*

LaChapelle 1969

LaChapelle 1969



52. *Depth hoar crystals slightly altered by equitemperature metamorphism. 20X*

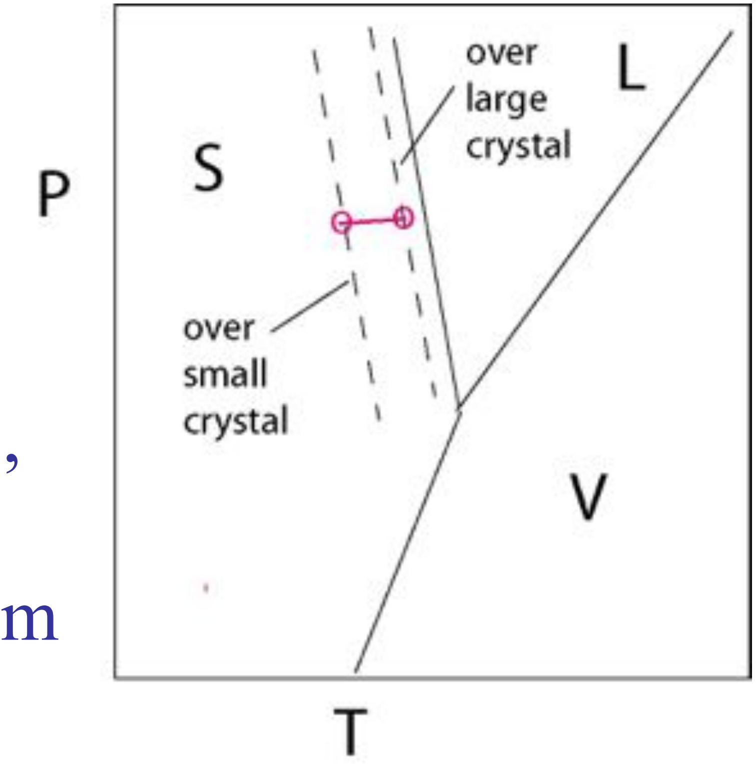


53. Depth hoar crystals profoundly altered by equitemperature metamorphism. 30X

LaChapelle, 1969:
Field Guide to Snow Crystals

Slush

- Temperature is pinned at local melting point everywhere on the ice-water interface
- Melting temperature is reduced more over more-convex surfaces, i.e. over smaller ice crystals
- Heat flows through the water from large crystals to small crystals



- Larger crystals cannot cool; heat must be obtained by freezing liquid (to release latent heat)
- Smaller crystals cannot get warmer; incoming heat must be absorbed by melting

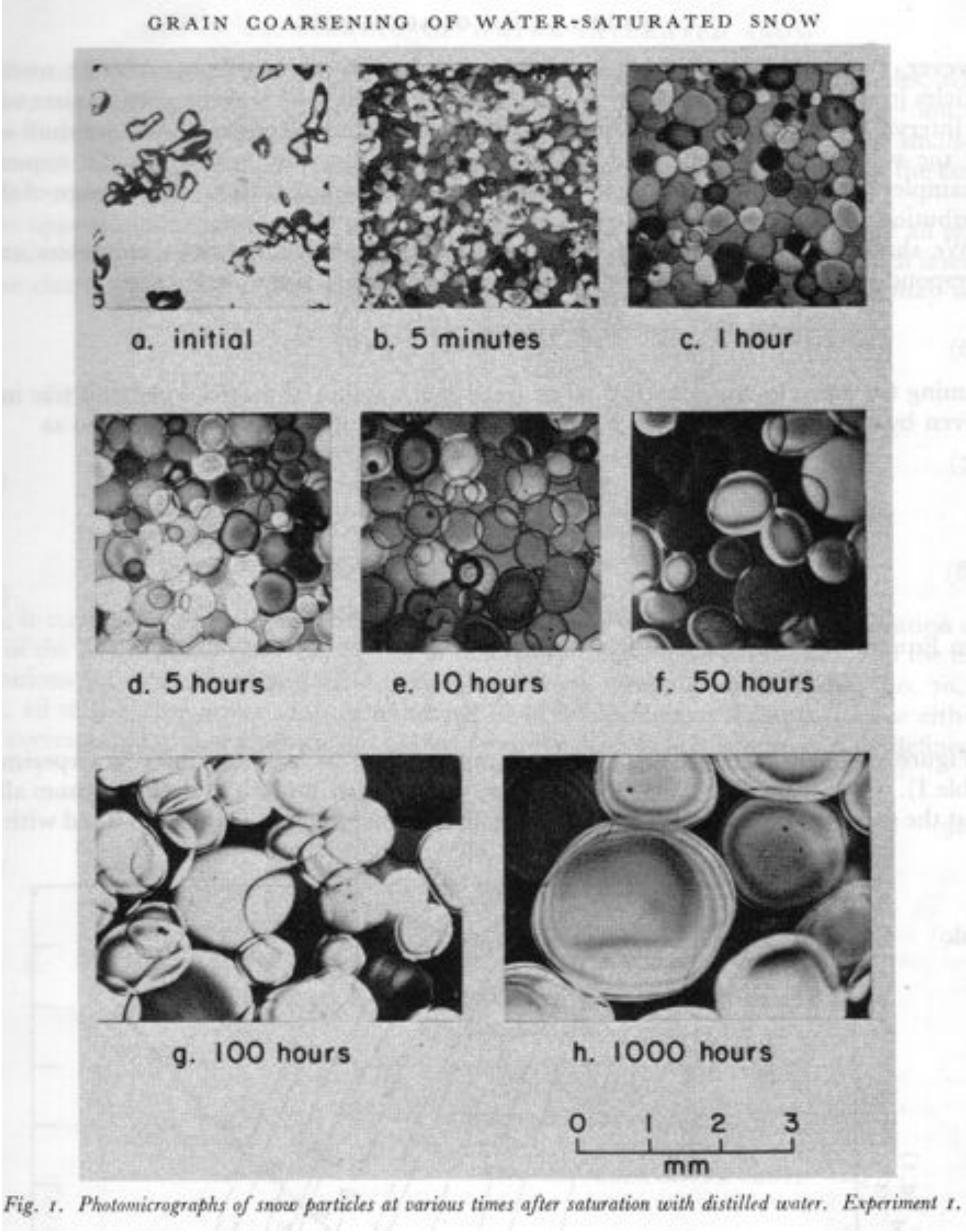

GRAIN COARSENING OF WATER-SATURATED SNOW

Fig. 1. Photomicrographs of snow particles at various times after saturation with distilled water. Experiment 1.

Grain growth in slush

Raymond & Tusima 1979
J. Glac. 22, 83-105

Rocky Mountain
National Park,
Colorado,
March 1979