

PRINCIPLES OF GLACIOLOGY
ESS 431

- SNOW -
DEPOSITION, WIND TRANSPORT,
METAMORPHISM

OCTOBER 10, 2006

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Housekeeping for the day

Field Trip

- Snow grain size changing?
- Questions on writing assignment?

Thursday Lecture – Howard Conway, on avalanches

Friday Discussion Session

- 1:30-2:30 Johnson 117 with Conway

Sources

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

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

Lecture notes from C.F. Raymond and E.D. Waddington.

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

We observe that 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

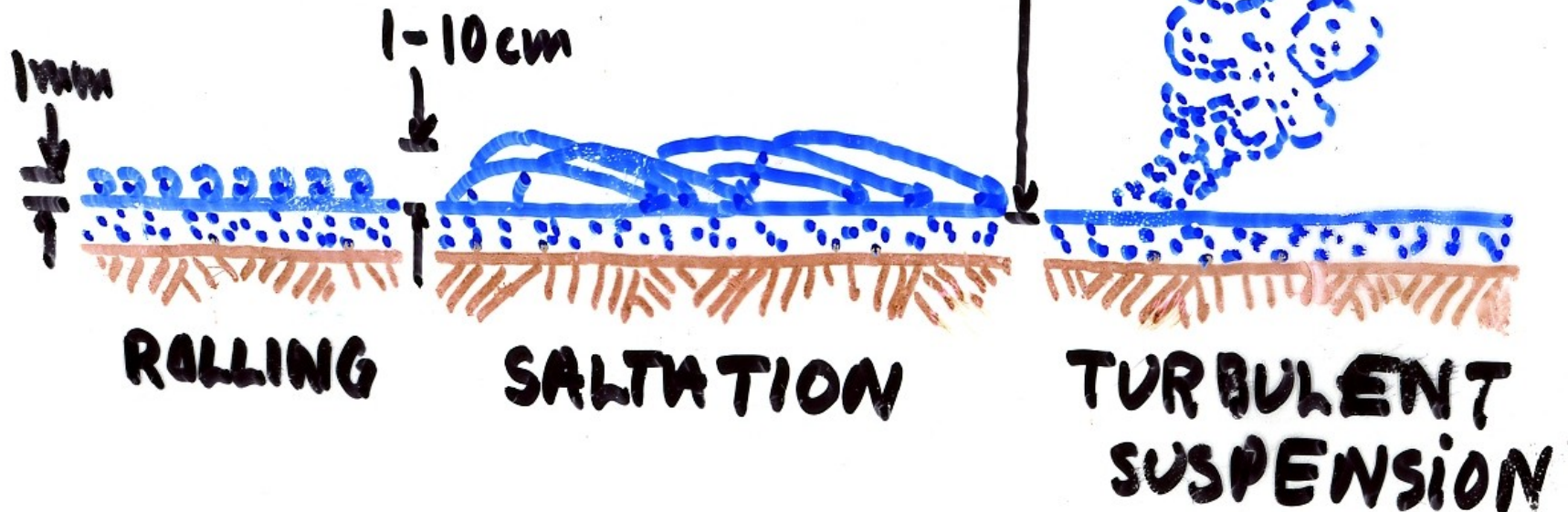
Wind speed varies with height.

Standard to measure w_c at 10 m above surface:

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

Modes of Snow Transport

Wind transport mechanisms



Rolling Snow

Grains move along the surface in a layer $\sim 1\text{mm}$ 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 $w \sim 5 \text{ m s}^{-1}$ in cold loose snow
- Saltating grains concentrated in $\sim 0.1 \text{ m}$ above surface.

Suspended Snow

Horizontal wind over rough surface can cause eddies.

- Turbulent eddies can pick up snow.
 - Snow crystals typically fall at $0.2 - 2.0 \text{ m s}^{-1}$
 - Upward eddy speed must exceed rate of fall
 - Saltation $\rightarrow$ suspension when $w > 15 \text{ m s}^{-1}$
 - Most mass is transported within $\sim 1 \text{ m}$ of snow surface
-
- “blowing snow” vs. “drifting snow”

Eddy Velocities and Wind Speed

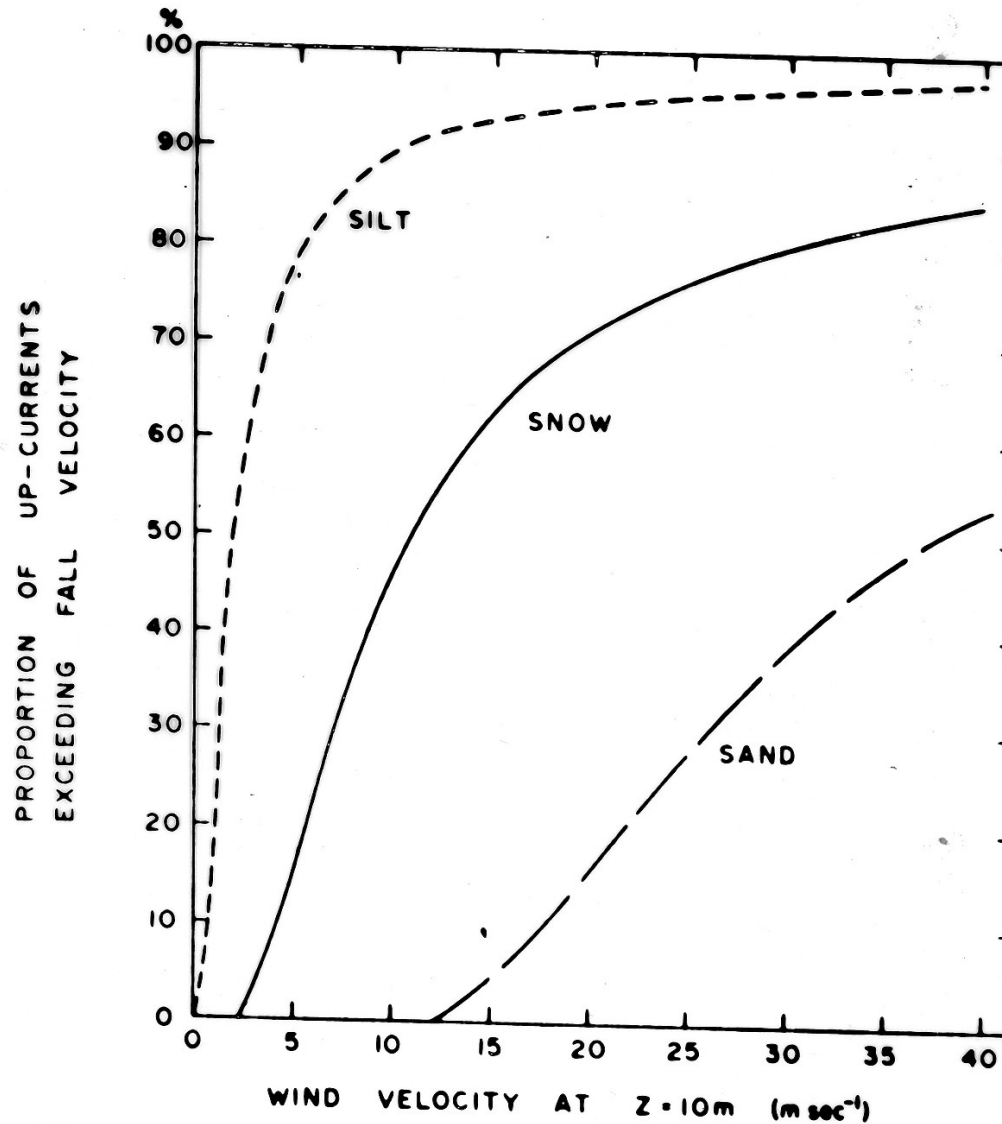


Fig. 17. Cumulative frequency of upward eddy velocities capable of supporting suspended particles of silt, snow and sand. [From Radok (1968)].



South Pole Station in blizzard, 8 March 1992

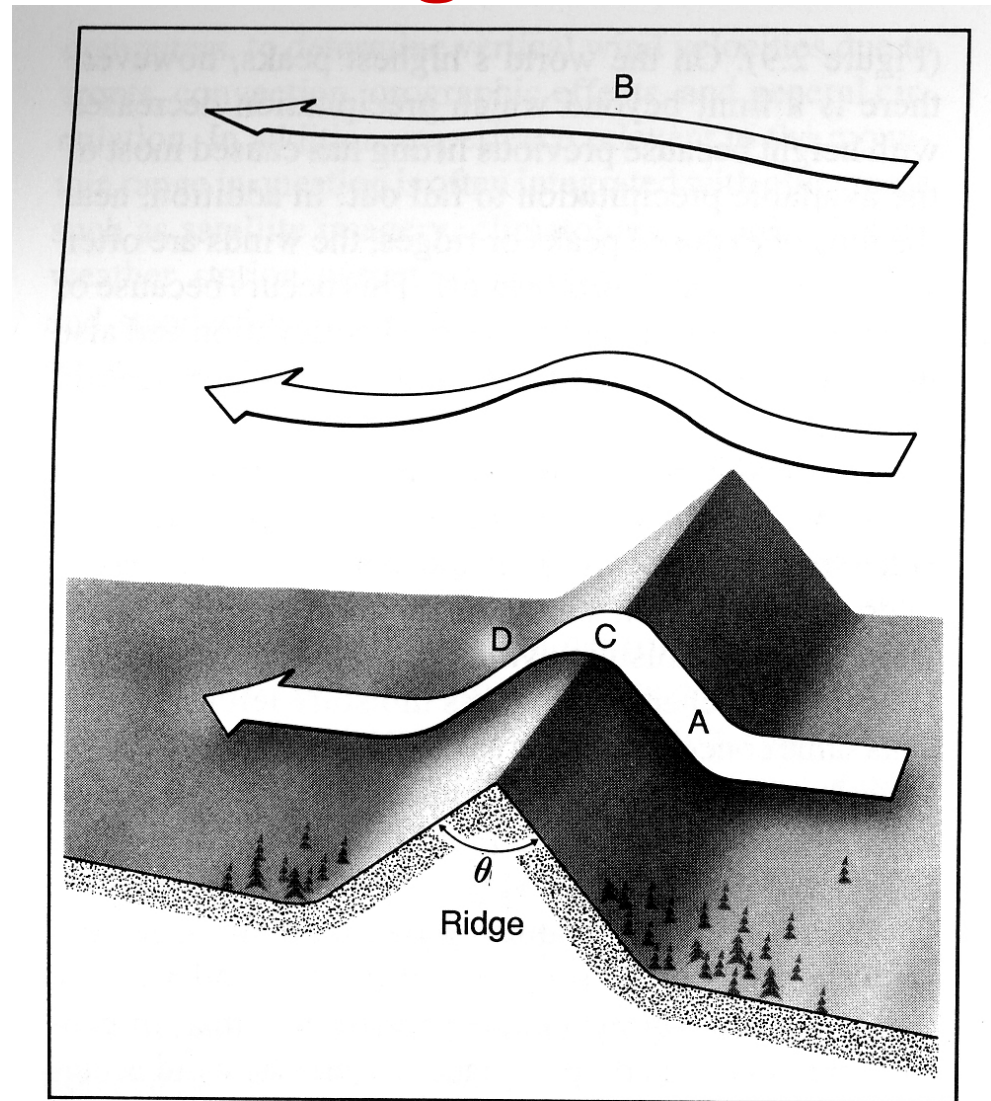


Clean Air Facility at South Pole Station, March 1992

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



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

Sastrugi

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



Fig. 73. **SASTRUGI.**



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



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

Physical properties of snow

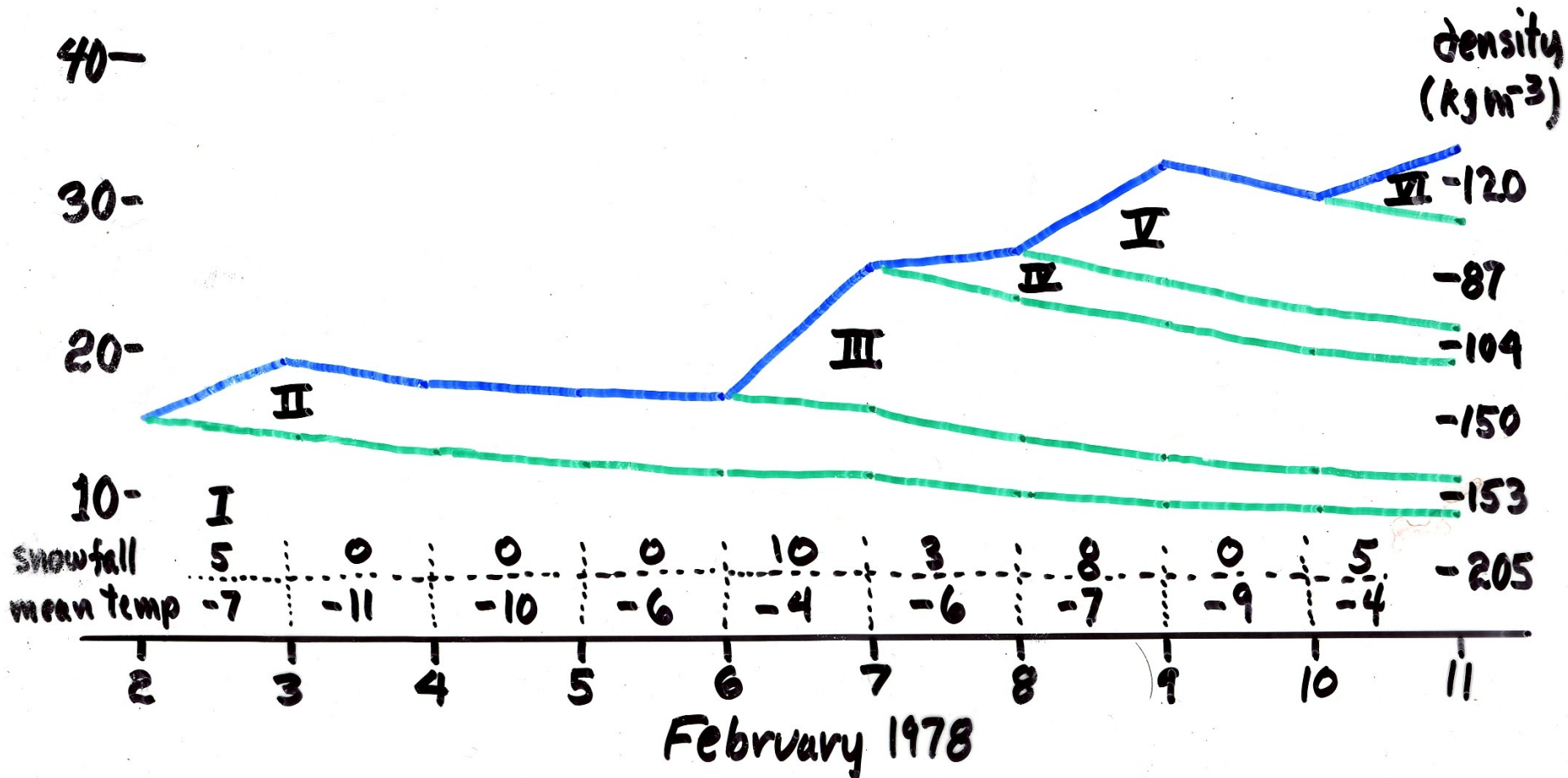
1. Density (water is 1000 kg m^{-3} or 1 ton m^{-3})

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

2. Thermal conductivity

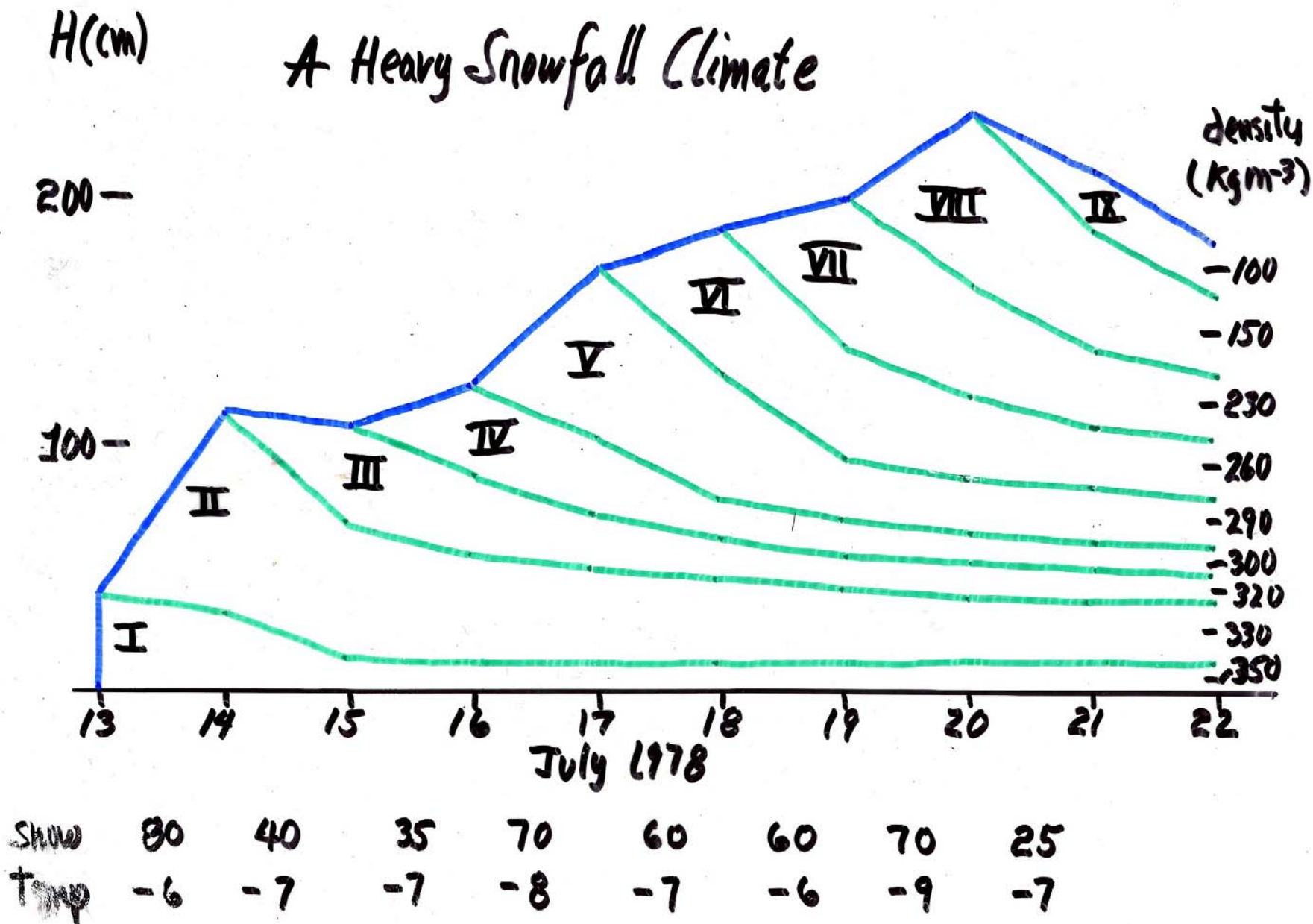
Snowpack Evolution I

A Light Snowfall Climate



Snowpack Evolution II

A Heavy Snowfall Climate



Physical properties of snow

2. Thermal conductivity

Deposited Snow

Snow Stratigraphy

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

Causes of Stratigraphy

- 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

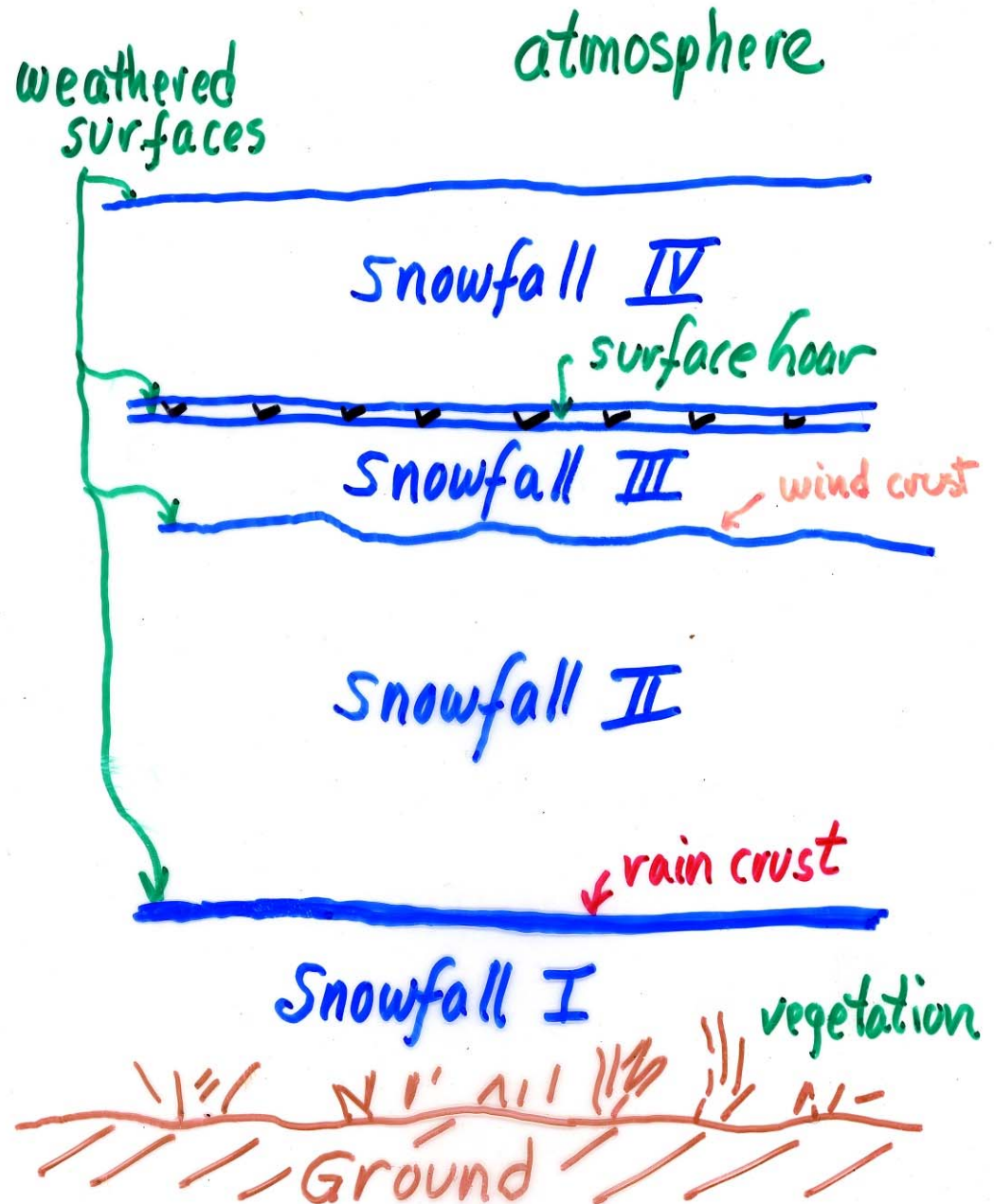
Important Properties of Snowpack

- layered structure
- state of stress
- distribution of temperature

Factors affecting these Properties

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

Snowpack Layered Structure



Equilibrium-form Metamorphism (“Destructive” Metamorphism)

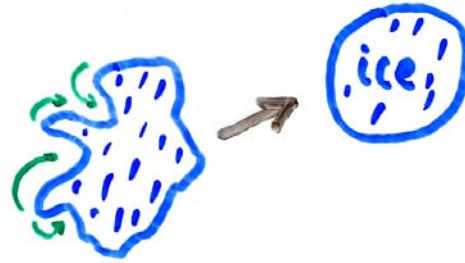
- Ice-air surface area represents stored energy (broken bonds)
- New snow has high surface-to-volume ratio (small grains, complex shapes)
- Old snow with large rounded grains represents a lower-energy state

Processes in snow act to:

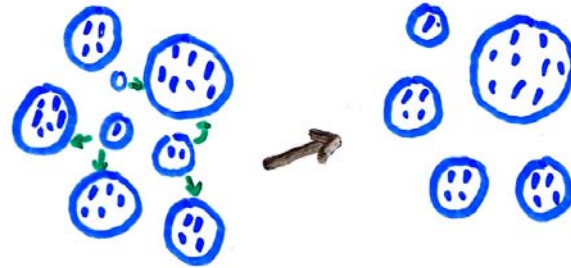
- Increase mean grain size (larger grains grow, smaller grains shrink and vanish)
- Make grains round
- Fill in cracks between grains (bond growth)

Mass Transfer Reduces Surface Area

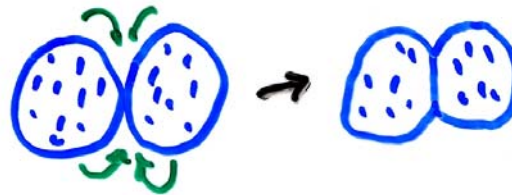
Result is equilibrium
forms



grain
rounding

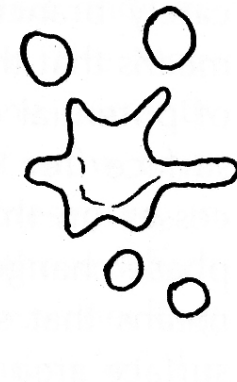
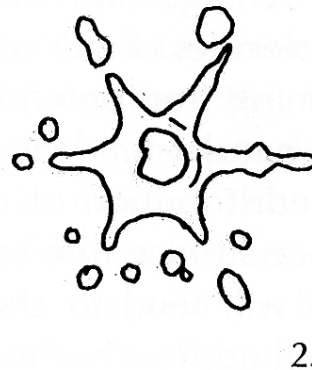
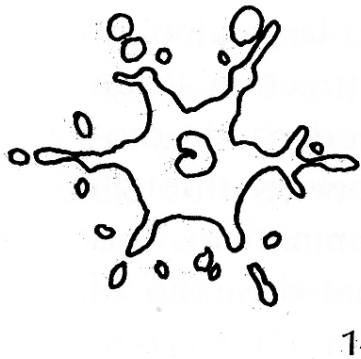
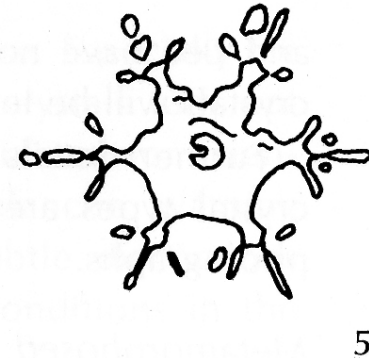
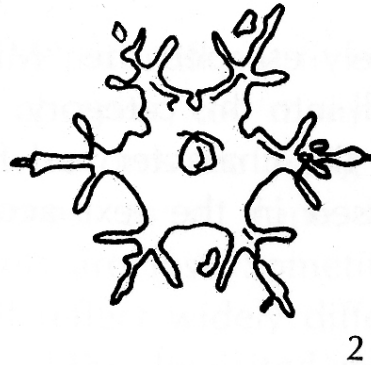
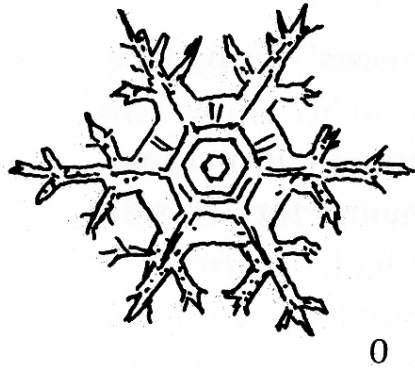


grain
growth
(ripening)



grain
bonding
(sintering)

Destructive Metamorphism of a Snow Crystal



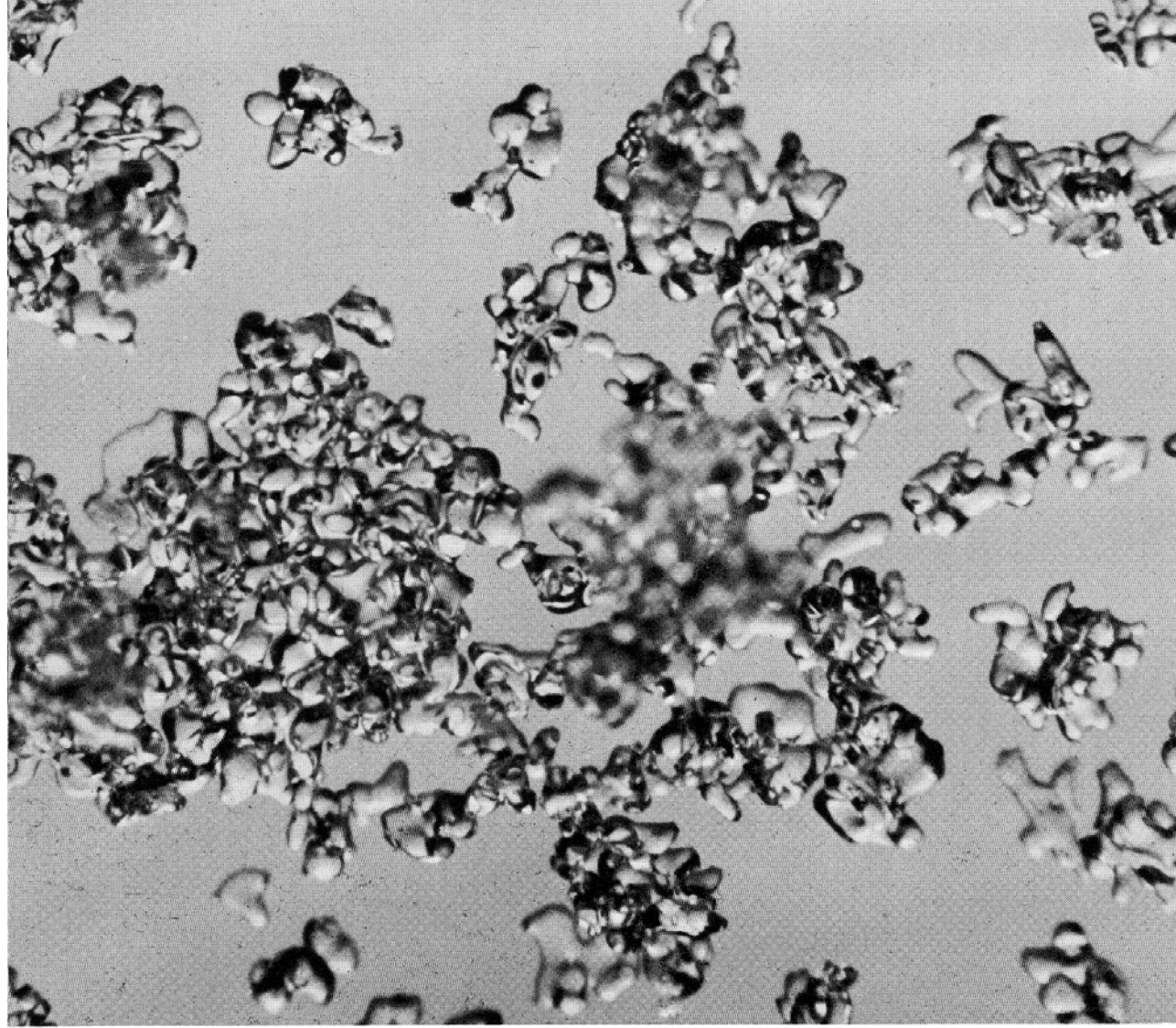
6. The destructive metamorphism of a stellar snow crystal. The numerals give the age of the snow crystal in days.

Early Destructive Metamorphism



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

Ongoing Destructive Metamorphism

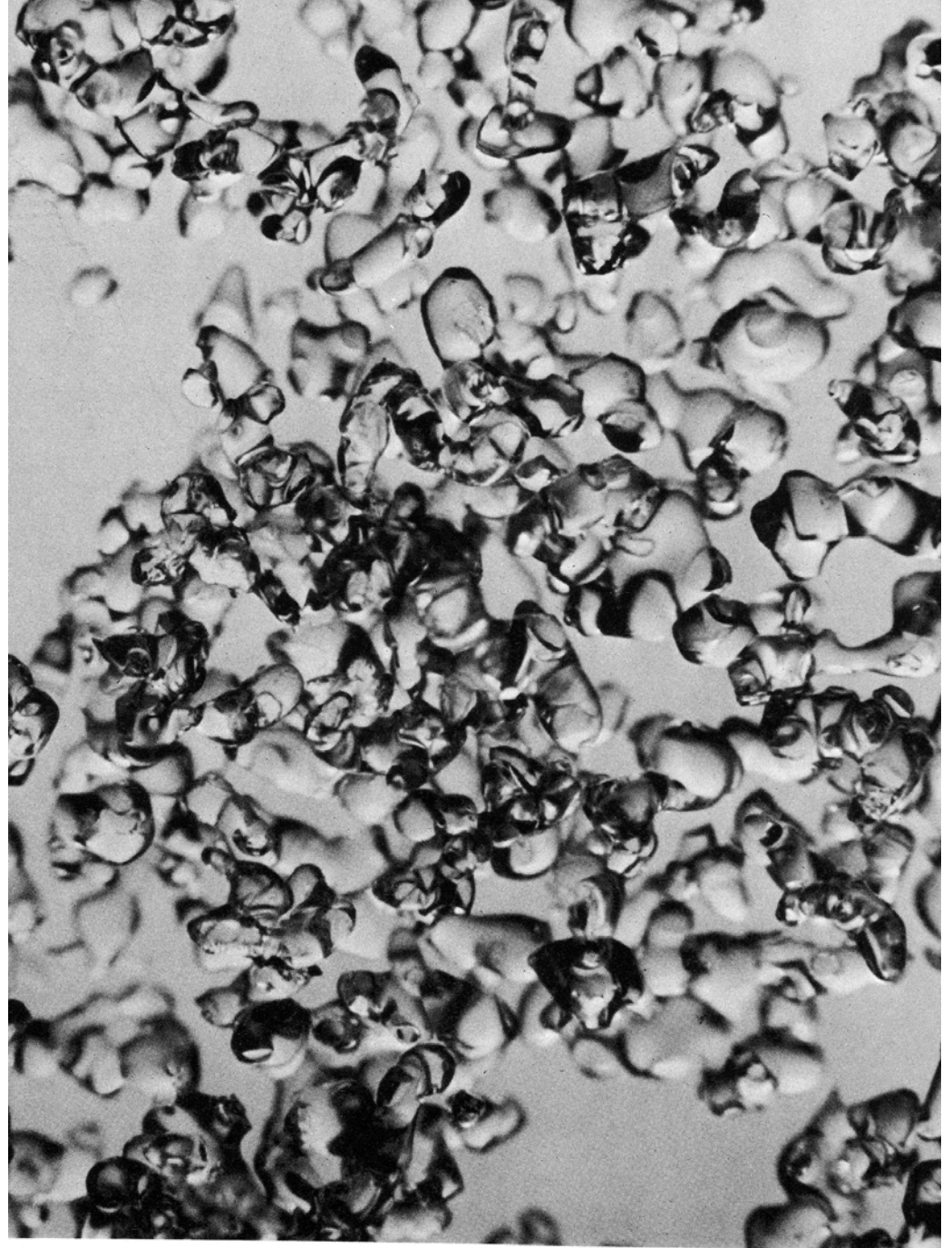


38. Stellar crystals which have lost almost all their identity through equitemperature metamorphism. 26X

“Old Snow”: the
equilibrium
form.

The end result of
destructive
metamorphism.

LaChapelle,
Field Guide to Snow Crystals



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

Destructive Metamorphism

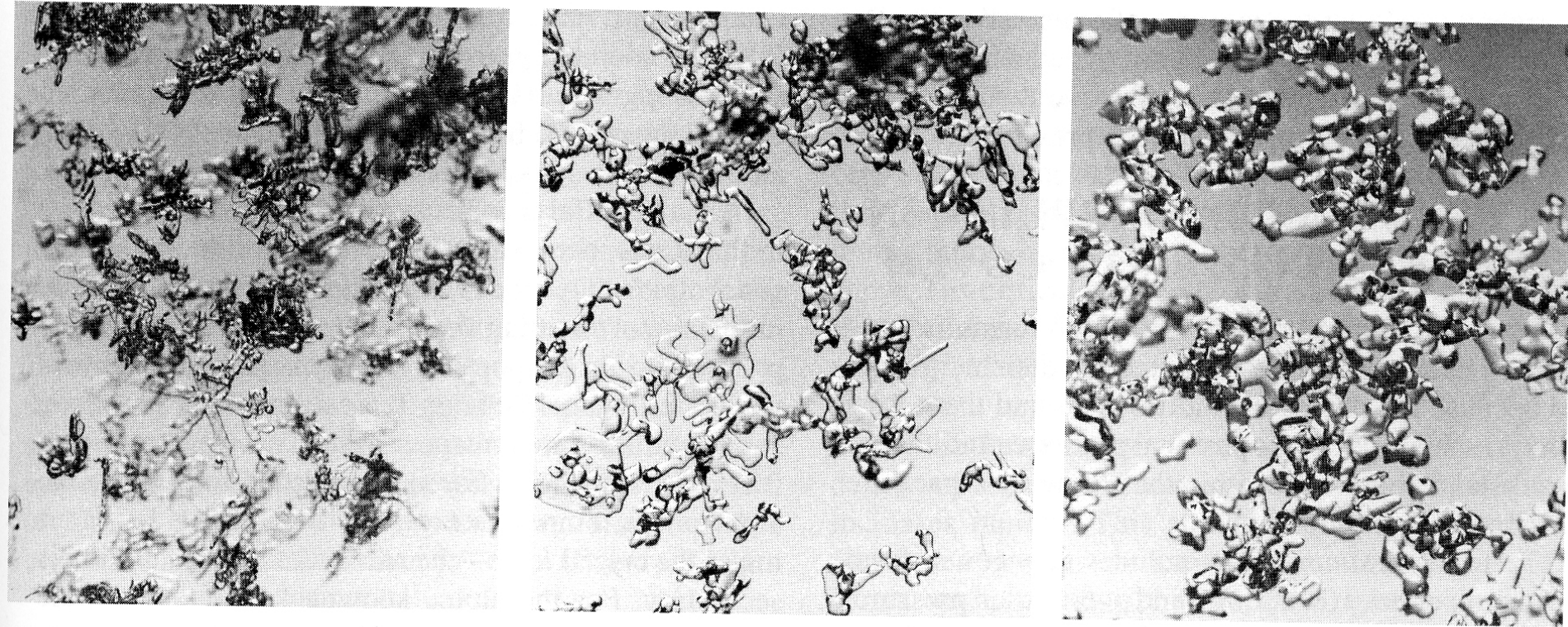


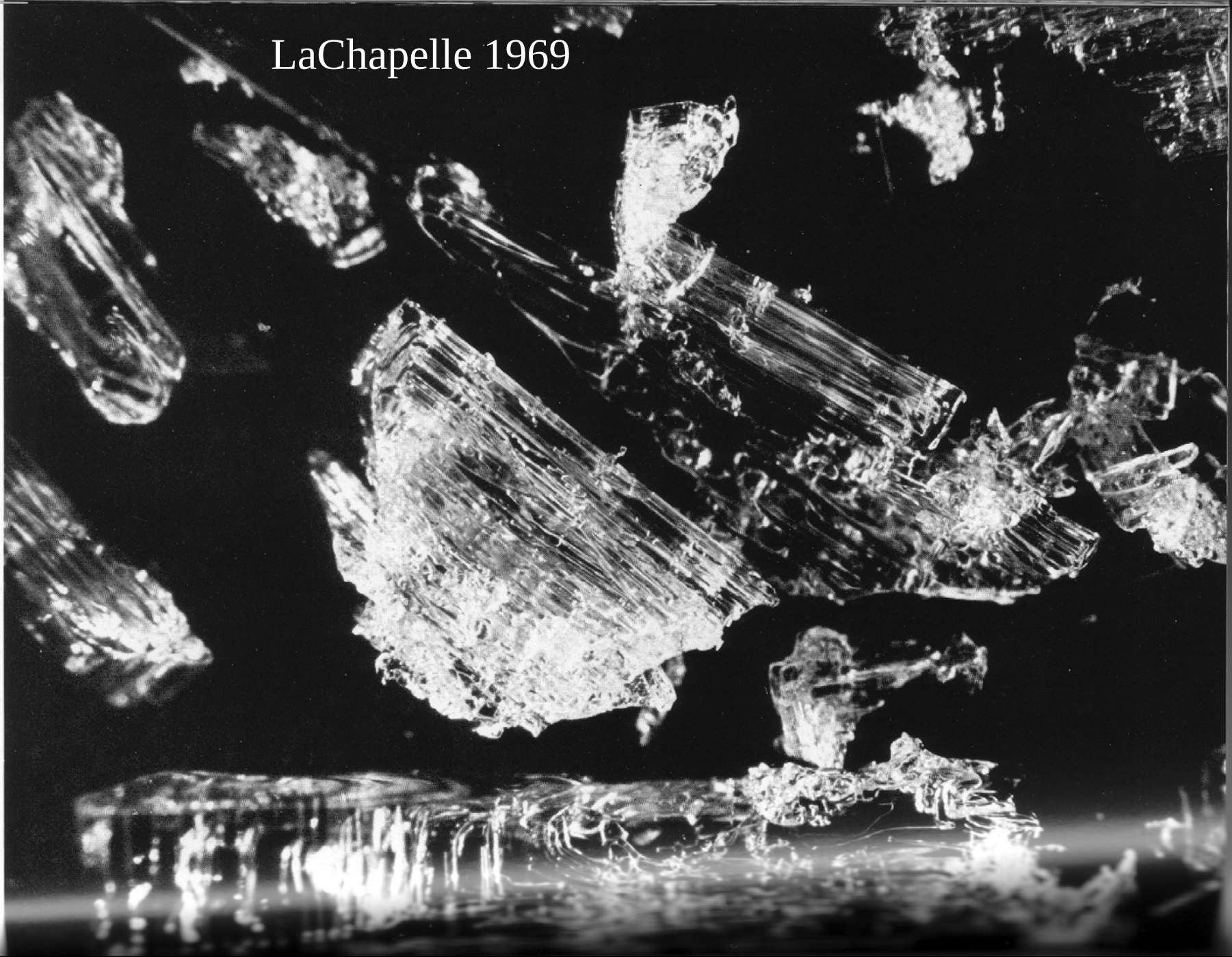
Figure 3.11. Transformation of newly fallen snow to rounded forms in three stages. (Photos by E. LaChapelle)

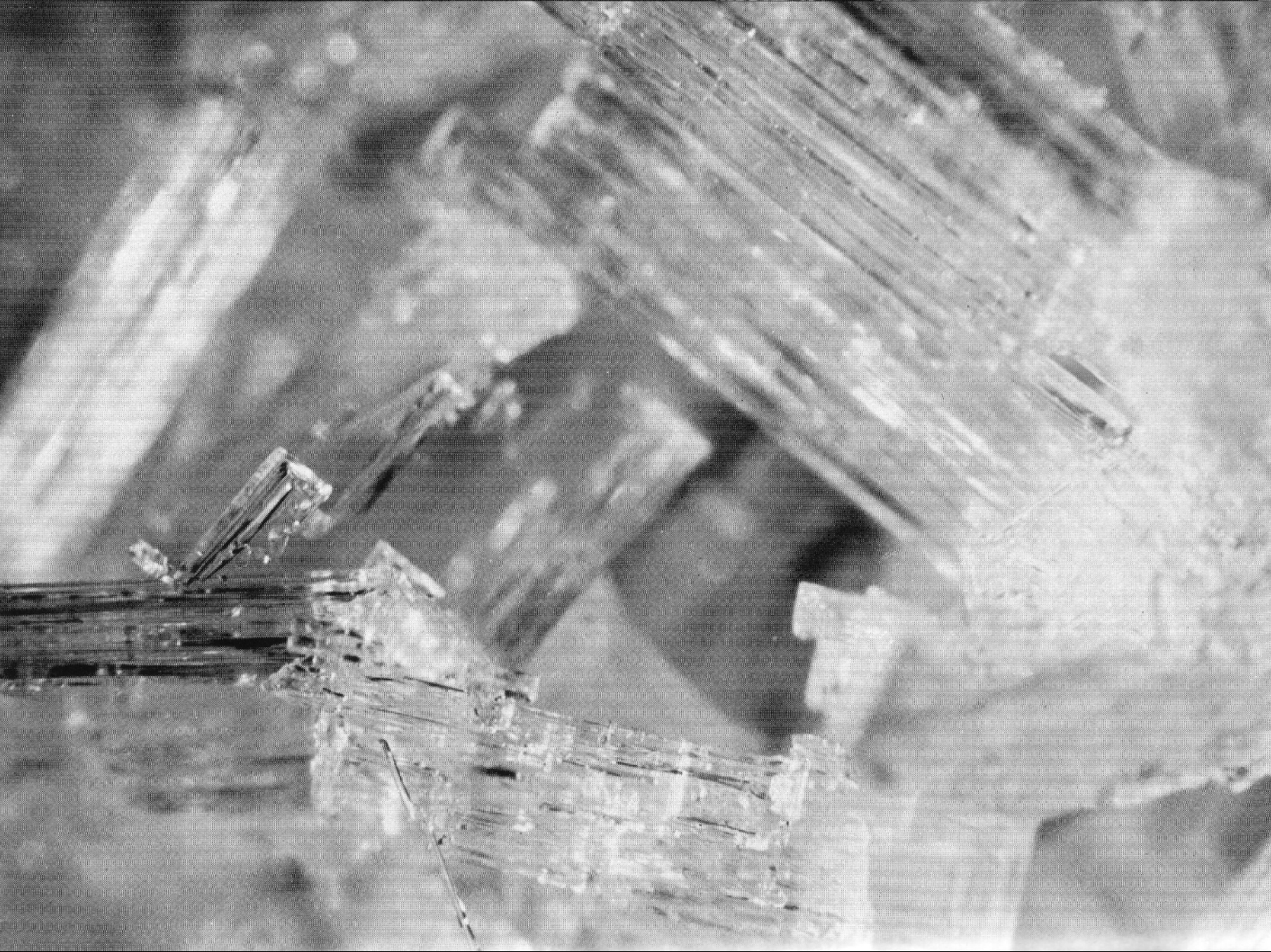
Kinetic-Growth Metamorphism

["Constructive" Metamorphism]

- Formation of frost and hoar
- Complex shapes *increase* surface area
- vapor-pressure gradients created by temperature gradients when $dT/dz > 10 \text{ deg m}^{-1}$

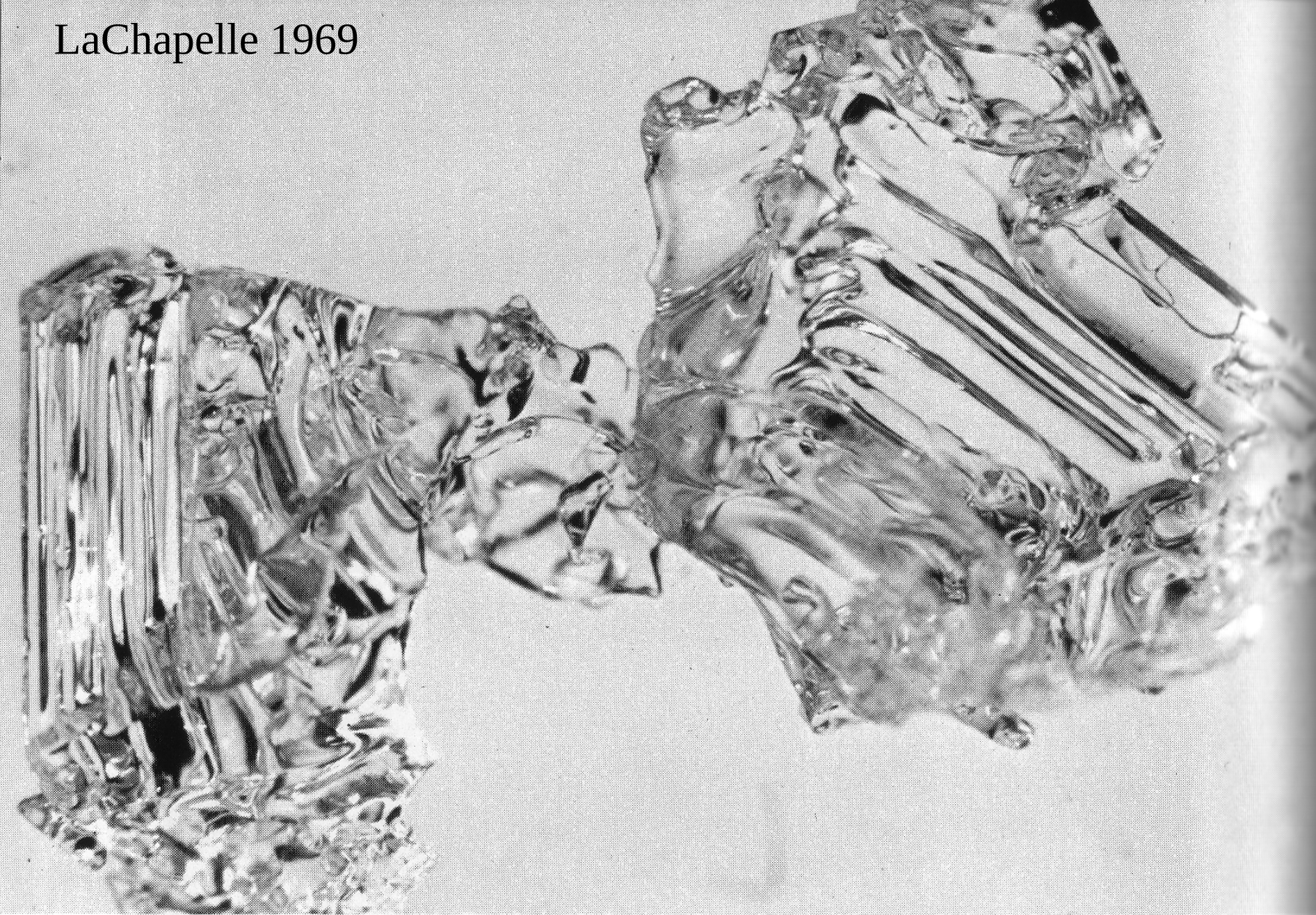
LaChapelle 1969



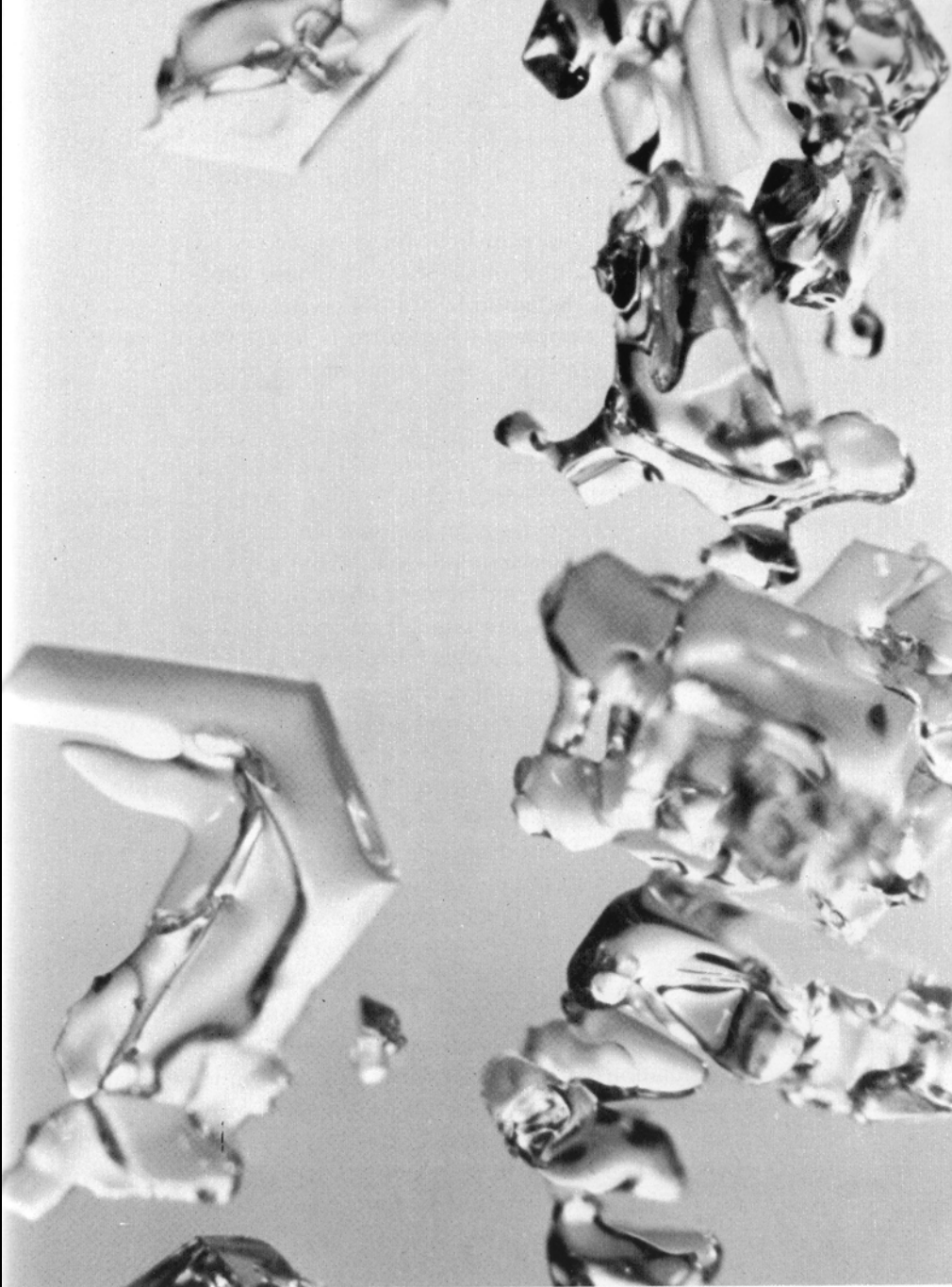


49. Undisturbed sample of depth hoar showing natural arrangement of crystals. 24X

LaChapelle 1969

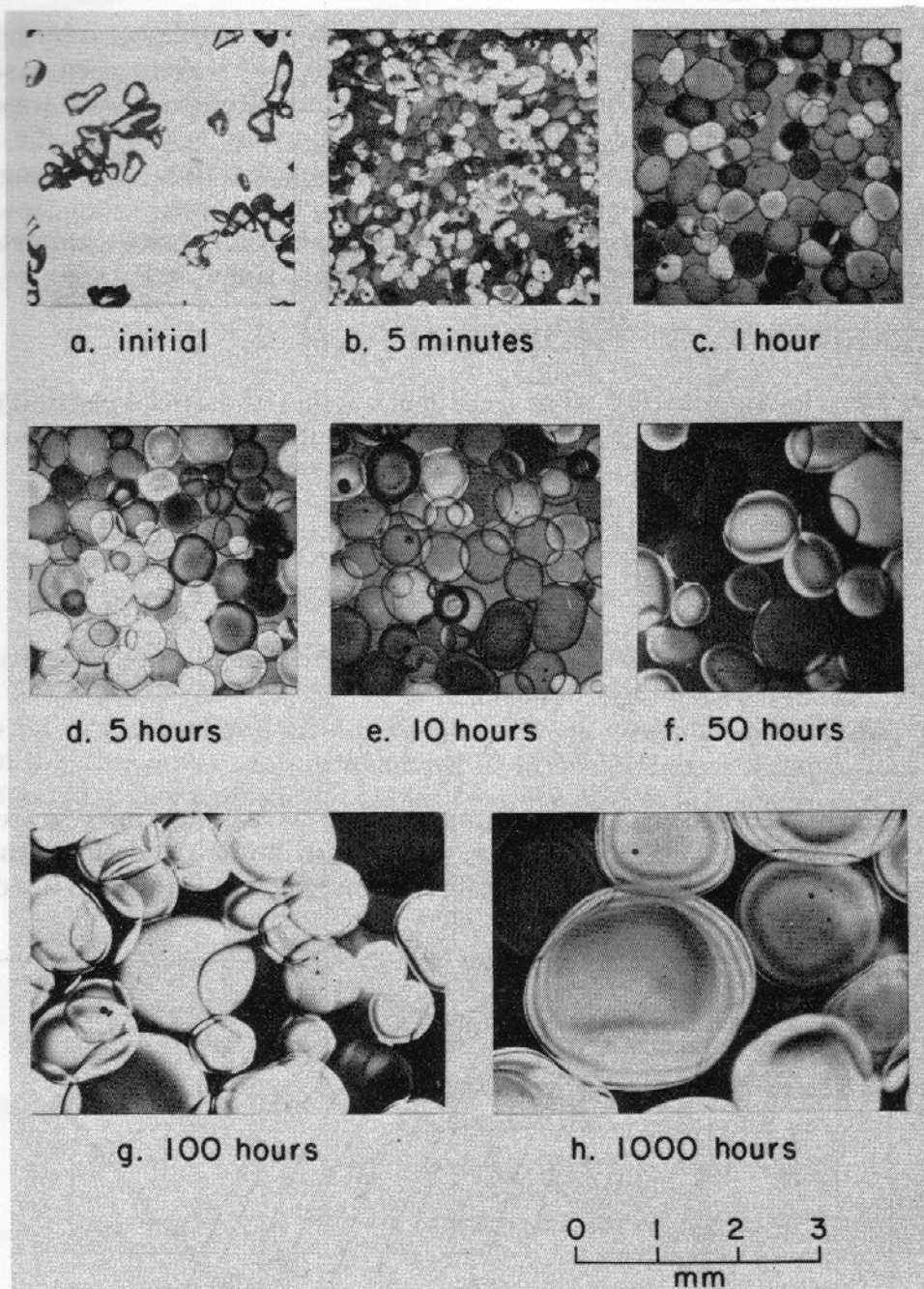


52. *Depth hoar crystals slightly altered by equitemperature metamorphism. 20X*



LaChapelle, 1969:
*Field Guide to Snow
Crystals*

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



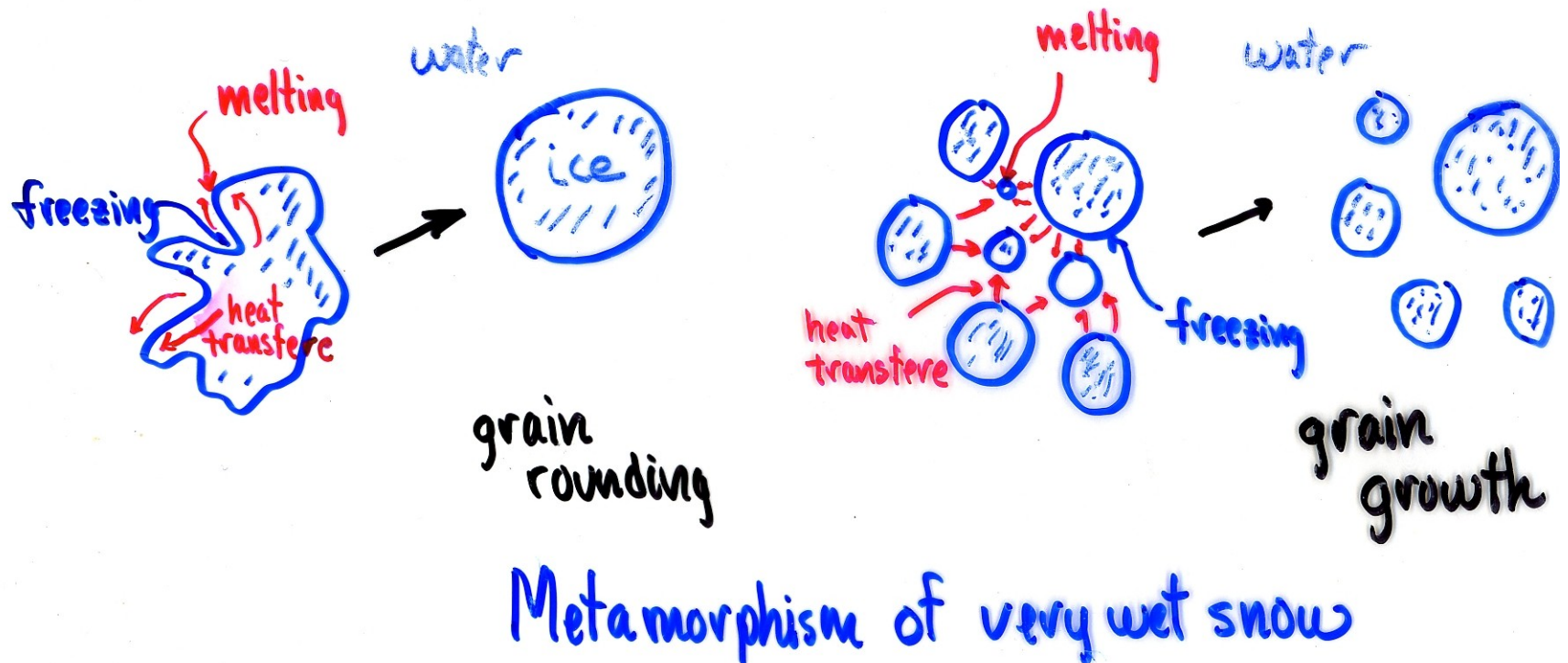
Grain growth in slush

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

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

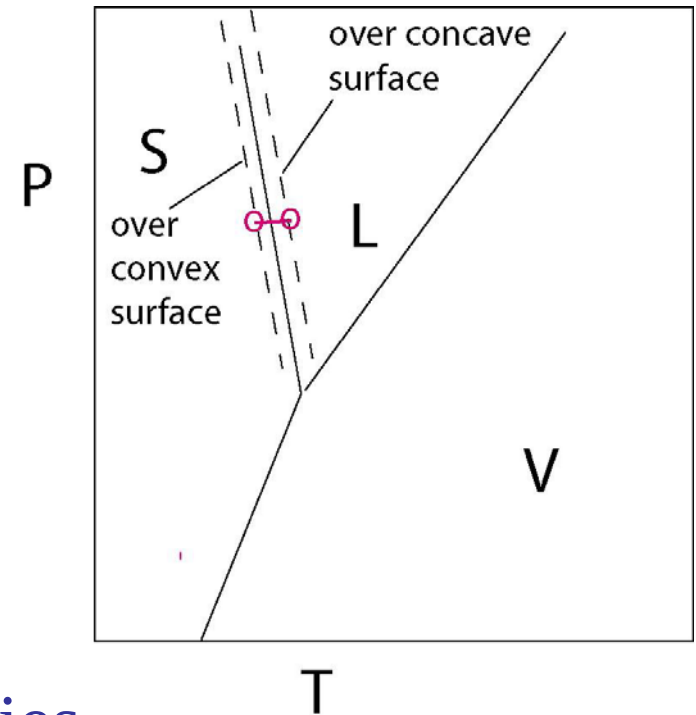
Wet Snow

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



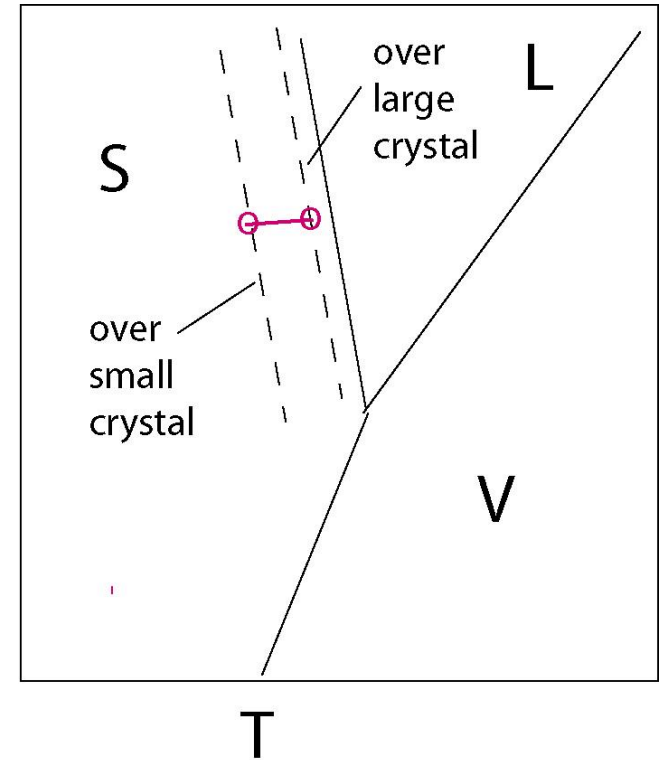
Wet Snow

- 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



Slush

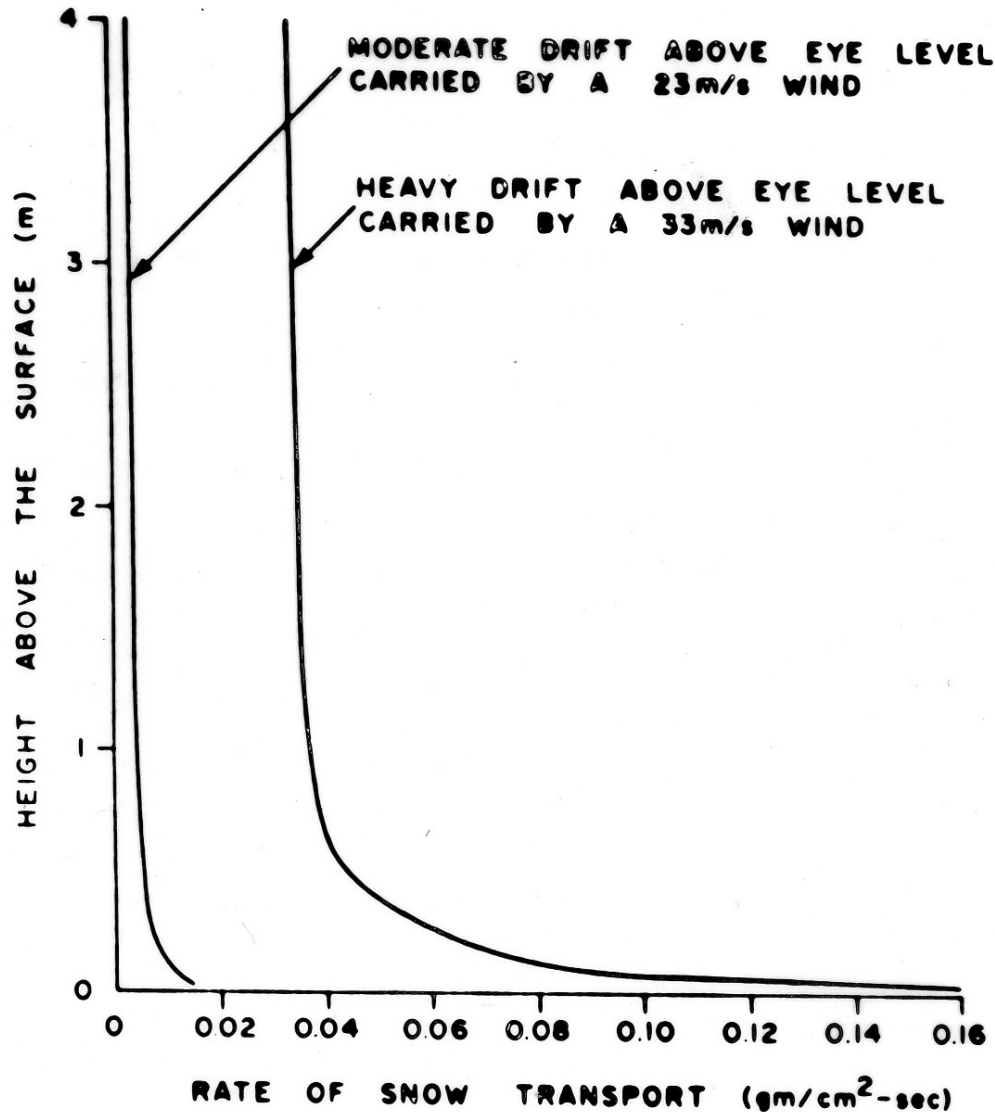
- Temperature is pinned at local melting point everywhere on the ice-water interface
- Melting temperature is reduced more over more-convex surfaces, i.e. over smaller ice crystals
- Heat flows through the water from large crystals to small crystals
- Larger crystals cannot cool; heat must be obtained by freezing liquid (to release latent heat)
- Smaller crystals cannot get warmer; incoming heat must be absorbed by melting





Rocky Mountain
National Park,
Colorado,
March 1979

Horizontal Mass-Flux Profiles



More suspended snow at higher elevation in stronger wind

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

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



Dunes

Saltating snow
forms moving
dunes

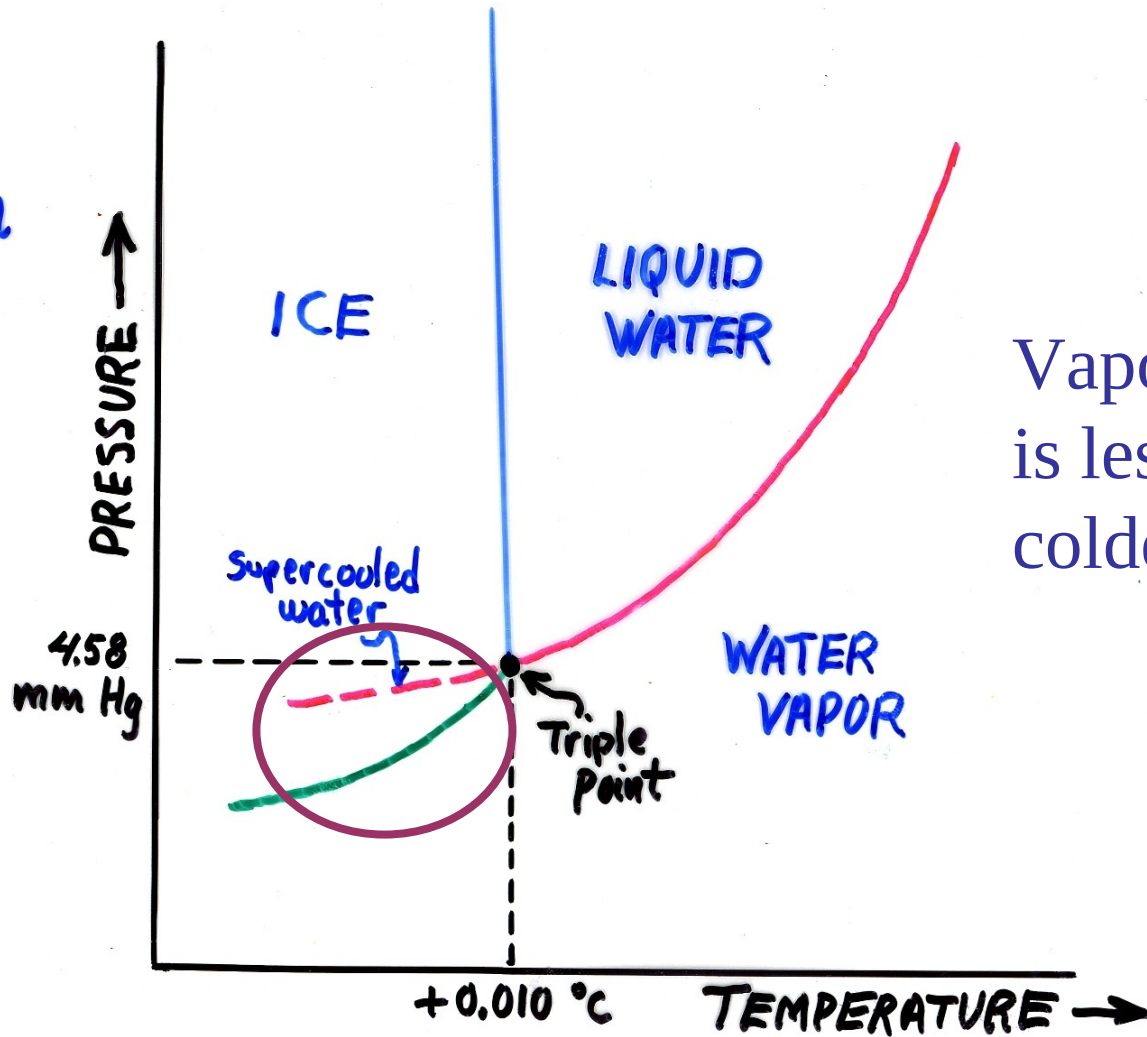
Crusts

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

figure

Why?

Phase Diagram for Water



Vapor pressure is less over colder snow

Temperatures in Snow

- air is cold, ground is warm

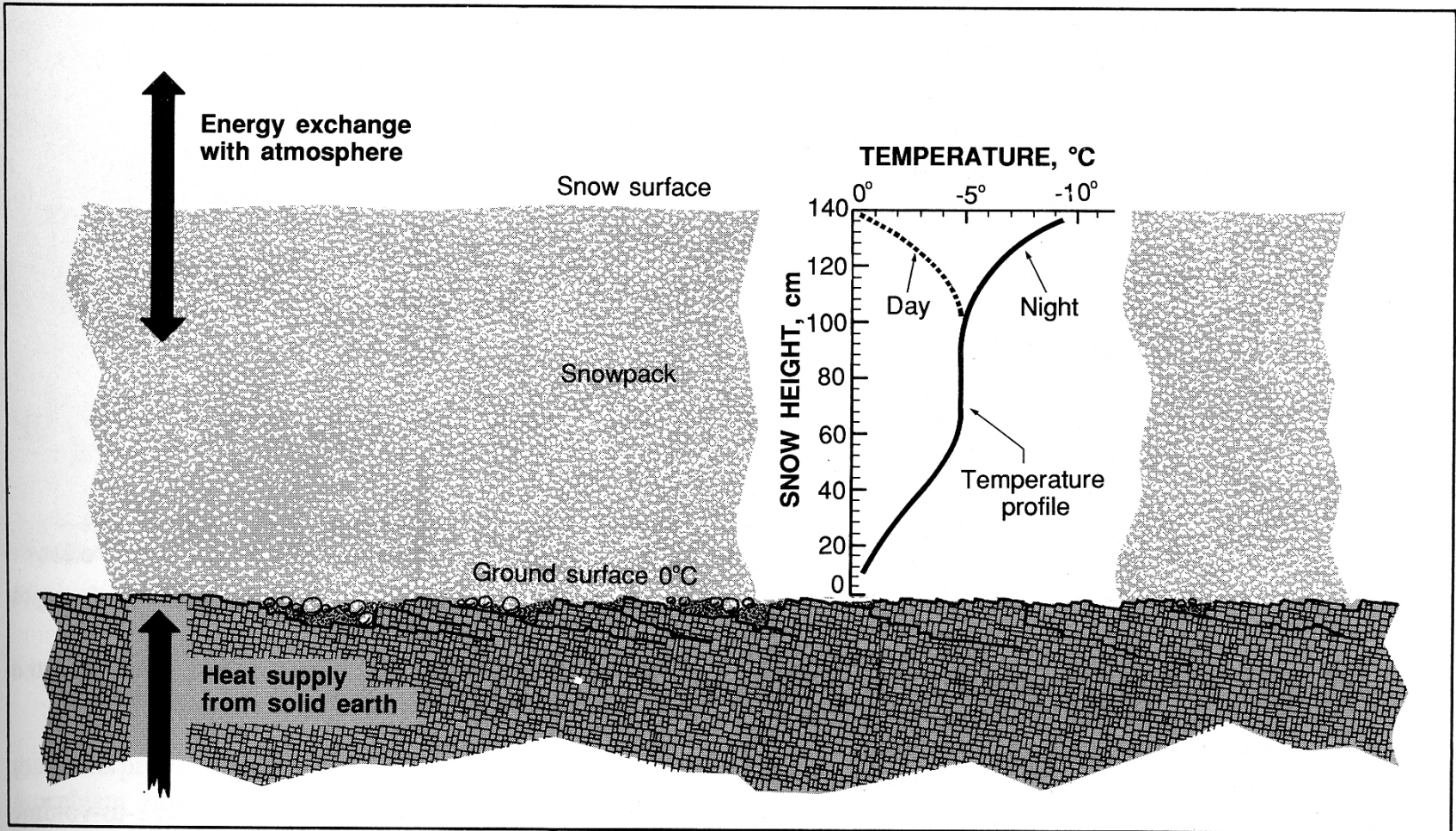
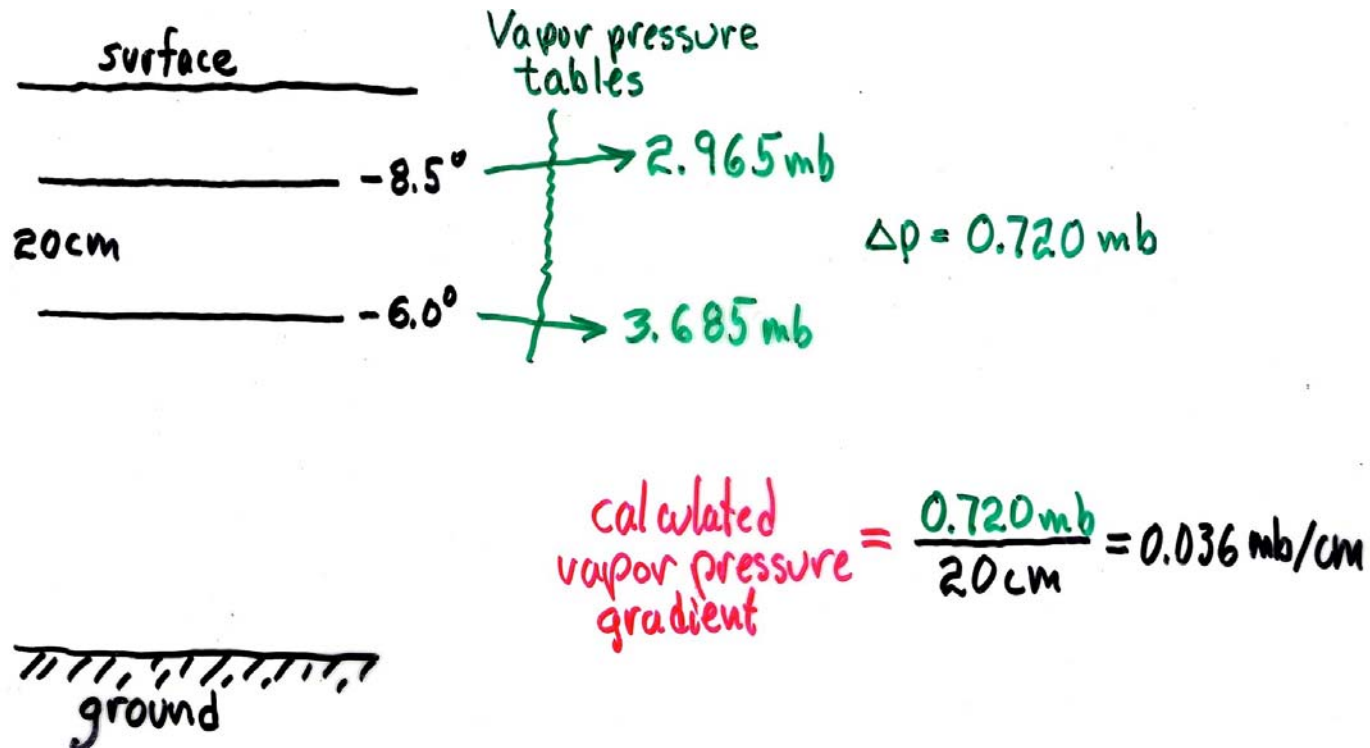


Figure 3.9. Illustration of the temperature variations in a snowpack. Diurnal variations occur in the upper portion. A temperature gradient of 10°C/m is strong enough to produce facets in the snowpack.

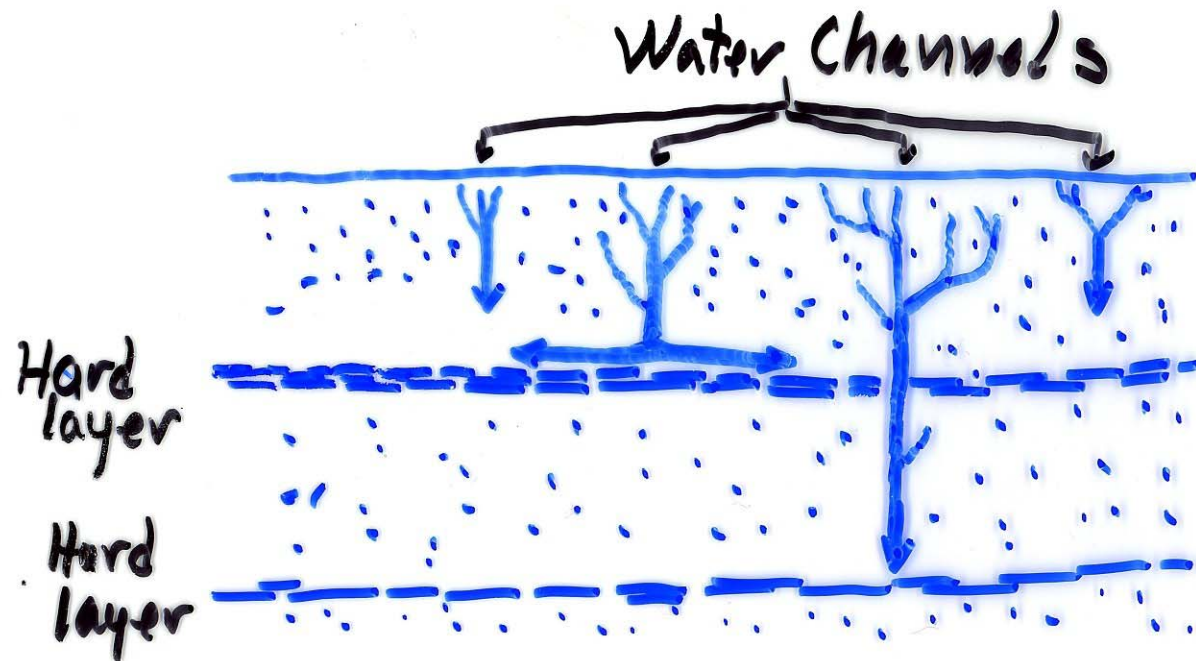
Vapor-Pressure Gradients

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



Water Motion in Wet Snow

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



Relict Pipe



P. Marsh

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

Mountain Wind and Snow

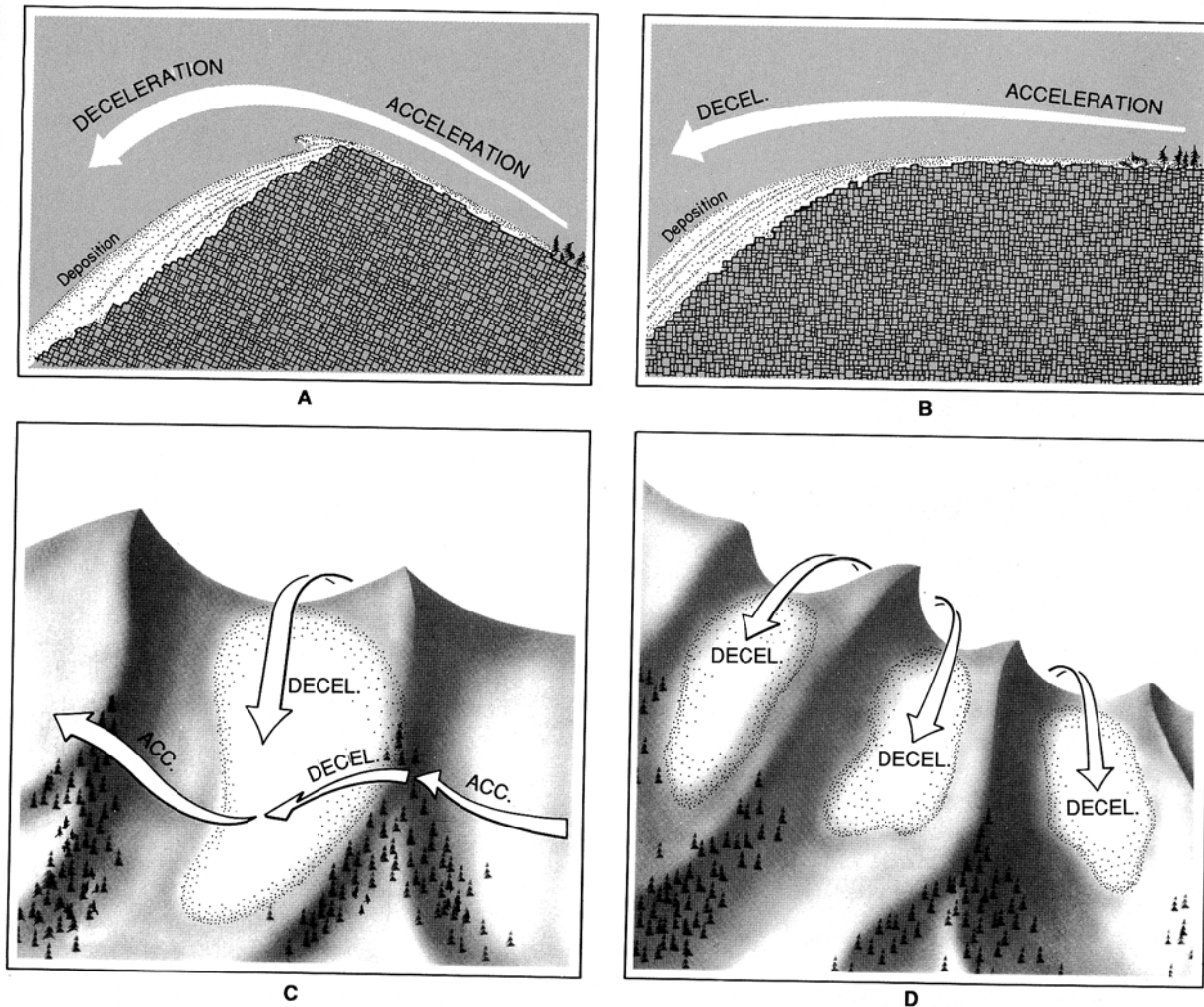


Figure 2.15. Snow is picked up in acceleration regions and deposited in deceleration regions (A, B). This produces lee zone deposition, cross-loading, and deposition in gullies and notches (C, D).

Cornice Structure

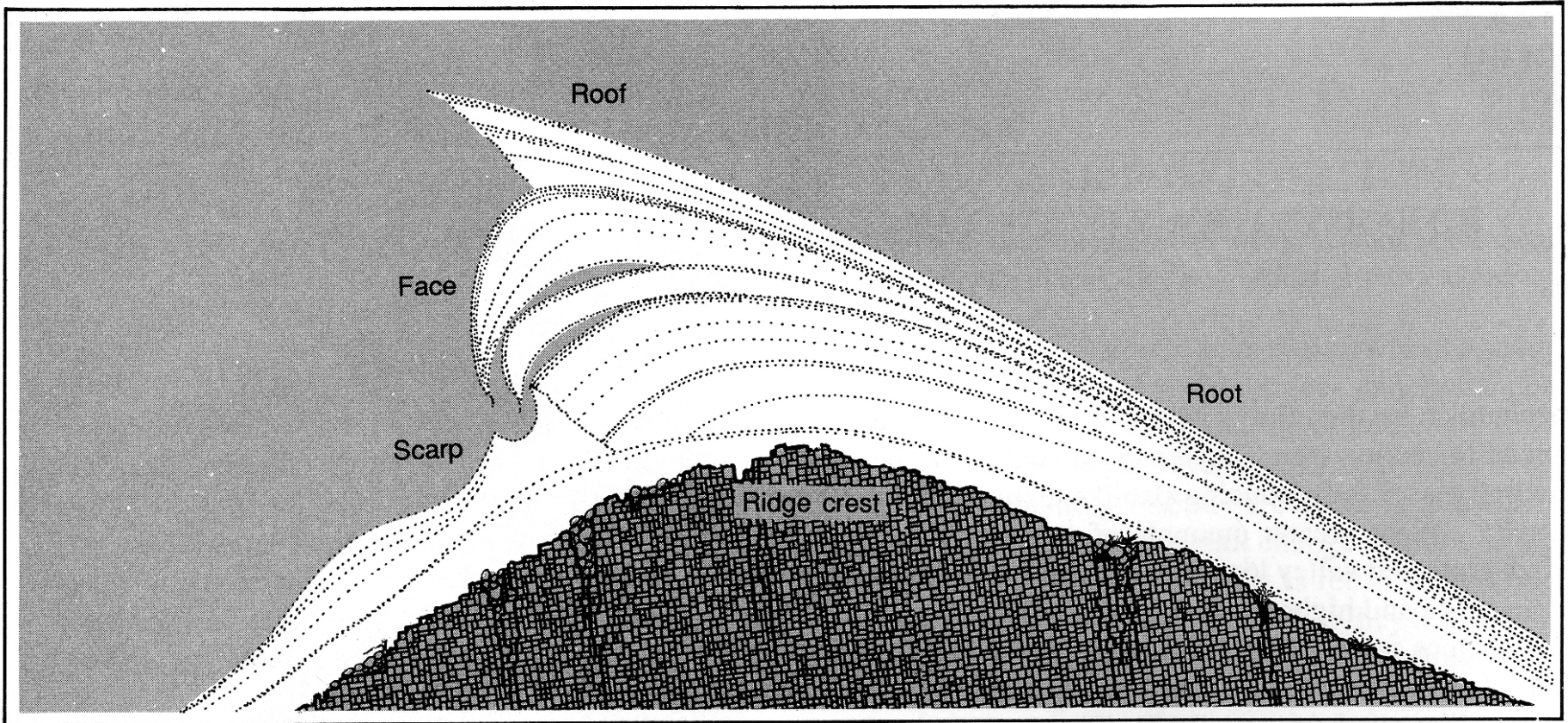


Figure 2.17. Cornice structure and nomenclature. Prevailing wind direction is from right to left.

Cornice on a ridge crest



Ridge Turbulence

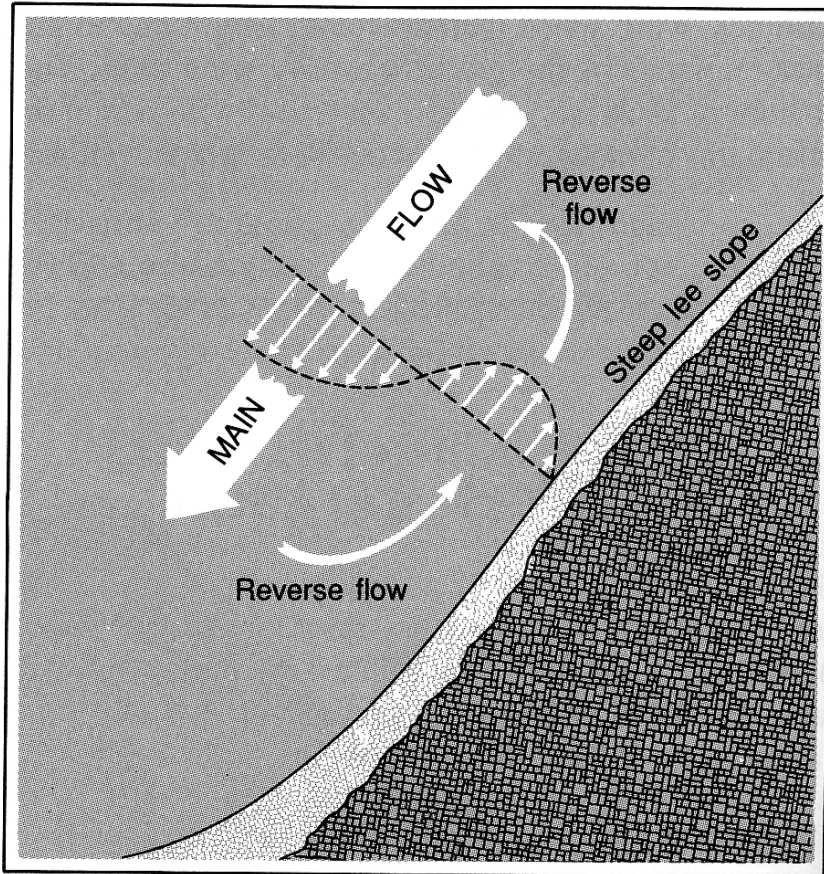


Figure 2.11. Reversal of flow on steep lee slopes. This pattern allows cornice and avalanche formation.

Flow separation over sharp ridges

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