ESS 432 PRINCIPLES OF GLACIOLOGY
ESS 505 THE CRYOSPHERE

Snow deposition, wind transport, metamorphism, and the transformation of firn to glacial ice

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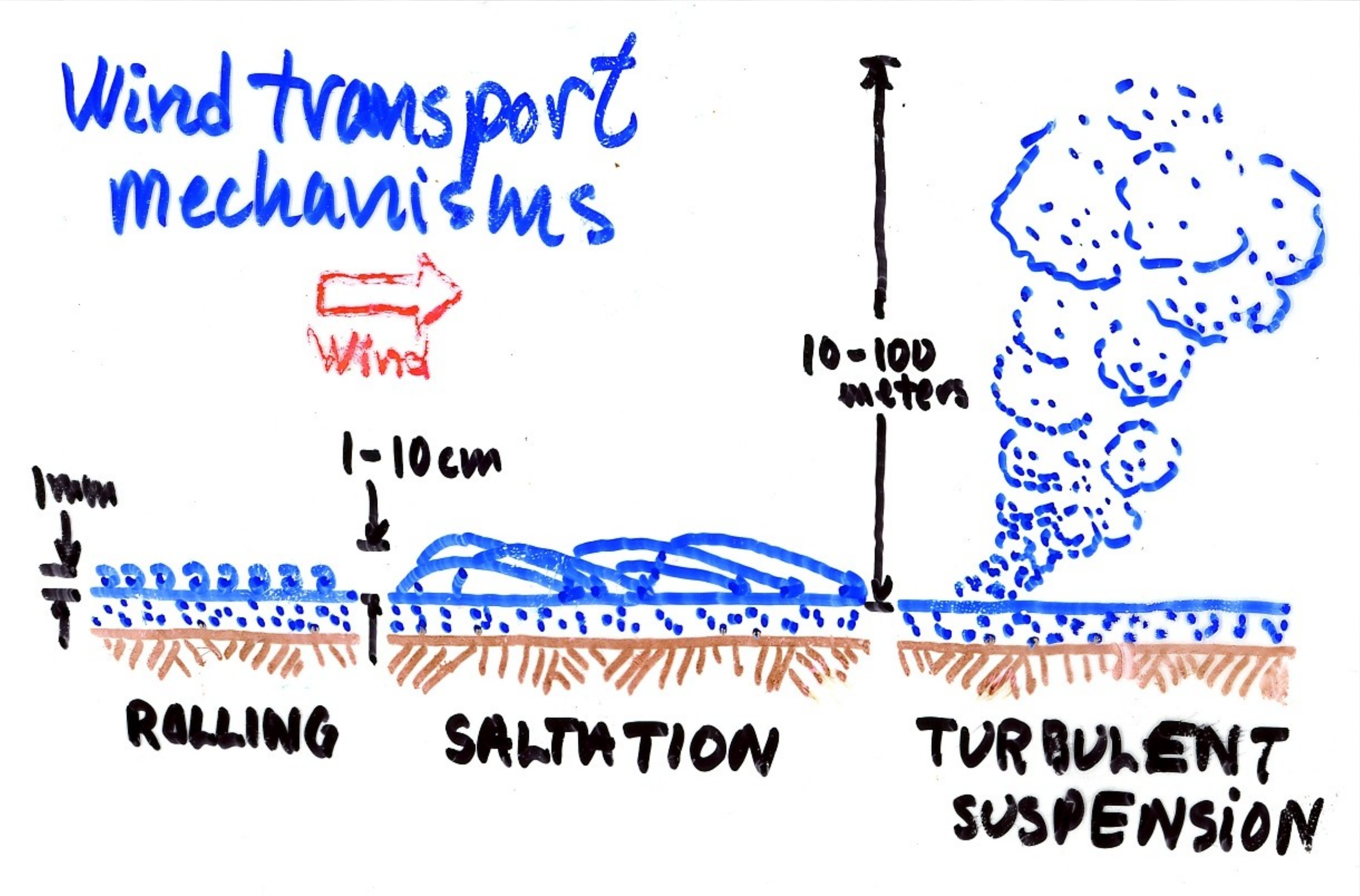
Today's Questions

- How does wind affect the distribution, surface morphology, and density of snow?
- How do temperature gradients influence the evolution of the snowpack?
- How does the temperature and crystal structure of ice control snow metamorphism?
- What is firn? How does it densify into ice? How does gas transport in firn occur?

Snow distribution

- **How can snow be transported? How does it alter the surface morphology?**
- **Why is snow transport important in mountain systems?**

How can snow be transported?
Modes of Snow Transport



Rolling Snow

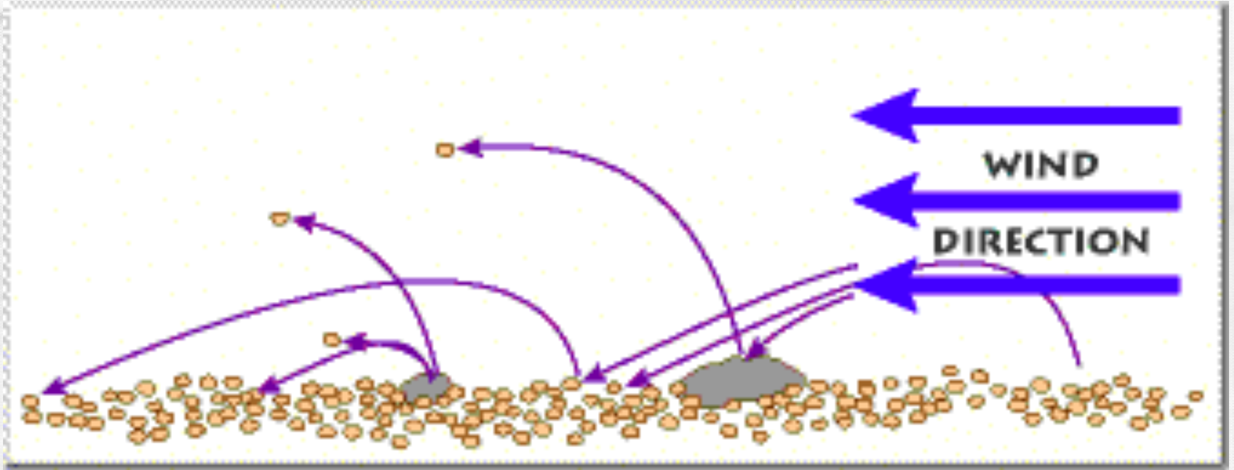
Grains move along the surface in a layer ~ 1mm thick.

- 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 grains

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



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

Suspended Snow

Horizontal wind over rough surface can cause eddies.

- Turbulent eddies can pick up snow.
- **Upward eddy speed must exceed rate of fall**
- Most mass is transported within ~1 m of snow surface
- Snow crystals typically fall at 0.2 –2.0 m s^{-1}


ANTARCTICA
WAIS
Divide
McMurdo
Station

Consequences of Snow Transport

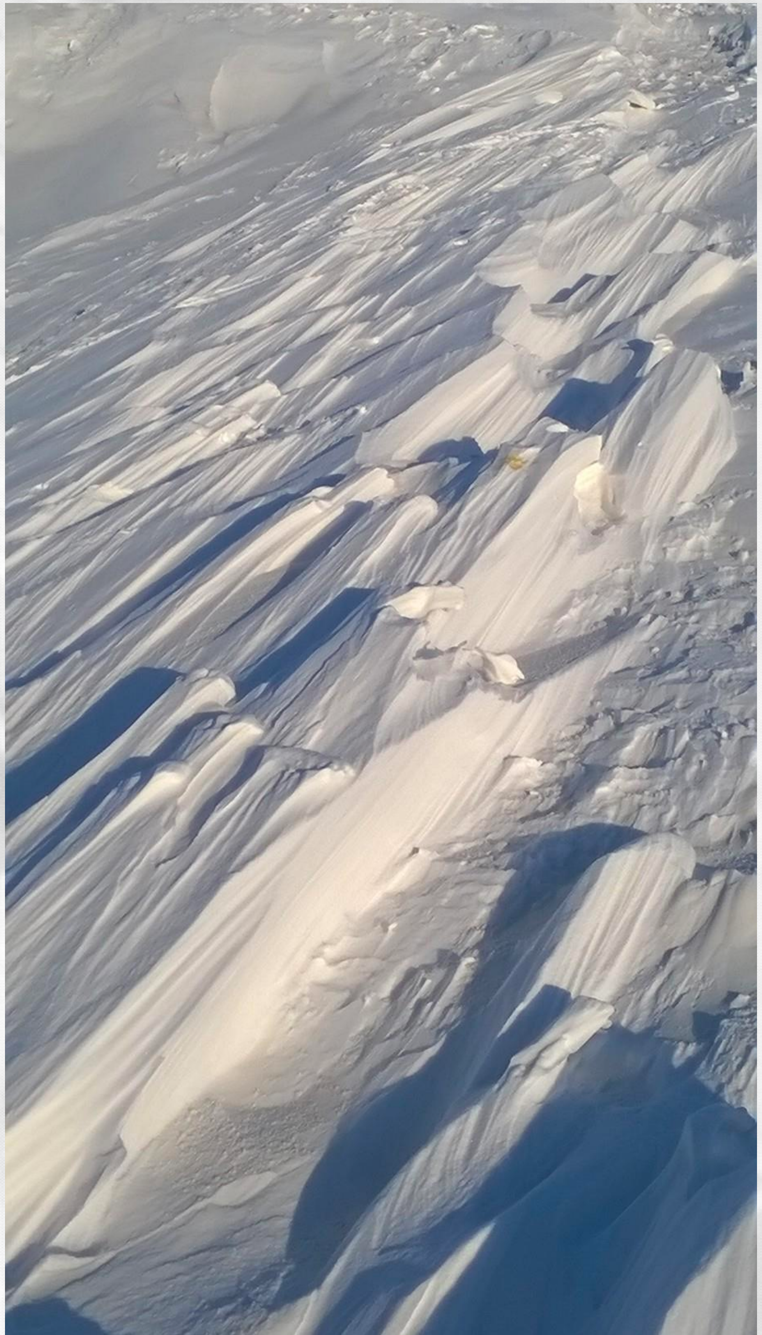
Snow can be redistributed on the ground.

Surface morphology can be altered

1) Dunes
2) Sastrugi
3) Wind crust/ wind packing

Sastrugi

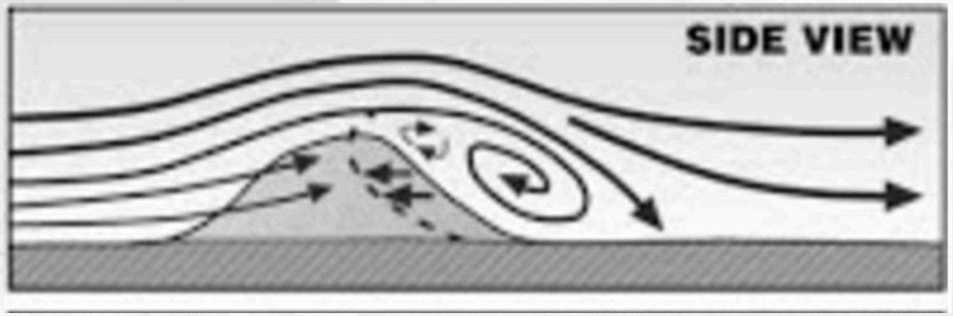
- Irregular grooves and ridges on snow surface
- Formed by wind erosion, saltation, and deposition



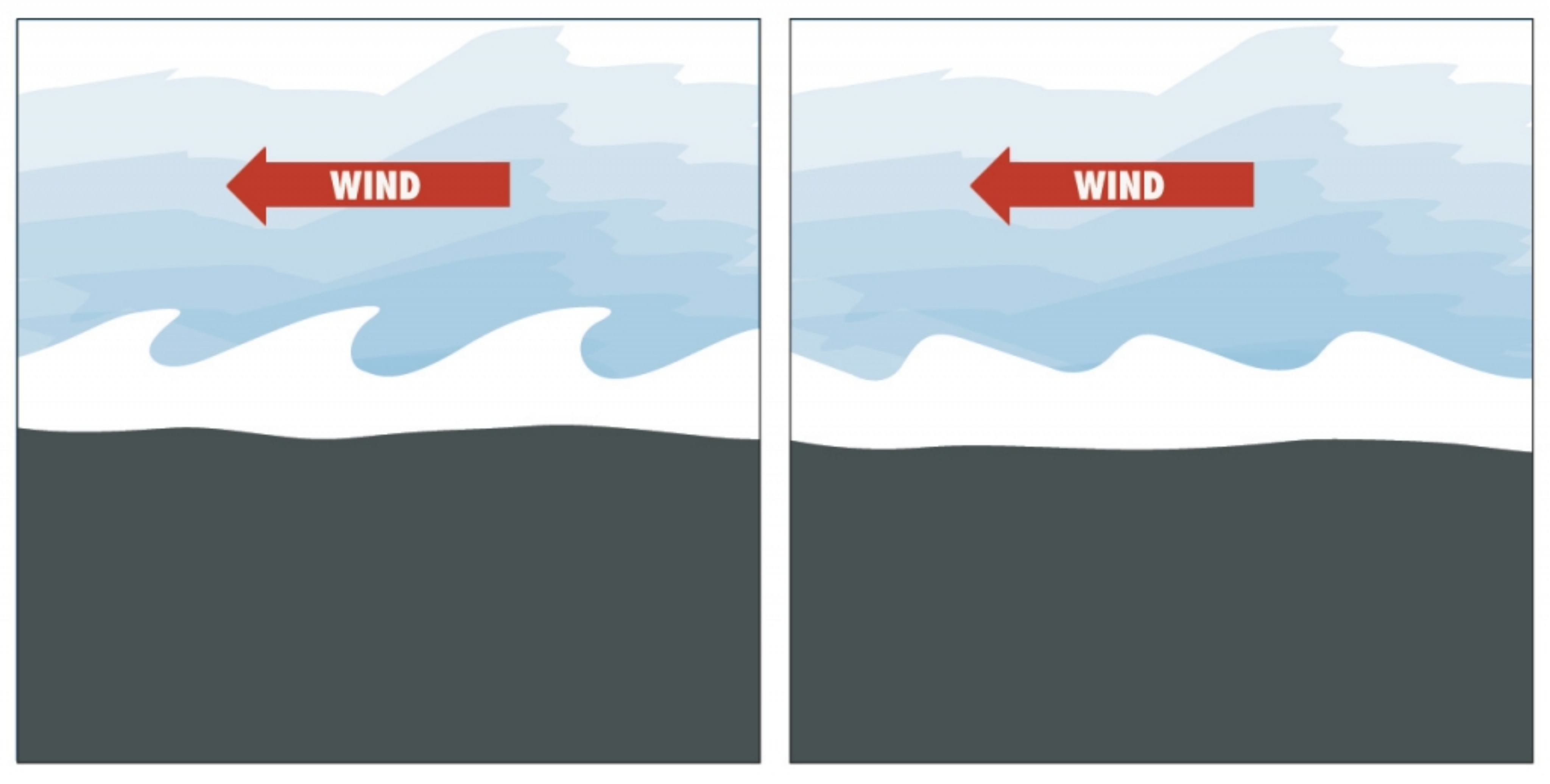
Dunes

- Snow dunes consist entirely of eroded snow, ‘raised’ by blizzard winds

- Saltating snow forms moving dunes



Sastrugi vs. Dunes



Crusts

- Saltation can break crystals into fine fragments
- Often denser and less permeable than snow below.
- Result is called “wind slab”

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

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

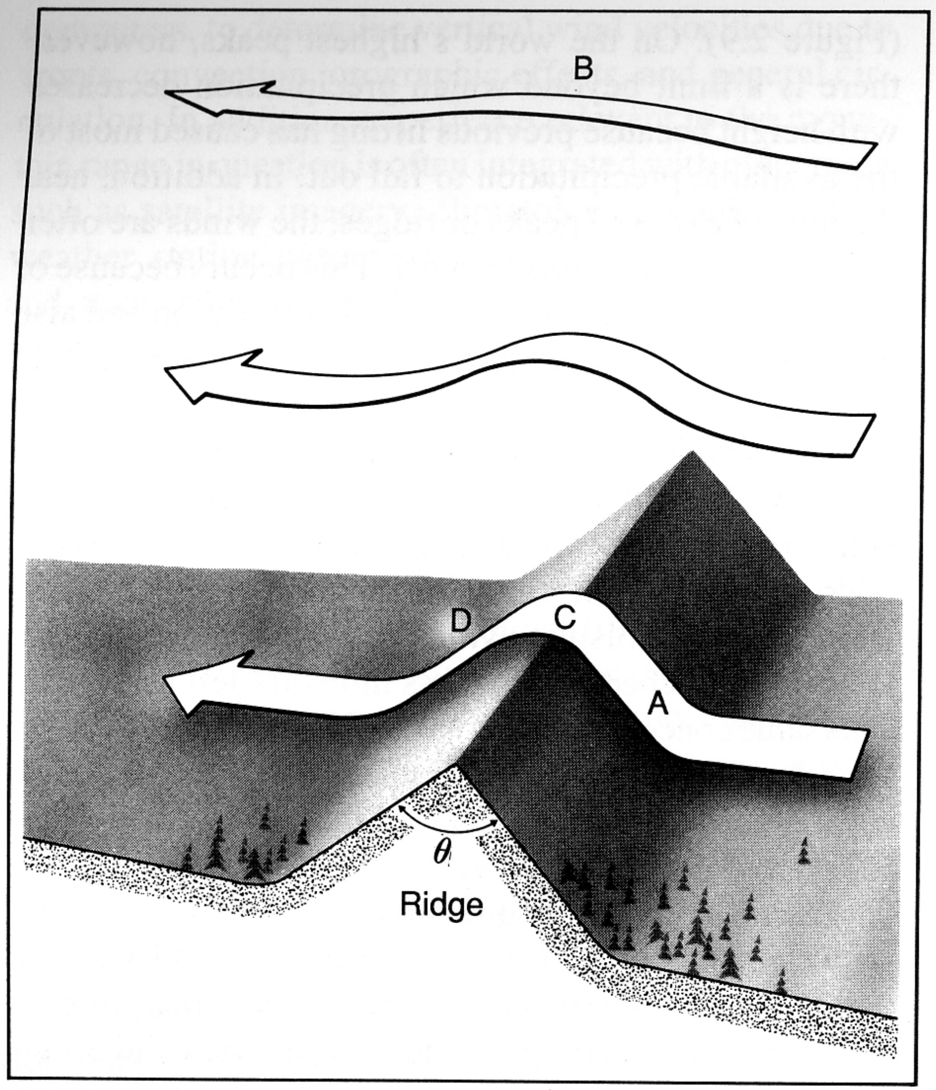


Figure 2.10. A: Airflow over a ridge; B: free-air motion; C: ridge crest; A, D: acceleration and deceleration zones.

Mountain Terrain and Snow

Snow transport depends on wind speed

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

Mountain Wind and Snow

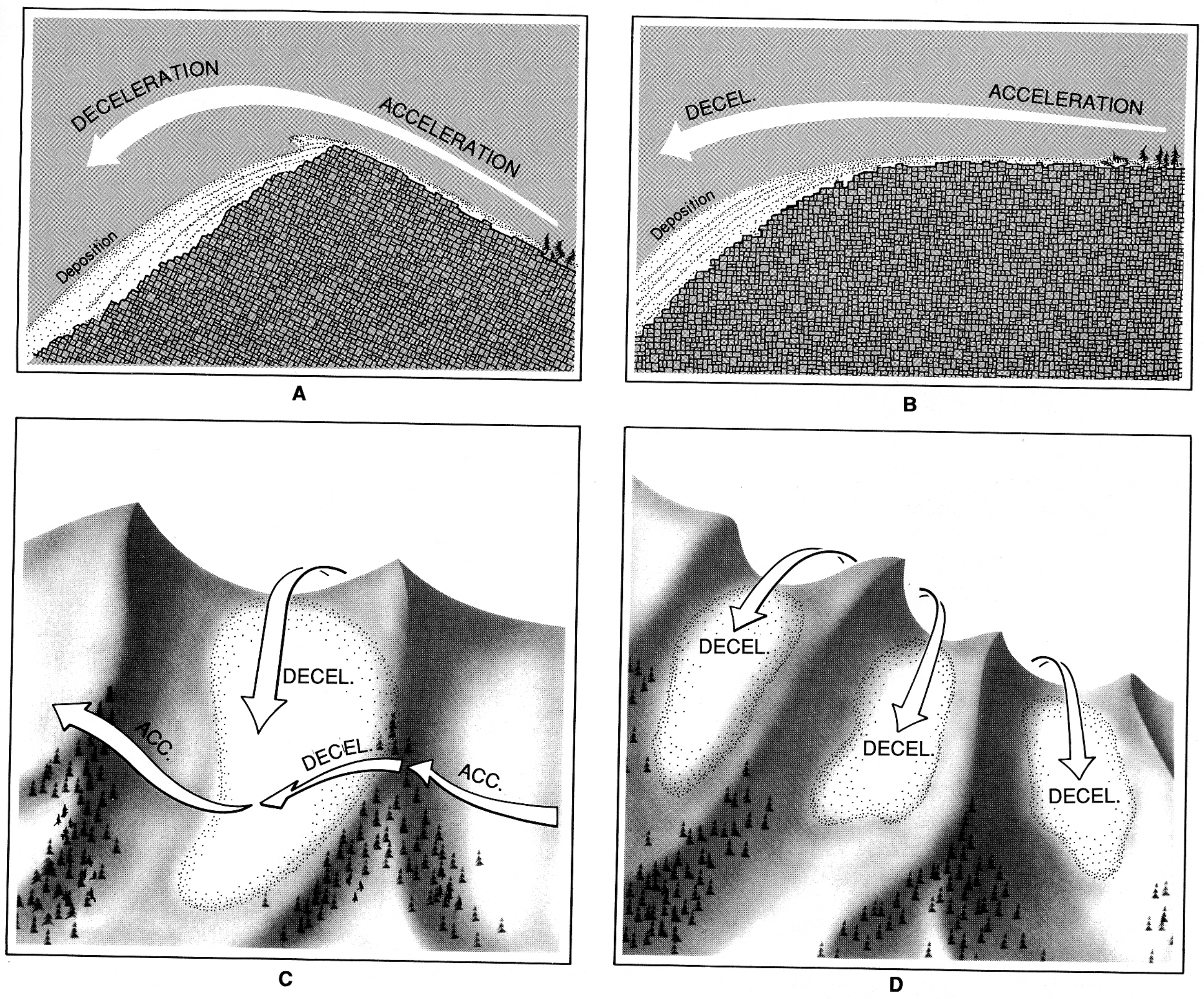
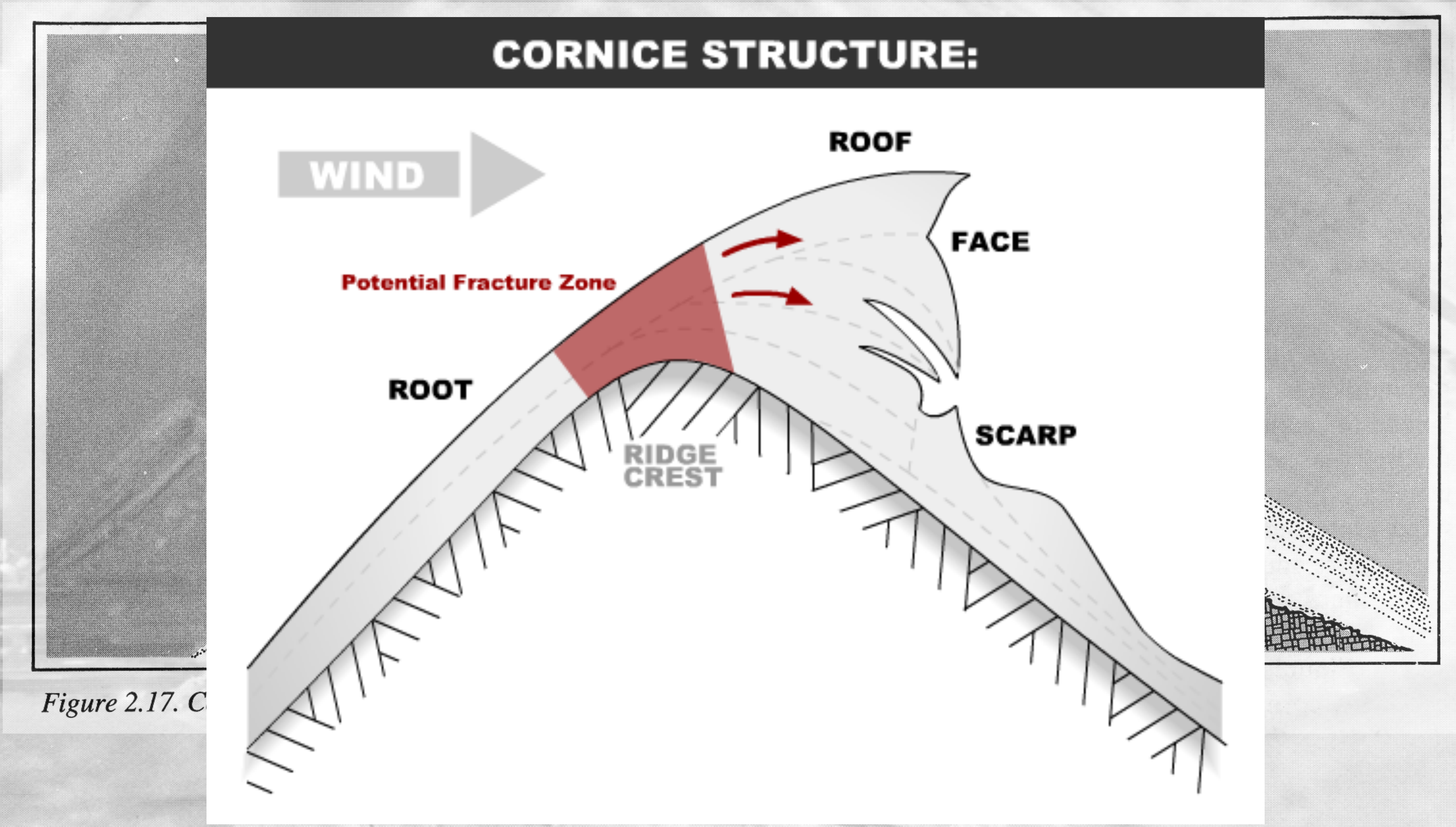


Figure 2.15. Snow is picked up in acceleration regions and deposited in deceleration regions (A, B). This produces lee zone deposition, cross-loading, and deposition in gullies and notches (C, D).

Avalanche Handbook

Cornice Structure



Avalanche Handbook

Snow Metamorphism

- What is snow metamorphism? What are associated changes that occur in the snowpack?

- How does heat flow through the snowpack?

- How do temperature gradients influence metamorphism within the snowpack?

Snow Metamorphism

(changes in snow crystal form due to heat flow and pressure)

- *Associated changes*
  - Density
  - Porosity
  - Microstructure
  - Water content
  - Strength
  - Albedo

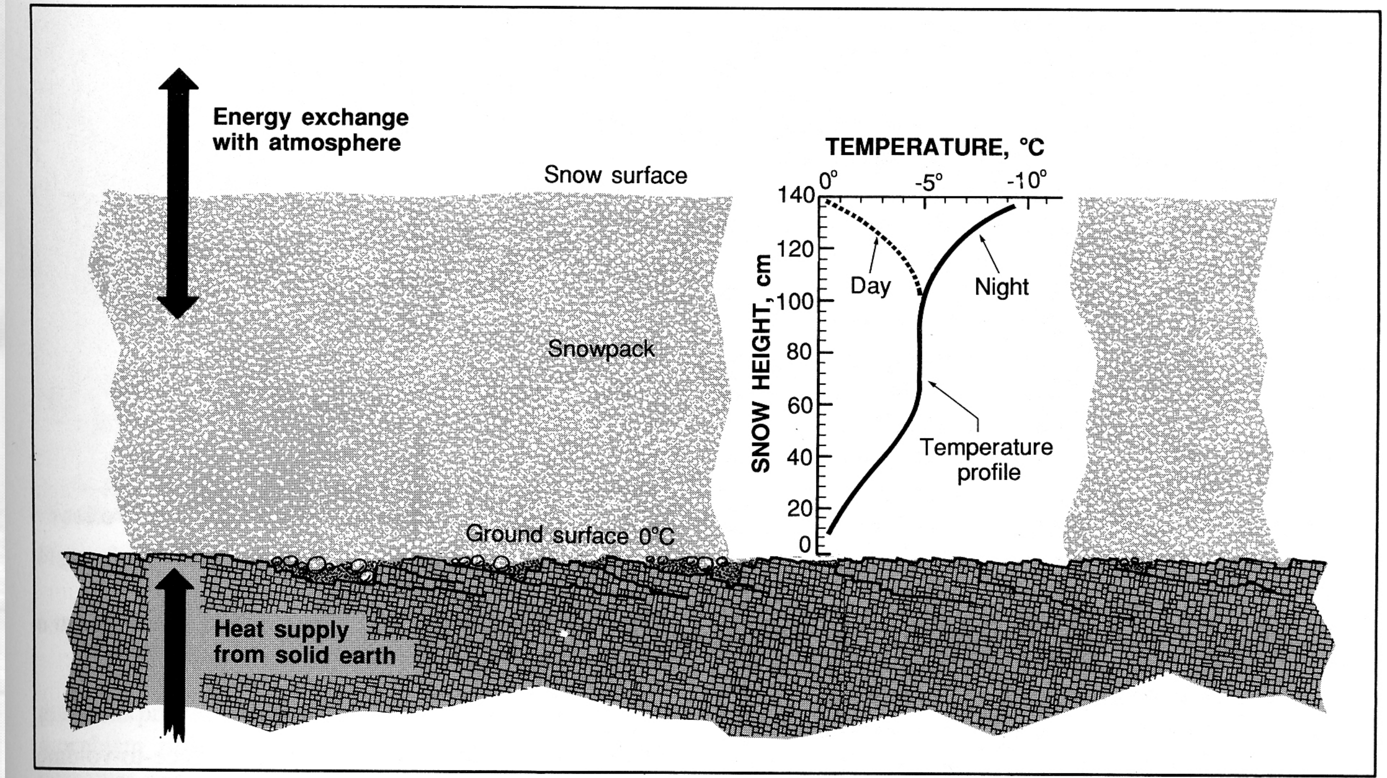
Temperature gradients/Heat flow in the snowpack

- Air is cold, ground is warm

- Fourier's Law

$$Q = -K_{eff} \frac{\mathrm{d}T}{\mathrm{d}z}$$

Q = heat flow
K = thermal conductivity
dT/dz = temperature gradient



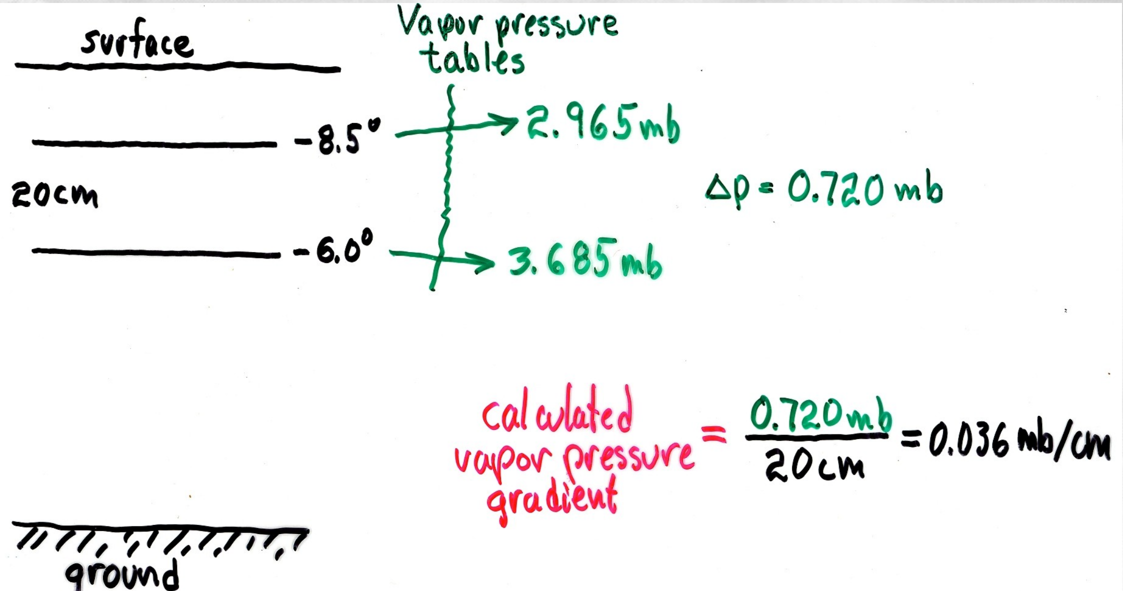
Coupling of temperatures and temperature gradients

Vapor-Pressure Gradients

•Air in pore spaces which are at a higher temperature can hold more water vapor than lower temperature pore space air

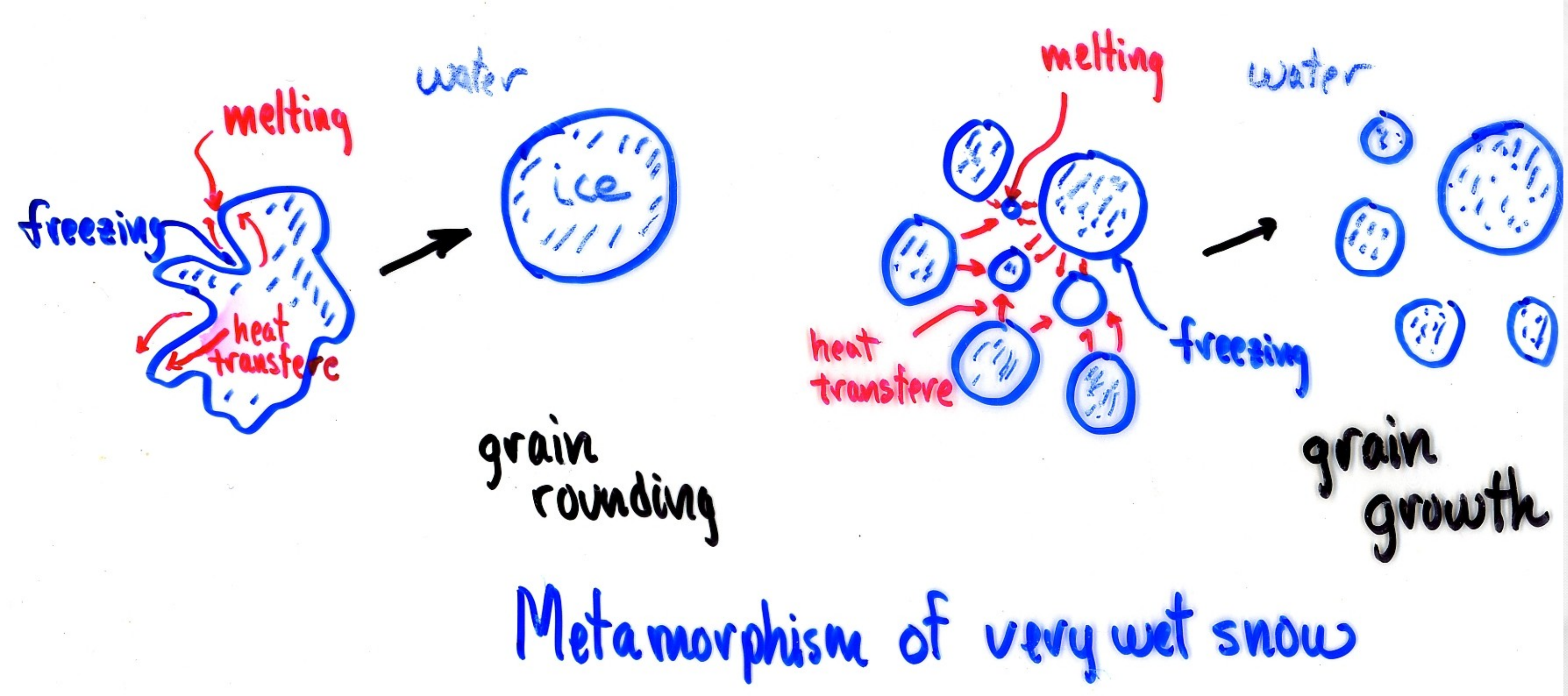
•This results in a vapor pressure gradient being set up within the snowpack

•Water vapor diffuses from high vapor pressure to low vapor pressure



Example: 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.



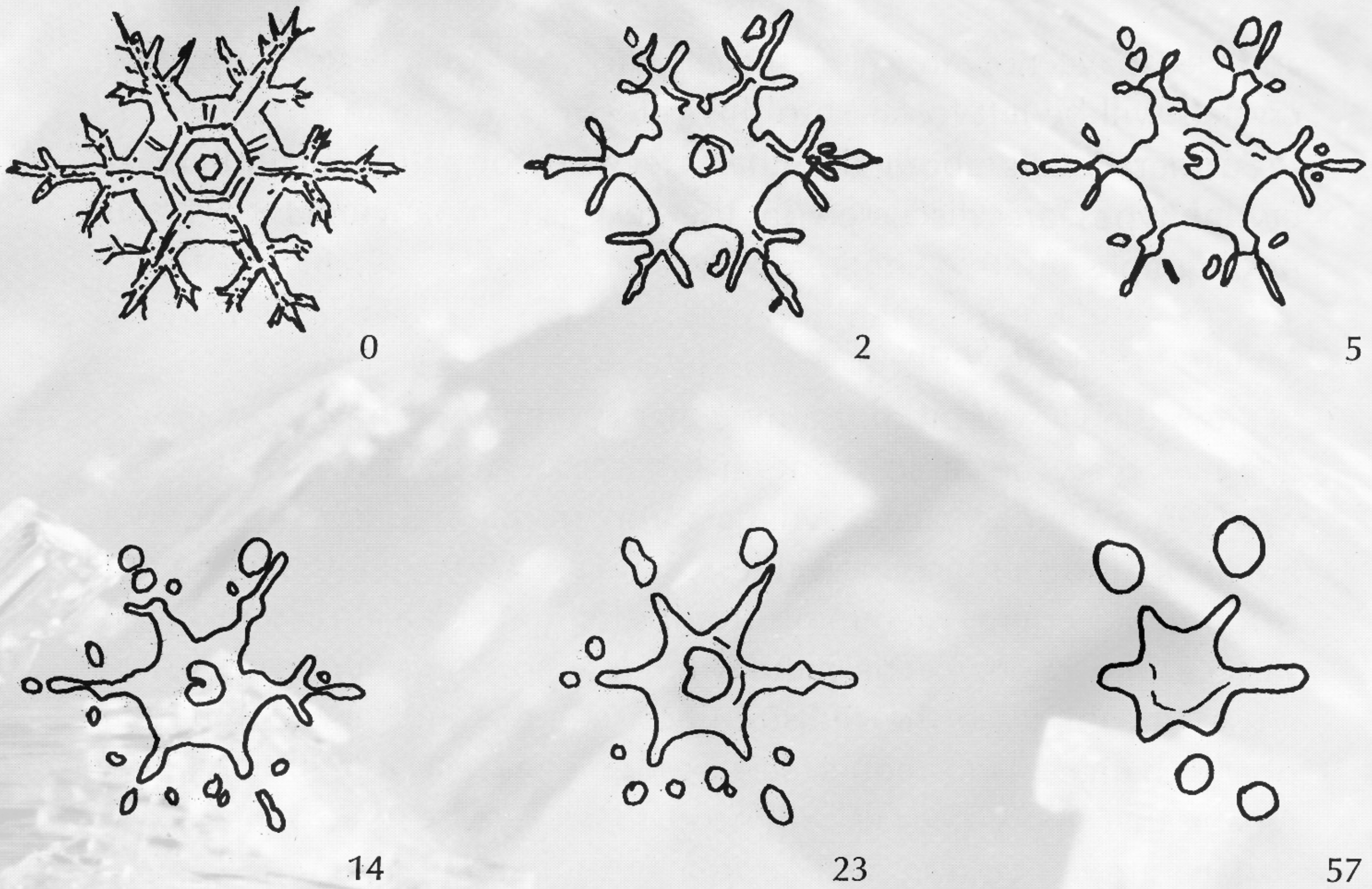
Temperature gradients and metamorphism

- **In general, the temperature and temperature gradient determine the rate of metamorphism of dry snow**

Equilibrium-form Metamorphism ("Destructive" Metamorphism)

- **Dominates when there is NOT a significant temperature gradient**
- 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

Destructive Metamorphism of a Snow Crystal

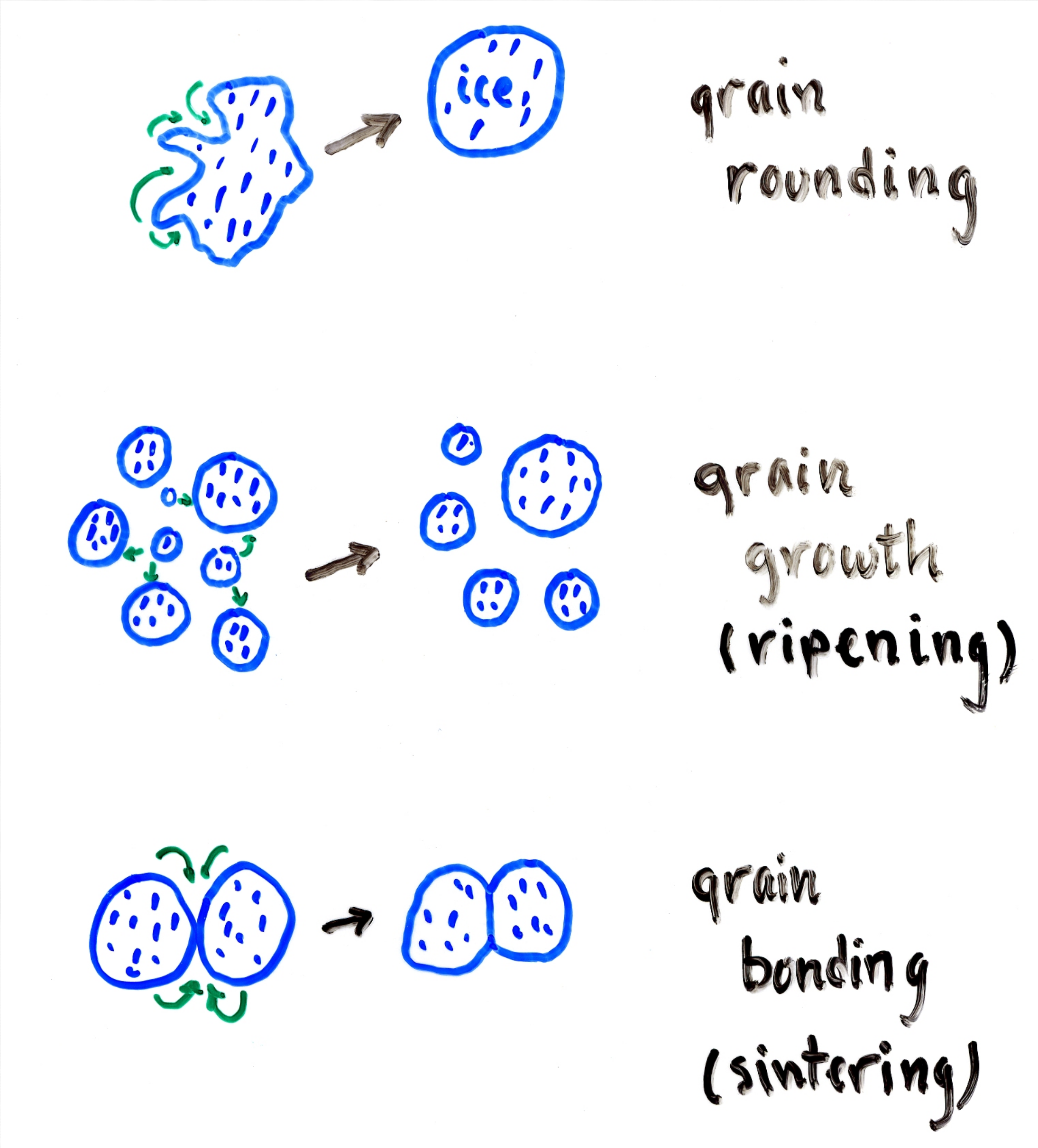


6. The destructive metamorphism of a stellar snow crystal. The numerals give the age of the snow crystal in days.

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

Mass Transfer Reduces Surface Area

Result is equilibrium forms



C.F. Raymond

Kinetic-Growth Metamorphism ["Constructive" Metamorphism]

48. Typical crystals of mature depth hoar. 24X

- Formation of frost and hoar
- Complex shapes ***increase*** surface area
- Mass is transferred from the top of one ice crystal to the bottom of the ice crystal above
    - Diffusion of vapor in direction of vapor pressure gradient
    - Deposition from vapor to ice

- (**Vapor-pressure gradients created by temperature gradients** are more important than **vapor-pressure gradients from grain curvature** (e.g., when $dT/dz > 10$ deg m^{-1}))

Some material from : http://www.naturfare.no/_attachment/534799/binary/859936

Metamorphism Comparison

- **Low temperature gradient (Destructive)**
  - Location of the areas where deposition of vapor occurs is influenced by the pressure gradient that results form the radius of curvature
  - Vapor tends to be deposited in concave areas which reduces the curvature – crystals become more rounded and bigger
- **High temperature gradient (Constructive)**
  - Creates a high vapor pressure gradient which is sufficient for crystal faces to grow
  - Results in faceted crystals

Slide by naturefare: http://www.naturfare.no/_attachment/534799/binary/859936

Deposited Snow

Snow Stratigaphy

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

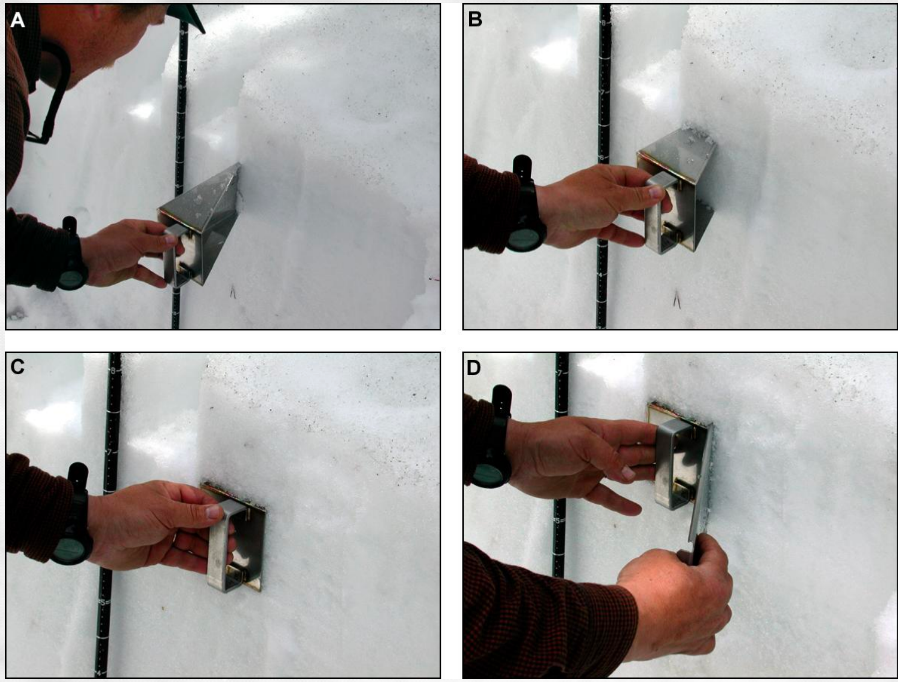
Causes of Stratigaphy

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

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



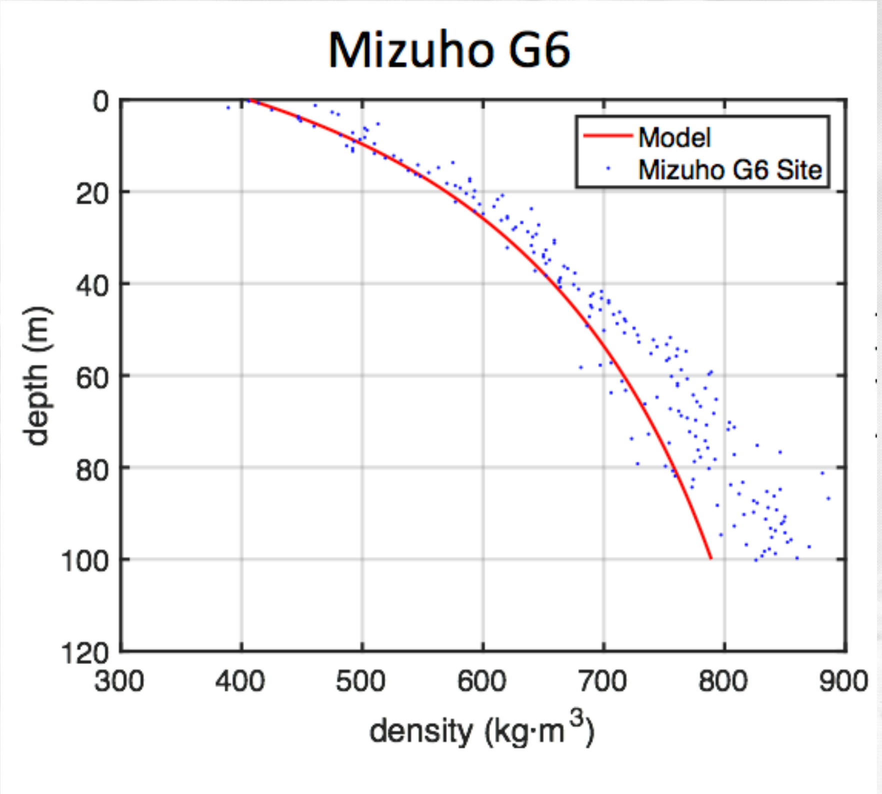
Firn and its transformation into glacial ice

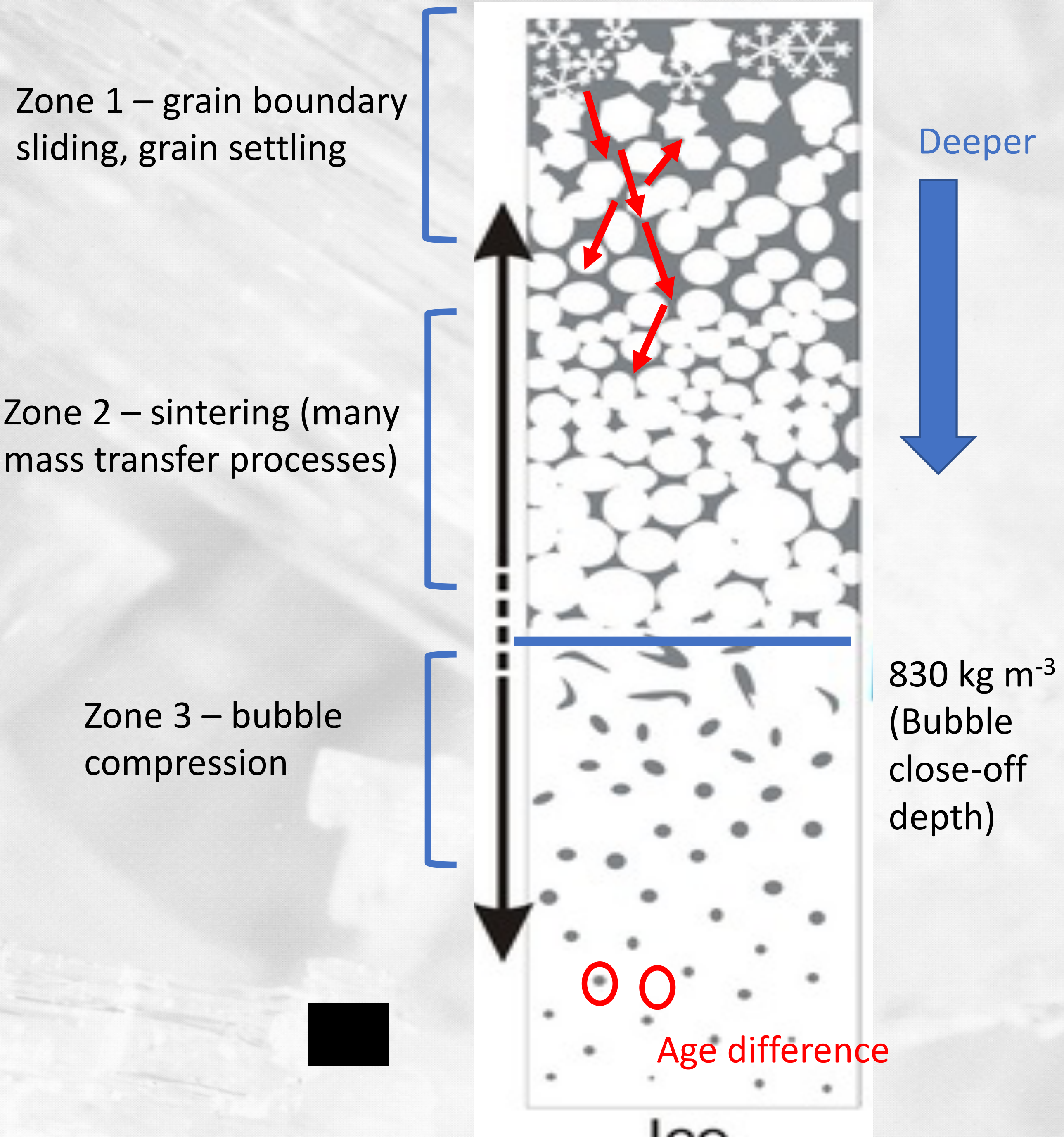
(changes in firn grains due to heat flow and pressure)

- What is firn?
- How does firn densify?
- Why is it important for ice core analysis and ice sheet mass balance approximations?
- How does gas transport in firn work?

What is firn?

- Firn is the transitional stage between snow and glacial ice





Why is studying firn important?

Ice core analysis

Ice-sheet mass balance approximations

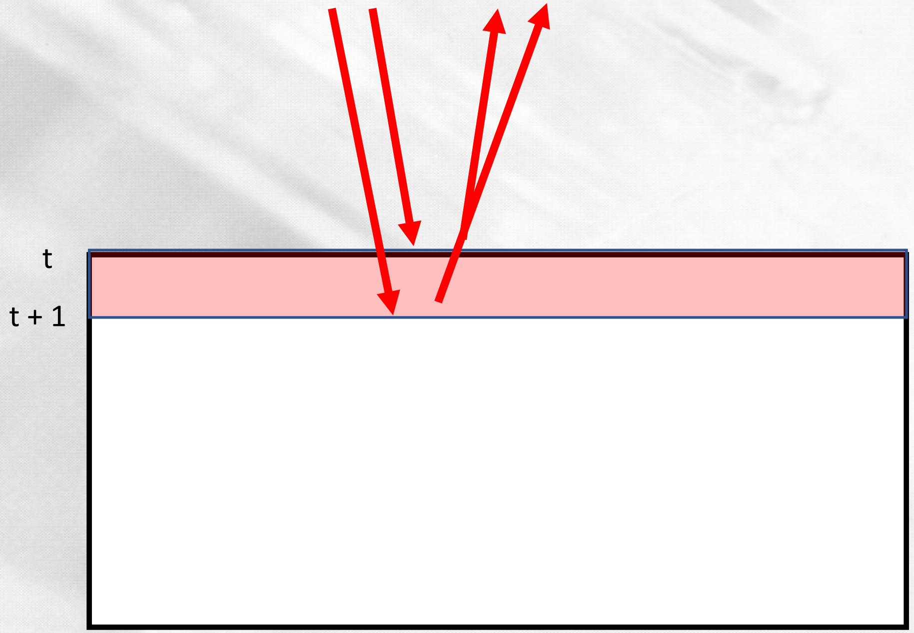
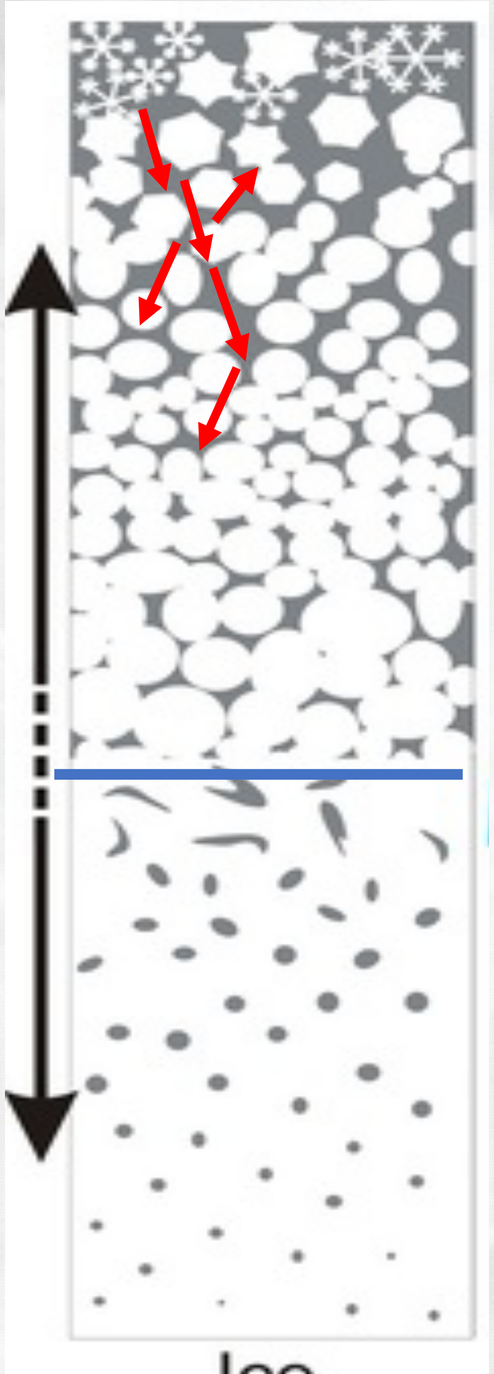


Photo credit: NASA

Gas transport in firn

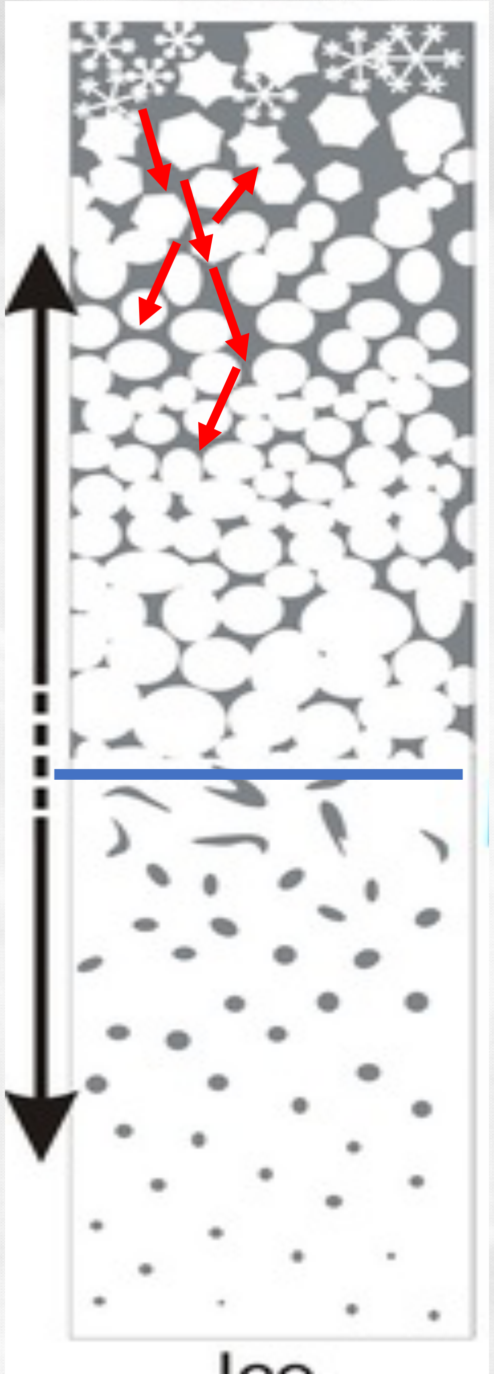
- Firn is porous and has open ‘channels’ where diffusion
- Air in channels is in contact with the atmosphere and changes in atmospheric composition diffuse slowly through firn column
- The composition of air stored in ice relative to the composition of the atmosphere is influenced by
  - gas diffusion
  - progressive trapping of bubbles at bubble close-off zone
- **Gravity acts on different species according to their mass**
  - Enrichment of heavier species relative to light ones
- Thermal diffusion causes heavier species to become enriched in colder parts of the firn
  - Seasonal temperature variations
  - Rapid changes in climate



Trudinger, 2001

Gas transport in firn – review from previous class

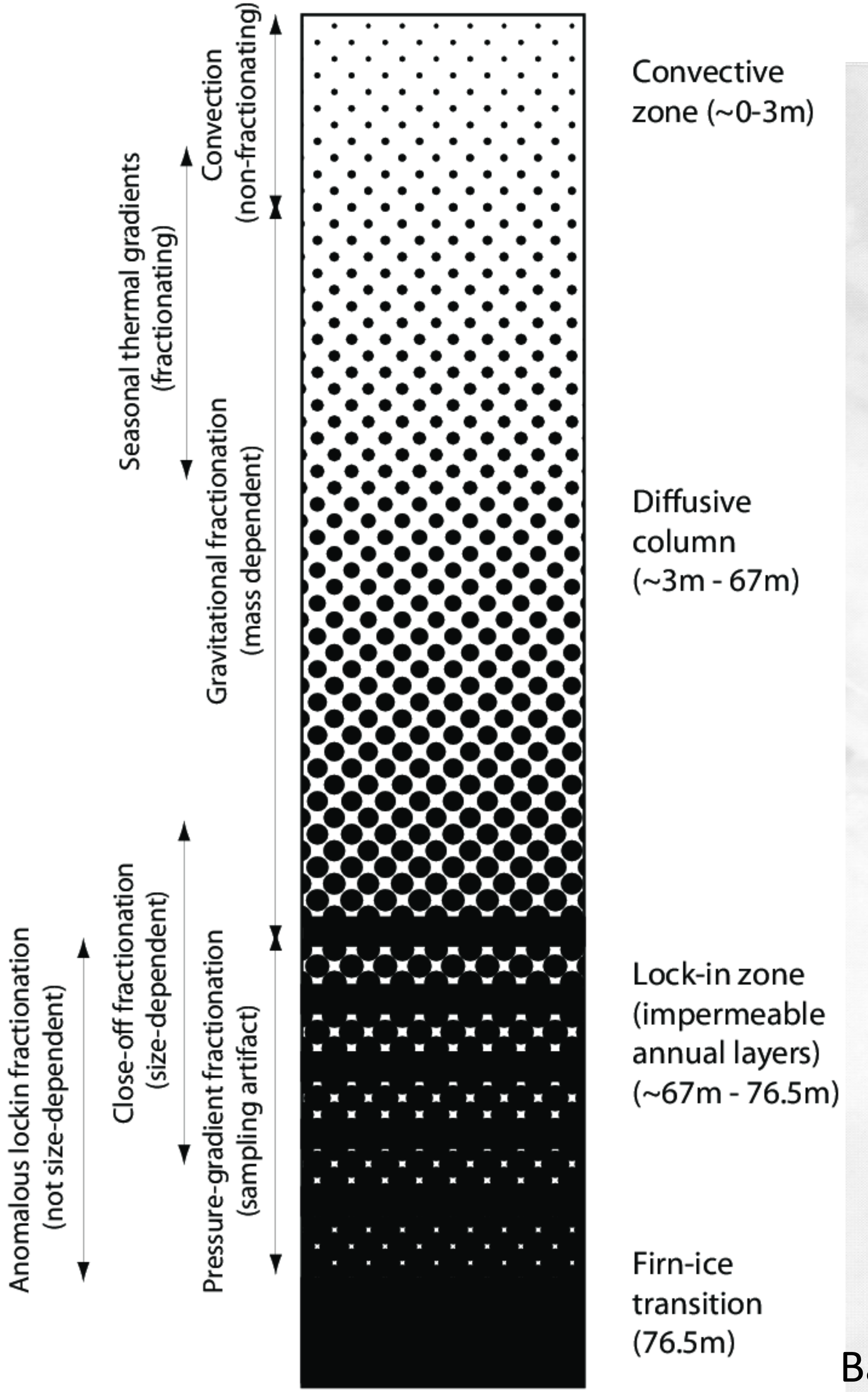
- Firn is porous and has open 'channels' where diffusion
- Air in channels is in contact with the atmosphere and changes in atmospheric composition diffuse slowly through firn column
- The composition of air stored in ice relative to the composition of the atmosphere is influenced by
  - Gas diffusion
  - Progressive trapping of bubbles at bubble close-off zone
  - Gravitational settling
  - Thermal diffusion



Trudinger, 2001

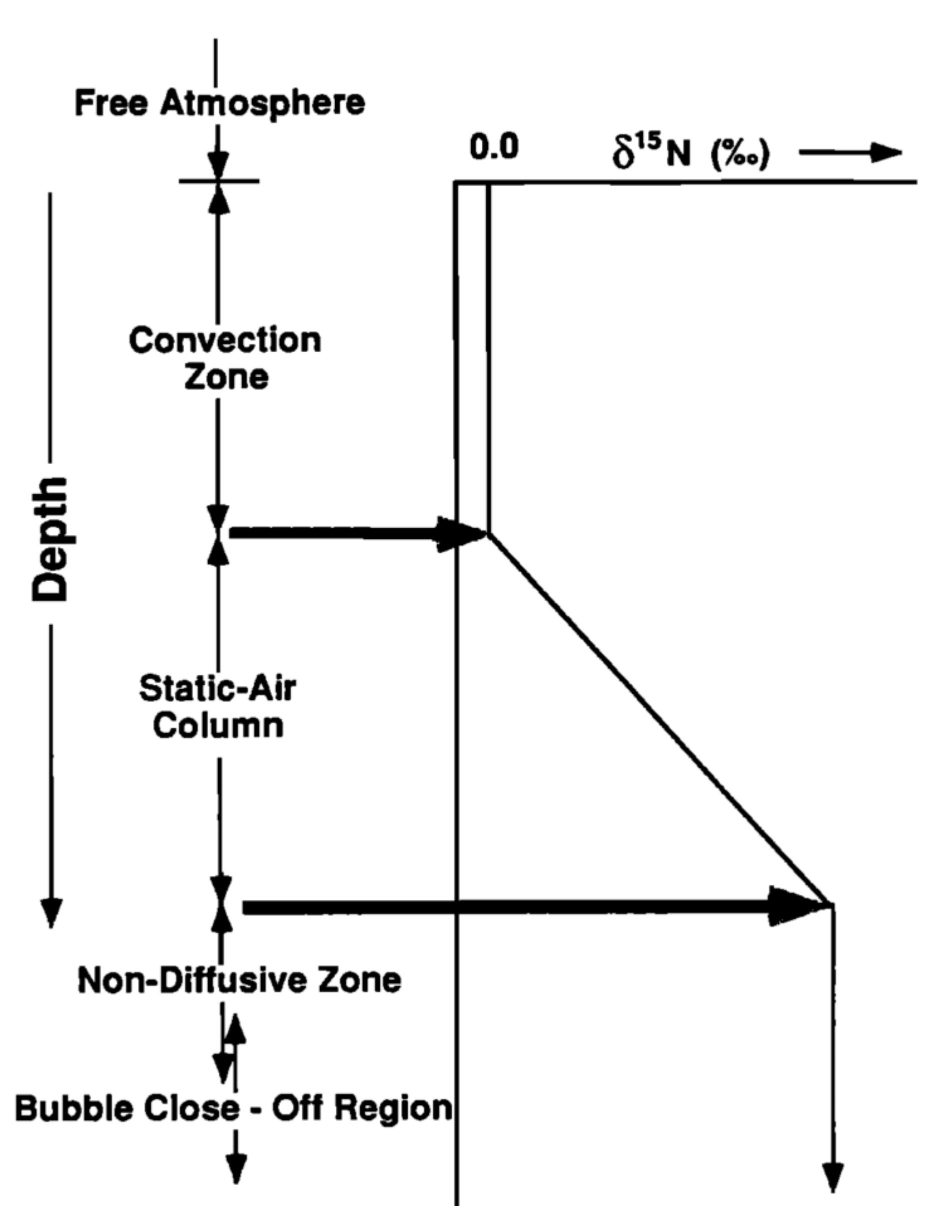
The Firn Layer

- *Convective zone:* movement of air governed by surface winds and atmospheric pressure fluctuations
- *Diffusive column*: not influenced by surface turbulence; gravitational settling of heavy isotopes
- *Non-diffusive zone*: diffusion is so slow, negligible gas transport



Battle et al., 2011

Example: δ-15N of N_2 in the firn column



Sowers et al., 1992