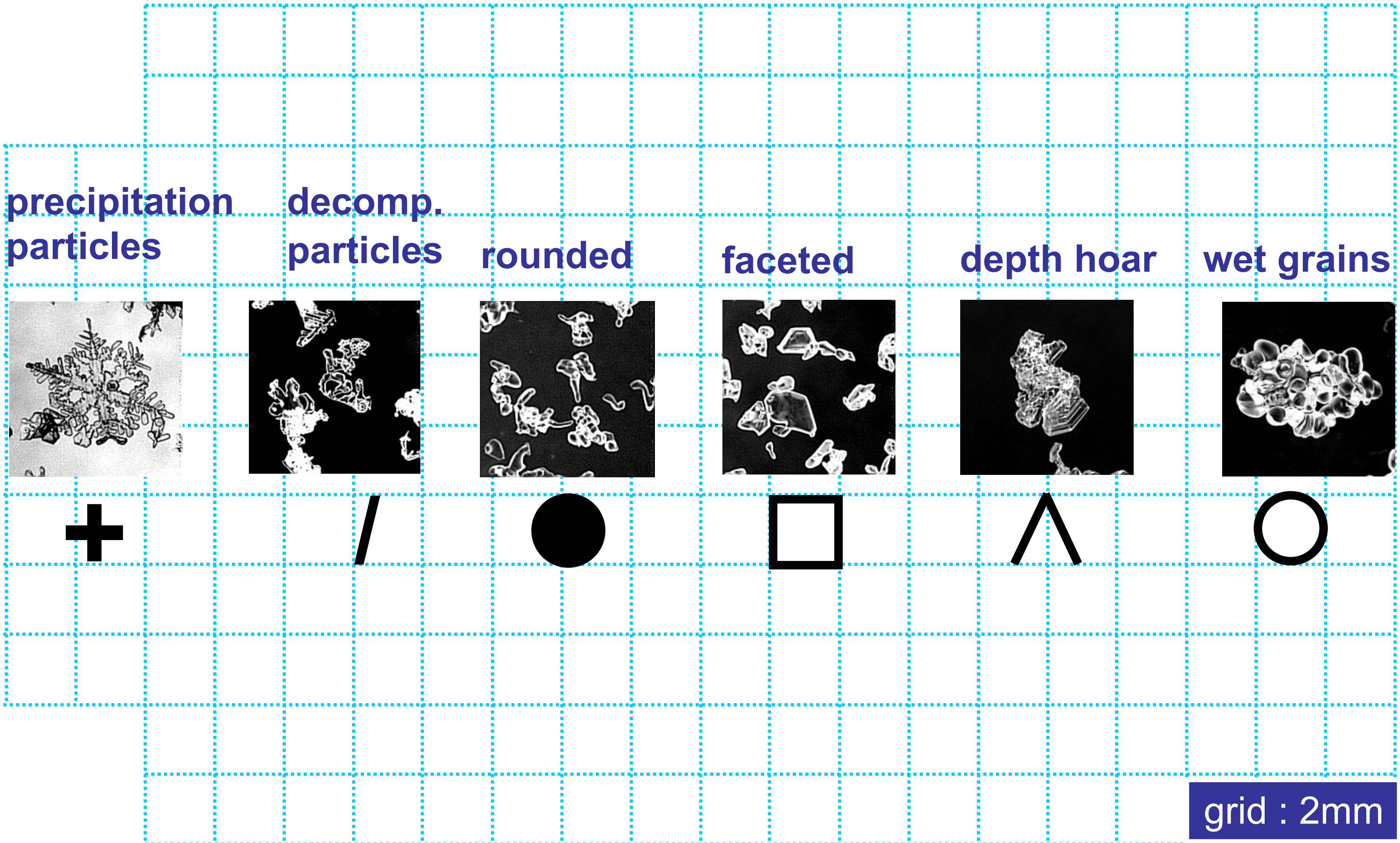
Snow Microstructure & Metamorphism

Principal snow grain types

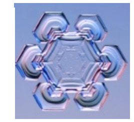


Outline:

Significance and “Ingredients”

- Dry Snow Metamorphism
  - Equilibrium metamorphism (EM) → Isothermal (or low T-gradient)
    - Destructive metamorphism (rounding)
    - Constructive metamorphism (sintering)
  - Kinetic metamorphism (KM) → Large temperature gradients
    - Faceted grains, depth hoar
- Wet Snow Metamorphism
- Densification / gravitational settling
- Classification of snow crystals

Significance of snow metamorphism



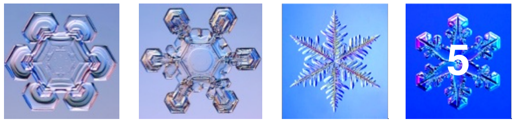

Metamorphism in snow affects:

- snowpack layering (avalanches, meltwater movement)
- structural strength (avalanches)
- permeability (meltwater percolation, ventilation, heat flux)
- surface albedo (radiation balance) and microwave emission
- thermal conductivity (heat transport)
- snow internal mass transport (vapor, air, isotopes)
- etc.

Ice crystals have a large surface area to mass (volume) ratio

- thermodynamically relatively unstable
- development towards equilibrium state

Saturation vapor pressure

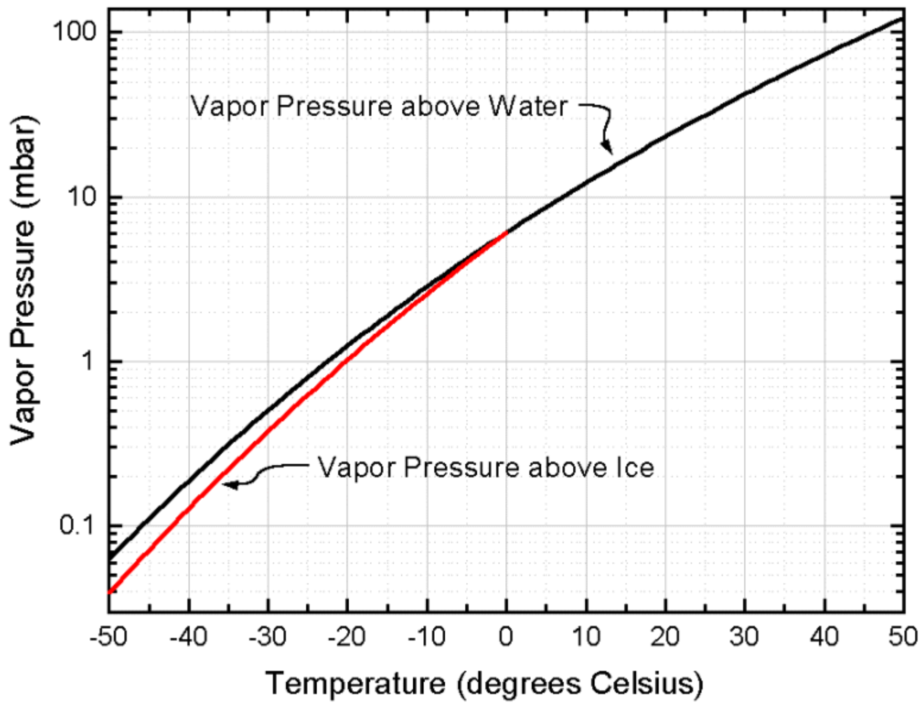


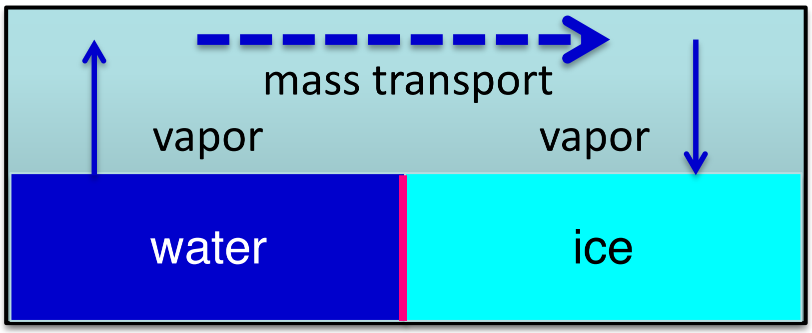
- strong f(T)
- different over water (T > 0^{o}C) and ice (T < 0^{o}C) surfaces
- various approximations (equations) available (both for water and ice)

$\Delta e_s = e_{s,w} - e_{s,i} \approx$ avg 0.2 mbar; max: 0.27 mbar

$e_{s,w} > e_{s,i}$ for all T

Log-scale!



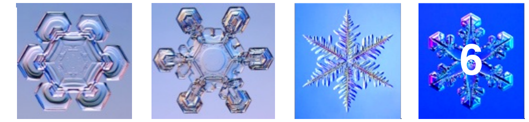


closed box, constant T ≤ 0^{o}C

$e_{s,w} > e_{s,i}$

See also slides in “Snow Properties”

(Saturation) Vapor Pressure

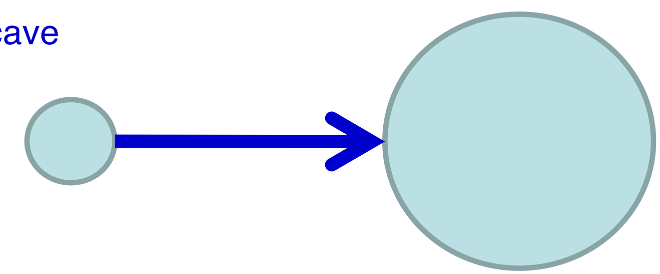


- e = f (T)
- e = f (geometry/diameter of droplets and crystals)
- e over convex surfaces (tips, points, corners, edges, ridges)

  > than over flat surfaces (weaker molecular bonds)
- e over concave surface (necks, depressions, grooves, etc.)

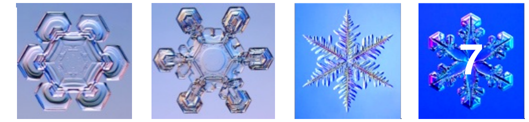
  < than over flat surfaces (stronger molecular bonds)

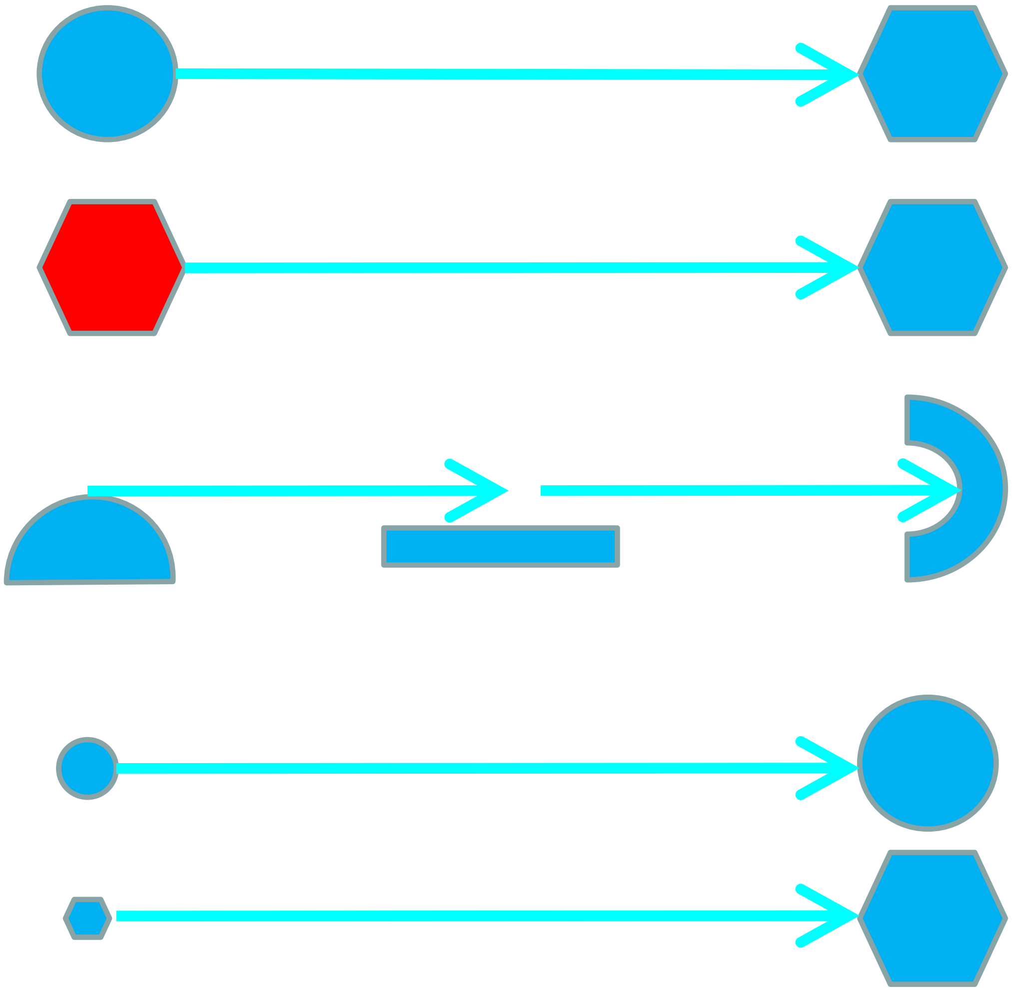
- $e_{convex} > e_{flat} > e_{concave}$



- → vapor transport: larger particles grow at cost of nearby smaller ones

Mechanisms of mass transport



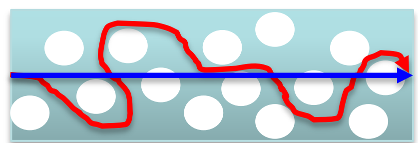


- a) $e_w > e_i$
- b) temperature
- c) curvature
- d) size (curvature)

Gas diffusion in porous media

The porosity ϕ of a medium restricts the cross-sectional area available for transport.

The τ tortuosity accounts for the increase in path length molecules must follow.
(τ = C/L, ratio of curve length C to distance between curve ends L.)



The diffusion coefficient in a porous medium in the Fick'ian diffusion regime, D_F, can be written as

$$D_F = \frac{\phi}{\tau} D_{12}$$

$D_{1,2}$ denotes the diffusion coefficient of gas #1 into gas #2
The ratio ϕ/τ is called "obstruction factor"..

Microscopic mass transport

Steady state concentration distribution in pore space:

$$\Delta c(x) = 0$$

Trace gas transport

external concentration gradient

$c_1 < c_2$

c_2

ice is an obstacle for diffusion

boundary condition
on ice-air interface:

$$\vec{n} \circ \nabla c(x) = 0$$

Water vapor transport

T-induced concentration gradient

ice is source/sink for water vapor

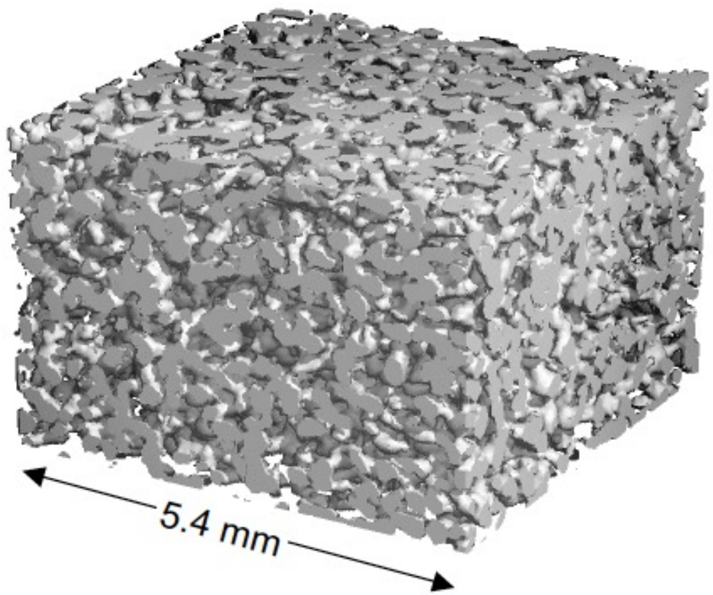
boundary condition
on ice-air interface:

$$c(x) = c_e(T(x))$$

$T_1 < T_2$

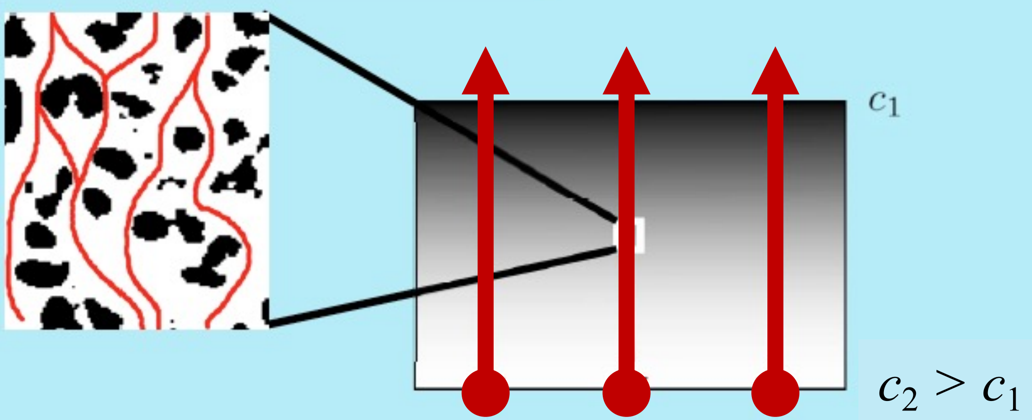
T_2

Microstructure vs. bulk properties



- "Microstructure":
  the 3-D distribution of
  ice and air

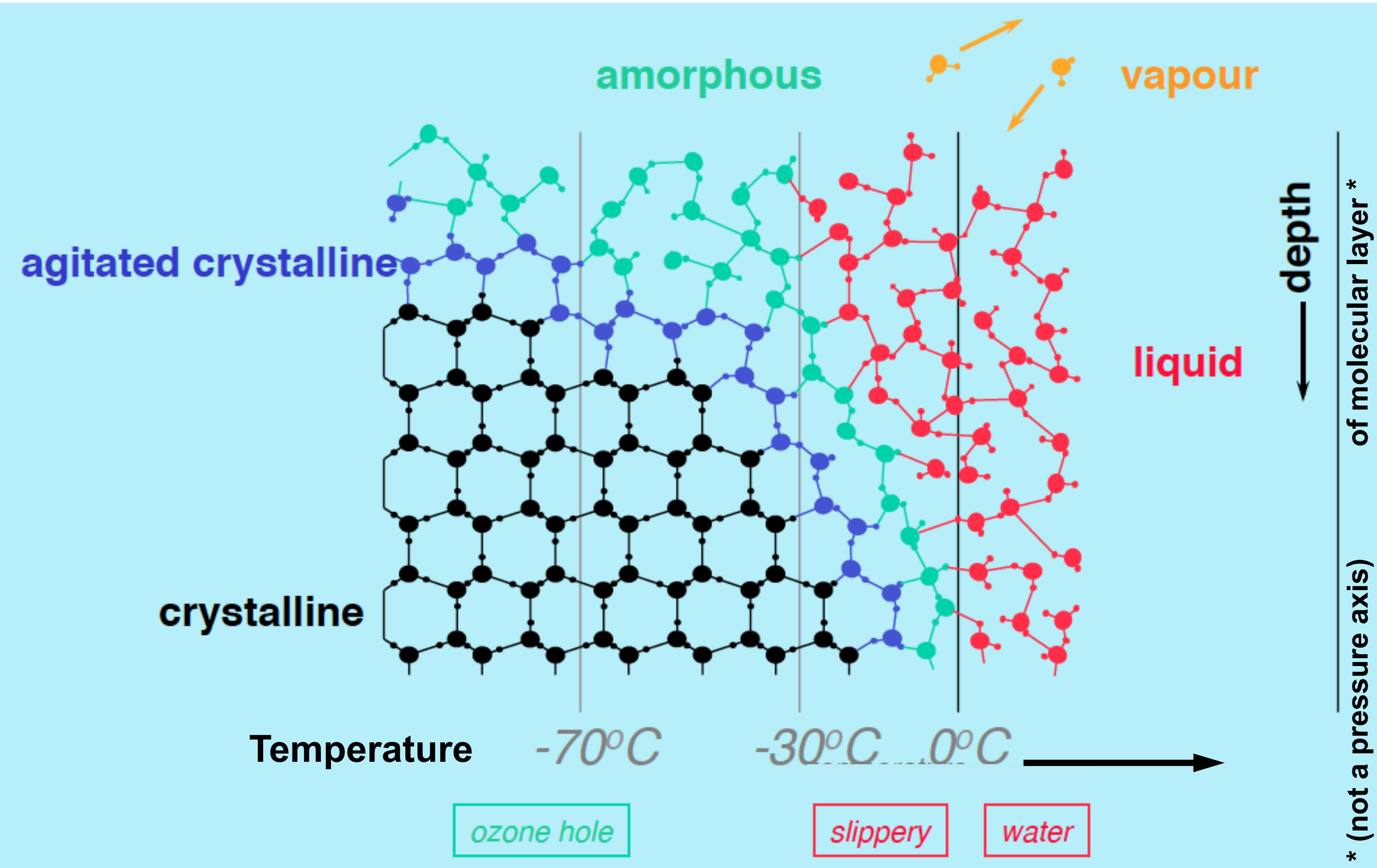
- Homogenization leads to effective
  quantities



$$j = -D_{\text{eff}} \nabla c$$

recall: $D_{eff} = D_{12}\phi\delta/\tau$
δ: constrictivity

Structure and surface conditions



Big changes occur…

… once the snow is on the ground!

- Snowflakes may be close to triple point (vapor, liquid, solid phases can all exist at 0.01^{o}C)
- Snowflakes are formed in a highly super-saturated environment, but snowpack only has low levels of super-saturation or none
- Snowflakes are thermodynamically unstable (due to their shape); in the air and on the ground, changes occur immediately

Types of snow metamorphism

Dry snow metamorphism:

- No liquid water present
- Temperature < 0°C

a) equilibrium (isothermal) metamorphism

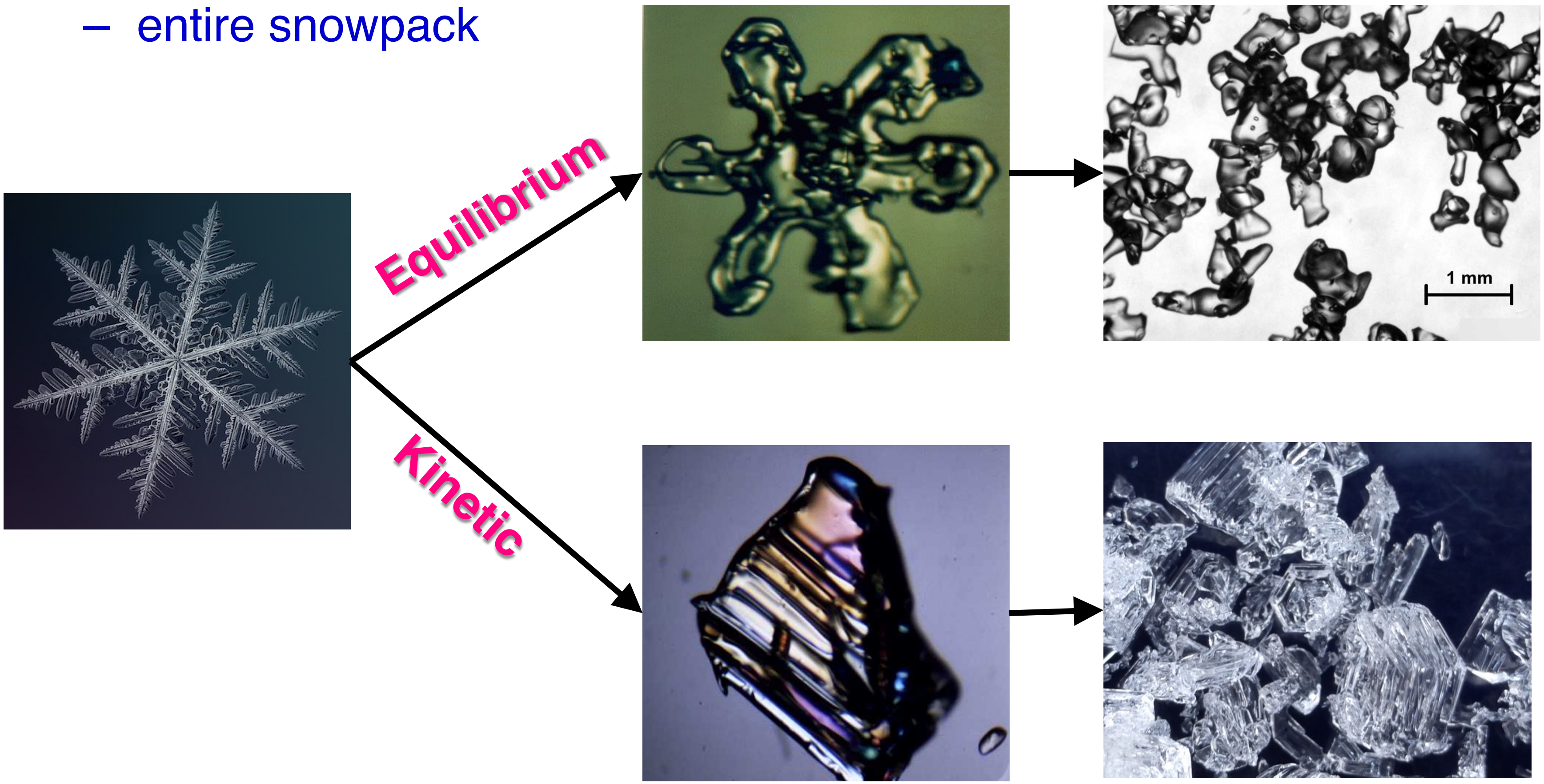
b) kinetic (T-gradient) metamorphism

Wet snow metamorphism:

- Liquid water present (partially instead of air)
- Temperature is at 0°C (isothermal)
- Curvature differences of the grains is driving gradient
- Partially conduction of heat in water instead of heat diffusion in air

Dry snow metamorphism

- Driven by water vapor transport (vapor gradients)
- Two spatial scales are important:
  - individual dendrites
  - entire snowpack



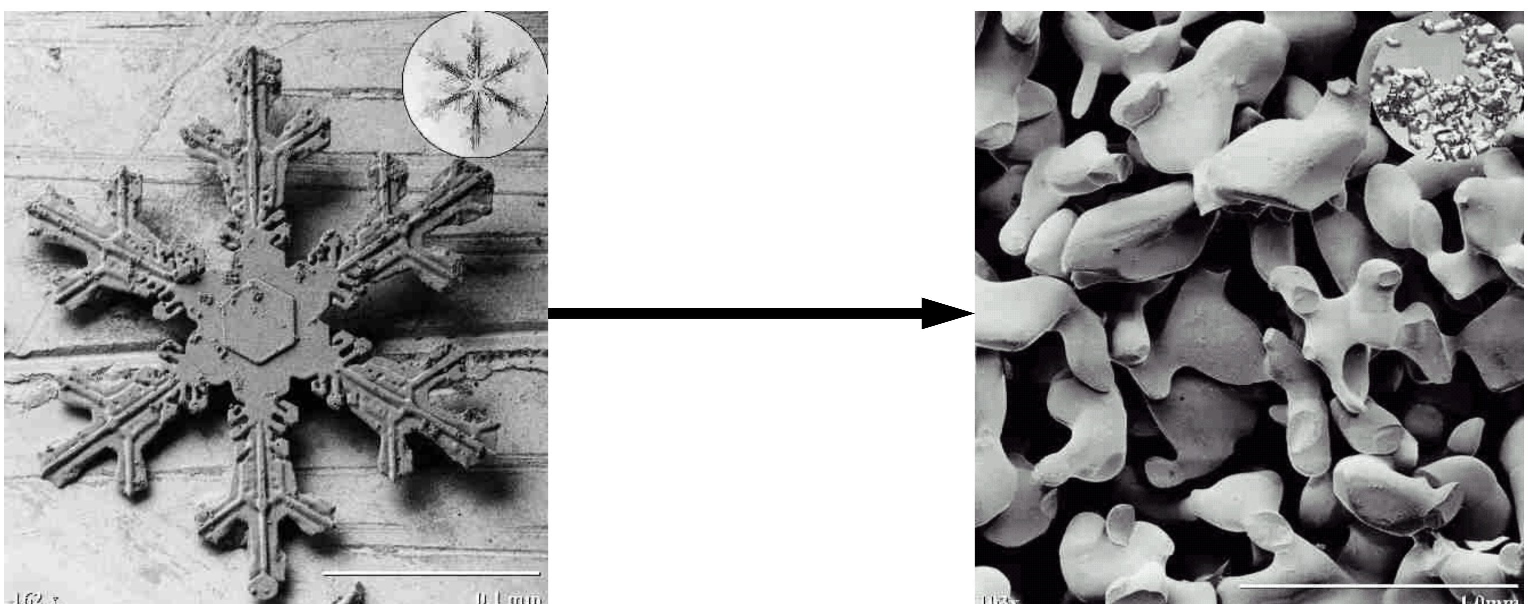
Equilibrium metamorphism (EM)

Occurs under quasi-equilibrium conditions

- low vapor pressure gradients (< 3.5 mbar m^{-1})
- low temperature gradients ($< 10^{\circ}C$ m^{-1})

Consequences:

- rapid destruction of original snow crystal shape
- bonding between grains
- formation of rounded shapes



Destructive Metamorphism

- Saturation vapor pressure (SVP) varies inversely with the radius of curvature
- Molecules sublimate from points of dendrites (high SVP) and move to the hollows / necks / cavities between branches (low SVP)
- Air over points then becomes under-saturated (RH < 100%)
- More water molecules sublimate from points and tips and move to hollows →
- Vapor pressure gradient between points and hollows decreases slightly → tendency to equilibrate

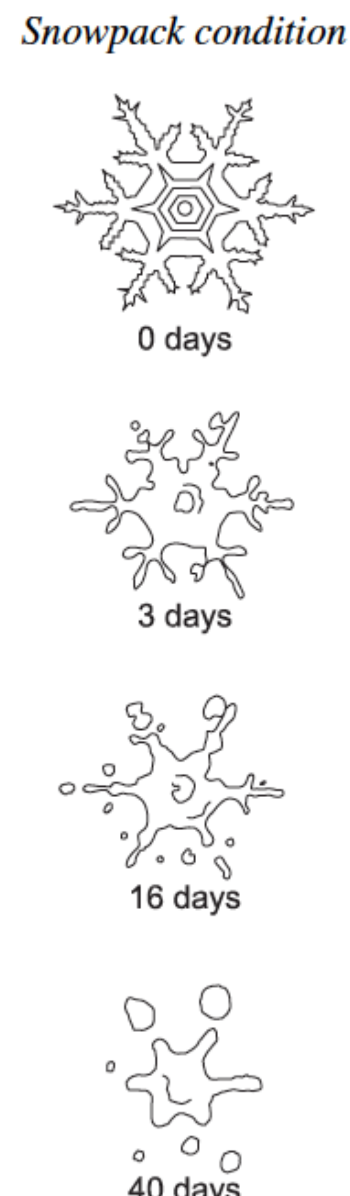
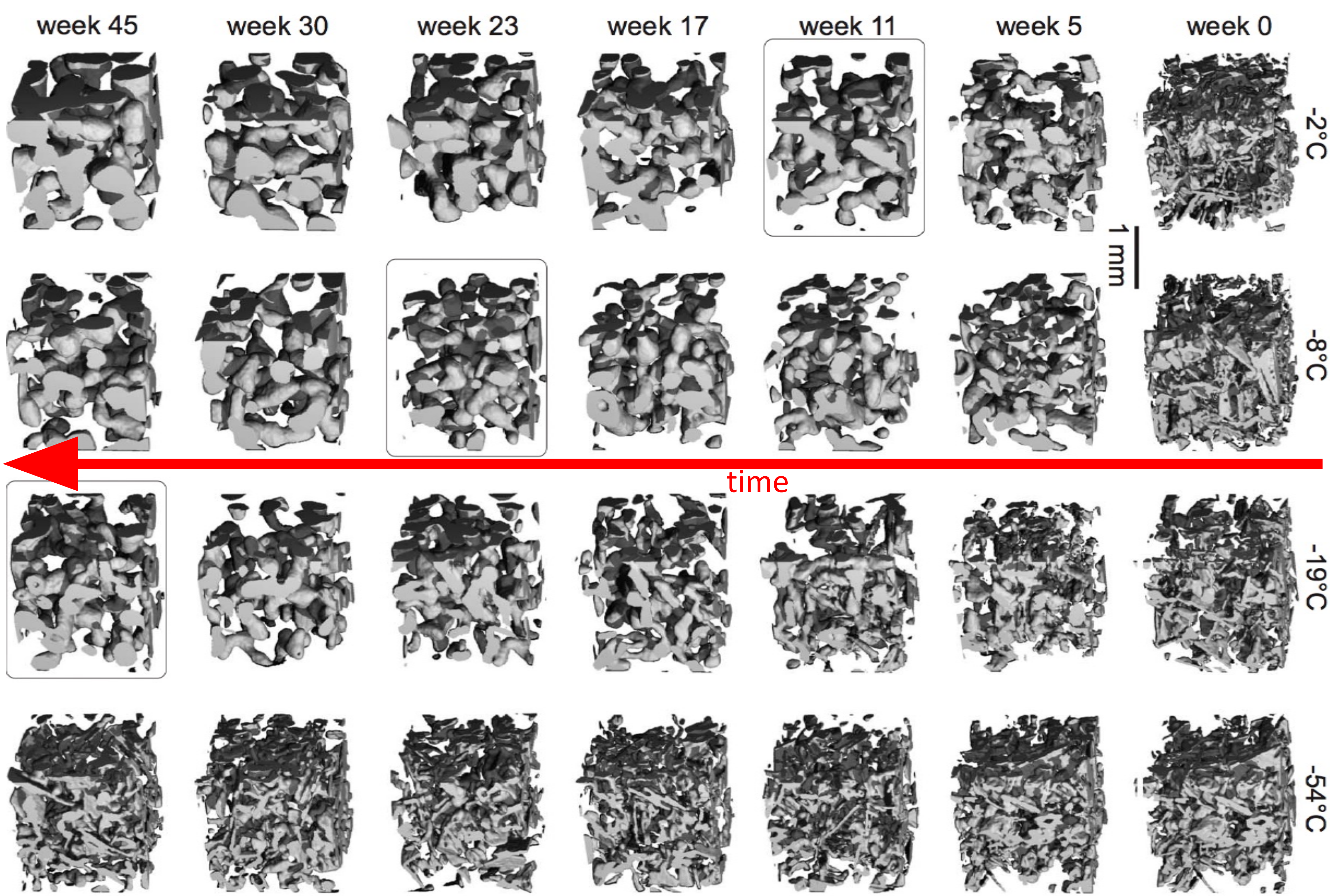


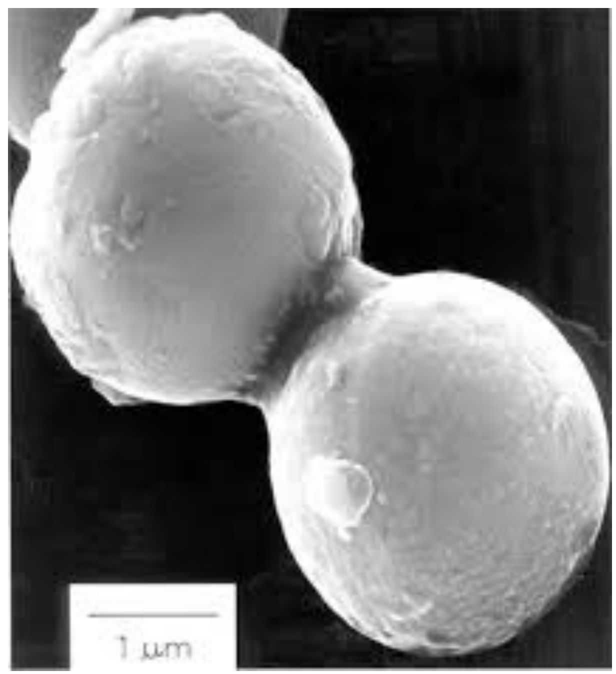
Figure at right: Transition of a stellar dendrite to a rounded grain over time from Bader 1939

Time series of EM



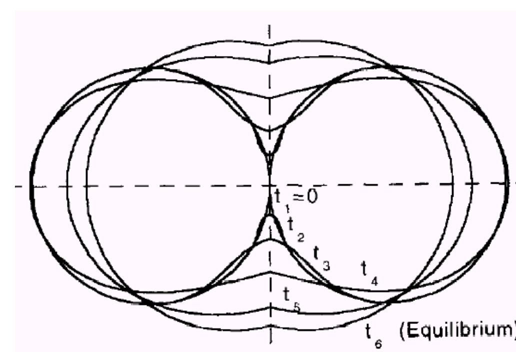
Isothermal grain growth & sintering

- Small grains disappear and large grains grow
- As branches vanish, individual grains become more spherical
- Equilibrium metamorphism is also responsible for bond formation between two or more snow grains: "sintering"



Sintering:

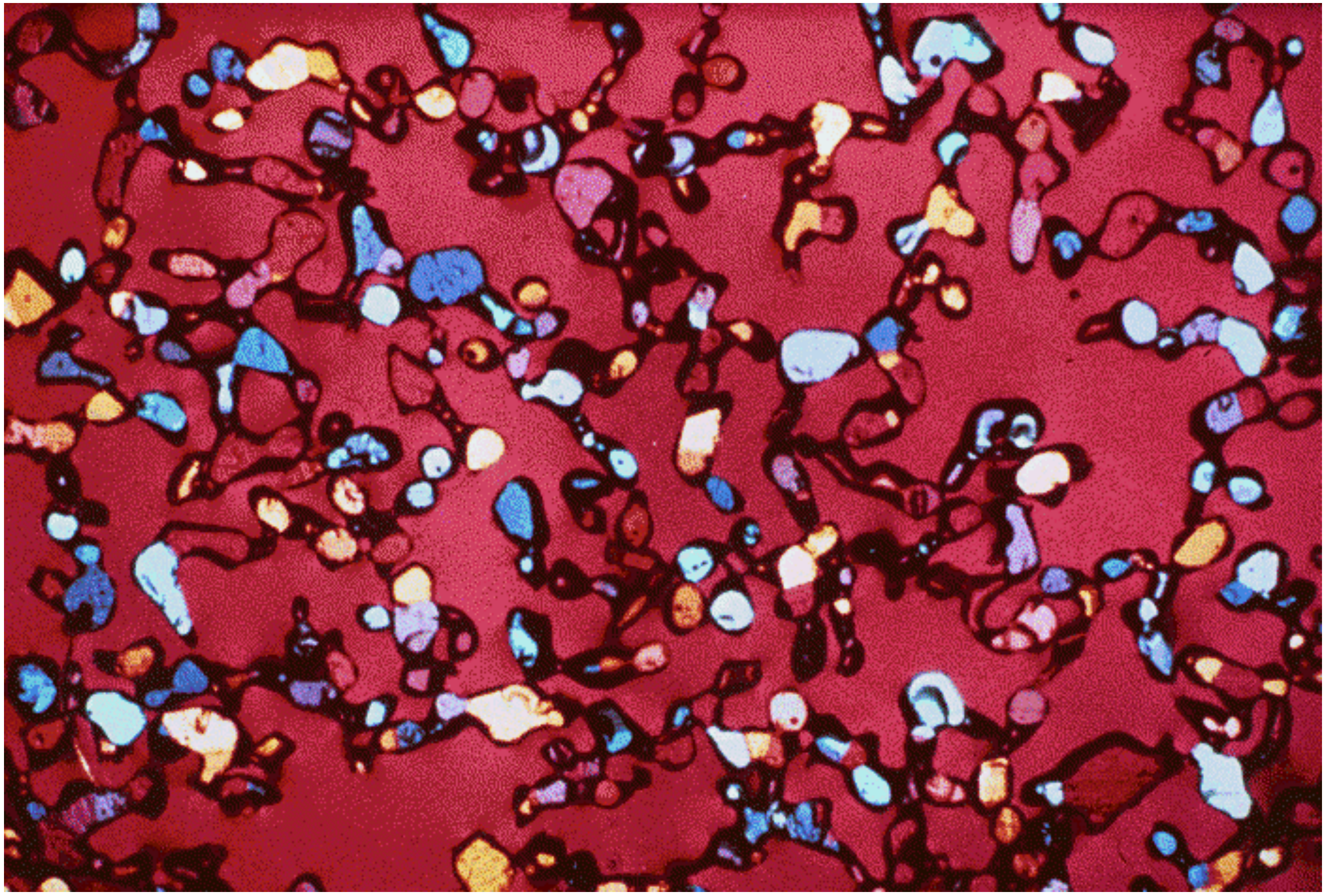
Formation of bonds between adjacent ice grains in dry snow



Zhang and Schneibel (1995)

Sintered snow grains

- Polarized image from thick-section snowpack sample showing chains of sintered snow grains
- (Different colors show different polarizations)



EM – summary

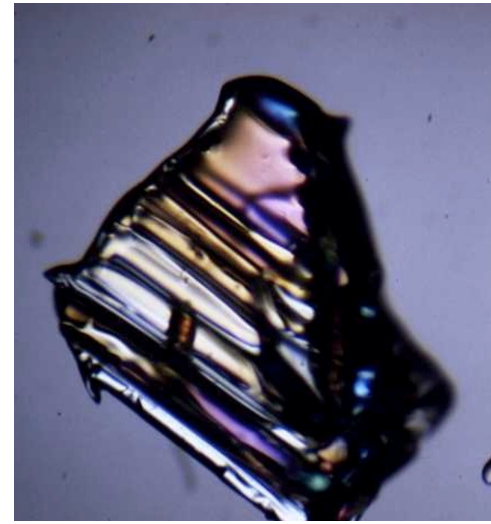
- No or negligible T-gradient in snowpack
- Surface-to-volume ratio (SSA) of individual snow grains is reduced
- Rounding of snow grains occurs
- Snow grains fill more pore space of the snowpack
- Density of the snowpack increases as settling happens
- Bonding (sintering) of snow grains occurs
- Increased strength of snowpack (compression, shear, and tensile)
- Rate of EM increases with increasing snow temperature
- Vapor gradients due to different curvature and local T-gradients

Kinetic metamorphism (KM)

Occurs under conditions of:

– large vapor gradients (> 3.5 mbar m^{-1})

– large temperature gradients (> 10°C m^{-1})



Results in:

– rapid growth of angular / faceted grains

– very weak bonding between grains

Snowpack temperature profile

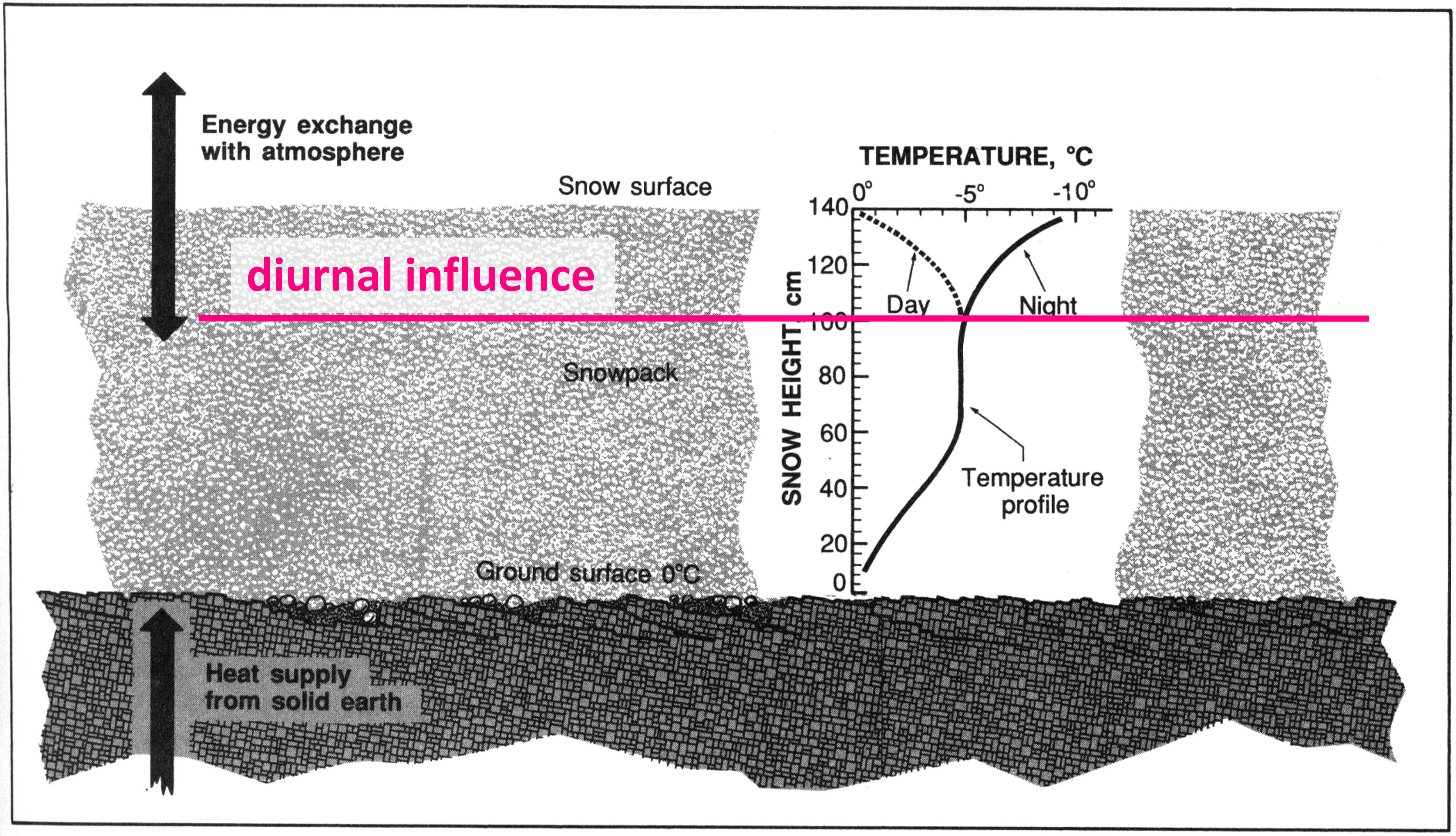
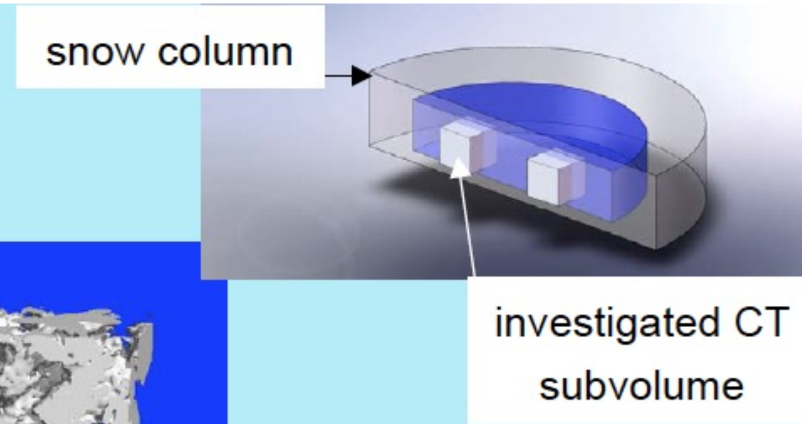
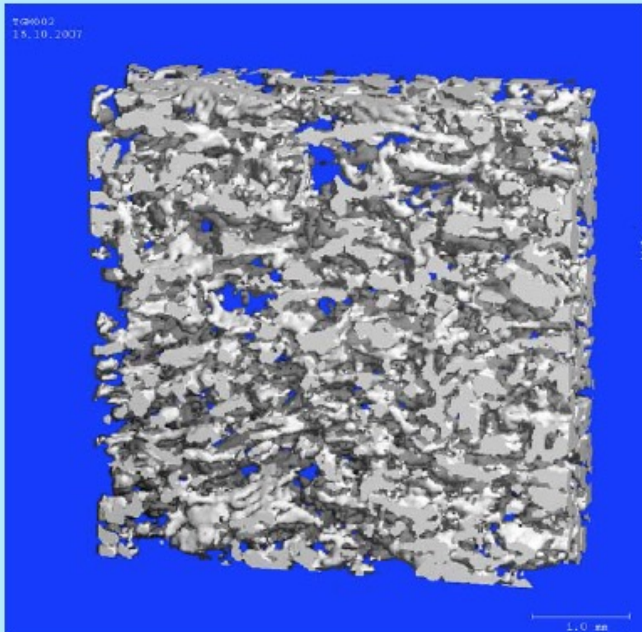


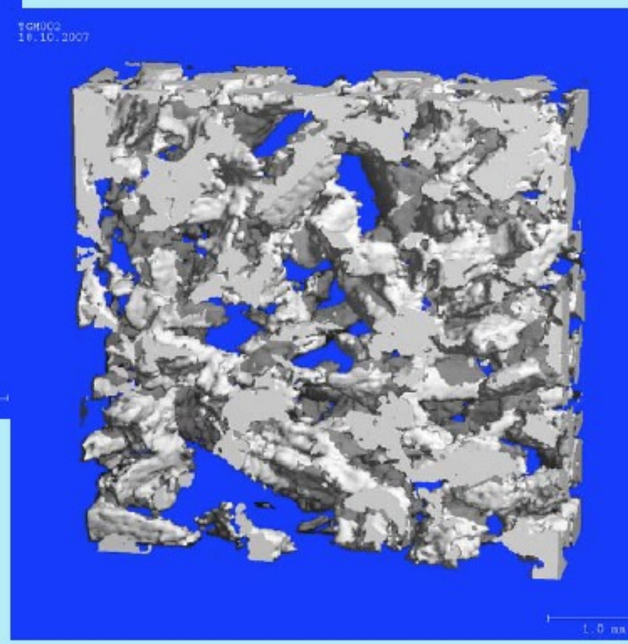
Figure 3.9. Illustration of the temperature variations in a snowpack. Diurnal variations occur in the upper portion. A temperature gradient of 10°C/m is strong enough to produce facets in the snowpack.

Structural change under T-gradient



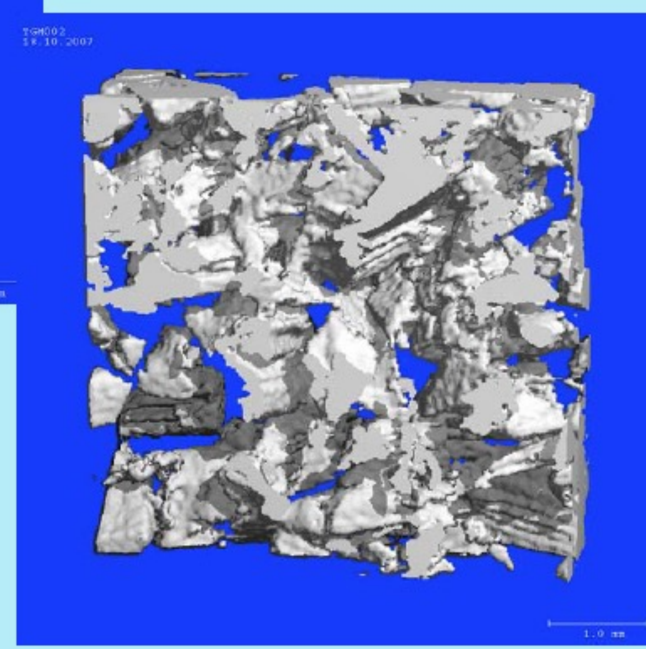


t = 0 h



t = 147 h

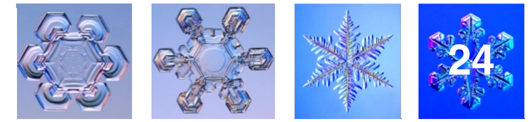
t = 286 h



- depth hoar formation

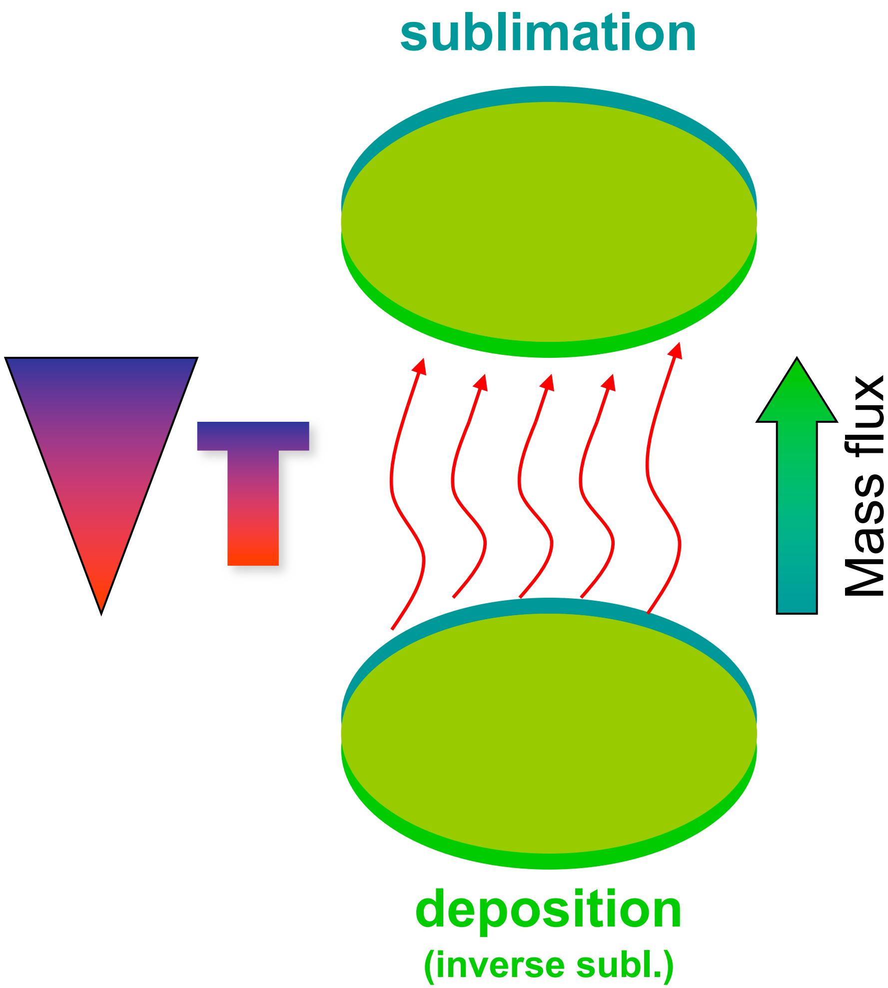
Schneebeli & Sokratov, Hydrol. Proc., 2004

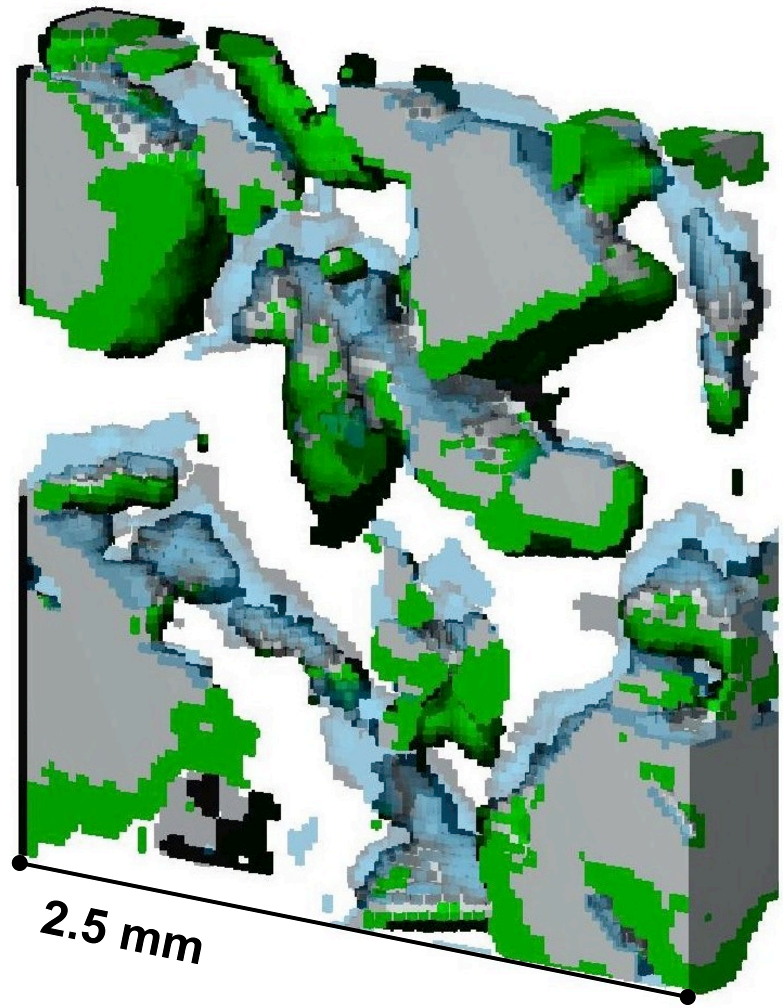
Drivers of KM: Gradients !



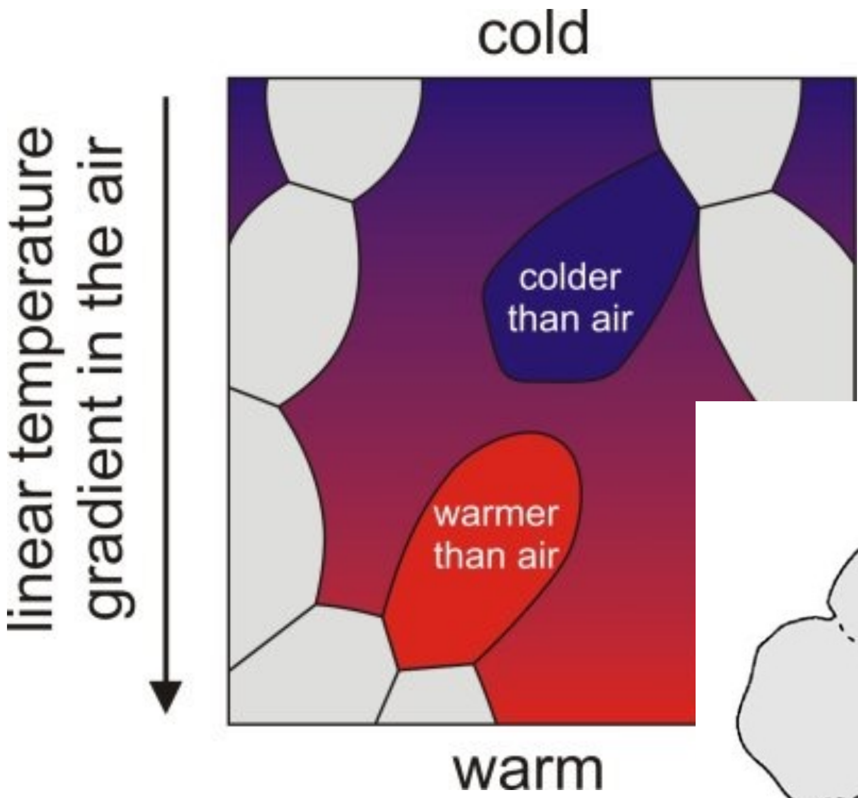
- Temperature gradient imposes a vapor pressure gradient
- Super-saturation increases as vapor moves into colder layer of the snowpack
- Water molecules are deposited on an ice particle which acts as a nucleus for further deposition
- Water molecules are then deposited as facets on a plane (varying thickness of depositional planes)
- Crystals grow in the direction of the vapor source [direction in typical snowpack ?]
- Vapor gradient is stronger at warmer temperatures (given the same T-Gradient)
- Kinetic growth is more pronounced under stronger vapor gradients
- Therefore, more pronounced at base of snowpack (i.e., "depth hoar" formation)

Mass transport & crystal formation





Vapor transport in a snow matrix



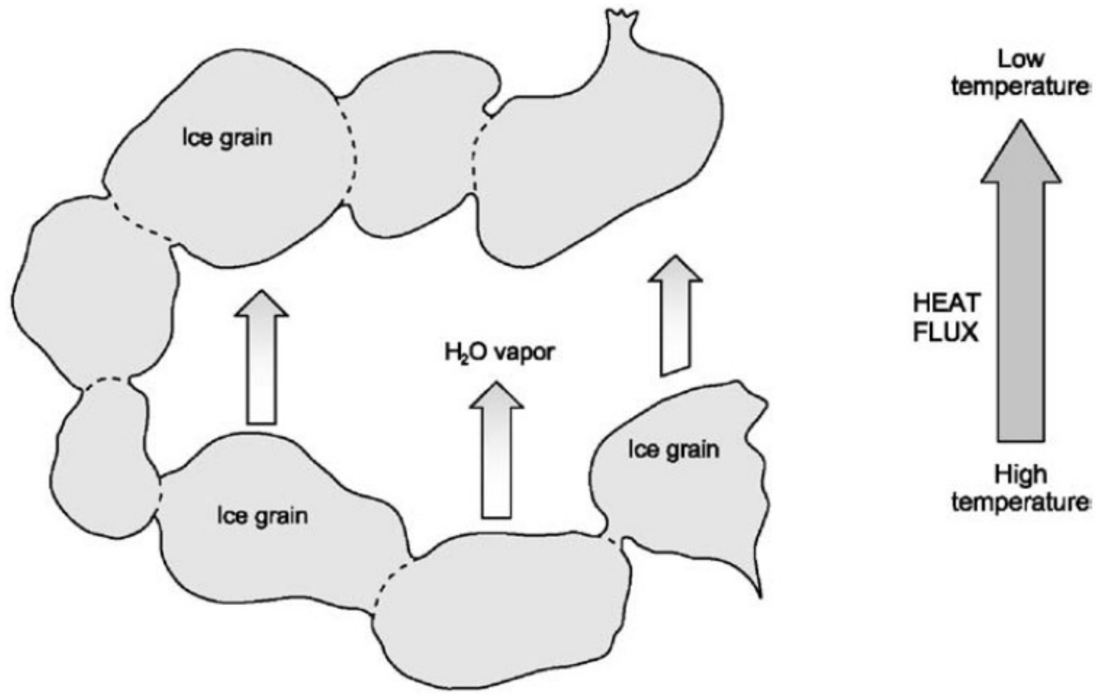
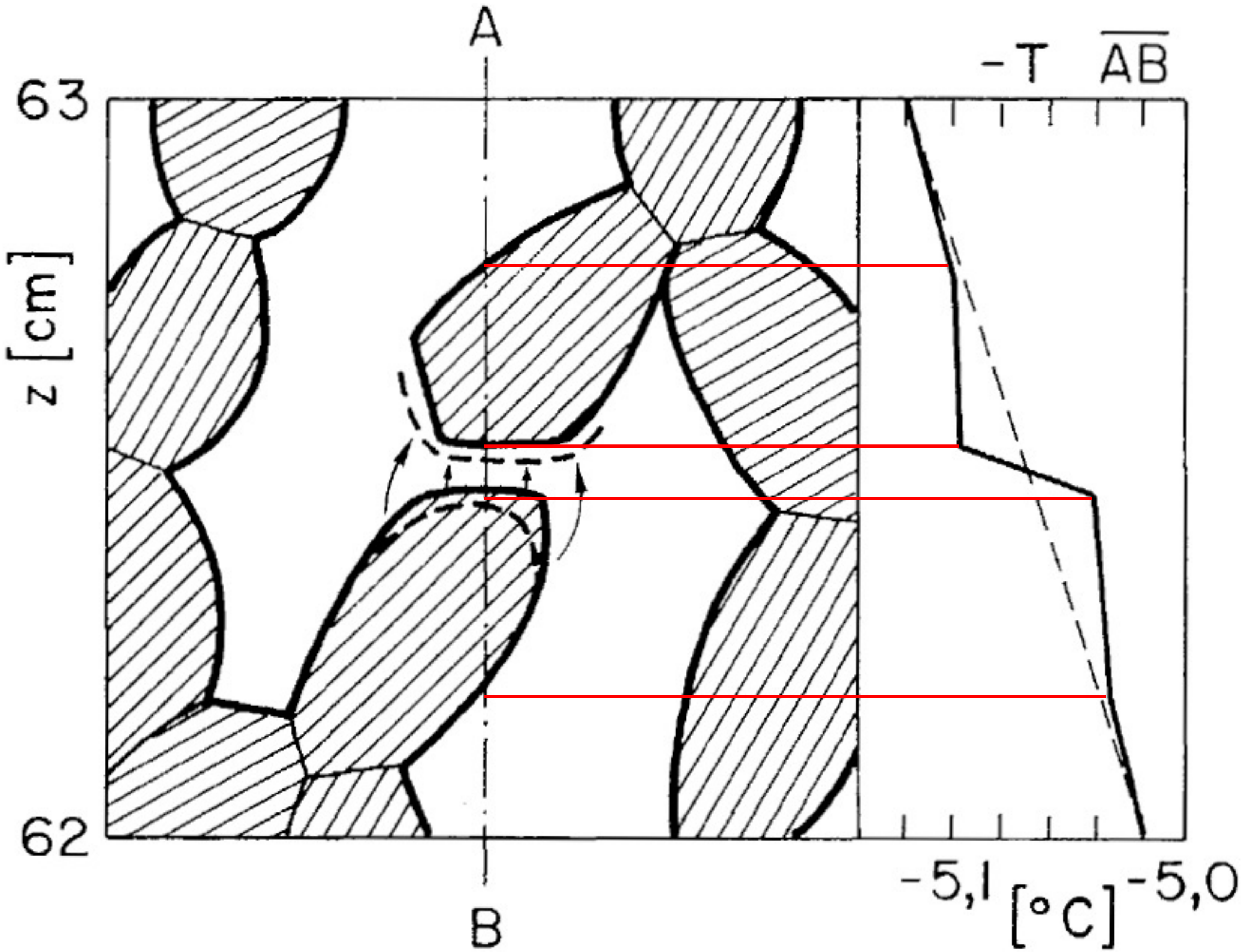


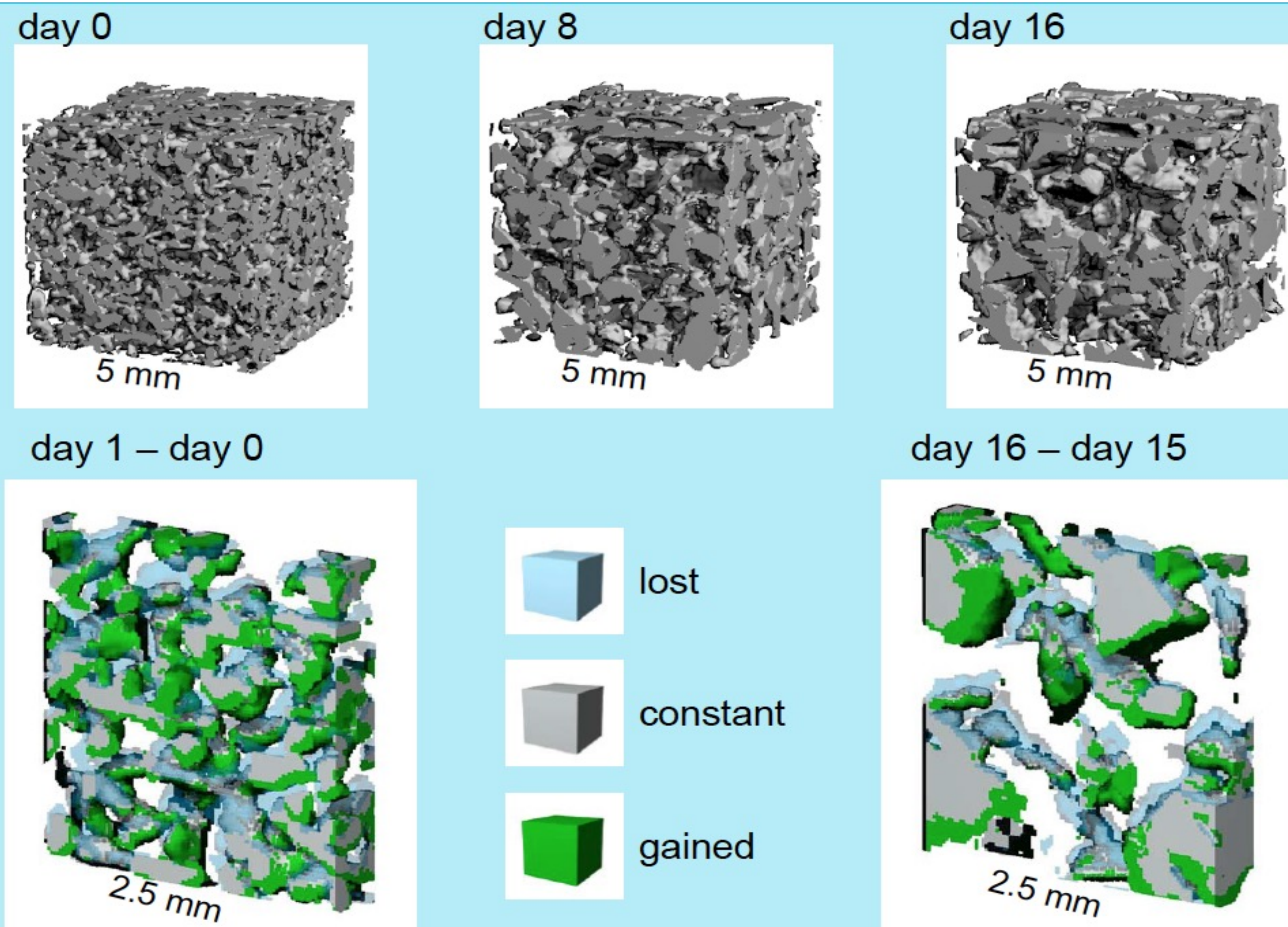
Figure 3.3 Water vapor flowing along a temperature gradient within the snowpack (Perla and Martinelli, 1978, courtesy US Forest Service).

De Quervain model (1973)



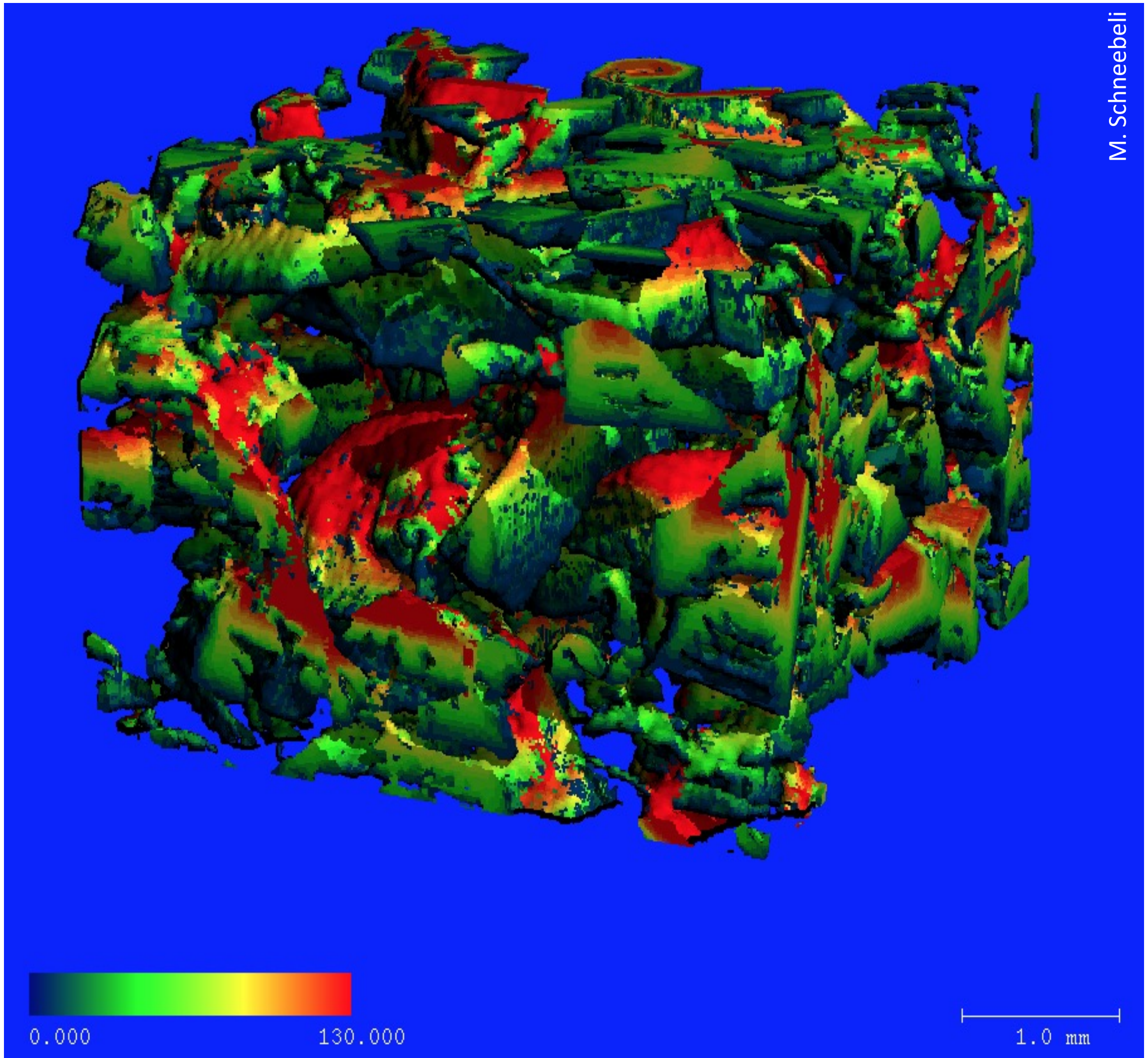
Water vapor transport

Sublimation ←→ Deposition under uni-directional T-gradient



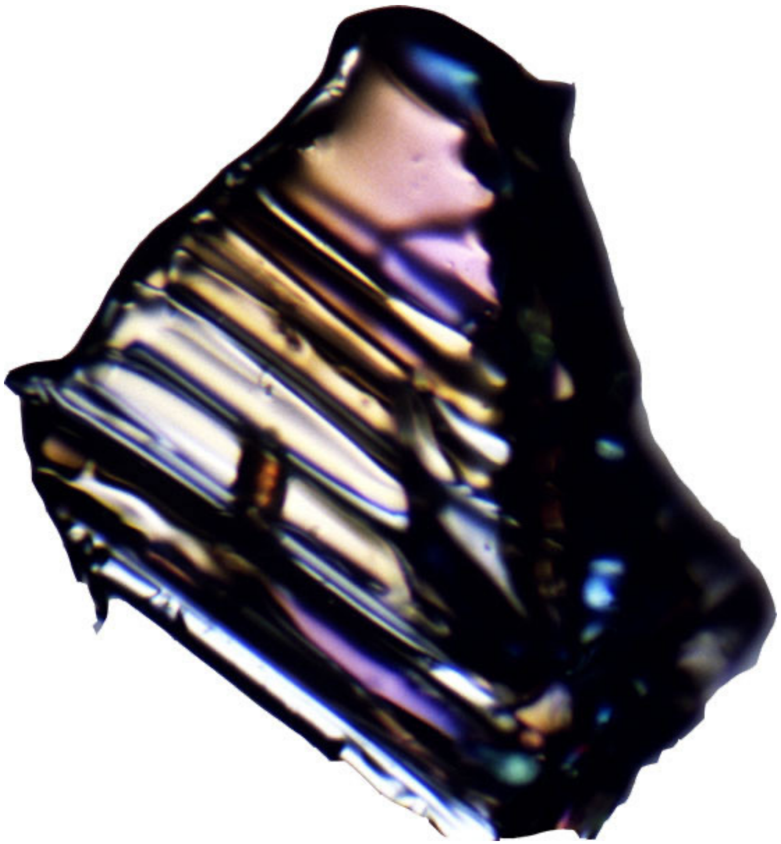
Residence time distribution

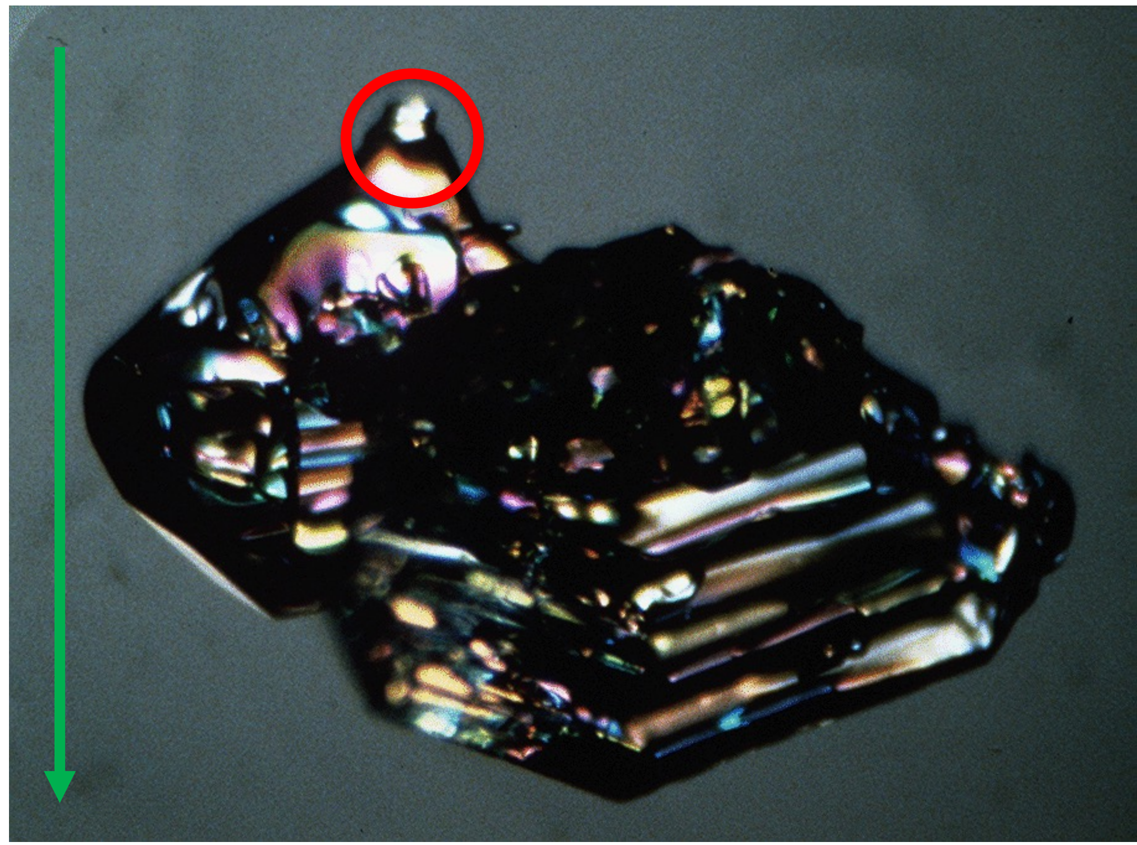
After 625h (4 weeks), the oldest crystals are about 130h (< 1 week) old, cups are the youngest form. The # of ice recrystallization events (lifetime) can be estimated.



Examples of KM crystals

The direction of growth is towards the vapor source
and away from the point of original nucleation (cup crystals)

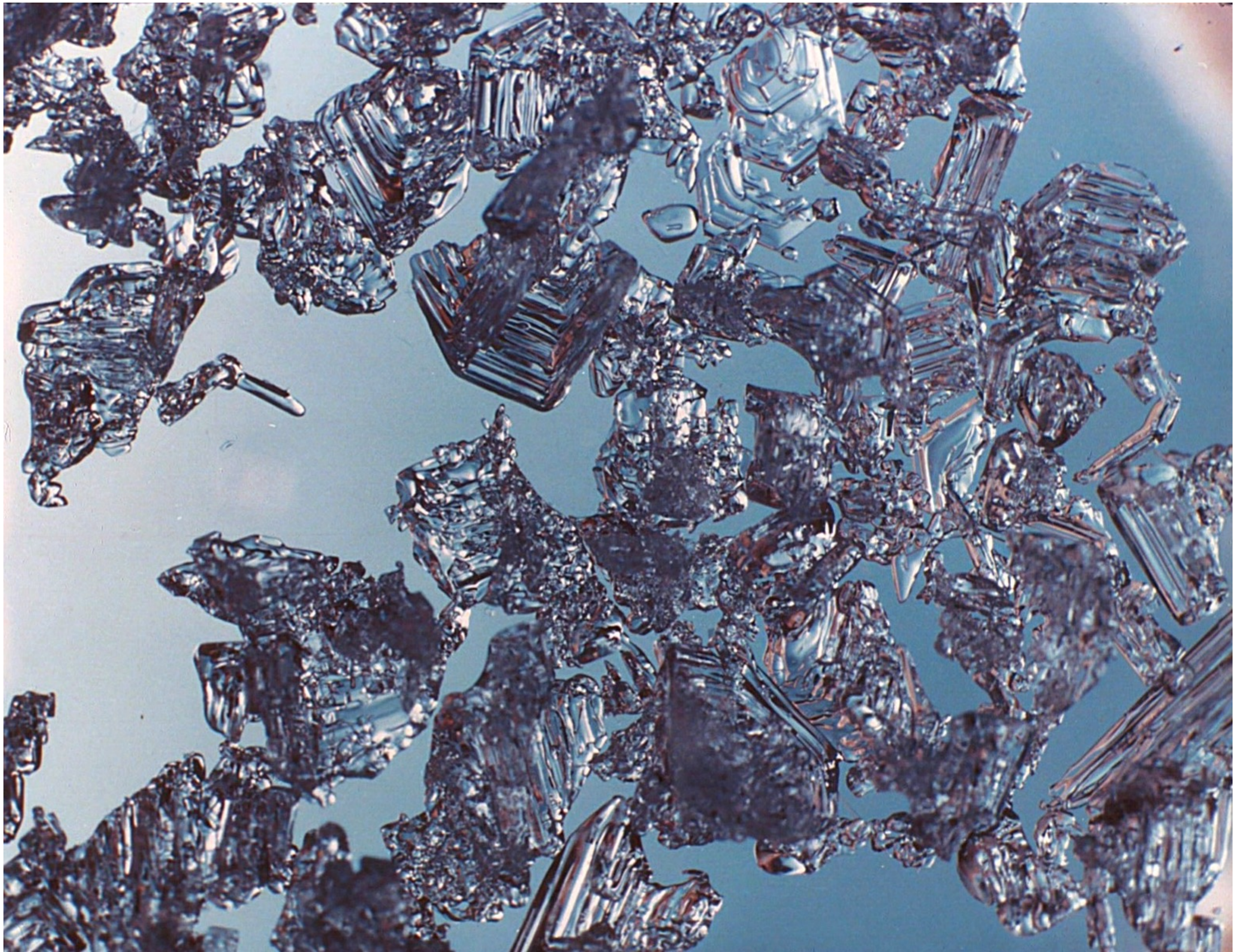


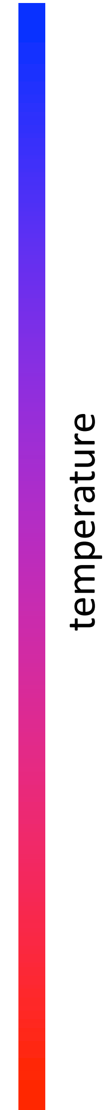


Examples of depth hoar

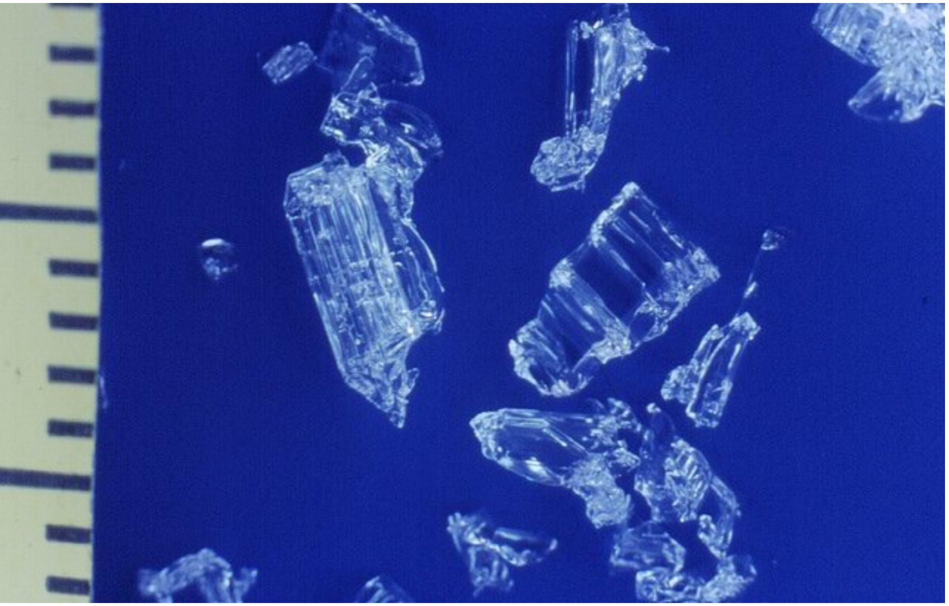
Examples: depth hoar

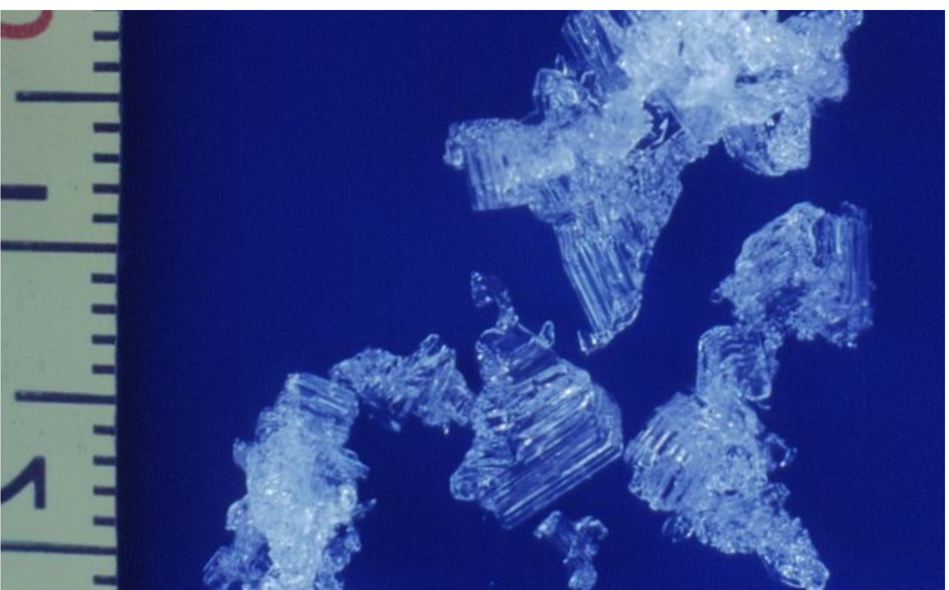
Neither the density nor the thickness of the snowpack changes, but a mechanically weak, unstable (against shear) layer forms





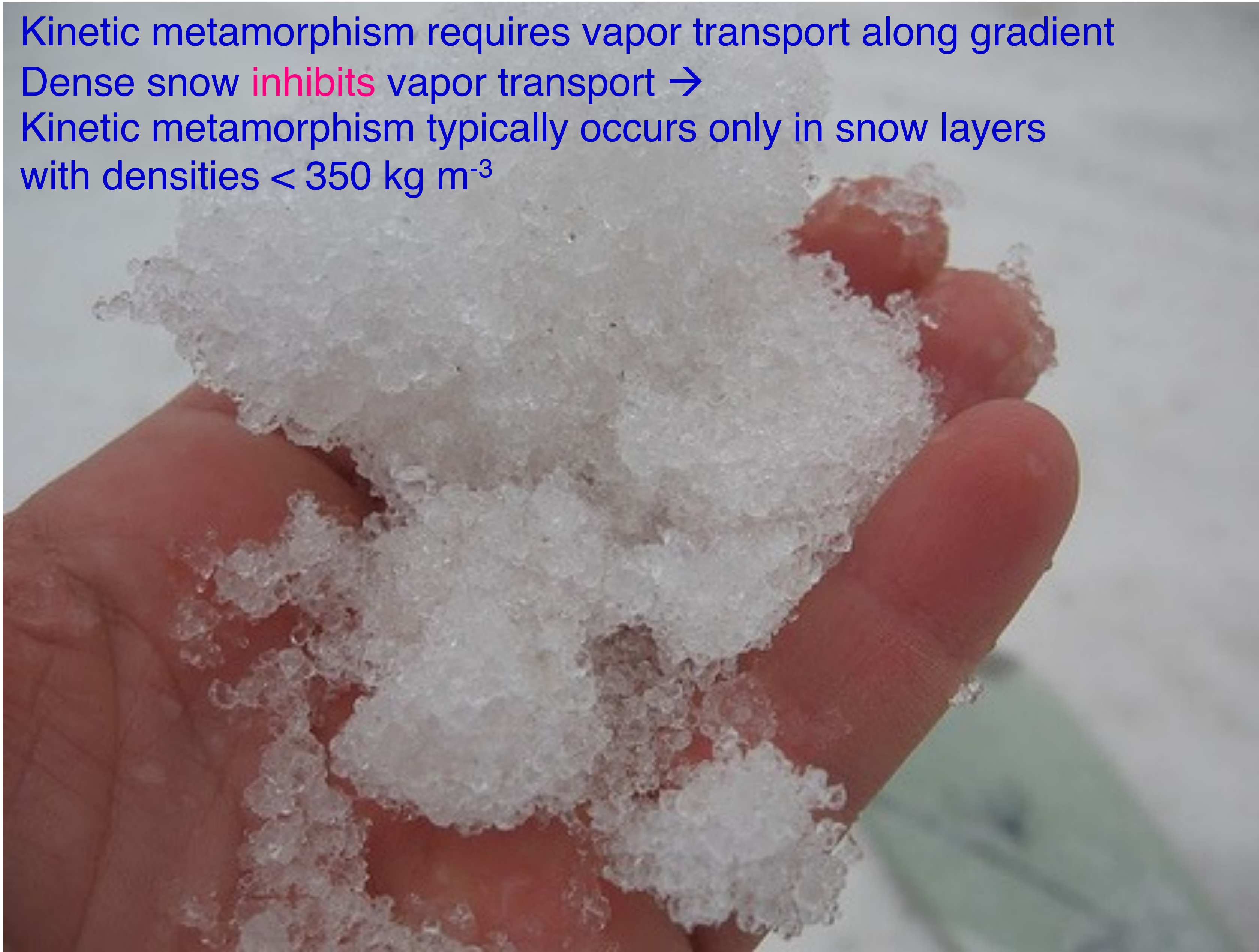
More depth hoar





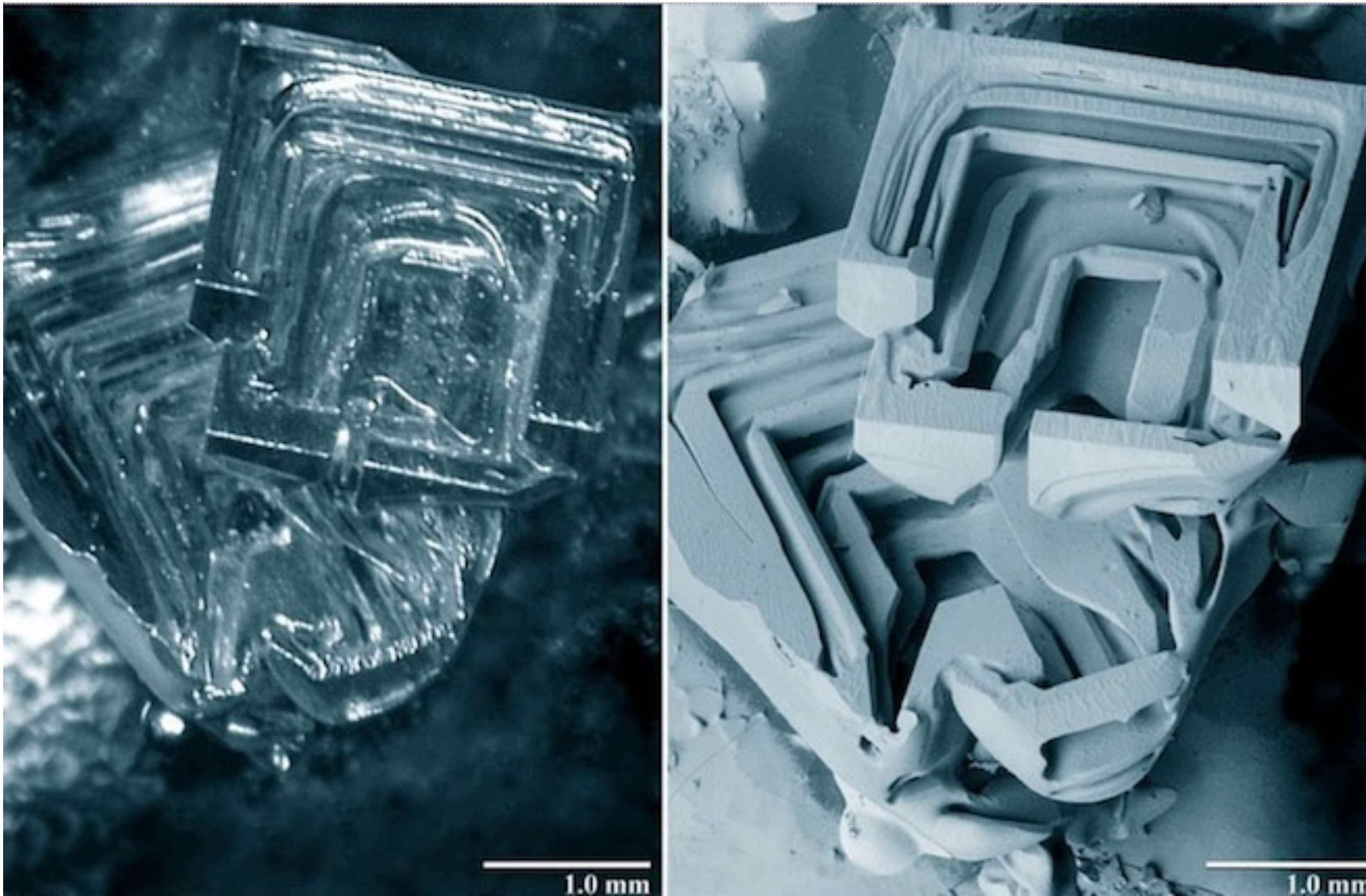
KM and snowpack density

- Kinetic metamorphism requires vapor transport along gradient
- Dense snow inhibits vapor transport →
- Kinetic metamorphism typically occurs only in snow layers with densities < 350 kg m^{-3}



Ice crystal imaging

light microscope vs. electron microscope



KM – summary

- Density remains nearly constant (up to 350 kg m^{-3})
- Necks between snow grains don't grow much
- Crystal size > 3mm
- Grains grow towards vapor source, and are usually vertically oriented
- Vertical orientation resists compaction
- Vertically oriented grains act as levers with little bonding to neighboring grains →
- Mechanical (shear) strength is low (domino stones)
- Forms a weak layer in the snowpack

- These layers form at the snowpack base, on the underside of ice layers, near rocks and trees, on snowpack surface (anywhere there is a strong vapor gradient)

Kinetic growth forms

Depth hoar

Large (5 mm) facets

Vapor source at depth

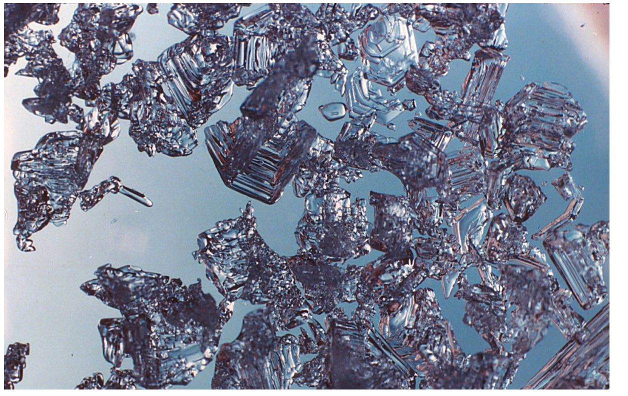
Surface hoar

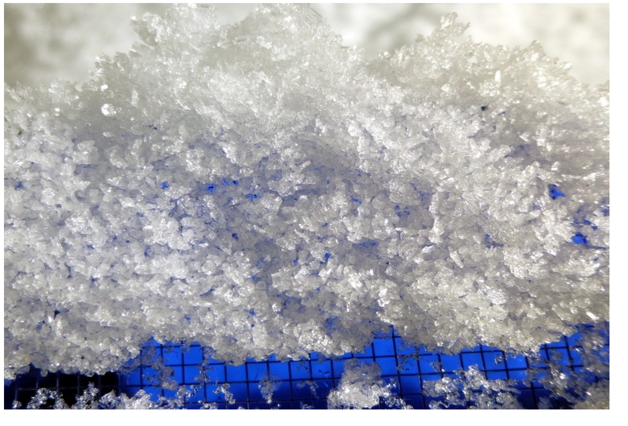
> 1 cm

Atmospheric vapor source

Radiation re-crystallization

- Longwave emission at surface under clear sky conditions
- Large vertical temperature gradients (over small distance)
- Vapor gradient oriented toward snowpack surface
- < 1mm near-surface facets





Surface hoar

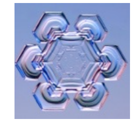
- Deposition of water vapor (sublimation onto the surface)
- Positive vapor flux from atmosphere to surface
- Formation of flat crystals (feathers)

Surface hoar

Surface hoar

Big surface hoar crystal

Surface metamorphism - overview




Surface Metamorphism			
	Surface hoar	Firnspiegel	Near-surface faceted crystals
Crystal type	Feathers, angular	Thin ice crust	Faceted grains
Size	1-10 cm	1-5 cm depth	0-20 cm, ~1 mm
Process	Cold snow surface cools overlying air below the dew point; technically, this is not snow but frost	High incoming solar radiation melts a very thin layer at the snowpack surface; refreezing from longwave emission	South-facing slopes, low density or new snow Kinetic growth from large temp & vapor gradients at surface; NOT much grain growth
Conditions	Warm days, low wind, supersaturated air condenses on snow	Clear conditions, south-facing slopes, temperature $< 0^\circ C$	Strong diurnal temperature fluctuations

Wet snow metamorphism

- Liquid water is present in the snowpack
- Acts like super-charged version of equilibrium metamorphism
  - transport and transformation rates are accelerated
  - small grains are destroyed preferentially
  - large grains become rounded

    (reaching equilibrium form)

(1) Low water content (1-5%)

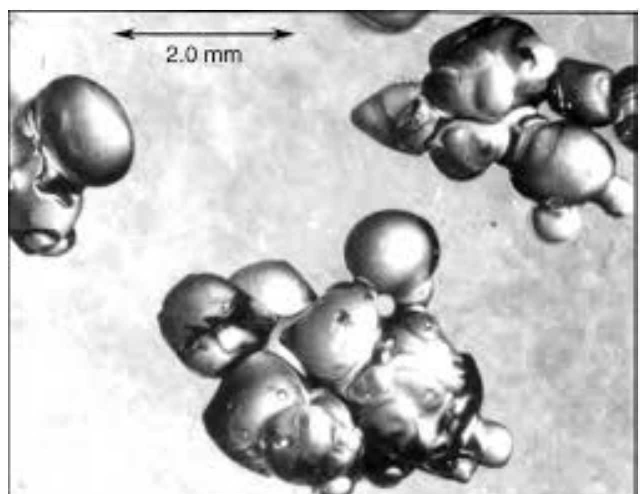
(2) High water content (> 5%)

Class 6cl, clustered single crystals at low liquid content. Photo by S. Colbeck.

Wet snow metamorphism

(1) Low water content

- Water is held by capillary tension in the crevices between grain clusters
- Spherical grains are unstable at low liquid water content, hence clusters are formed (minimize surface free energy)
- Clusters form rapidly when first wetted
- Grain-growth in snow with 3-5% water is much faster than grain growth in a dry isothermal snowpack (Isothermal does not mean wet)
- Ice bonds typically remain



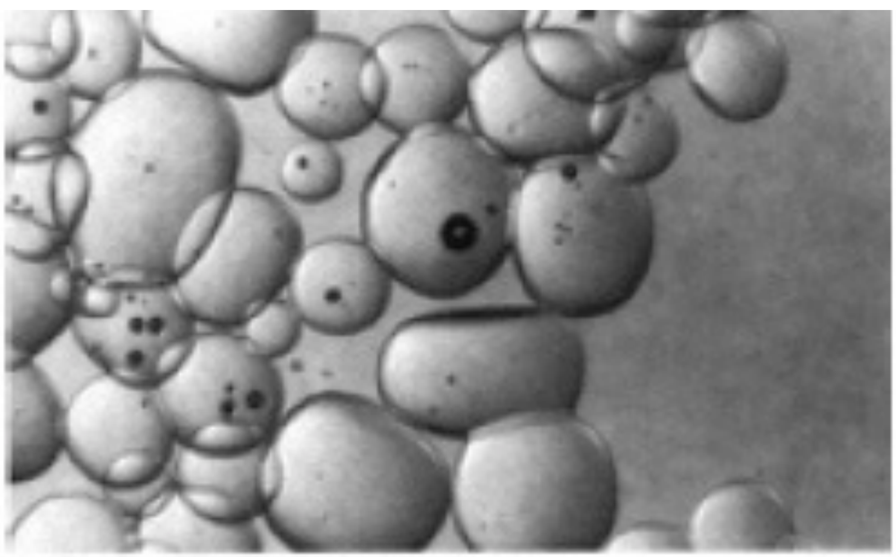
Wet Metamorphism Crystal Example

USDA

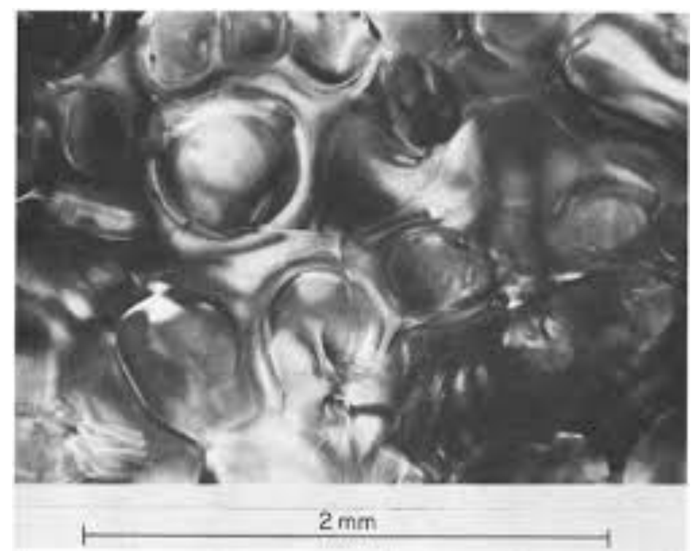
Wet Snow Metamorphism

(2) High water content (slush)

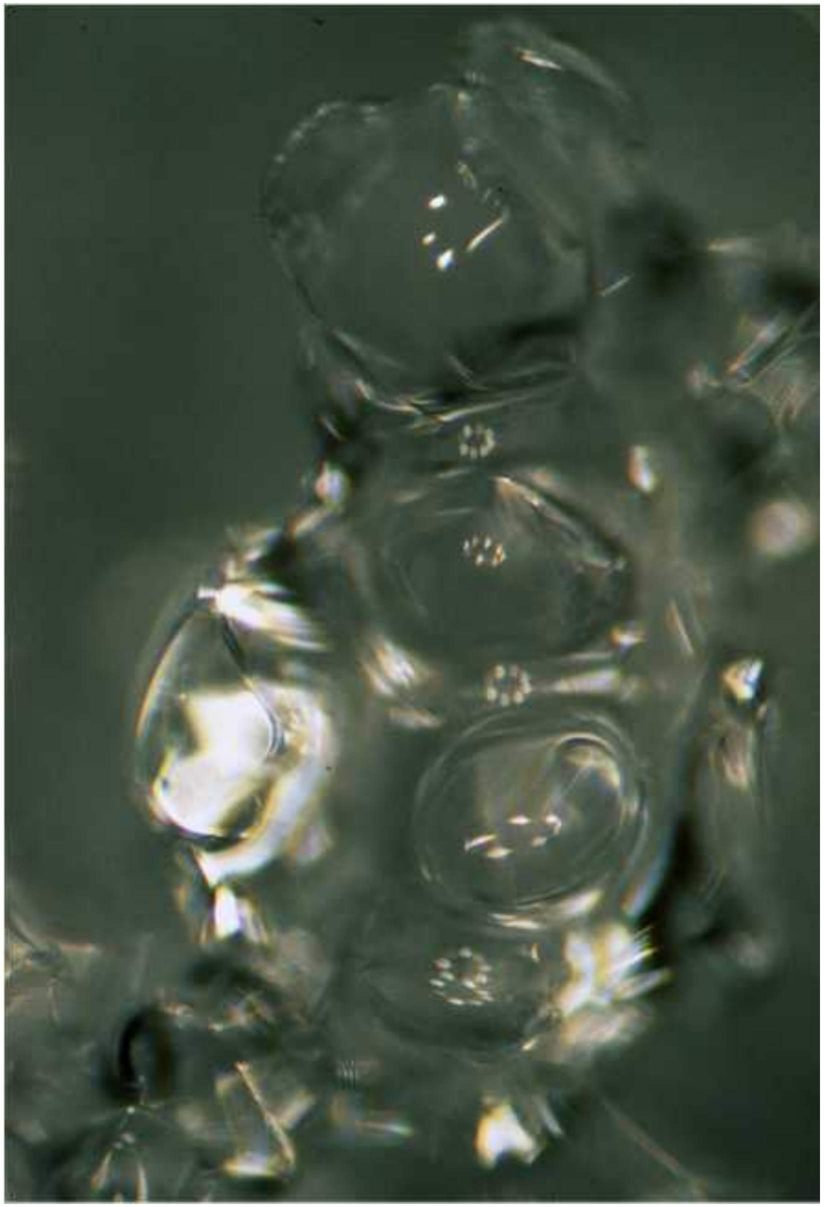
- Continuous connection between water inclusions, i.e., the water surrounds the grains
- Rapid grain growth, big grains get bigger
- Lack of inter-granular bonding



Class 6sl slush. Photo by S. Colbeck.



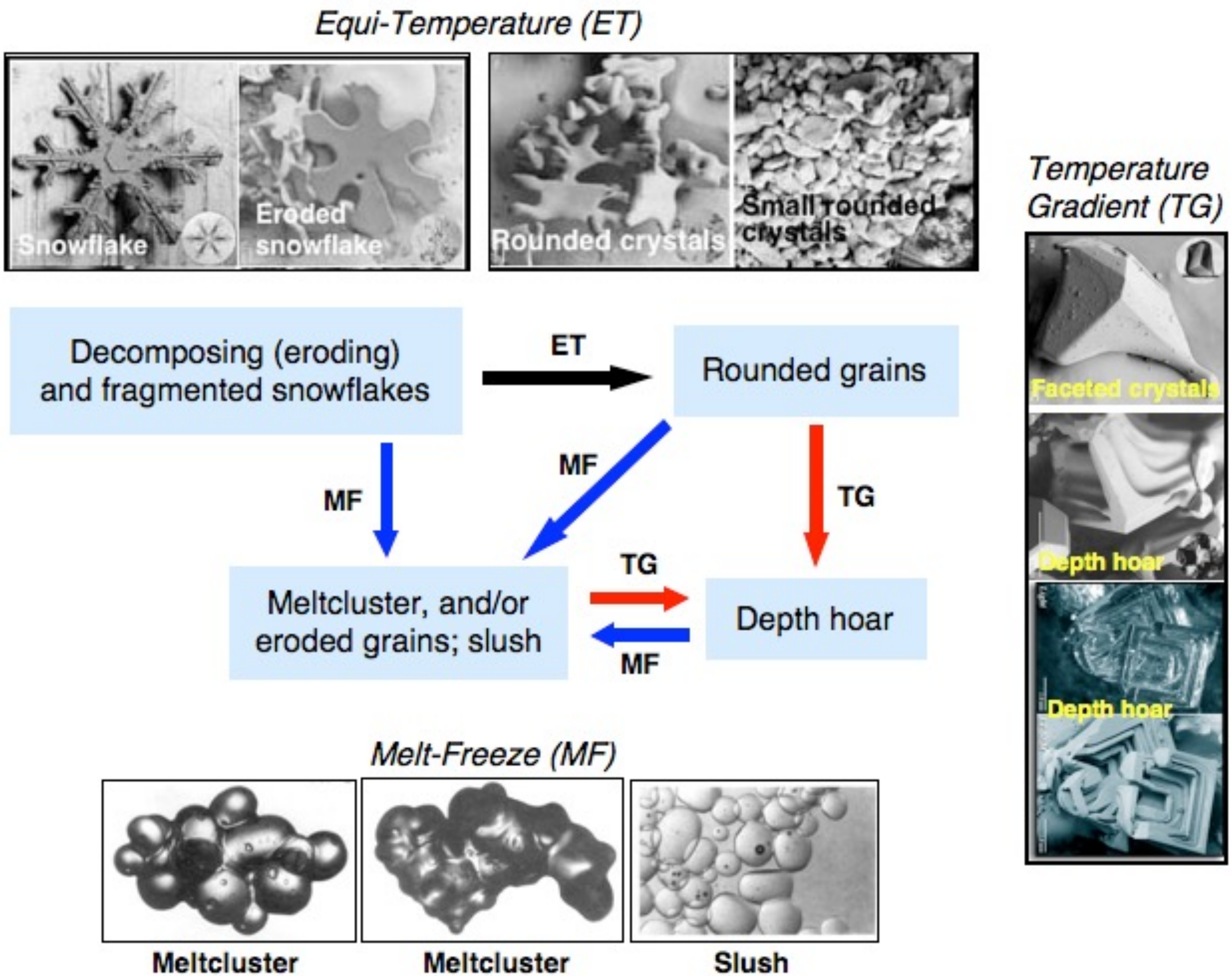
Grain clusters in wet snow



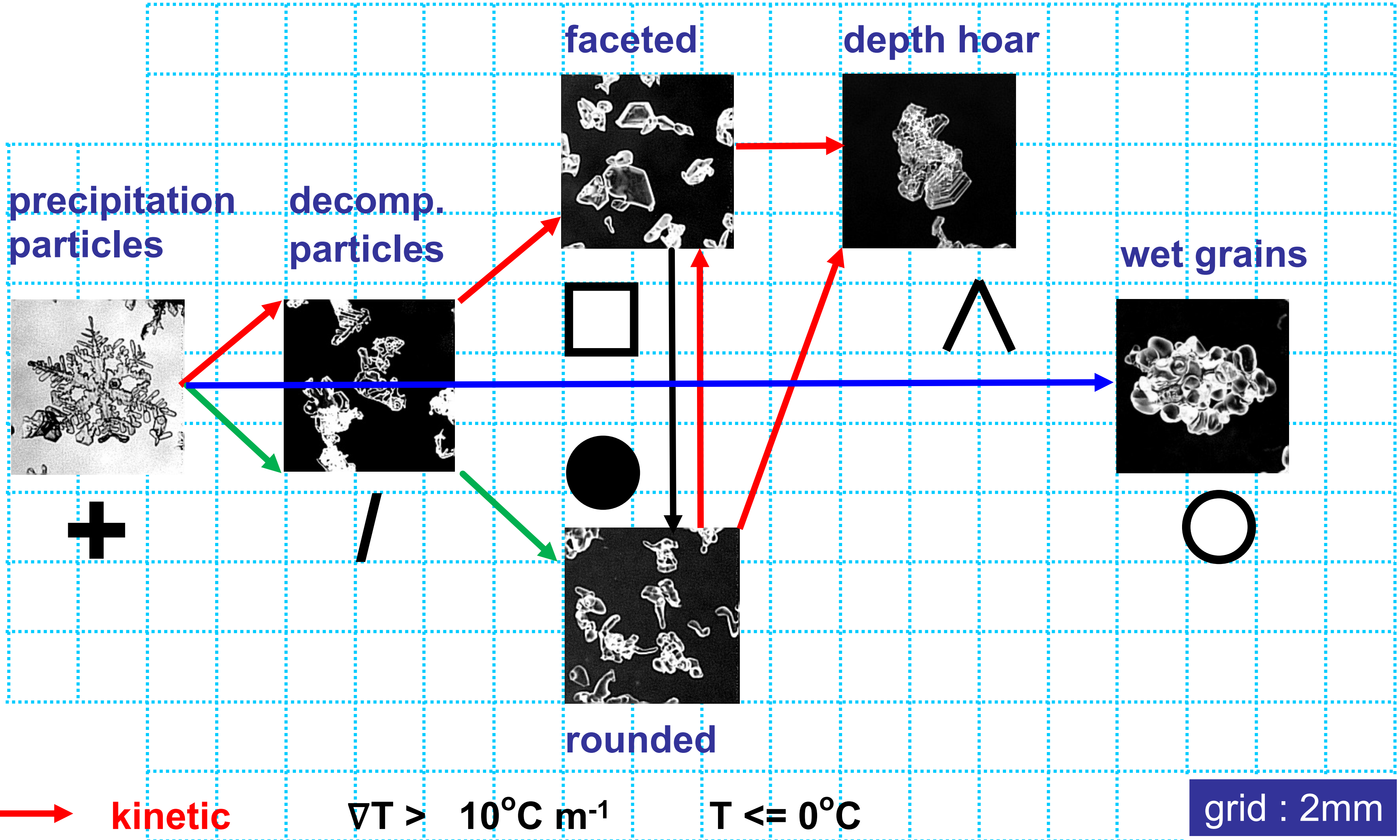
Wet snow metamorphism - summary

- Typically, first occurs at the surface of the snowpack
- Can occur prior to the entire snowpack becoming “ripe”
- Eventually, all snow grains reach equilibrium form
- Wet snow is either ice-bonded or cohesionless, depending on the amount of water present

Overview metamorphism processes

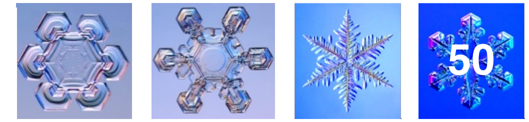


Grain types & pathways



kinetic	$\nabla T > 10^{o}C\ m^{-1}$	$T <= 0^{o}C$
equilib.	$\nabla T <= 10^{o}C\ m^{-1}$	$T <= 0^{o}C$
wet snow	$\nabla T == 0^{o}C\ m^{-1}$	$T == 0^{o}C$

Snowpack compaction



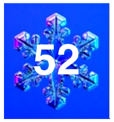
Controlled by:

- Gravitational settling
- Wind
  - sublimation causes rounding and shrinking of particles allowing more dense packing
  - mechanical destruction of dendritic and stellar shapes
- Metamorphism
  - reduction of crystal envelope size, denser packing
- Deformation strain
  - buried layers are compacted by pressure of overlying layers as a result of gravity

Classification of snow on ground

Classification of snow on ground



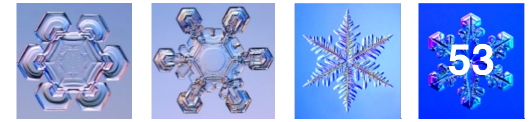



New International Classification for Seasonal Snow on the Ground (2009),

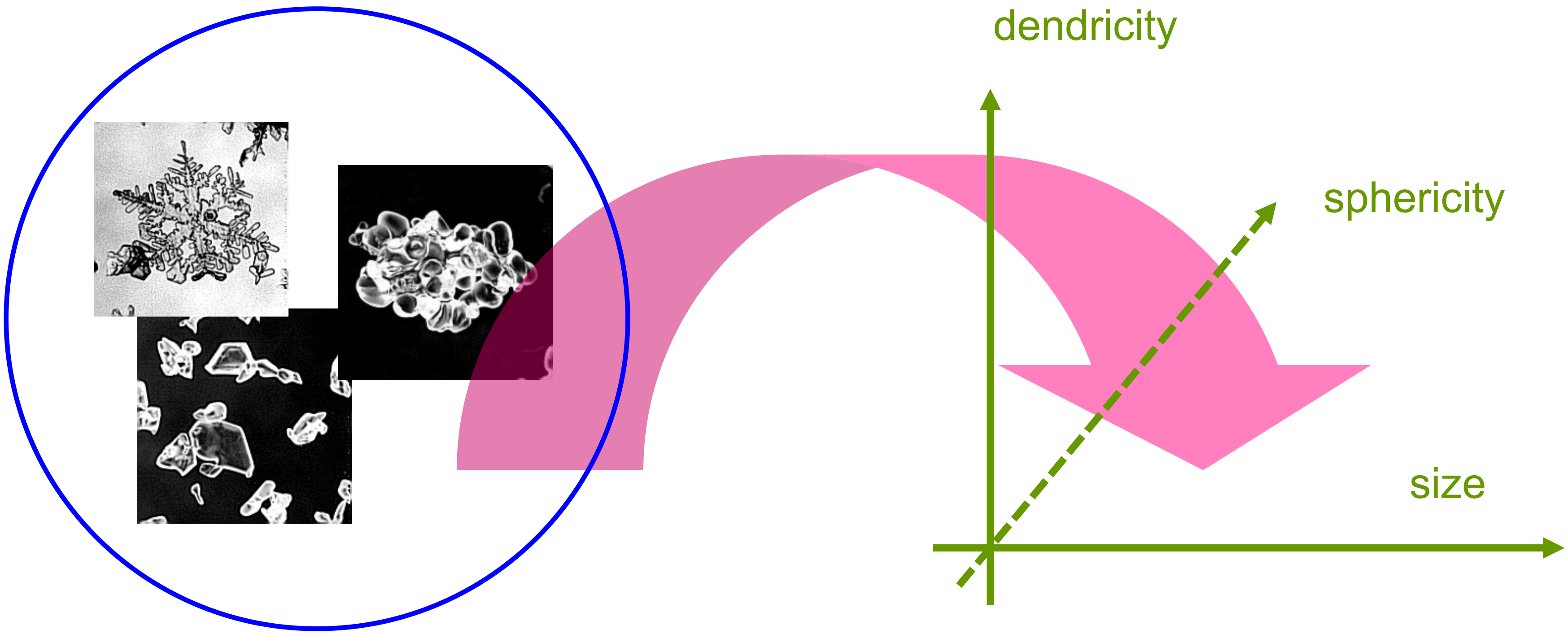
http://www.cryosphericsciences.org/snowClassification.html

Table 1.2 Main morphological grain shape classes

Class	*Symbol*	*Code*
Precipitation **P**articles	+	PP
Machine **M**ade snow	⊚	MM
Decomposing and **F**ragmented precipitation particles	⁄	DF
Rounded **G**rains	●	RG
Faceted **C**rystals	□	FC
Depth **H**oar	∧	DH
Surface **H**oar	∨	SH
Melt **F**orms	○	MF
Ice **F**ormations	▬	IF

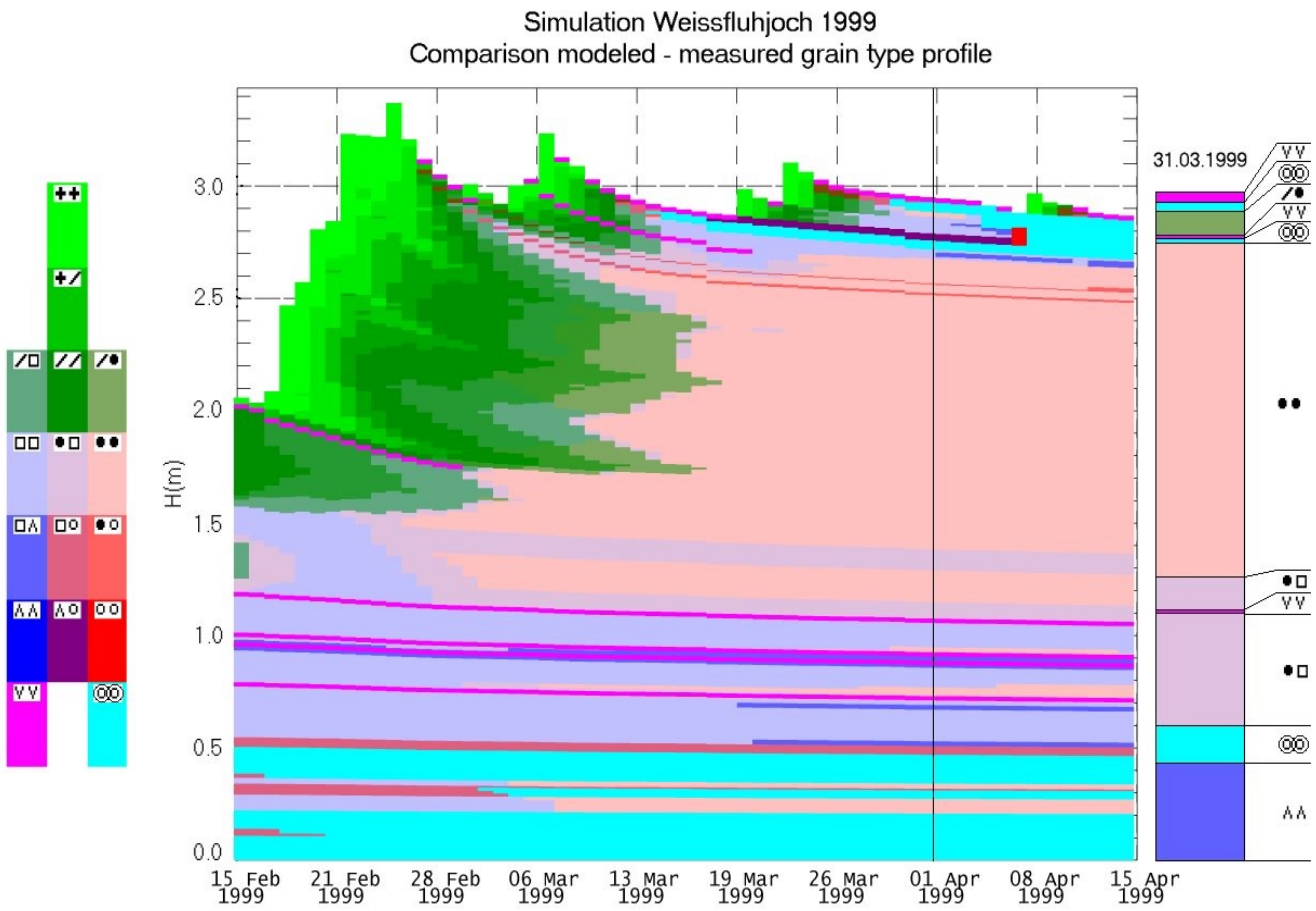


Observation **Model**



Crystal shape and size **Continuous parameters**

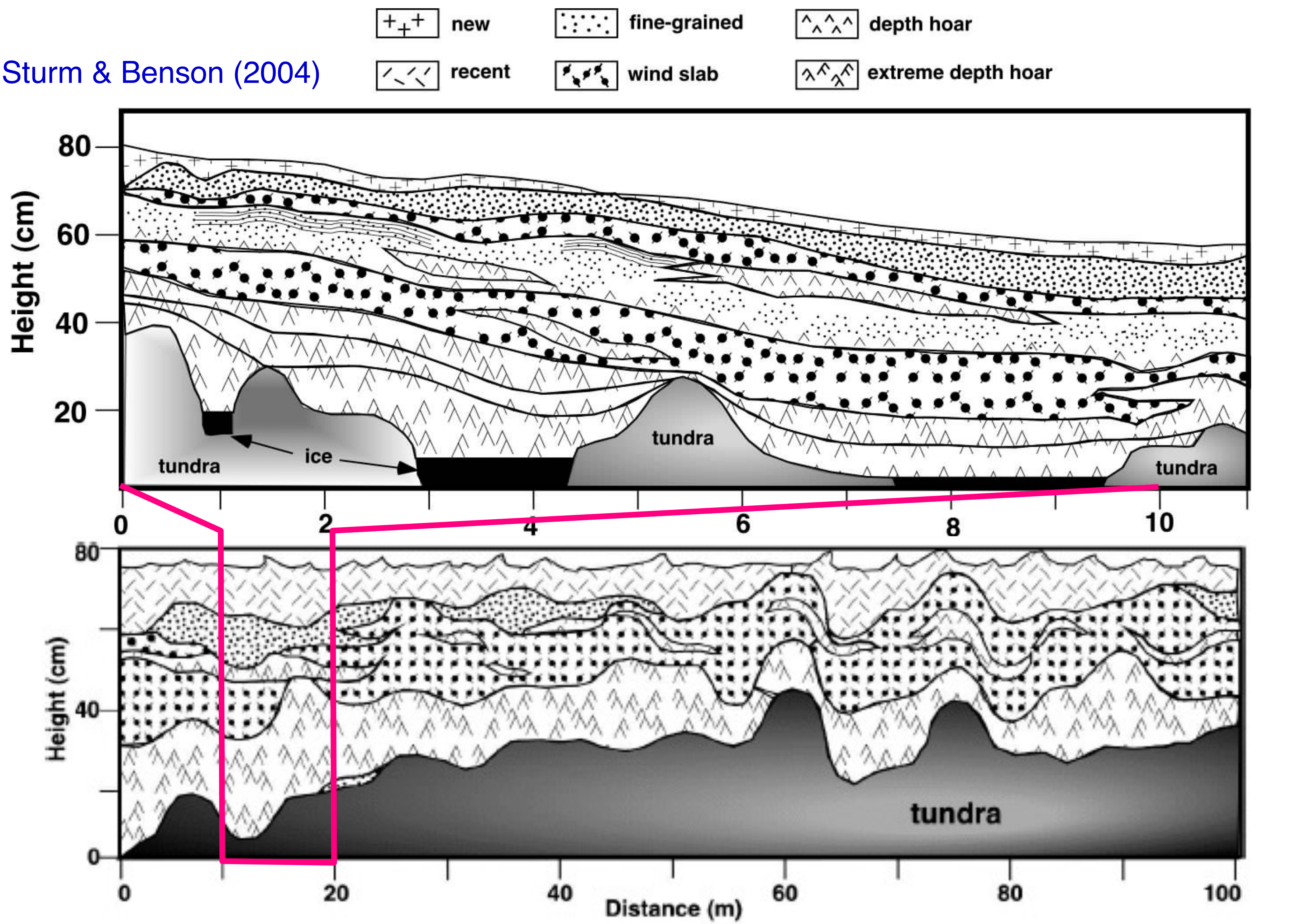
"Real" vs. model snowpack



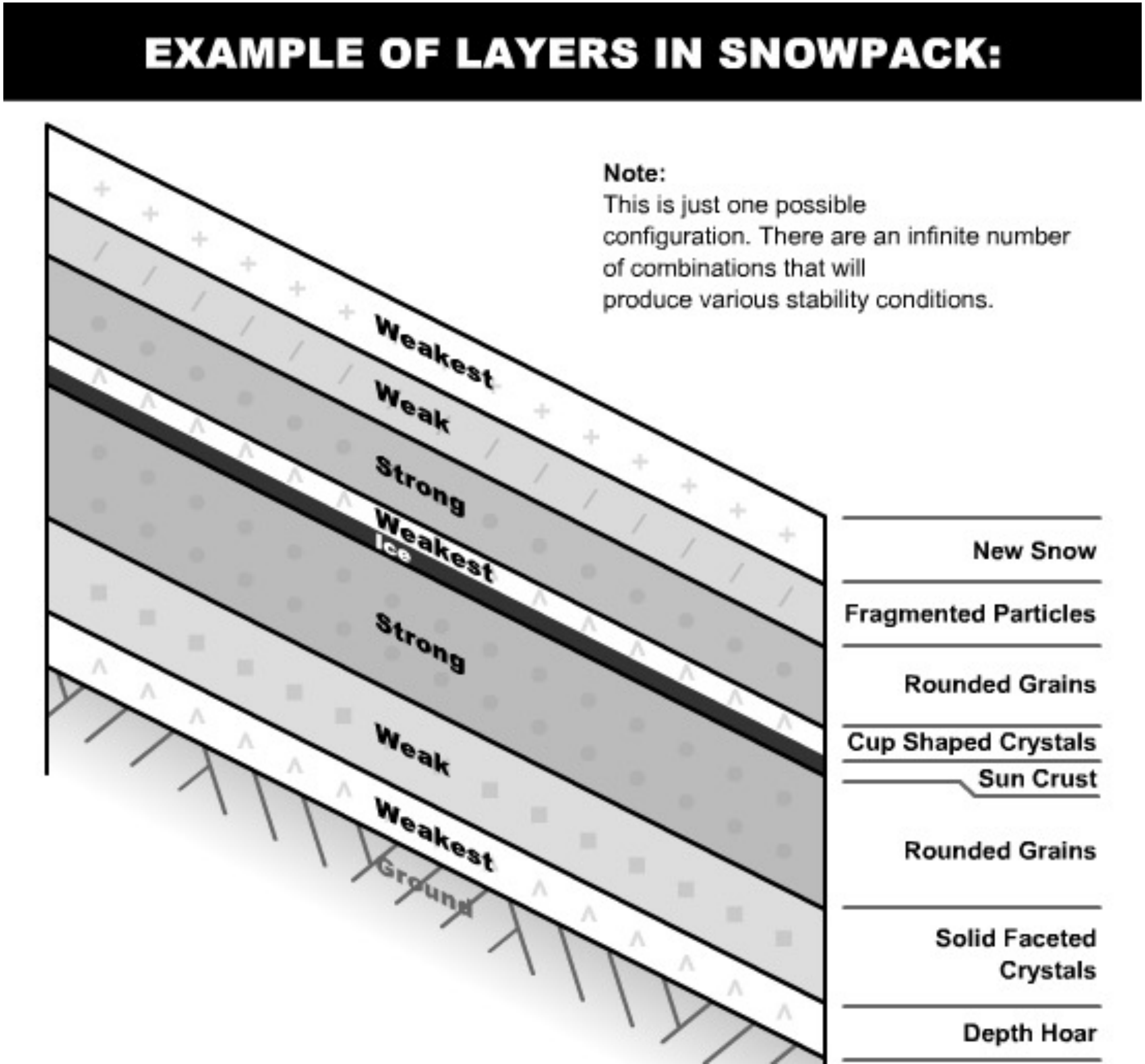
Snowpack stratigraphy

Stratigraphy in a tundra snowpack

Sturm & Benson (2004)



Crystal shape & mechan. properties

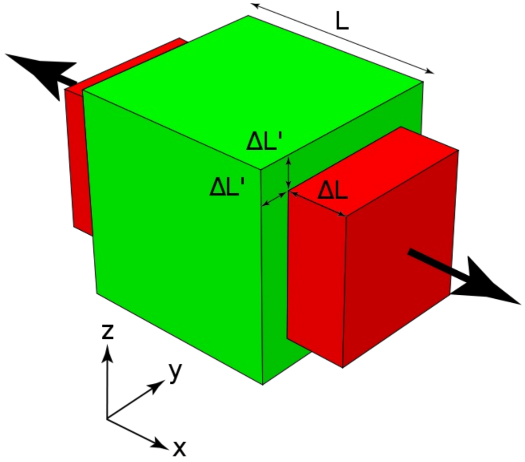


Snow strength ψ

strength = f
- snow type (grain shape, structure, density)
- condition of snowpack (temperature, humidity)
- type of load (stress, loading velocity)

Strength increases with
- new bonds (compaction)
- larger contact areas (sintering) and

Strength increases / decreases with
- destructive / constructive metamorphism



Recall: Poisson ratio
(in "Snow properties")

Influence of temperature:

ΔT without change of structure → reversible process

ΔT plus densification (compaction) → irreversible process

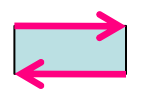
Snow strength (qualitative)

variable	snow strength	
	small for:	**large for:**
density	low	high
grain shape	concave, spiky	round
grain size	large	small
temperature	≈ 0	< 0
humidity	wet	dry

compressive strength > tensile strength > shear strength

4 – 400 kPa

2 – 200 kPa



0.3 – 100 kPa

Next: