Snow

&

Snow Characterization

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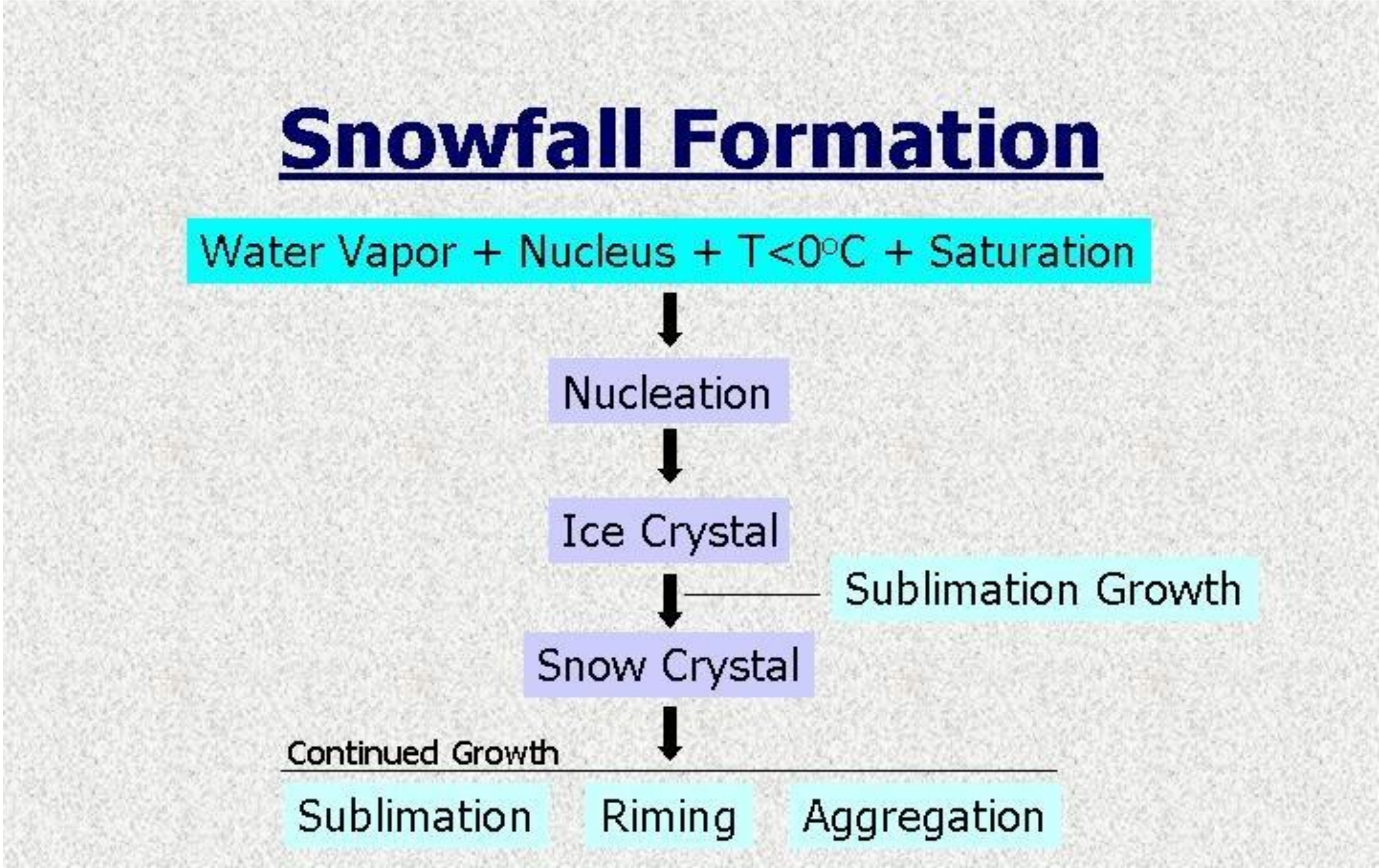
OUTLINE

- Snow Formation
- Snow Metamorphism
- Snow Properties
- Snow Characterizations
- Water and ice

Snowfall Formation

- Moisture Sources
- Vertical Motion
    - Horizontal convergence
    - Orographic lift
    - Convective lift
    - Frontal lift
- Formation of cloud

Snow Crystal Formation in the Atmosphere



Snowfall Formation

Water Vapor + Nucleus + T<0°C + Saturation

Nucleation

Ice Crystal

Sublimation Growth

Snow Crystal

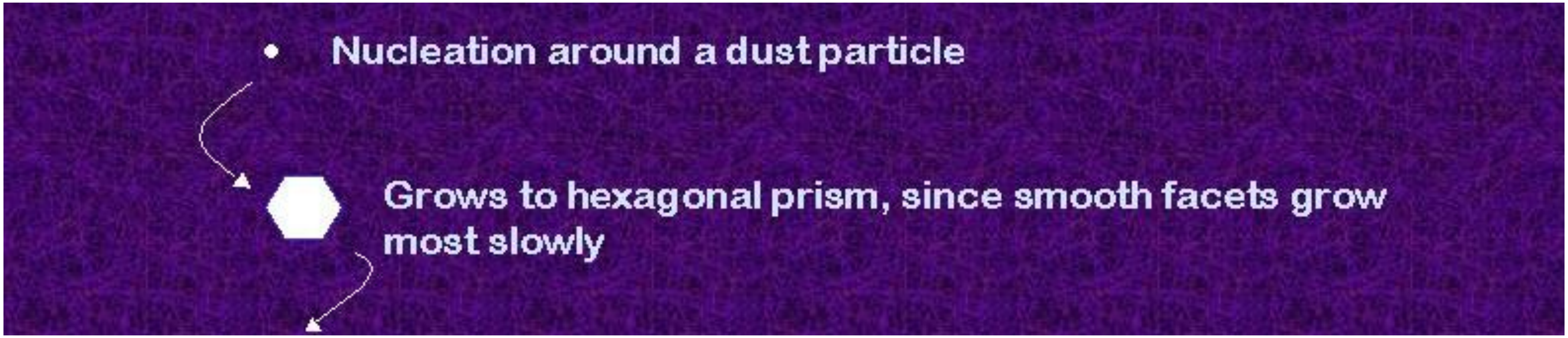
Continued Growth

Sublimation

Riming

Aggregation

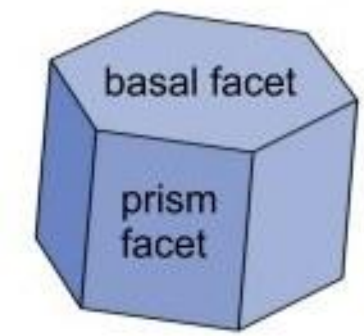
Snow Crystals and the Atmosphere



- Nucleation around a dust particle

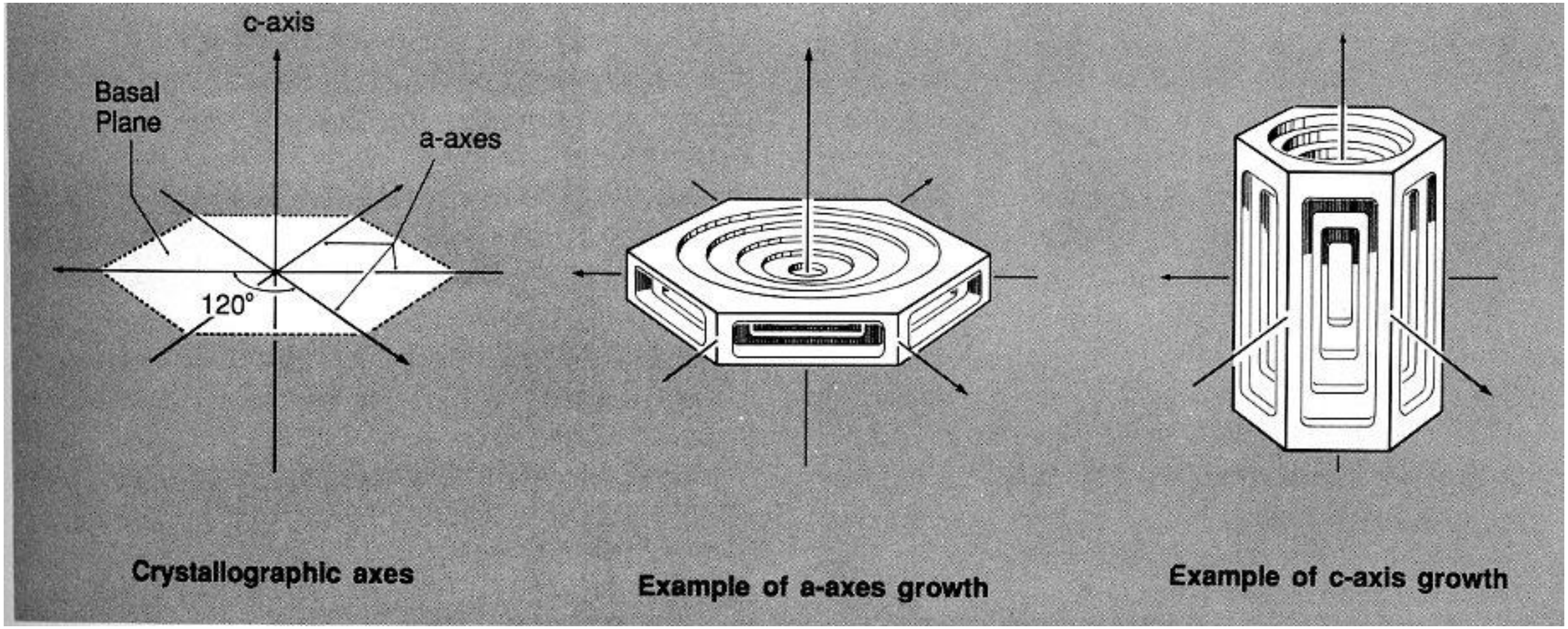
Grows to hexagonal prism, since smooth facets grow most slowly

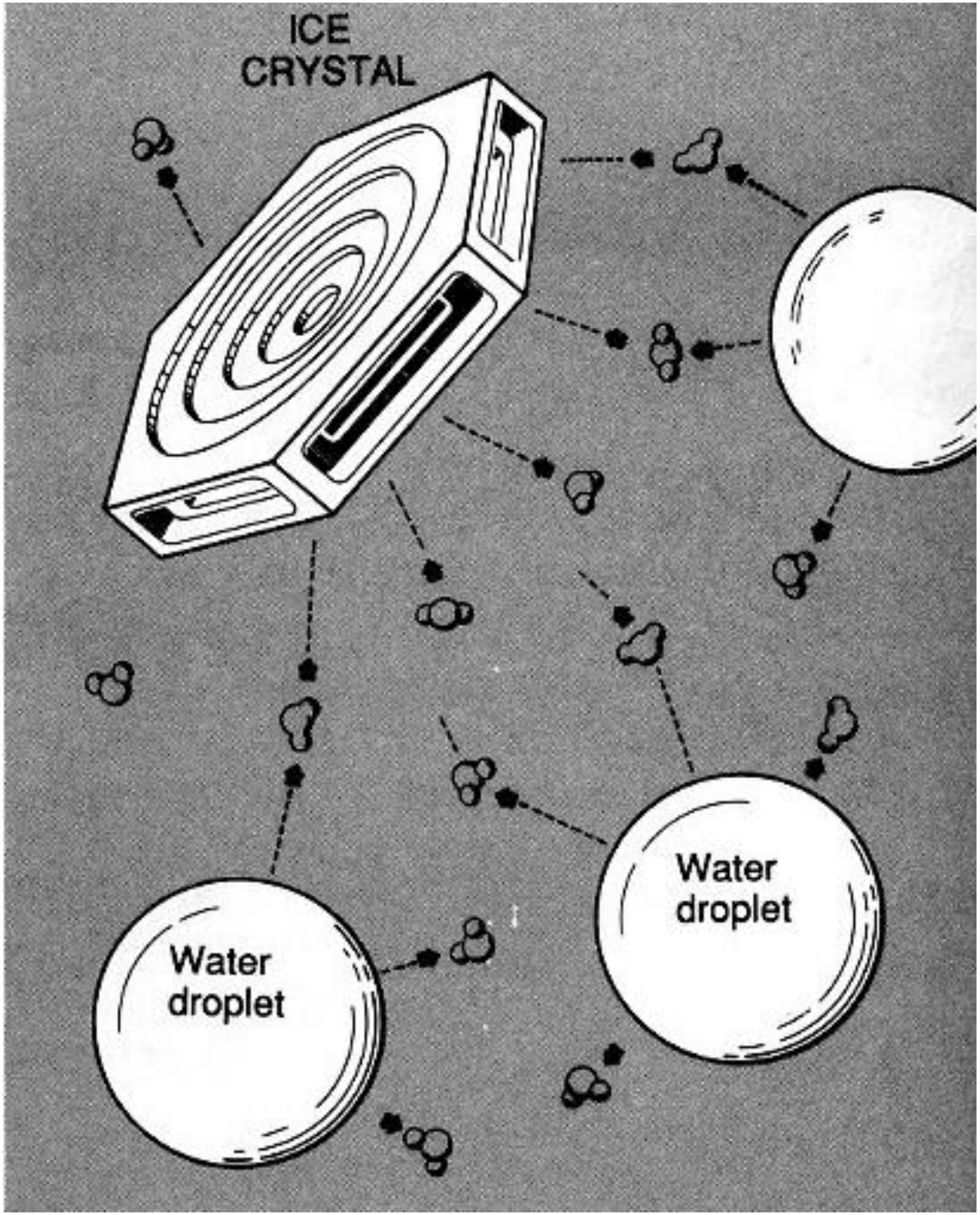
- Snow crystals begins in the atmosphere, when a tiny cloud droplet first freezes into a tiny particle of ice.
- As water vapor starts condensing on its surface, the ice particle quickly develops facets, thus becoming a small hexagonal prism.
- For a while it keeps this simple faceted shape as it grows.



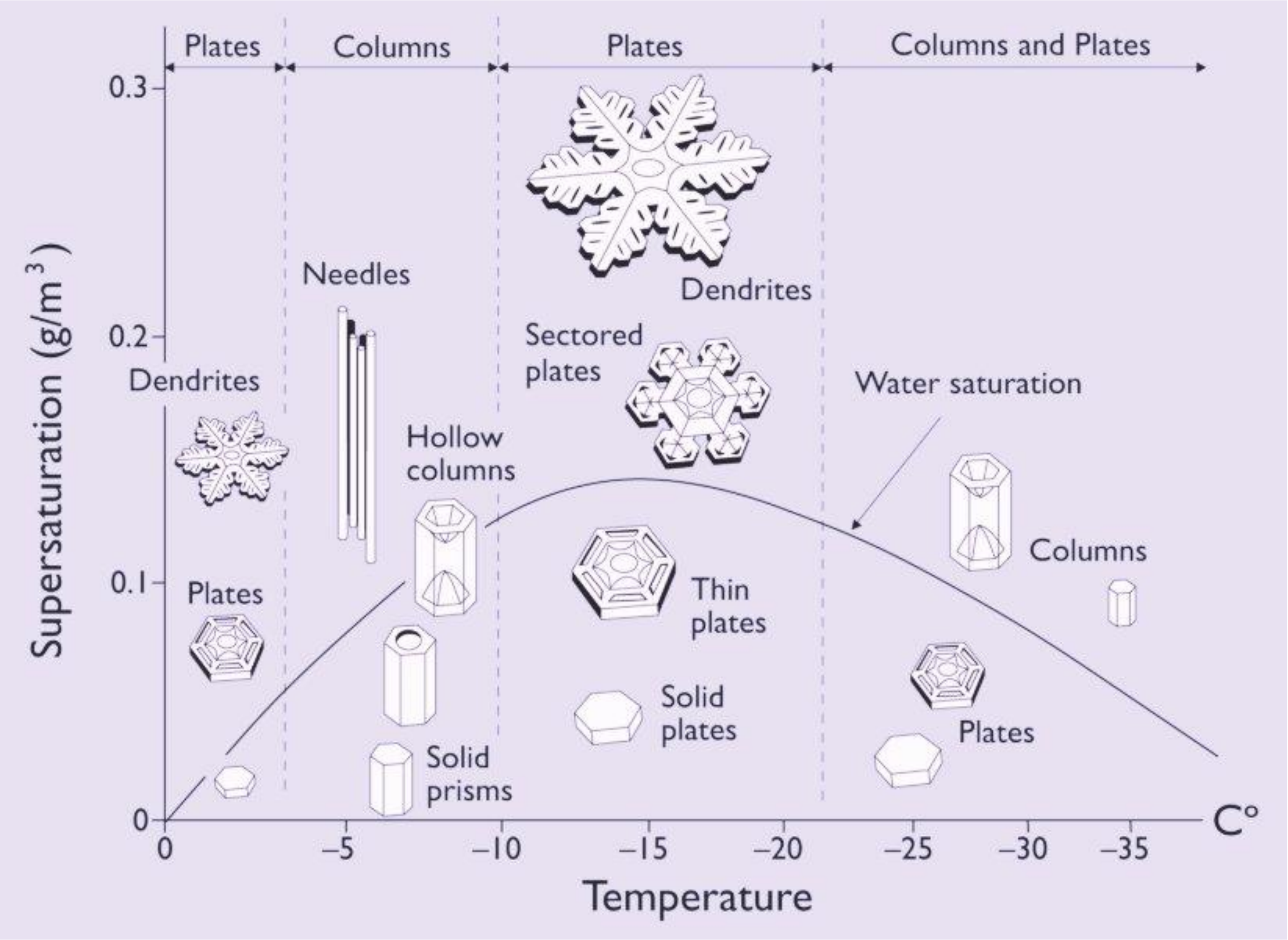
Snow Crystal Formation in the Atmosphere

By growing snow crystals in the laboratory under controlled conditions, crystal shapes depend on the temperature and humidity.




ICE CRYSTAL
Water droplet
Water droplet

Snow Crystal Formation in the Atmosphere



Why temps are important

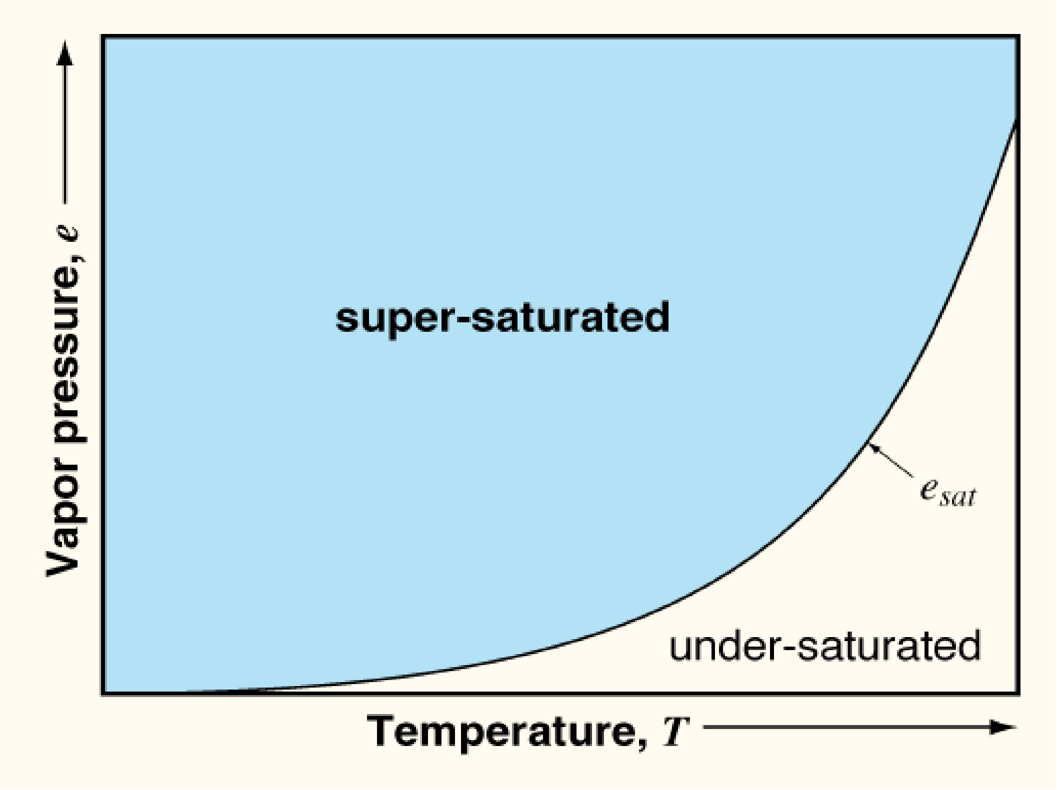
Temperature is only important because vapor pressure decreases with temperature !!!

Clausius relation

$$\frac{dP}{dT} = \frac{L}{T\Delta V}$$

- Warm air at 25^{o}C → 50times higher vapour pressure than at -25^{o}C

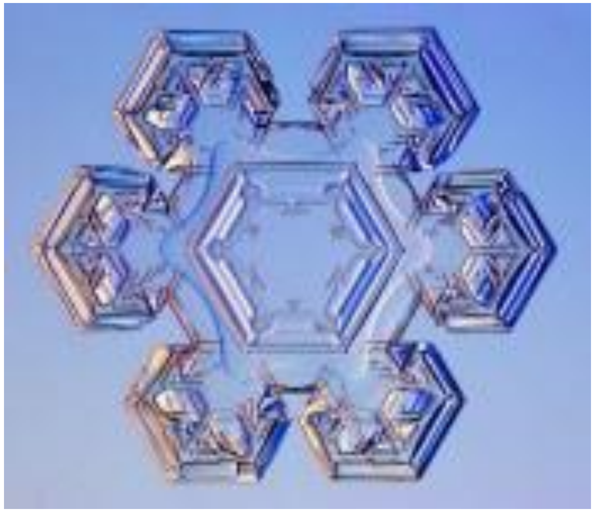
- Low snowfall in Polar region



Grain Shapes of Precipitation Particles

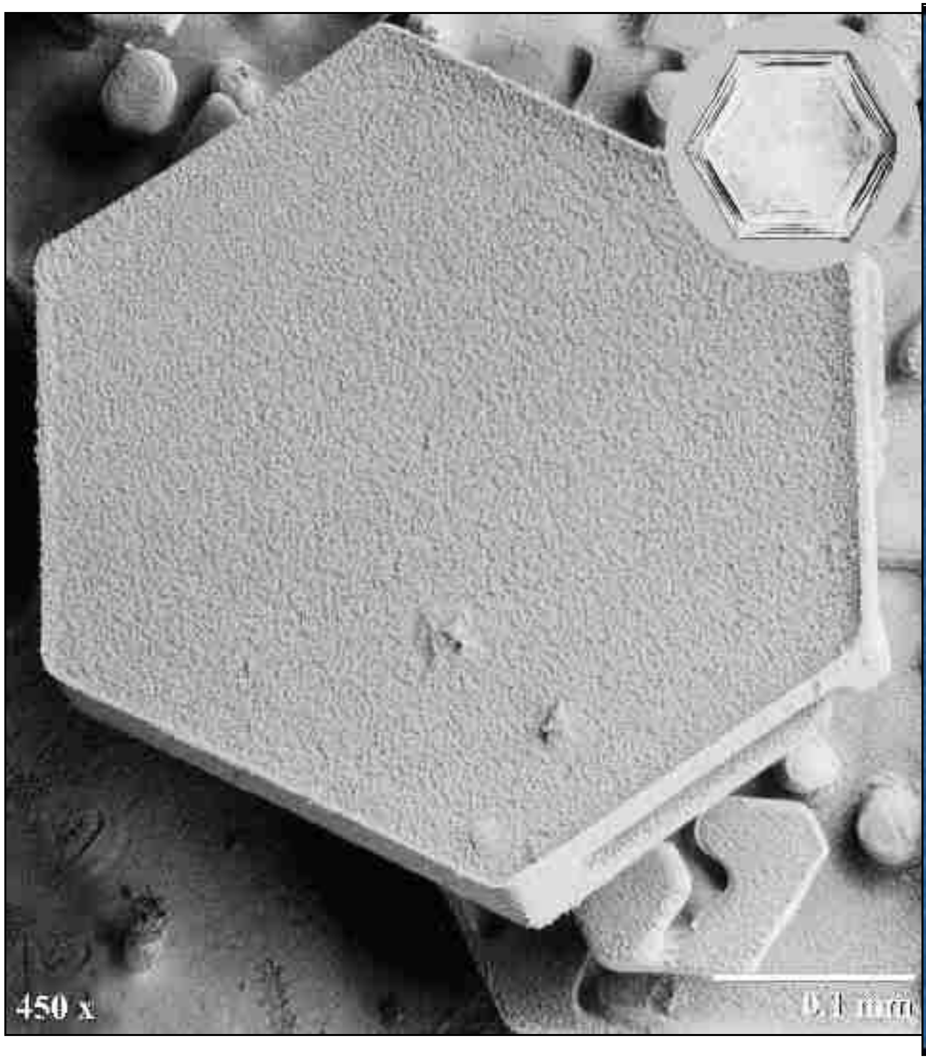
Sub-class	**Shape**	**Growth Environment**
Columns	Short prismatic crystal, solid or hollow	High super-saturation at -3 to -8^{o}C and below –22^{o}C
Needles	Needle-shaped, approximately cylindrical	High super-saturation at -3 to -5^{o}C
Plates	Plate-like, mostly hexagonal	High super-saturation at 0 to -3^{o}C and -8 to -25^{o}C
Stellars (dendrites)	Sixfold, star-like, planar or spatial	High super-saturation at -12 to -16^{o}C
Irregular Crystals	Clusters of very small crystals	Varying environments
Graupel	Heavily rimed particles	Super-cooled water in air mass causes riming
Hail	Laminar internal structure, translucent surface	Growth by accretion of supercooled water (>5mm)
Ice Pellets	Transparent, mostly small spheriods	Freezing of rain drop
Rime	Irregular deposits or longer cones pointing into the wind	Accretion of small, supercooled fog droplets

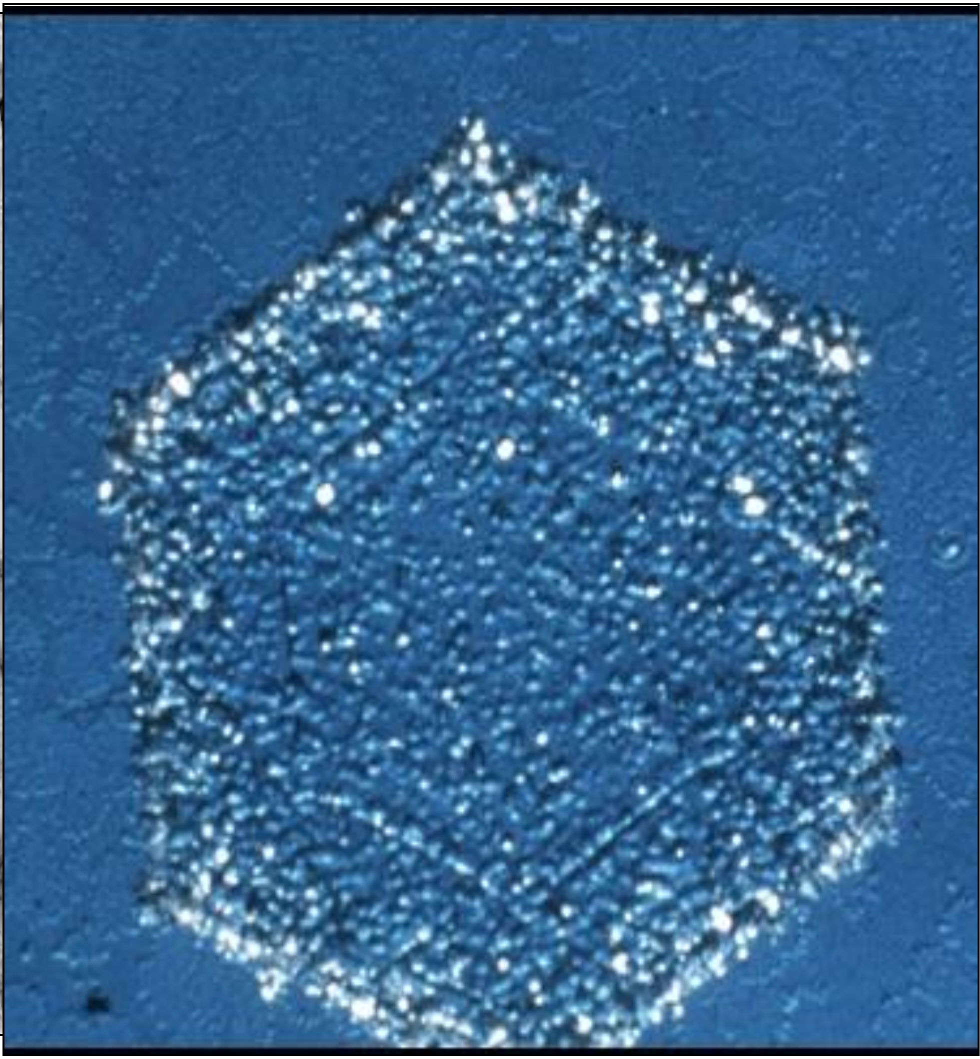
Stellar Plates



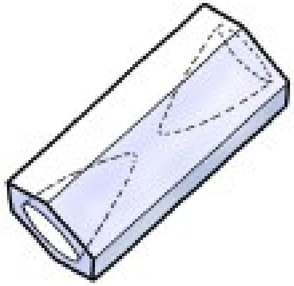
Stellar Dendrites

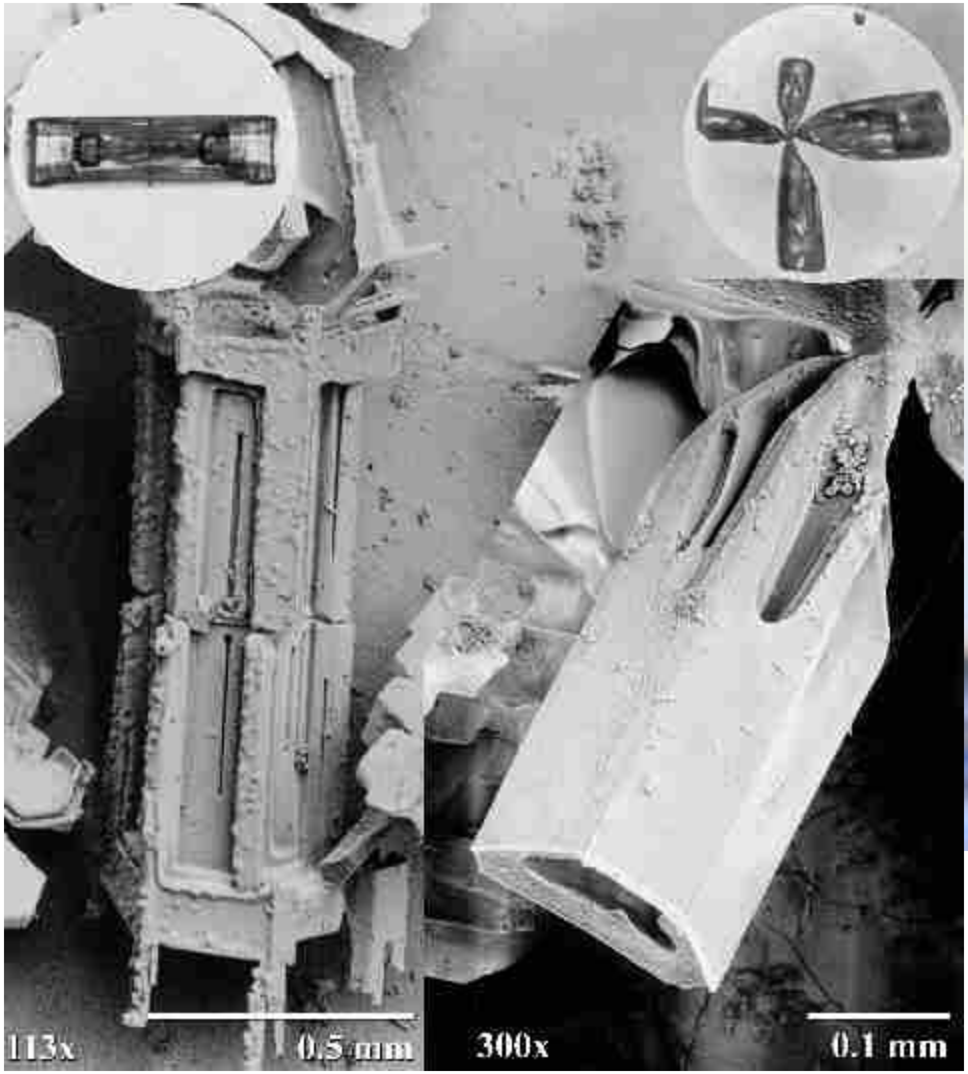
Plate





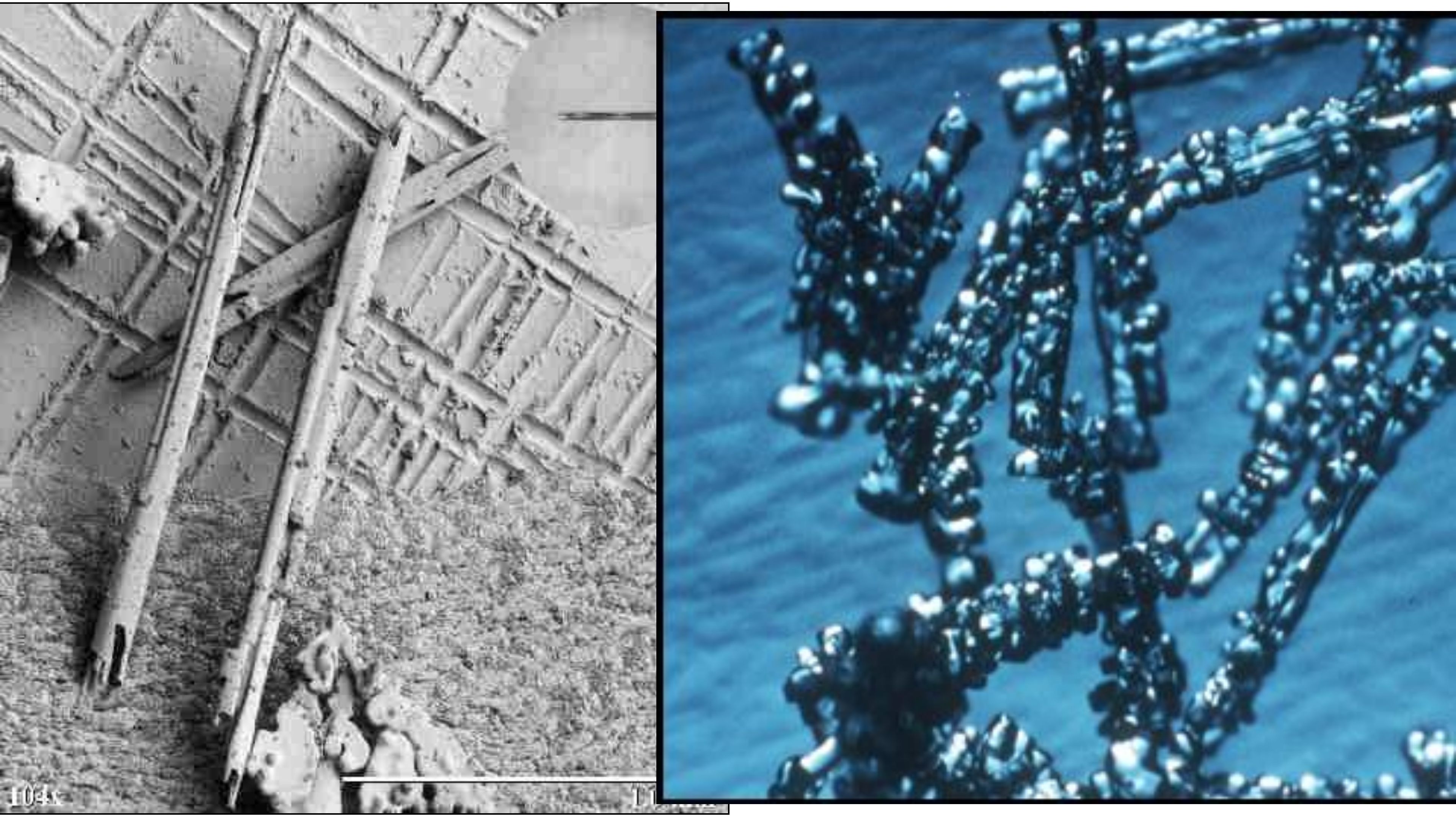
Columns



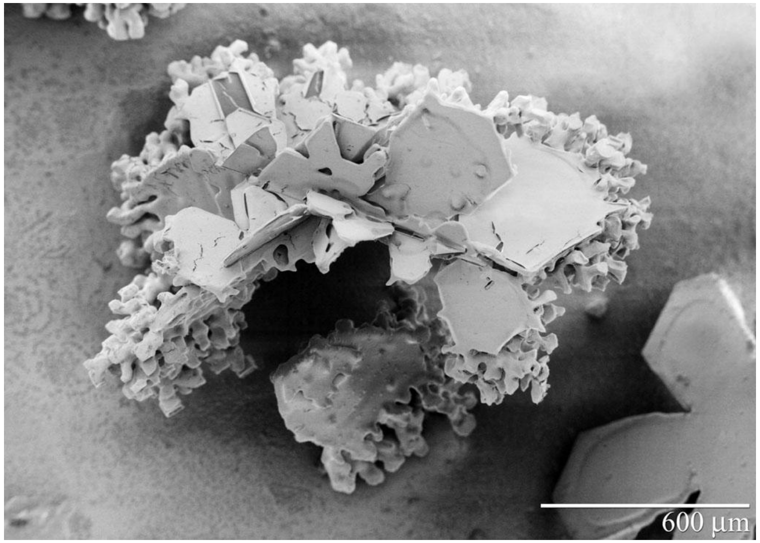


Capped Column

Needles



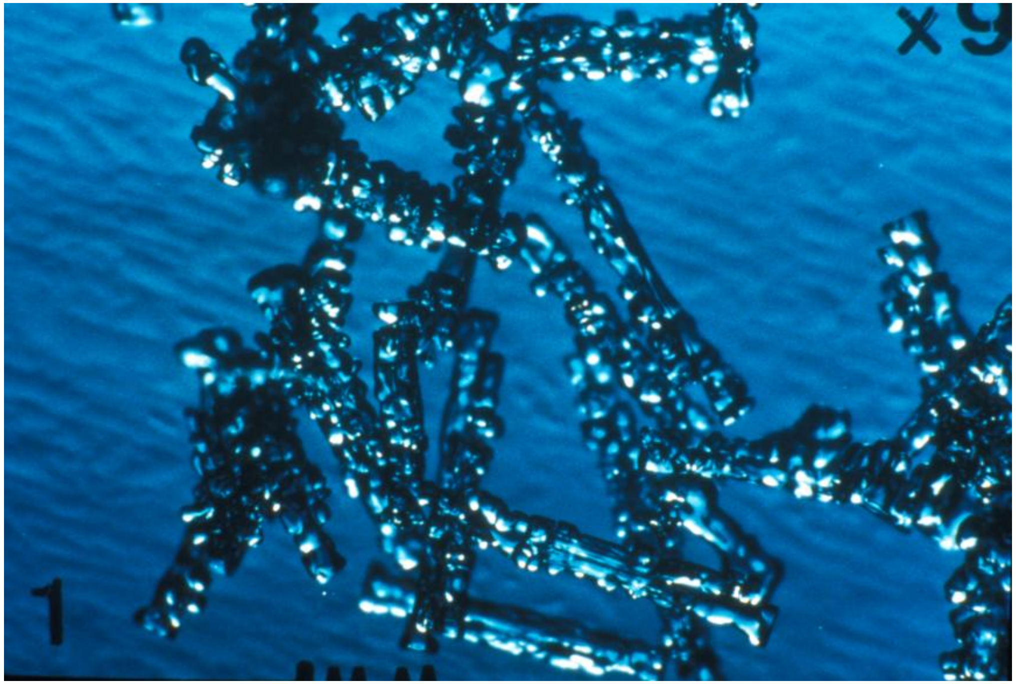
Riming



Under some conditions, tiny water droplets form in the atmosphere and remain in a liquid state at temperatures below 0º C.

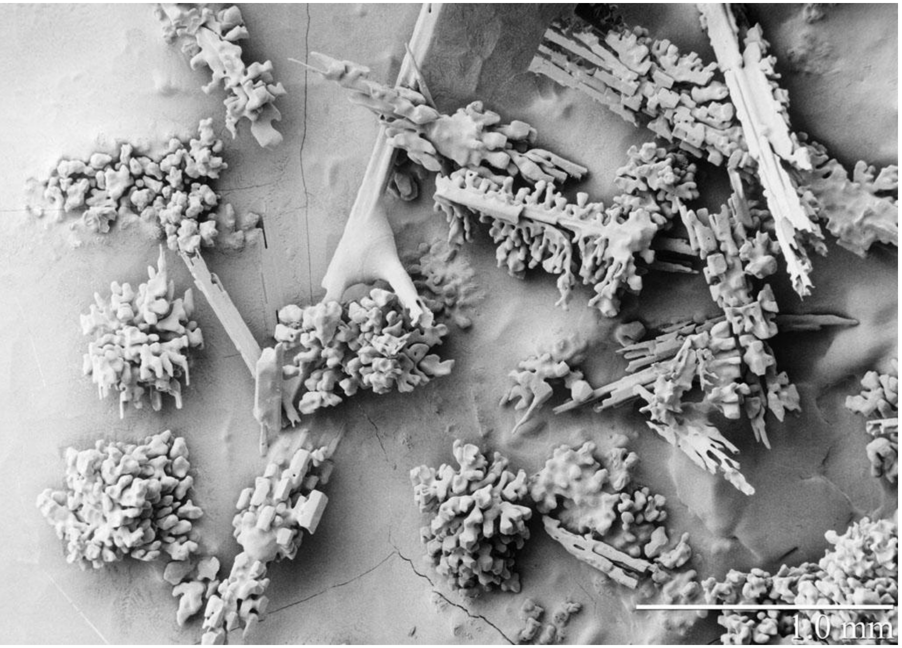
These water droplets are described as *super-cooled*.

When a super-cooled water droplet comes into contact with any surface or object, it immediately adheres to the surface or object and freezes, forming a small spherical piece of ice.

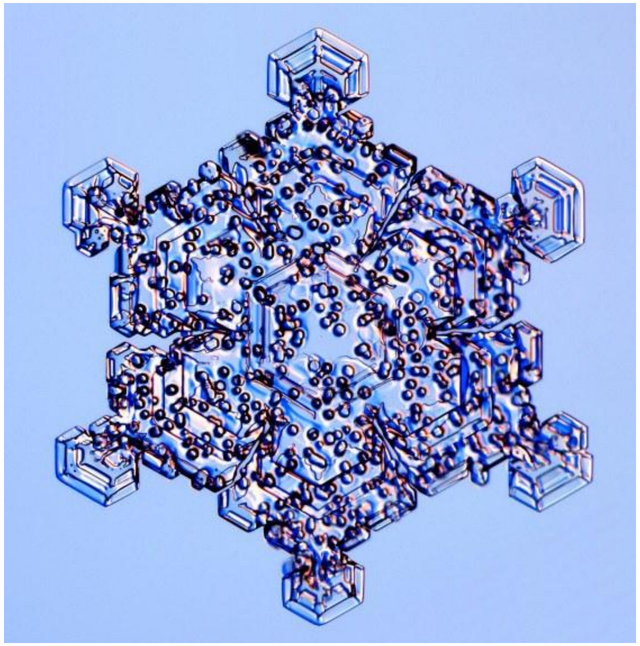


New snow, needle (rimed)

Water droplets, ~50 µm on the surface of the snow crystals



Rimed Crystals



This creates a ‘Snowpack’ with Different and Distinct Layers

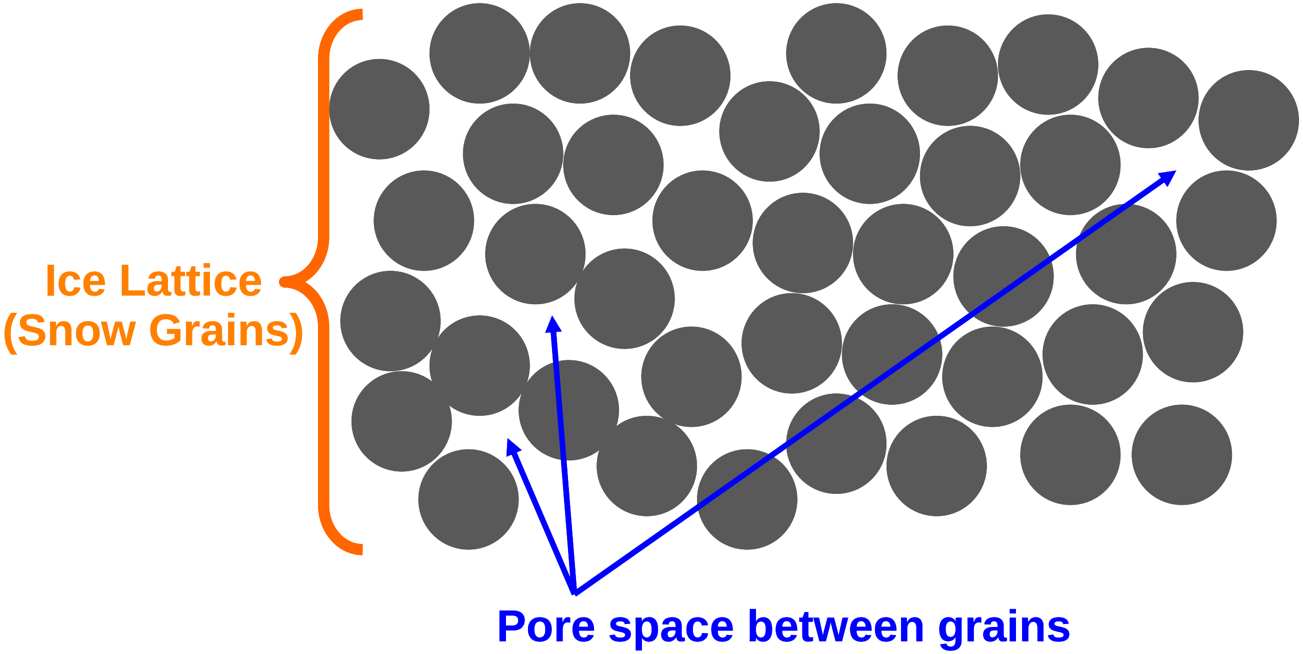
It is the layers with different characteristics that are the source of avalanches

Strong layer over weak layer

What is a Snowpack?

- A snowpack is a porous medium composed of ice and air (and perhaps liquid water)
- Generally composed of layers if different types of snow
- Ice is in the form of snow crystals and grains that are usually similar within a layer

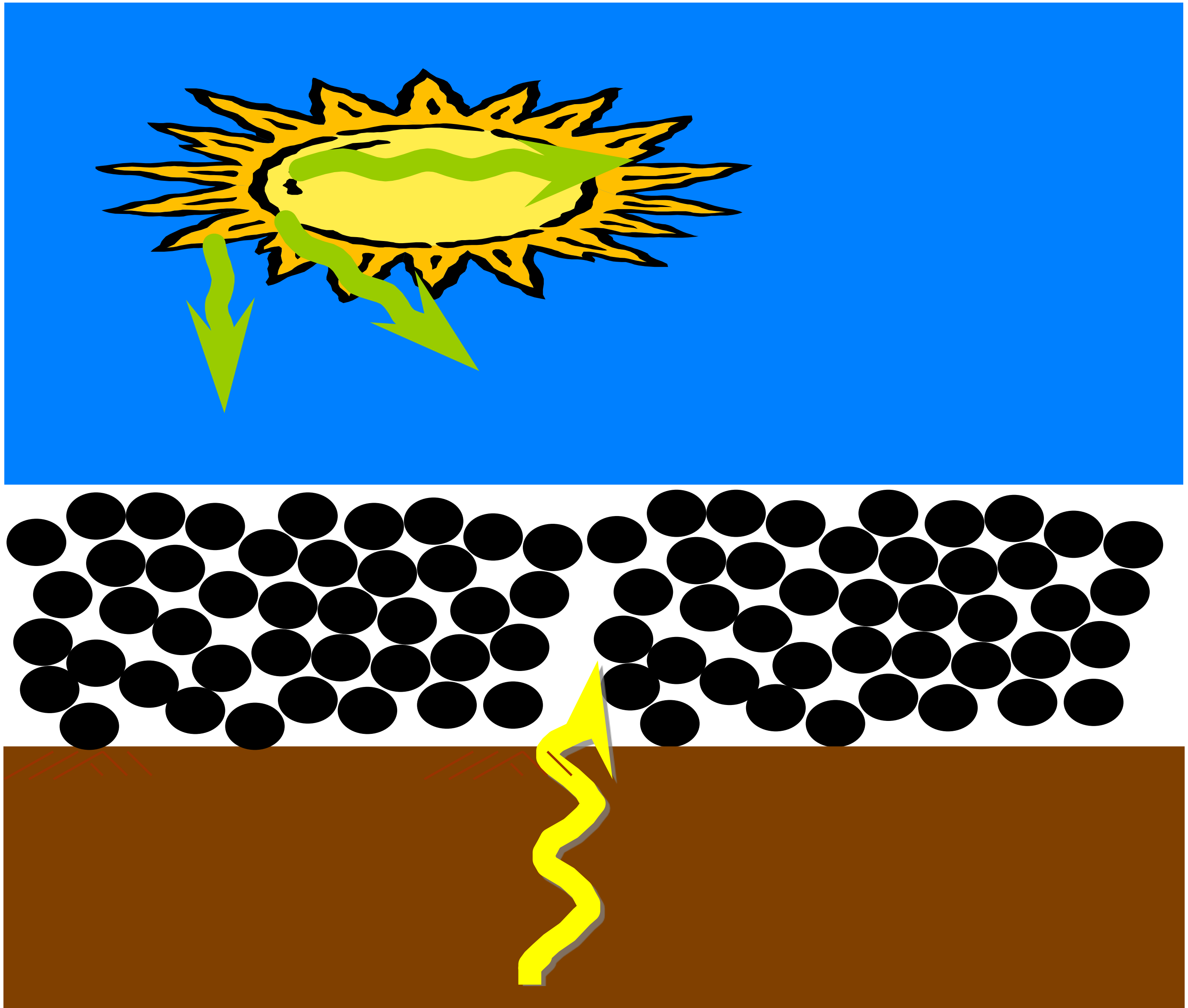
Snowpack Generalized



Ice Lattice (Snow Grains)

Pore space between grains

Snowpack interacts with its environment



Air

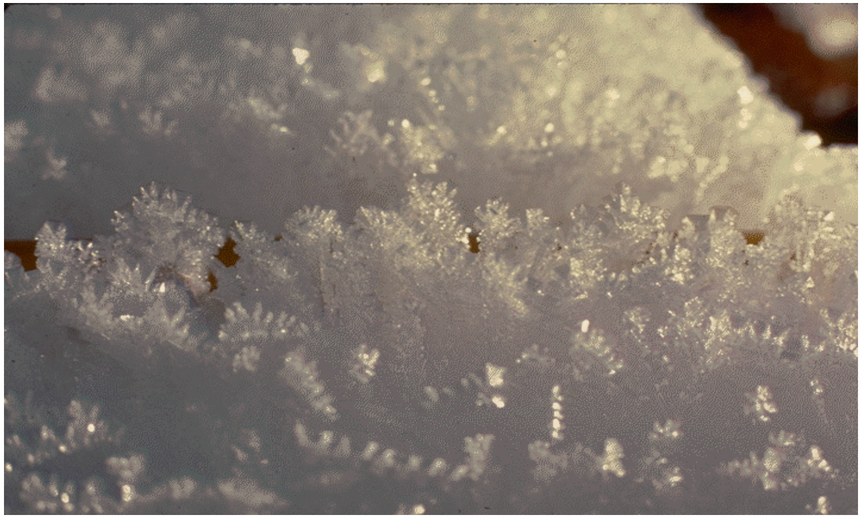
Colder

Snowpack

Ground

Warmer

Processes Affected by Energy (Heat) Exchanges:



- Snow formation in the atmosphere
- Snowpack metamorphism
- Surface hoar formation
- Near-surface facet formation
- Temp regimes and gradients

Energy Exchange at the Snow Surface

Energy gained or lost at the snow surface is transferred within the snowpack by two primary mechanisms:

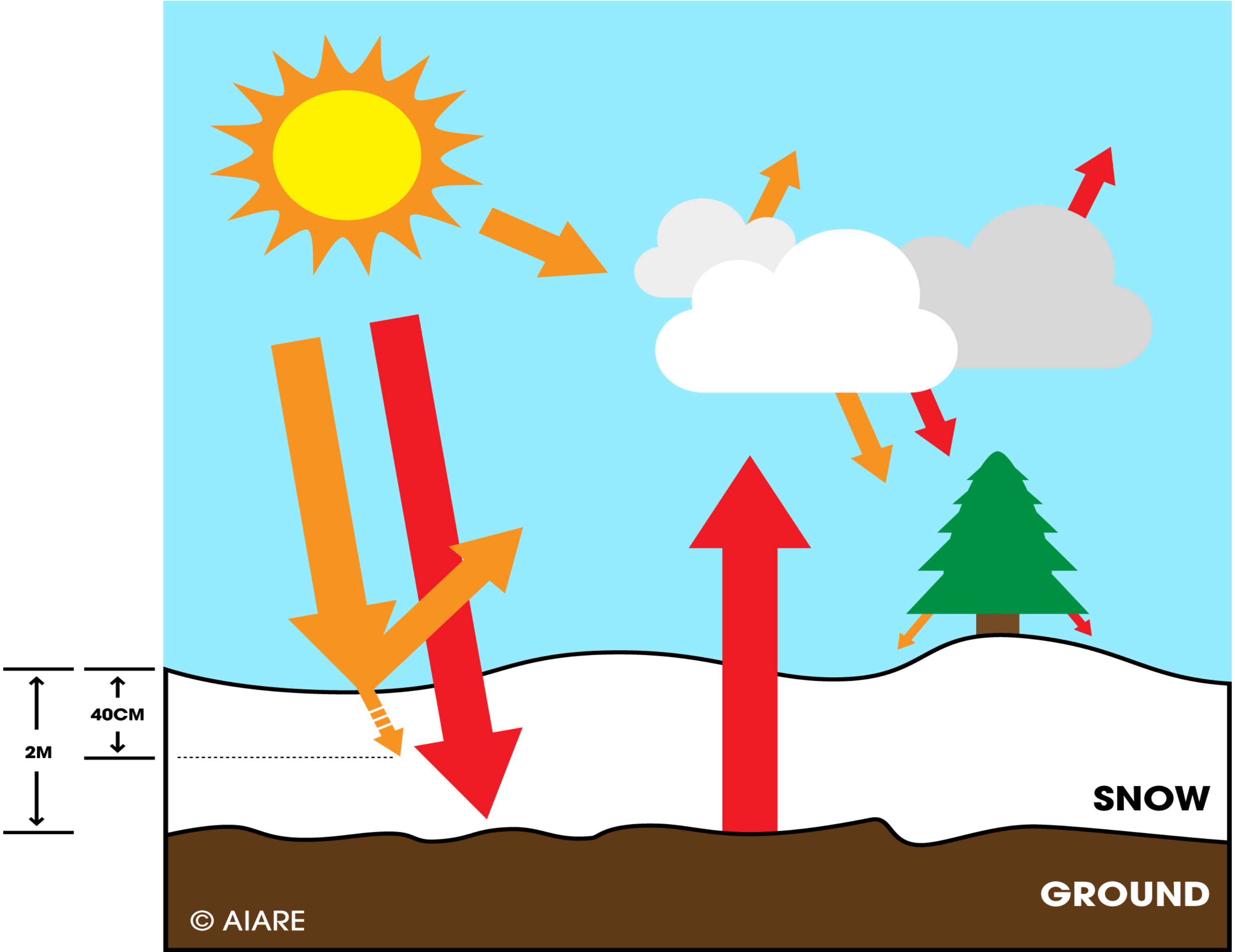
1) **Conduction through the ice skeleton**
2) **Vapor movement through the pore spaces**

Energy exchanges at snow-atmosphere interface are driven primarily by:

1) **Radiation**
2) **Wind blowing over the snow surface**

Heat Exchange at the Surface: Radiation Balance

Total Balance



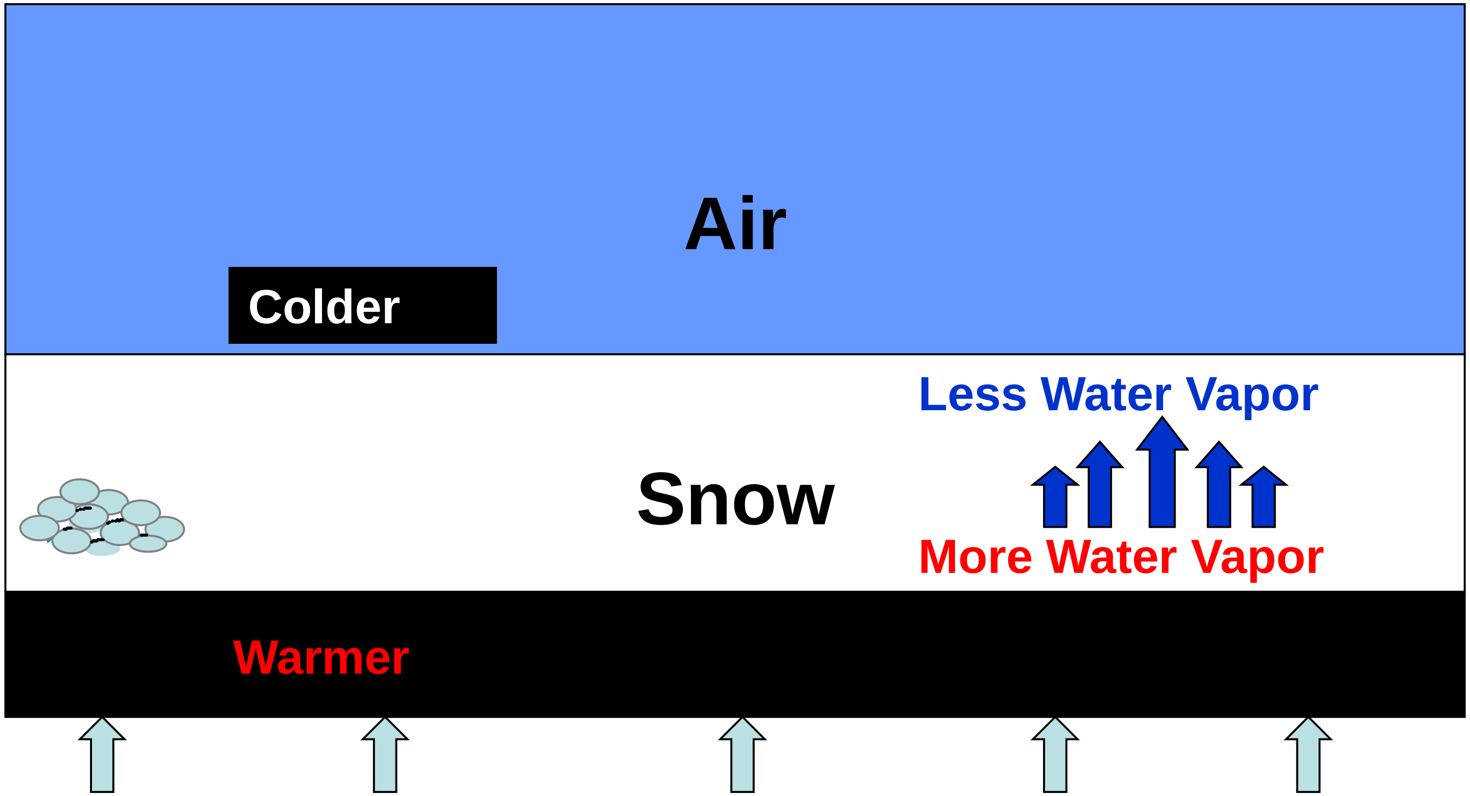
Why Heat Exchange is Important to Metamorphism

- Snow metamorphism is dictated by vapor movement to , from, and within the snowpack →
- Vapor movement is driven by heat (energy) transfers to and from the snowpack
- Occurs mostly at the surface, but also between the snowpack and the ground

Water Vapor in the Snowpack

- Much mass exchange across pore spaces within a snowpack by sublimation, vapor diffusion, and re-deposition

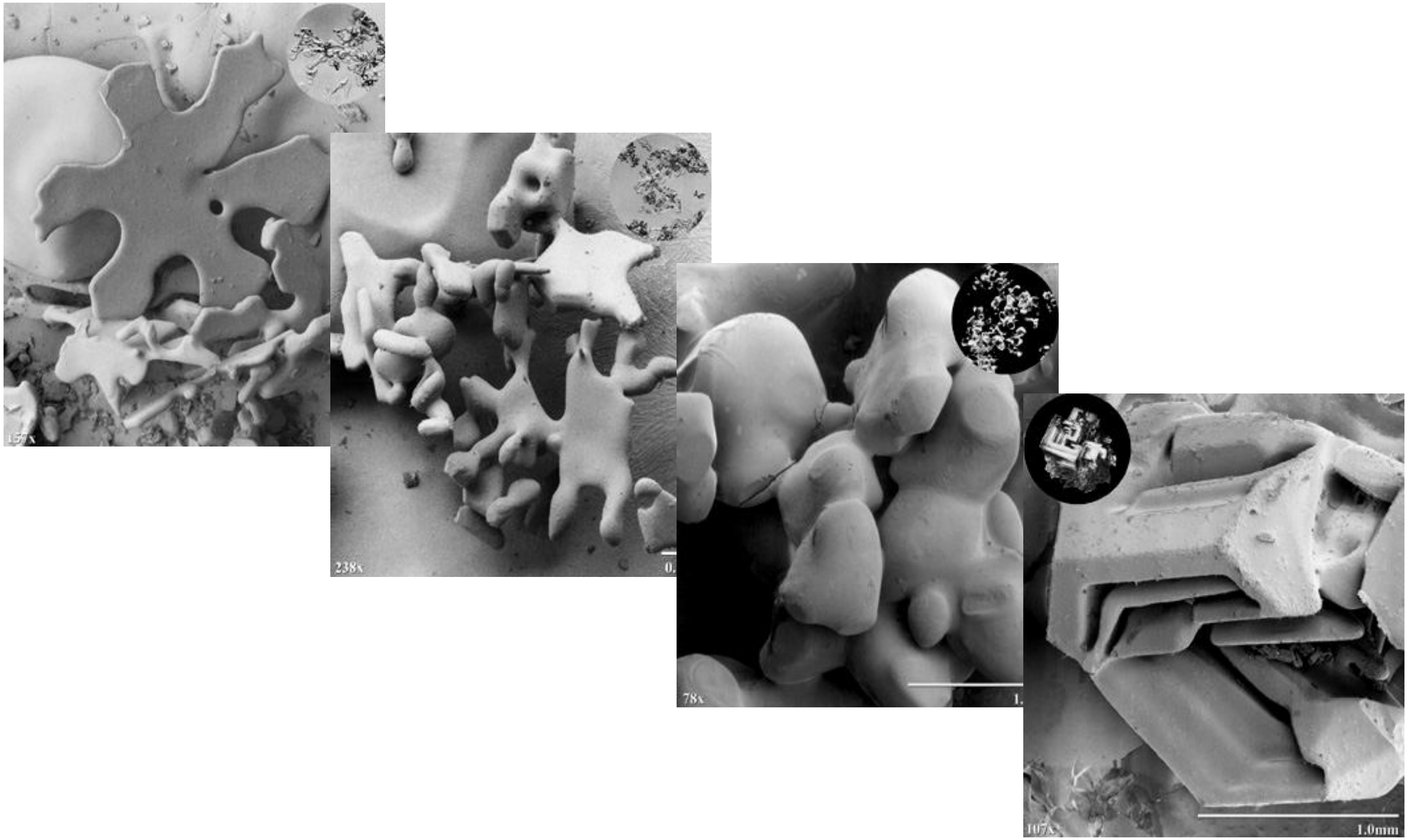
- Water vapor then diffuses from warmer (higher vapor pressure) to colder (lower vapor pressure) areas



Stored heat in the ground from summer warming (most important), and geothermal heat from the interior of the earth

Snow Metamorphism

“Change of the snowpack over time”



Snow Metamorphism

“Change of the snowpack over time”

Factors changed by metamorphism:

- Shape and size of grains
- Bonds between grains
- Density
- Temperature, Reflectivity of radiant energy (albedo)
- Hardness
- Porosity
- Deformation properties
- Shear and tensile strength
- Thermal conductivity

Metamorphism Within the Snowpack

Vapor pressure gradients → Vapor movement

Controlled by:

- **Temperature**
- **Temperature gradients**
- **Grain size**
- **Radius & curvature**

Dry Metamorphism

- No liquid water present
- Temperatures less than 0° C

- **Result of vapor movement**
- **Vapor movement is driven by vapor pressure gradient,**

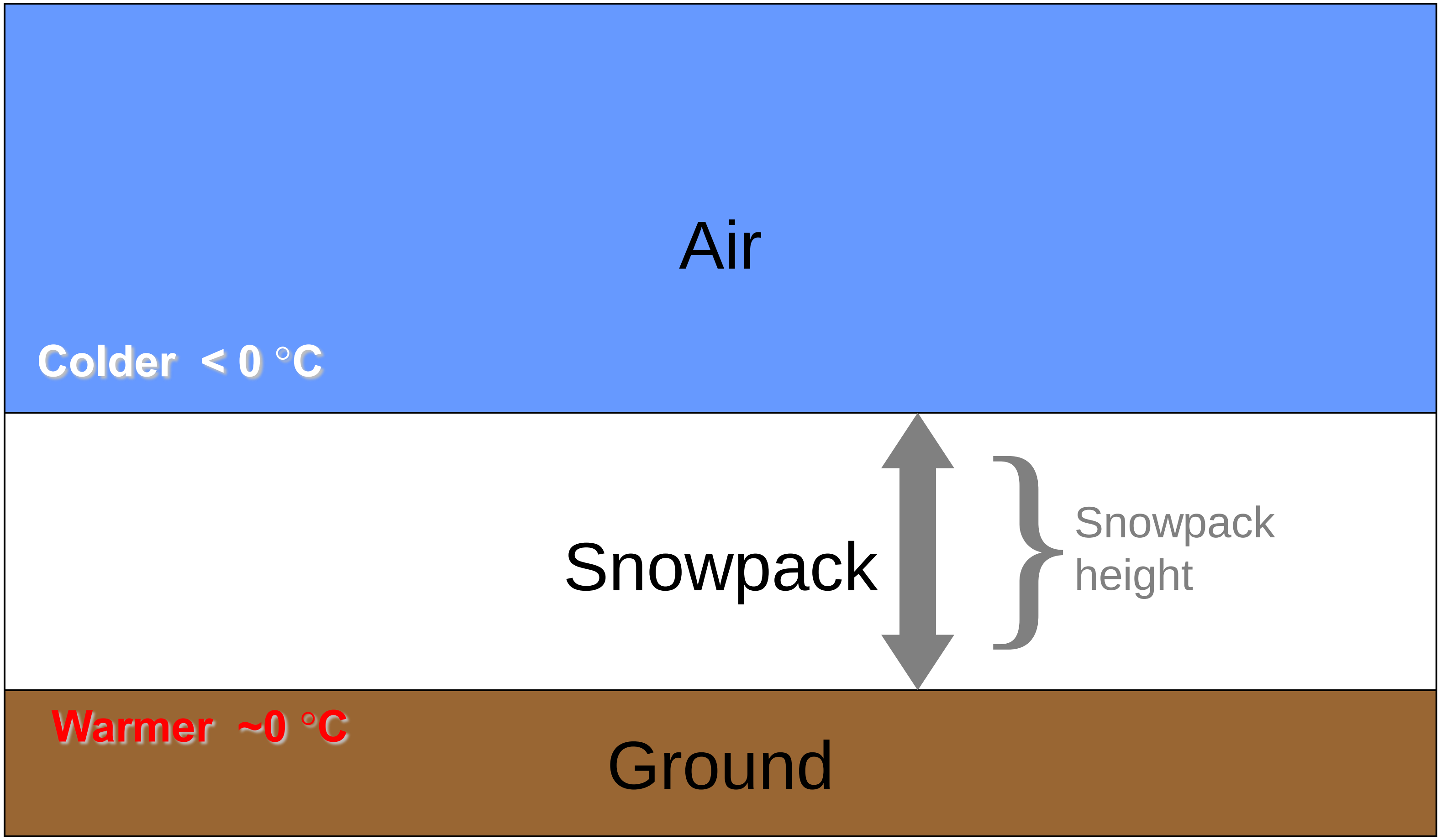
  controlled by:
  - **Temperature**
  - **Grain size**
  - **Radius and curvature**

Temperature gradient

“The change in temperature over height”

Primary factors:

- Air temperature
- Ground temperature
- Snow height



Air

Colder < 0 °C

Snowpack

Snowpack height

Warmer ~0 °C

Ground

Amount of change in temperature between the ground and snow surface influences metamorphism

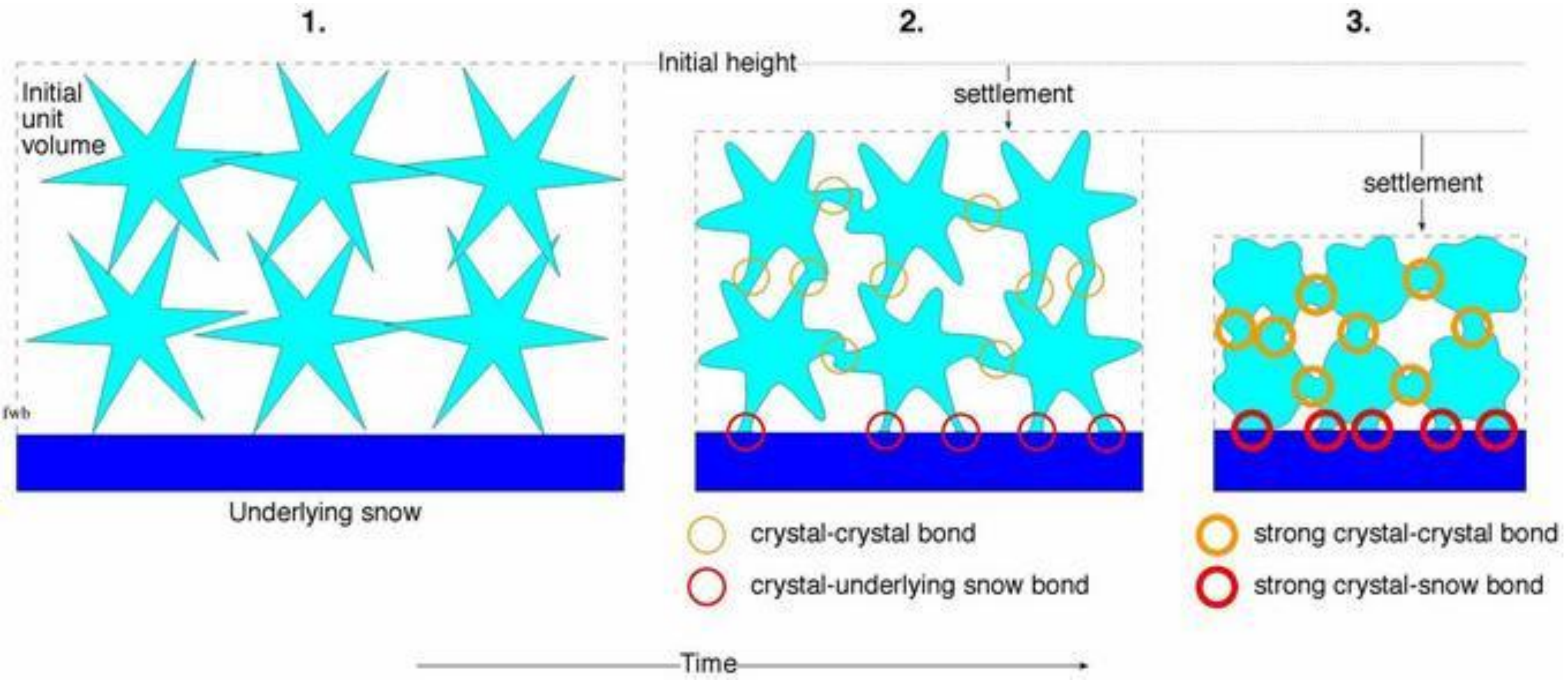
Big Change = High Gradient

Small Change= Low Gradient

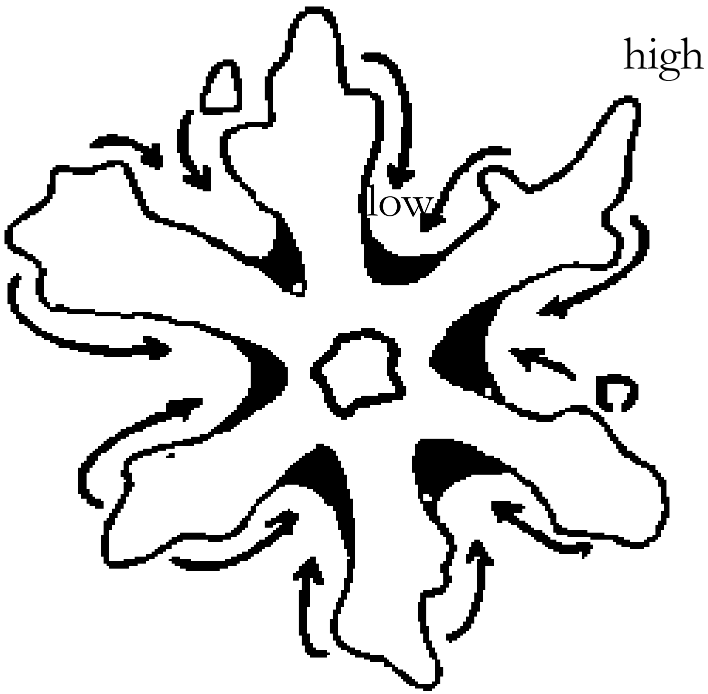
TG < 1°C per 10 cm = LOW (rounding)

TG > 1°C per 10 cm = HIGH (faceting)

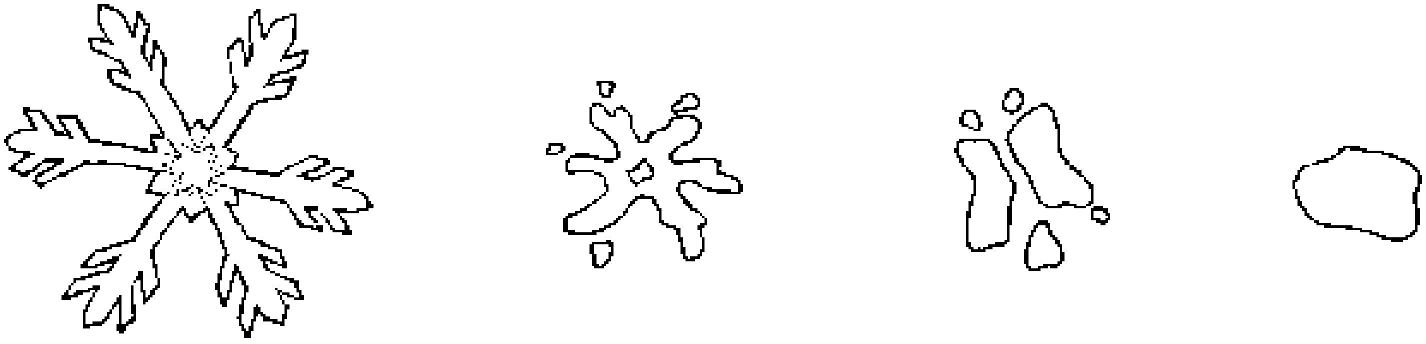
1. Equi-temperature Metamorphism (ET)



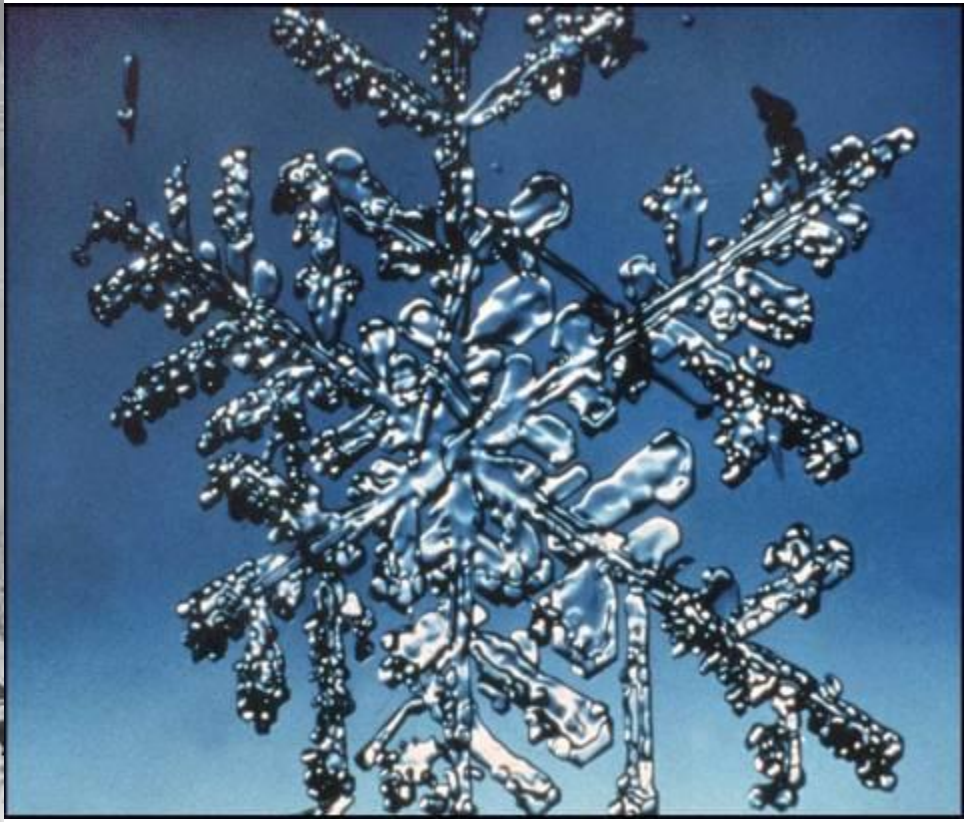
Low Temp. Grad. → Rounding



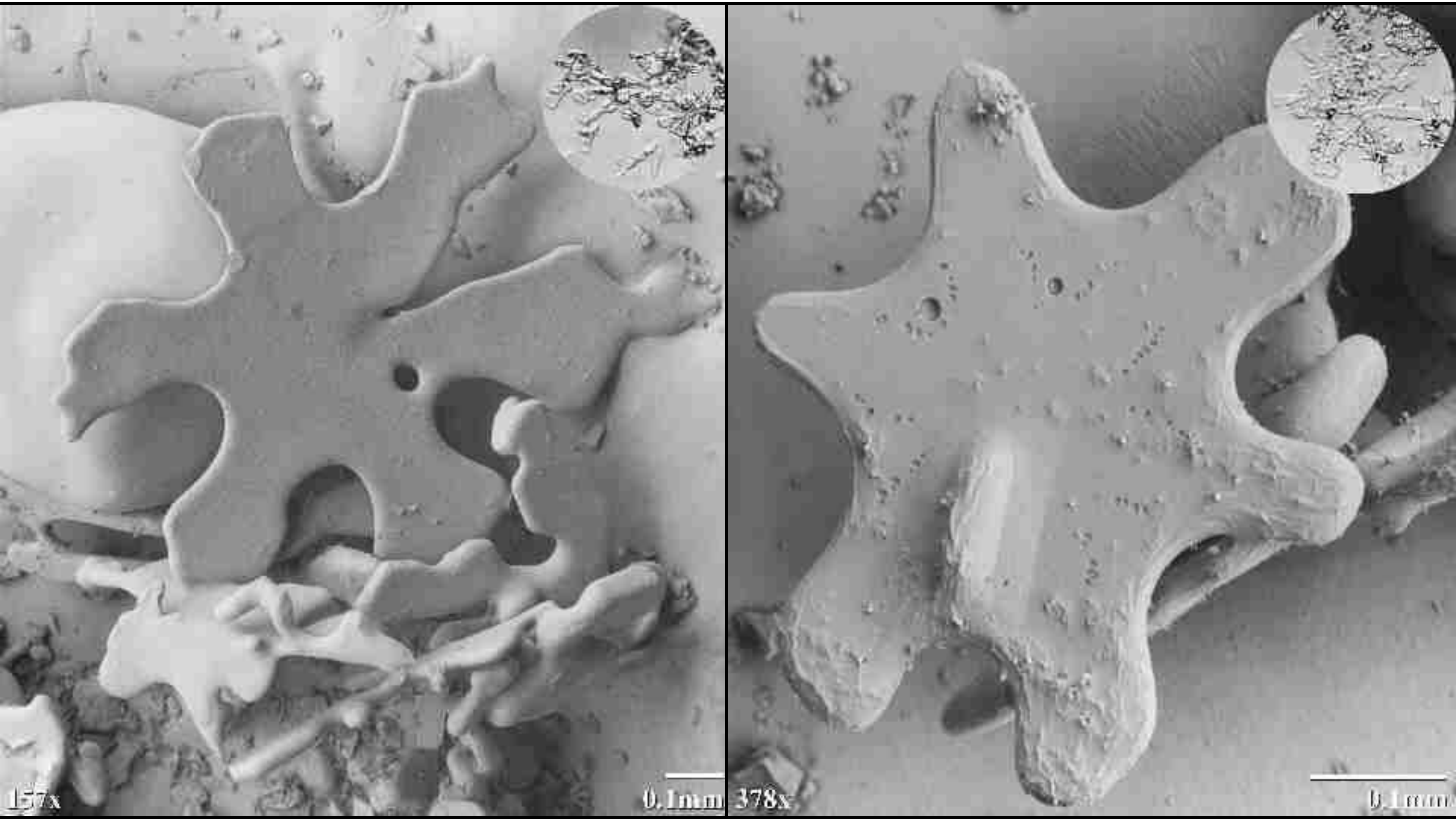
- Vapor is moved at a “micro-scale”
- Vapor gradient from convex to concave areas



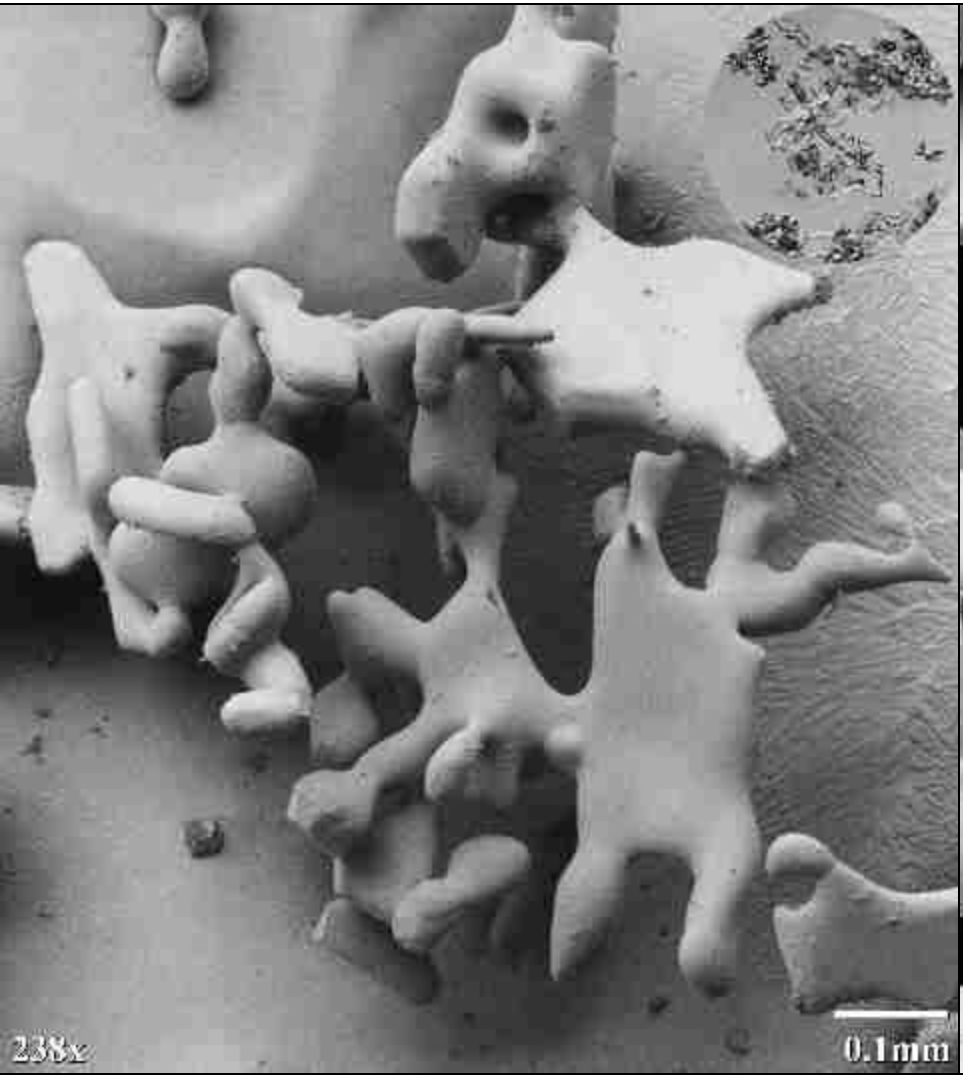
Beginning Stage Rounding



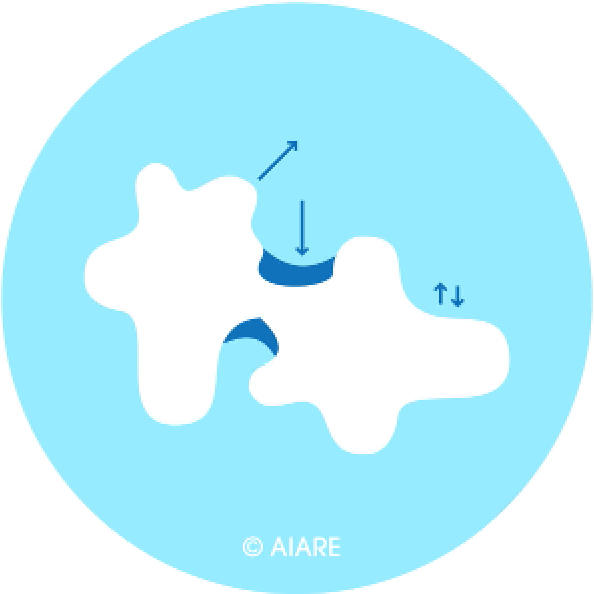
Early Stage Rounding



Advanced Stage Rounding



Sintering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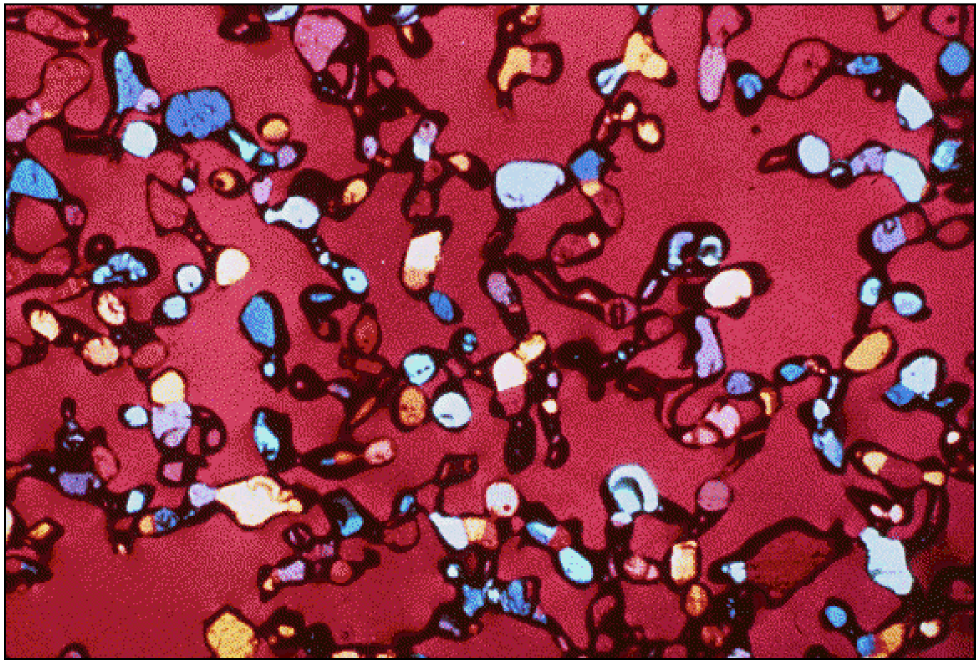
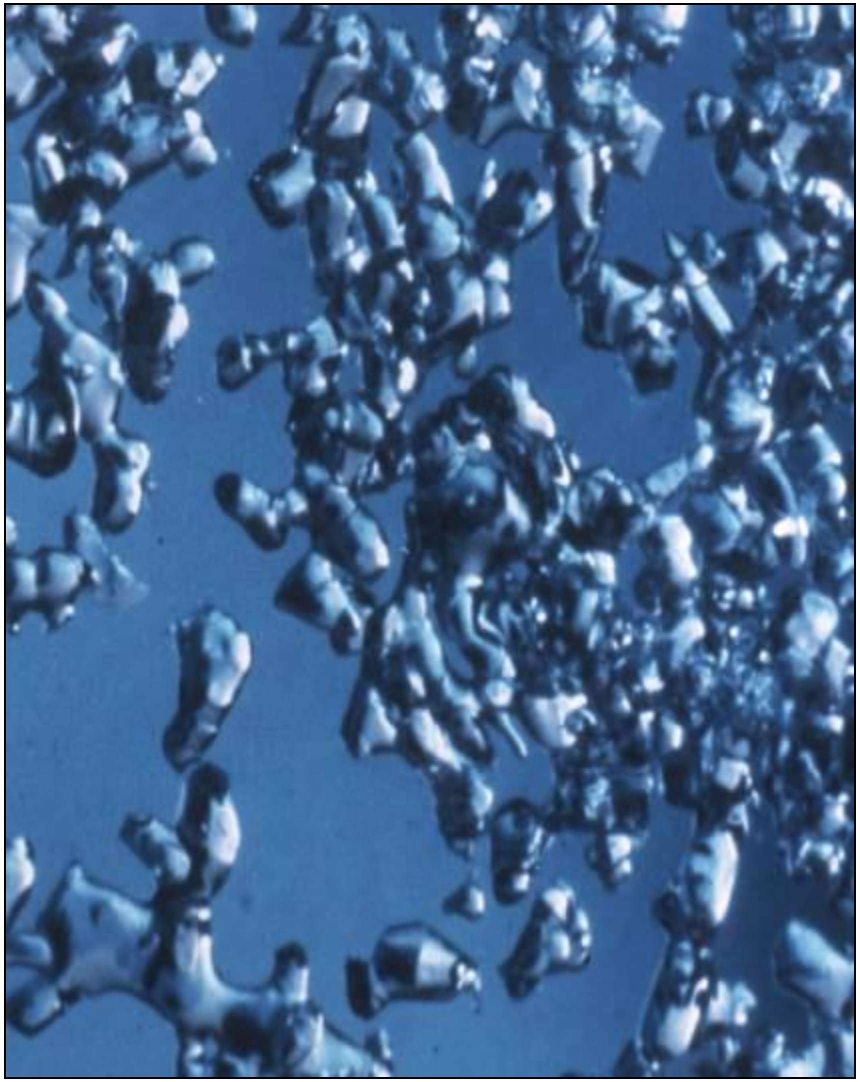
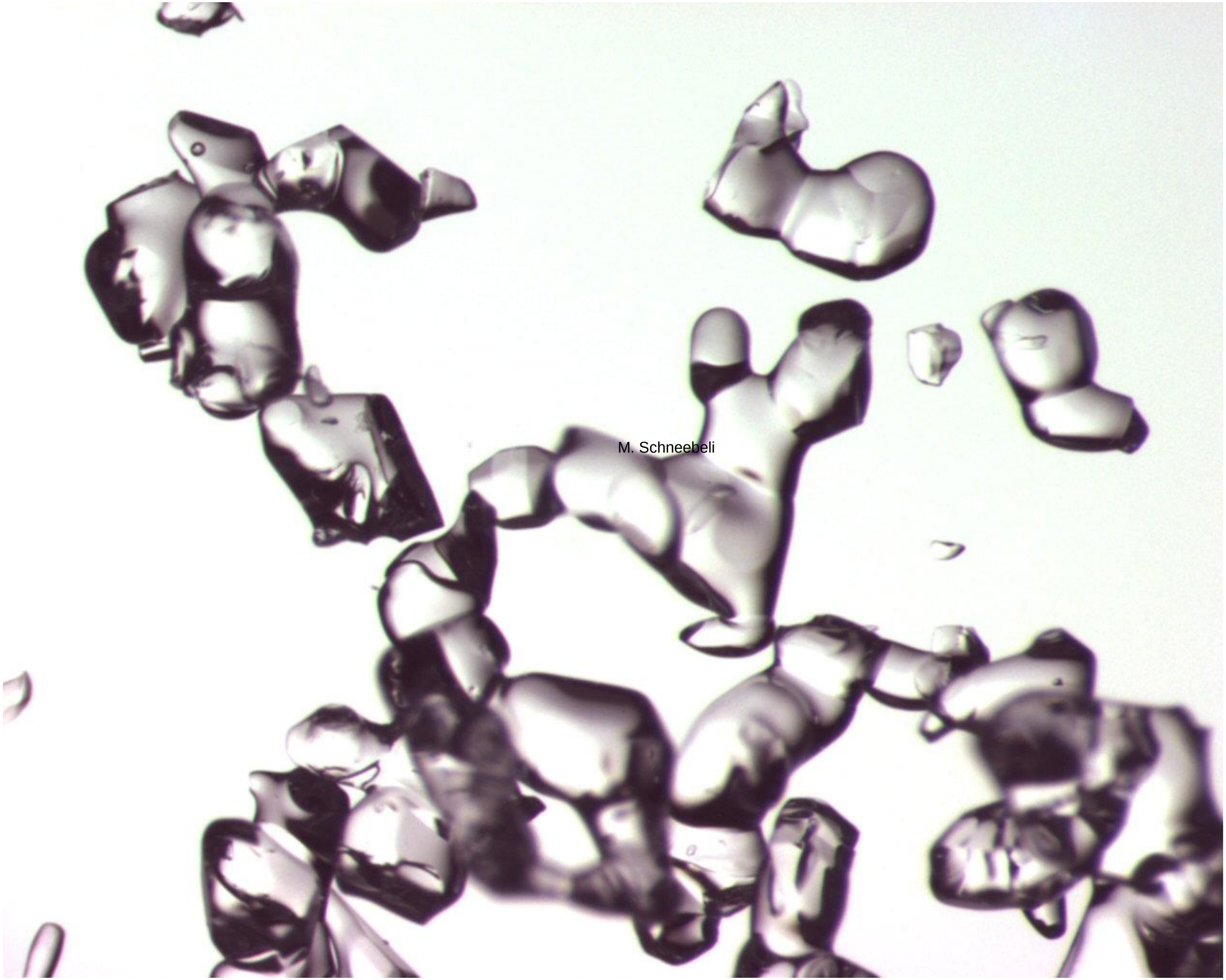
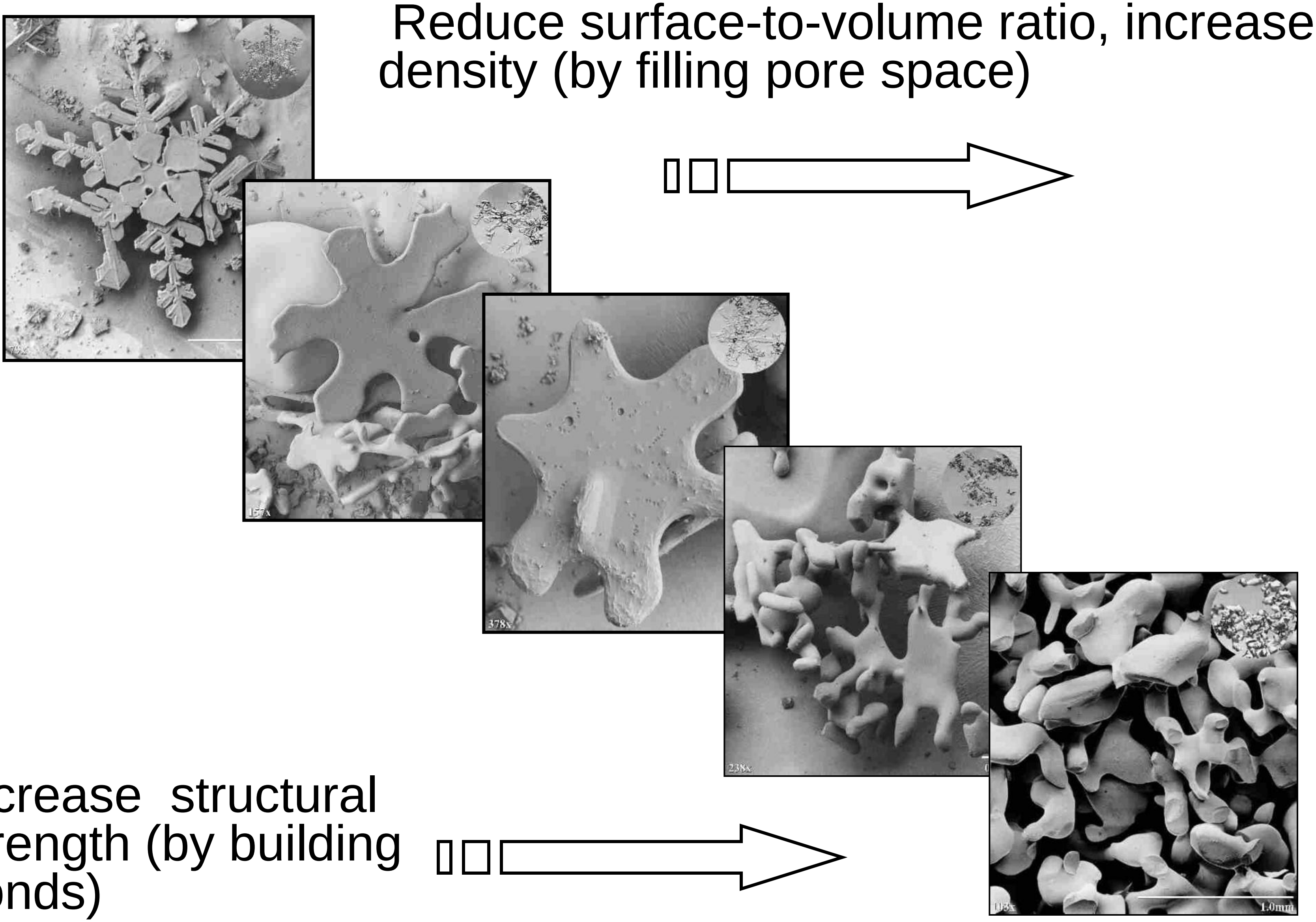





M. Schneebeli

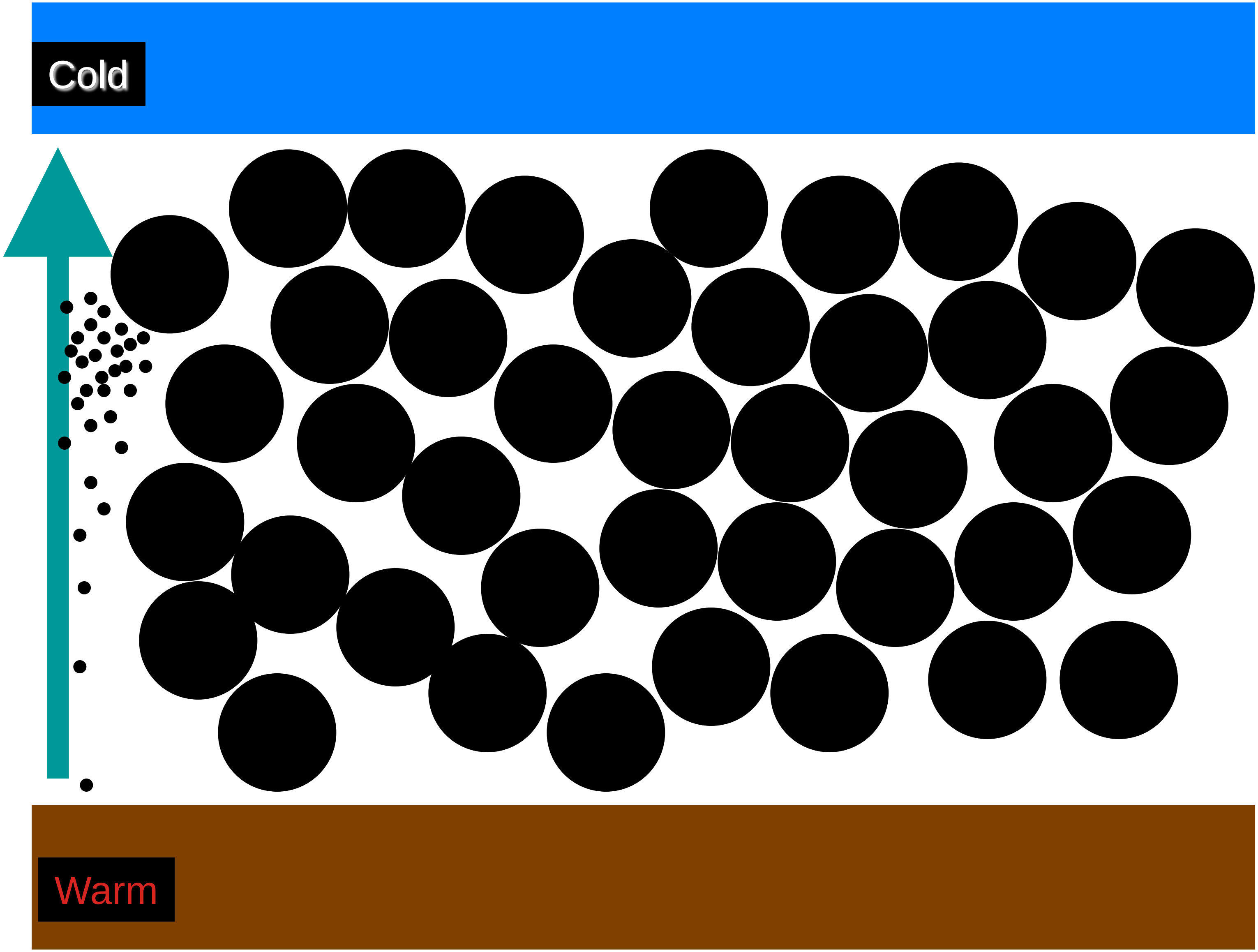
Stages of Rounding

Reduce surface-to-volume ratio, increase density (by filling pore space)



Increase structural strength (by building bonds)

2. Temperature Gradient Metamorphism (TG)



High Gradient

=

Vapor
Moves

from

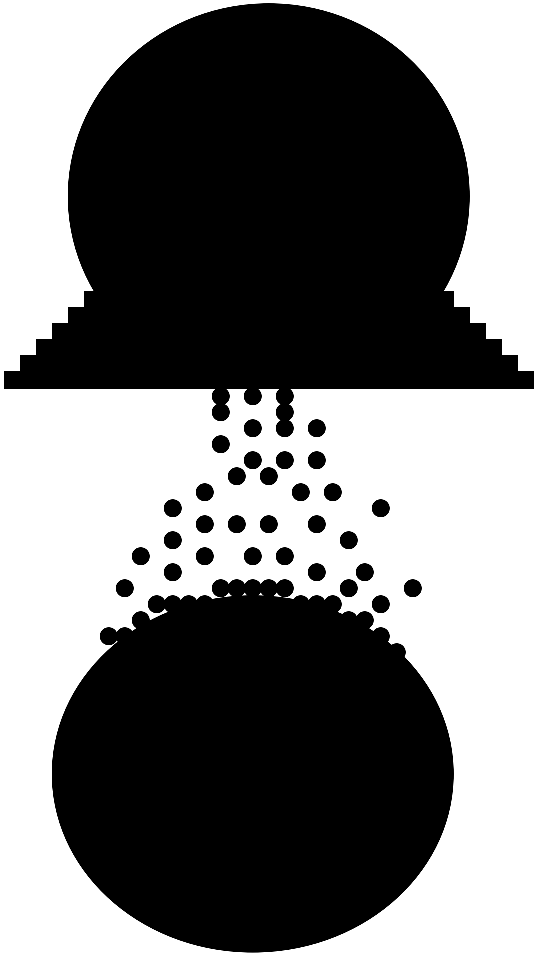
Warm

to

Cold

(macro scale)

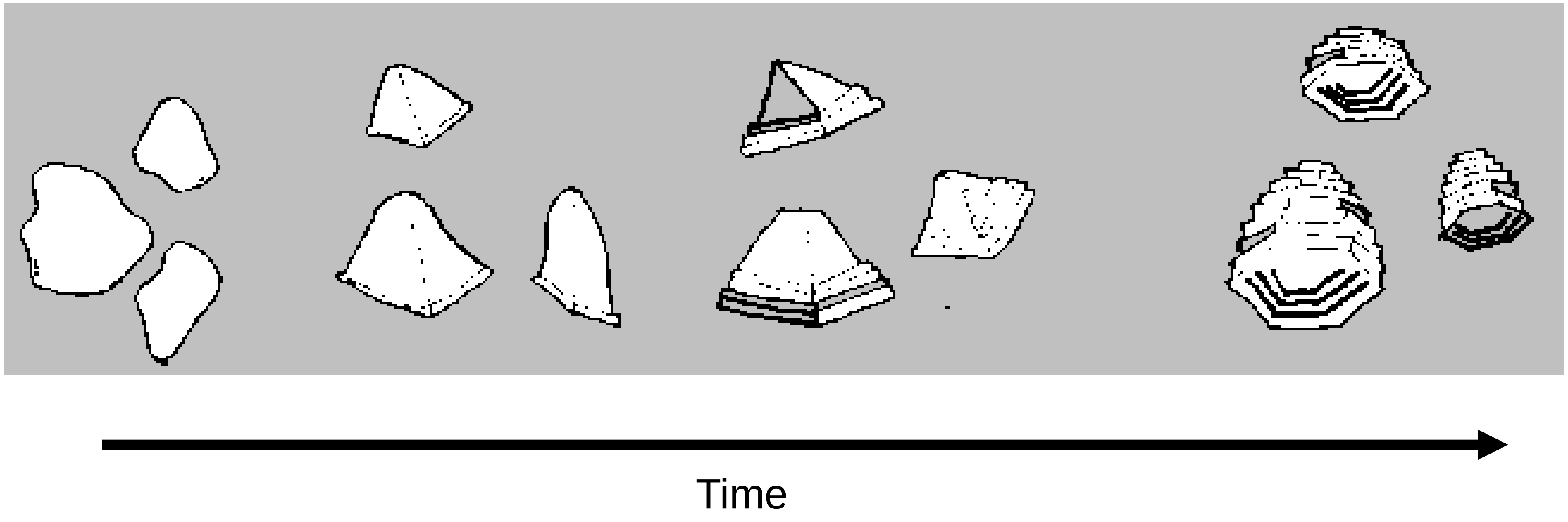
High Gradient →Large Growth Rate → Rapid Edge Growth → Faceted Grains



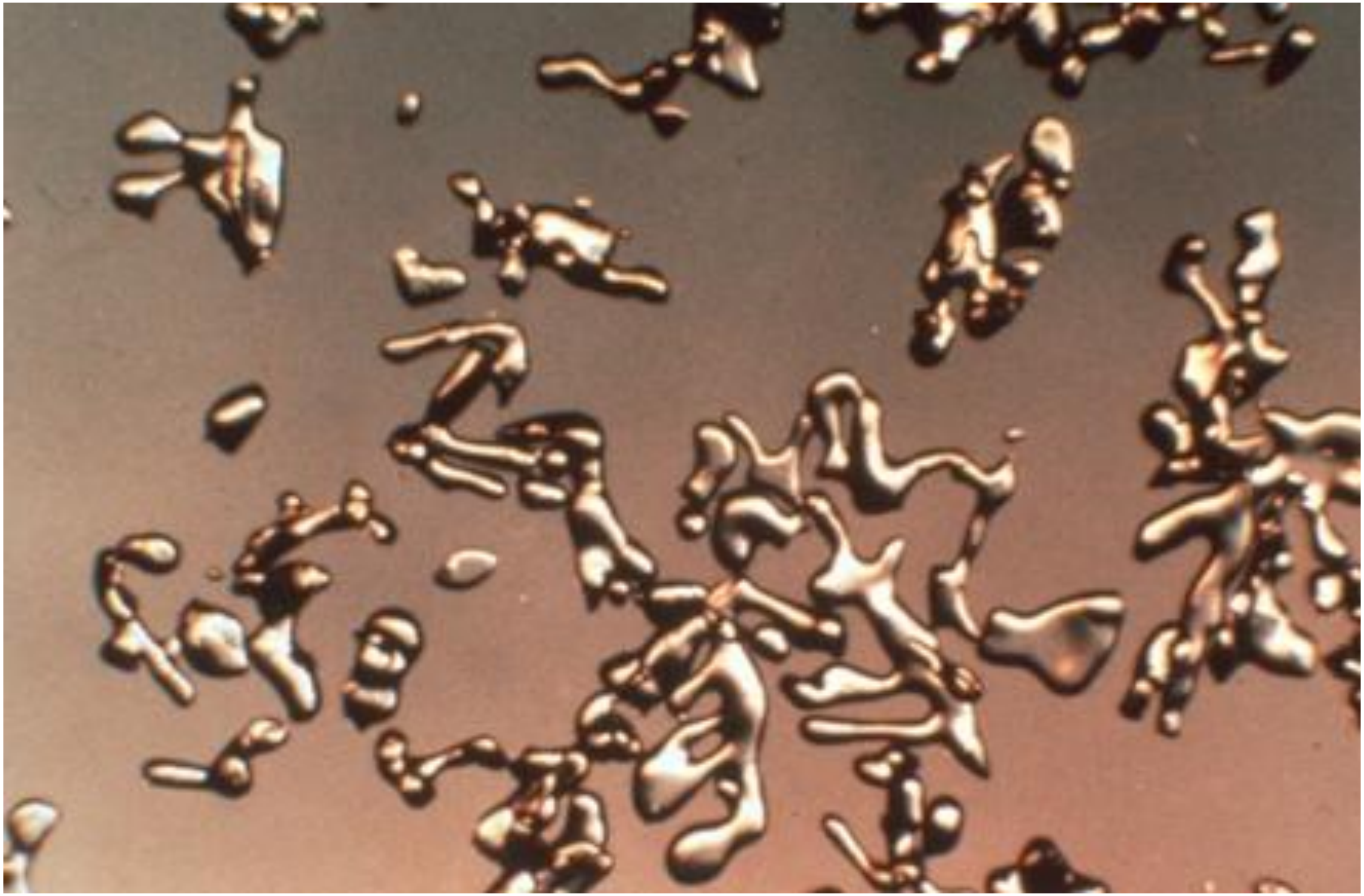
Faceting

Faceting is common when:

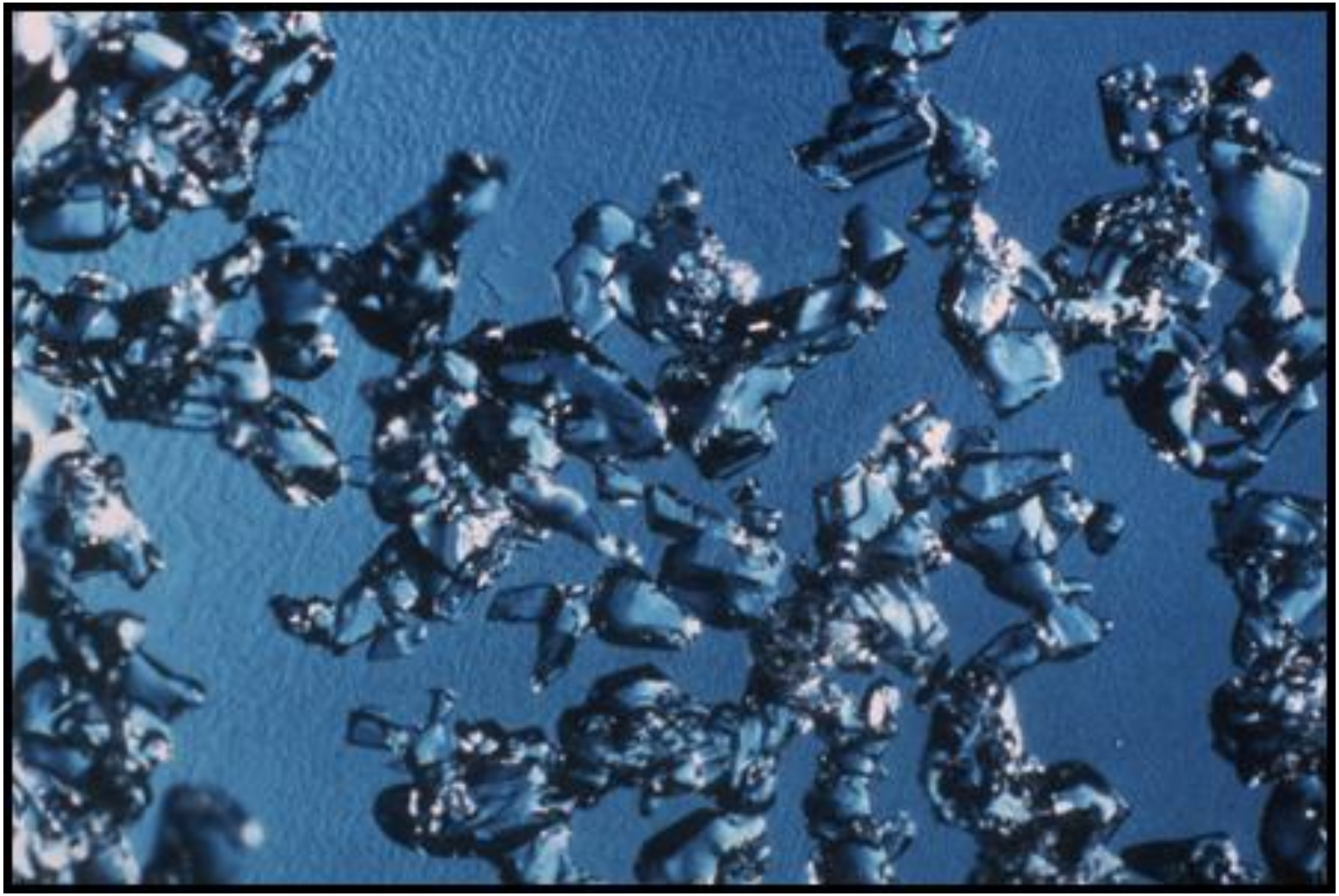
The snowpack is *shallow* and the air temperatures are *cold*



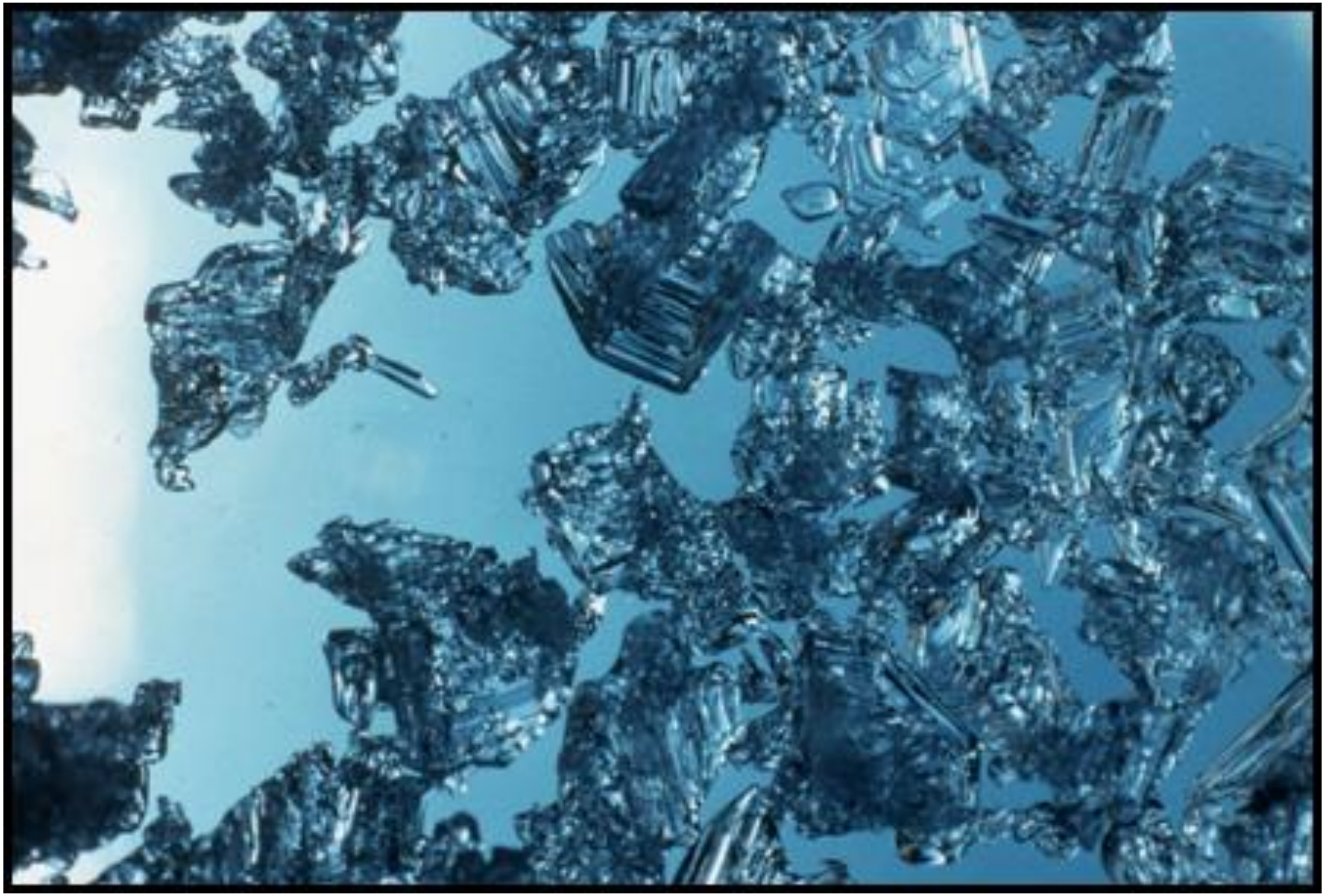
Rounds, beginning stage faceting



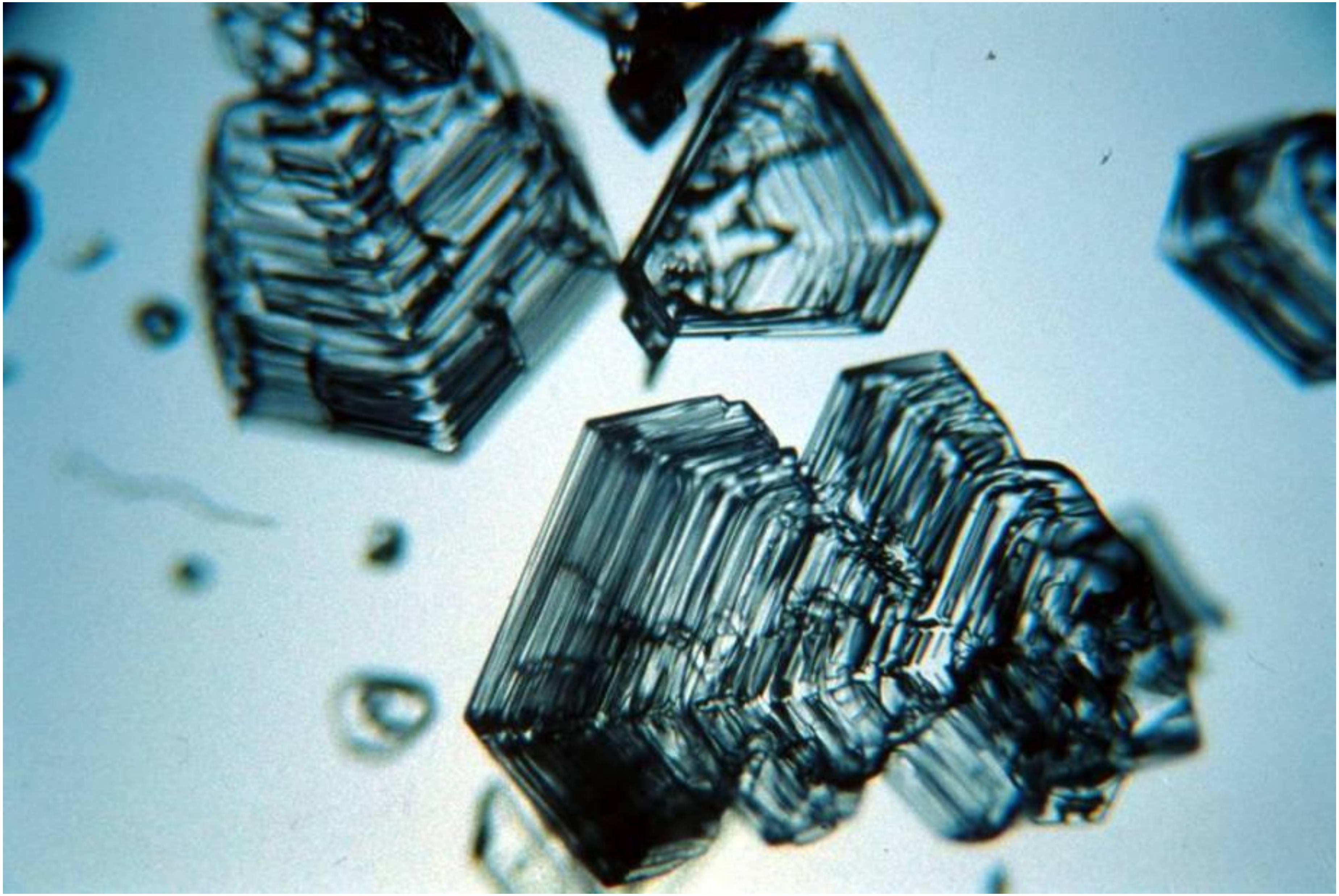
Early Stage Faceting



Advanced Stage Faceting



Advanced Facet - “Depth Hoar”



3. Melt Freeze Metamorphism (MF)

Conditions that Promote Melt-freeze:

- High daytime temperatures
- Strong solar radiation
- Cold night time temperatures
- Recurring cycle of melting and freezing
- High density wet snow
- Rain
- Sunny aspects
- Steeper slopes

SNOW - Index Properties

- **Fundamental Properties**
  - Grain Size
  - Grain Shape
  - Grain Fabric

- Help in the identification of snow type

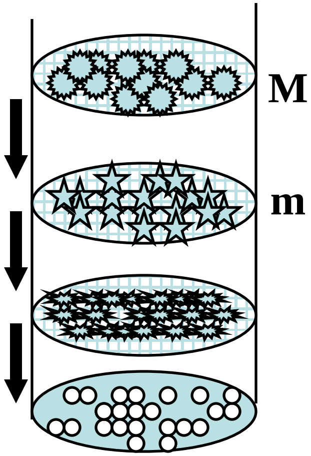
- **Derived Properties**
  - Density
  - Porosity
  - Void Ratio
  - Hardness
  - Permeability
  - Liquid water Content

Fundamental Index Properties

(a) Grain Size

Techniques of measurement -

- **New snow:**
  - **individual grain analysis by examining under microscope**
  - **Size varies from a fraction of a mm to about 2 mm**



For Deposited and metamorphosed snow -

- **Sieve analysis (most efficient and reliable)**

Mean grain diameter (d) of sieved fraction = √(M.m)

where, M = side length of mesh, letting the grain pass through

m = side length of mesh retaining the grain

- **Thick section analysis (reflected light image)**

- Use of Stereological parameters

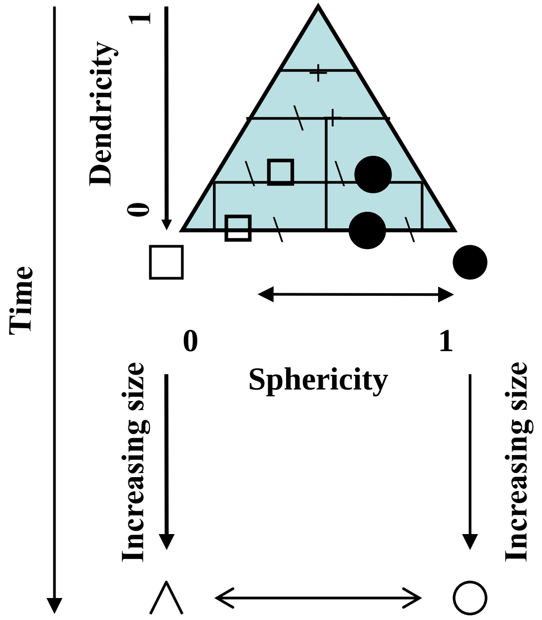
- **Thin section analysis (transmitted light image)**

Fundamental Index Properties of Snow

(b) Grain Shape

- Most difficult of the index properties to specify quantitatively

- Transformation of the shape during the process of metamorphism in deposited snow can be traced by:



- Sphericity (0-1.0): Ratio of spherical to the angular shape

- Dendricity (1.0-0): Fraction of the original angular shape still remaining in the crystal

Fundamental Index Properties of Snow

(c) Grain Fabric

- Refers to the mutual relationship between the grains in an aggregate and to the orientation of an individual grain.

- Determines the structure and governs the mechanical properties of the snow.

- Measurements are made generally by thin section photographs.

- Important parameters in determining grain fabric are:
  Bond diameter, Number of bonds per unit area and number of bonds per grain

- Mean number of bonds per grain is considered to be the most valuable index of fabric (increase with increase in density).

Derived Properties of Snow

(a) Density

- **Most extensively used derived property**
- **Correlates extremely well with the mechanical properties of snow (exception: wet snow and depth hoar)**
- **New snow density depends on -**
  - **Temperature**
  - **Surface winds**
  - **Crystal morphology**
- **Deposited snow density is a function of -**
  - **Initial snow density**
  - **Temperature regime and temp gradient**
  - **Overburden pressure**
  - **Time**

Derived Properties of Snow

(b) Porosity

“Ratio of volume of voids to that of snow”

$$Porosity = \frac{Volume\ of\ voids}{Volume\ of\ snow}$$

$$= \frac{V - V_i}{V}$$

$$= \frac{m_i / \rho - m_i / \rho_i}{m_i / \rho} \qquad (\rho = m_i / V, \rho_i = m_i / V_i)$$

$$= \frac{\rho_i - \rho}{\rho_i} = (1 - \frac{1}{0.917}\rho)$$

$$= (1 - 1.09\rho)$$

Derived Properties of Snow

(c) Void Ratio

“Ratio of volume of voids to that of solid portion in snow”

$$
\begin{aligned}
Void\ Ratio &= \frac{Volume\,of\ voids}{Volume\,of\ Solids} \\
&= \frac{V - V_i}{V_i} \\
&= \frac{m_i/\rho - m_i/\rho_i}{m_i/\rho_i} \\
&= \frac{\rho_i - \rho}{\rho}
\end{aligned}
$$

Derived Properties of snow

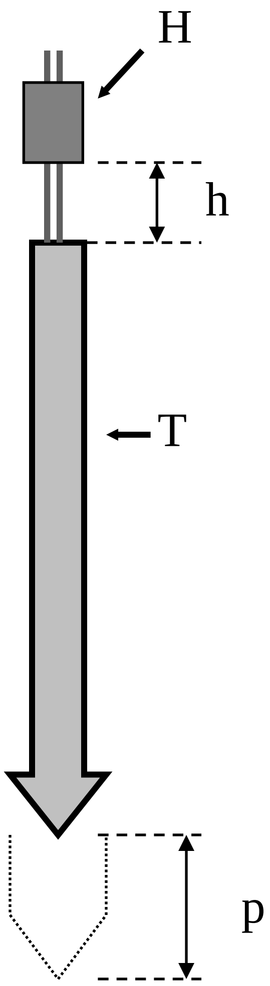
(d) Hardness

“ Resistance to the penetration by a rigid object”

- **Measurement is generally made by Ram Penetrometer with standard cone of 40 mm diameter and 60 ° apex angle**

Derived Properties of snow

Hardness



Ram Penetrometer

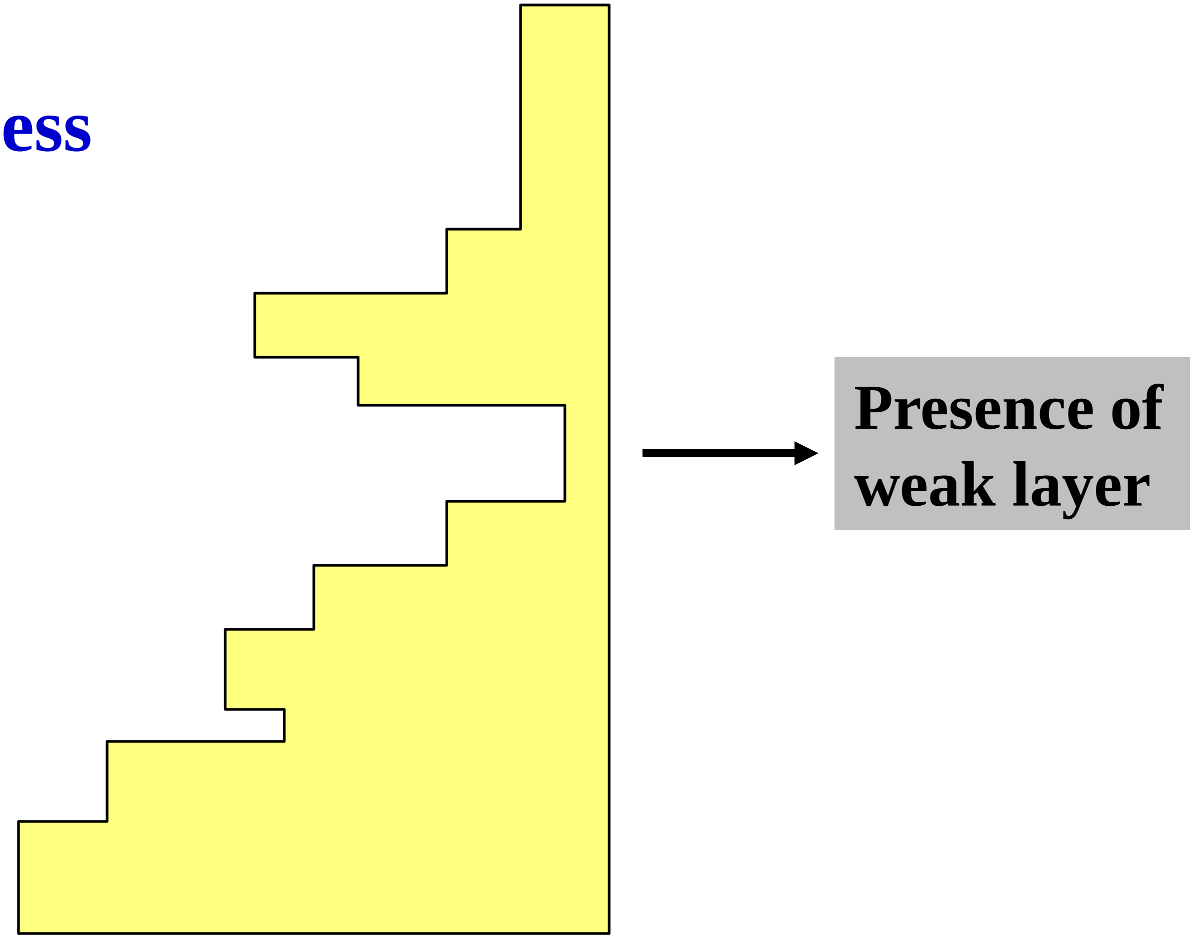
- **Ram Index (kgs) is given as -**

$$R = \frac{n.h.H}{p} + H + T$$

where, n = total no. of hammer blows
h = drop height of hammer (cm)
p = penetration in the snow (cm)
H = weight of hammer (kgs)
T = Total weight of ram penetrometer tubes (kgs)

Derived Properties of snow

Hardness



Presence of weak layer

Typical Shape of RAM profile

Assumptions in determining the Ram resistance -

- **The impact between the hammer and the guide rod is perfectly elastic.**
- **All energy produced by the impact of the hammer is transferred to the cone (i.e. there are no frictional losses between the ramrod and snow).**

Limitations of Ramsonde -

- **Lack of resolution for low Ram hardness (R < 1.0 Kg) e.g. for soft/fresh snow**

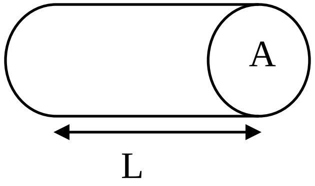
- **Limited resolution in the determination of the thickness of thin layers.**

Derived Properties of Snow

(e) Permeability

“ Inverse of the resistance to the passage of air through snow.”

- **The coefficient of air permeability (K) is defined as -**



$$K = \frac{Q.L}{A.\Delta p} = \frac{V}{i} \qquad \text{(cm/sec)}$$

where,
Q : Volume rate of air flow (cm^3/sec)
A : X-section of snow sample (cm^2) normal to the direction of air flow.
L : Length of sample in the direction of air flow (cm)
Δp : Air pressure head (cm, in terms of water column height)
V : Air velocity (cm/sec), calculated over x-section A.
i : Air pressure gradient (cm of water/cm length of sample)

- **Water may be used as fluid to determine the water permeability of snow.**

Derived Properties of Snow

(f) Liquid Water Content

- An important parameter from Hydrological point of view.
- Essential for the interpretation of snow pack remote sensing data using Microwave techniques.
- Includes three categories of water -

  i. Gravitational water moving downwards through snowpack

  ii. Capillary water held by surface tension between individual crystals

  iii. Hygroscopic or absorbed water held in the thin film on the individual snow crystals.

The International Classification for Seasonal Snow on the Ground

Prepared by the ICSI-UCCS-IACS
Working Group on Snow Classification

2009

Primary physical characteristics of deposited snow

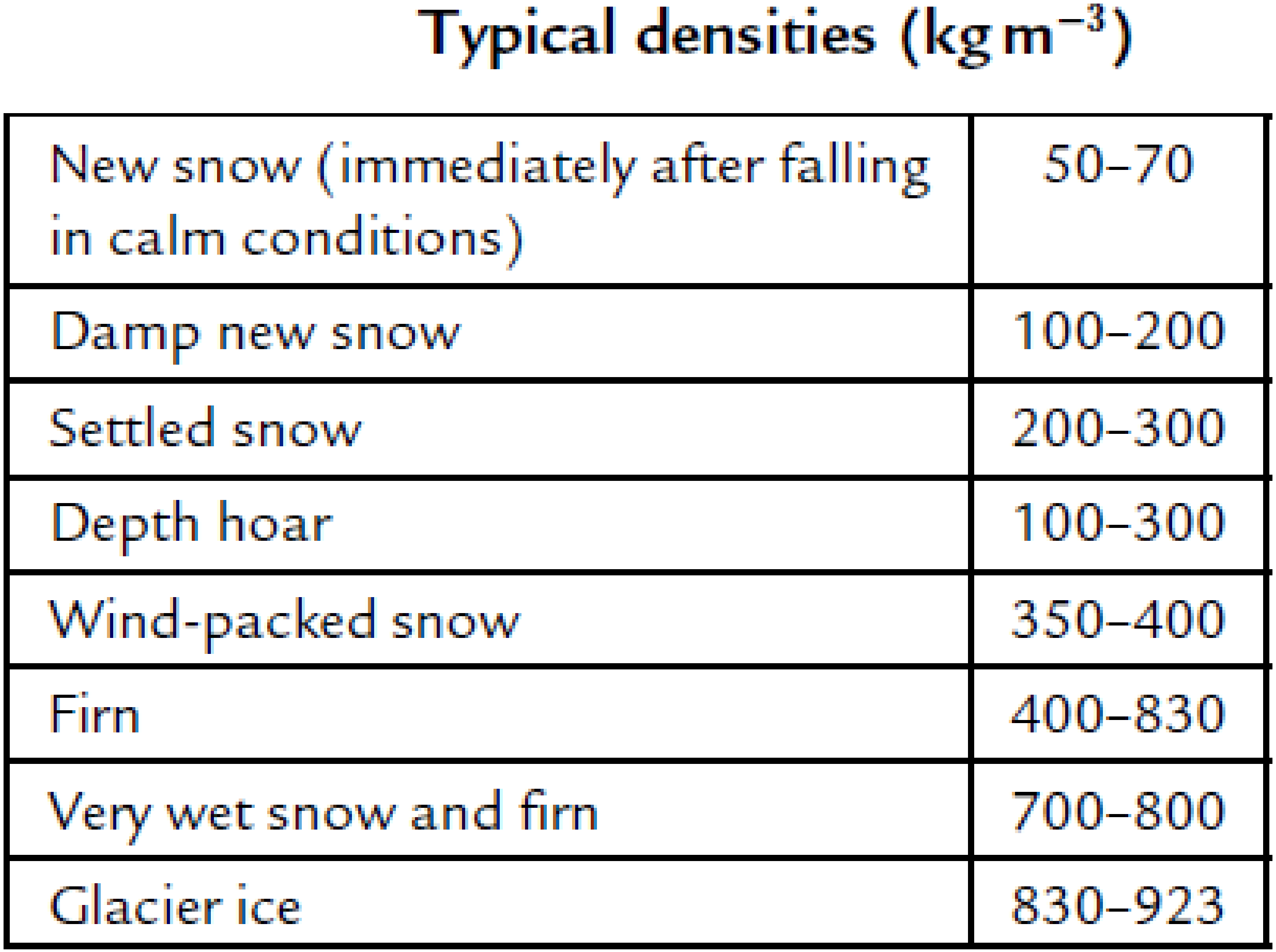
Characteristic	*Units*
Microstructure	
Grain shape	
Grain size	mm
Snow density	kg m^{-3}
Snow hardness	depends on instrument
Liquid water content	either volume or mass fraction
Snow temperature	°C
Impurities	mass fraction
Layer thickness	cm

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

Grain size

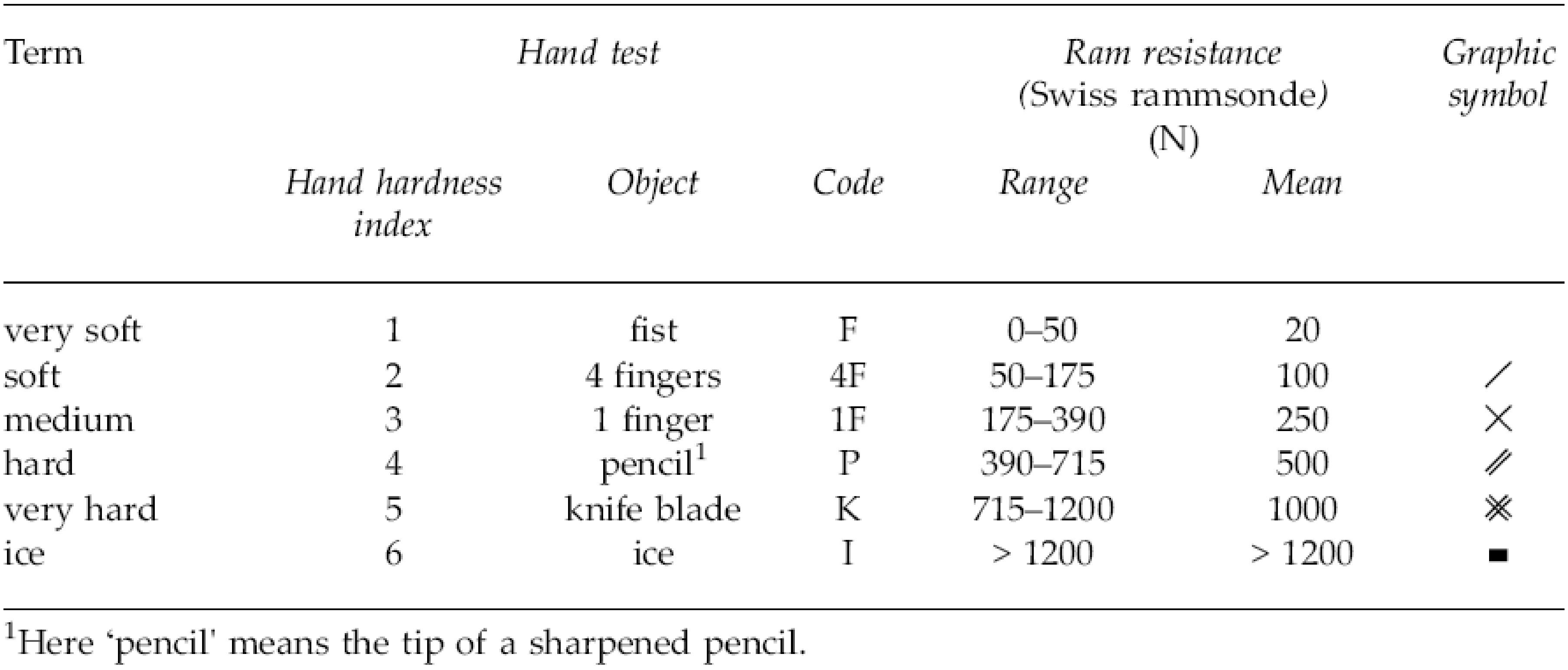
Term	*Size* (mm)
very fine	< 0.2
fine	0.2–0.5
medium	0.5–1.0
coarse	1.0–2.0
very coarse	2.0–5.0
extreme	> 5.0



	Typical densities (kg m^{-3})
New snow (immediately after falling in calm conditions)	50–70
Damp new snow	100–200
Settled snow	200–300
Depth hoar	100–300
Wind-packed snow	350–400
Firn	400–830
Very wet snow and firn	700–800
Glacier ice	830–923

Hardness of deposited snow

Hardness is the resistance to penetration of an object into snow.



Term	*Hand test*			*Ram resistance* (Swiss rammsonde) (N)		*Graphic symbol*
	Hand hardness index	*Object*	*Code*	*Range*	*Mean*	
very soft	1	fist	F	0–50	20	
soft	2	4 fingers	4F	50–175	100	∕
medium	3	1 finger	1F	175–390	250	×
hard	4	pencil[1]	P	390–715	500	⫽
very hard	5	knife blade	K	715–1200	1000	⨳
ice	6	ice	I	> 1200	> 1200	▬

[1] Here 'pencil' means the tip of a sharpened pencil.

Snow temperature

$T_s(H)$: Snow temperature at height H in centimetres above the ground

$T_s(-H)$: Snow temperature at depth $-H$ in centimetres below the surface

T_{ss}: Snow surface temperature

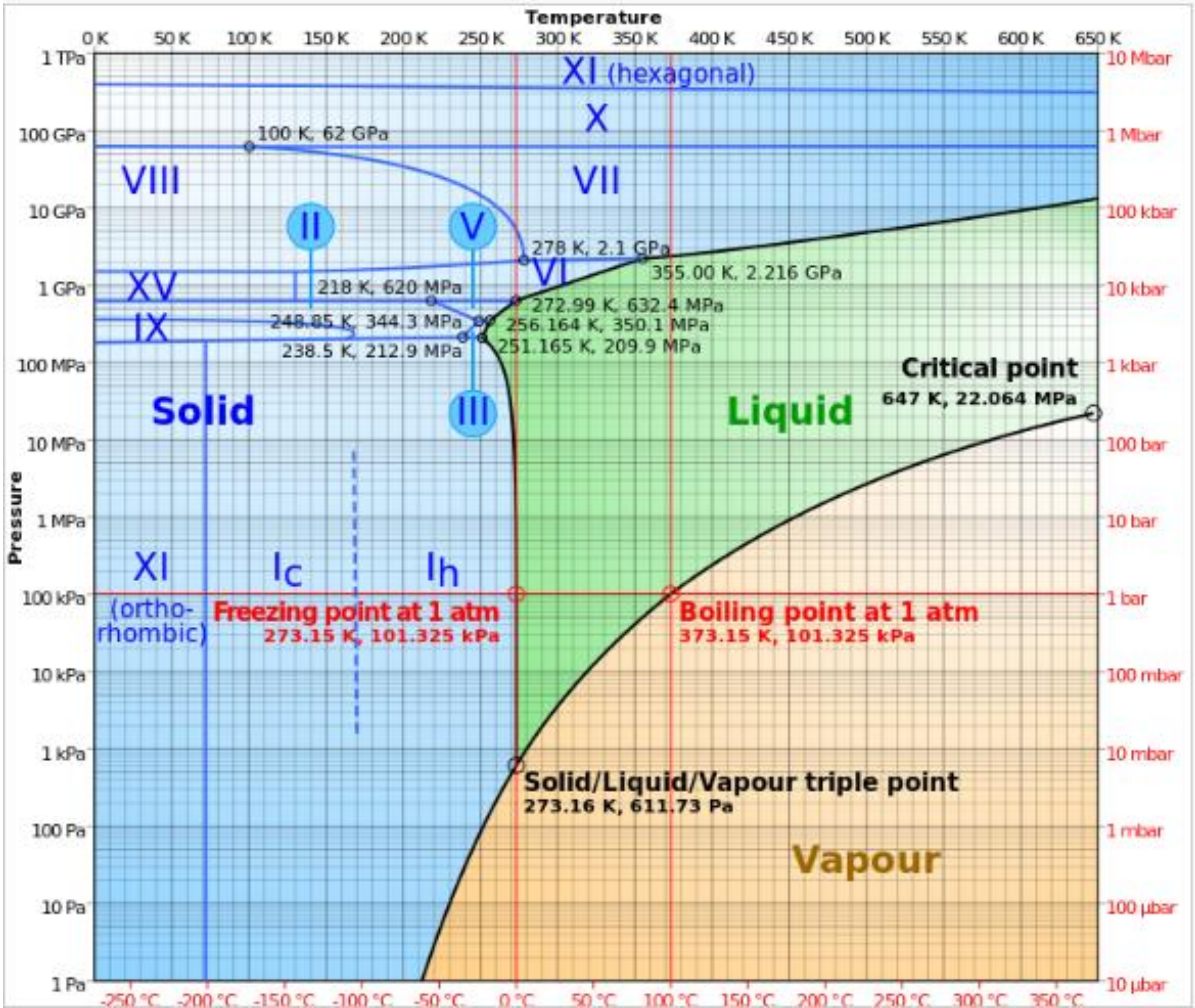
T_a: Air temperature 1.5 m above snow surface

T_g: Ground surface temperature (the same as Bottom Temperature of Snow, BTS, in the field of permafrost).

Liquid water content

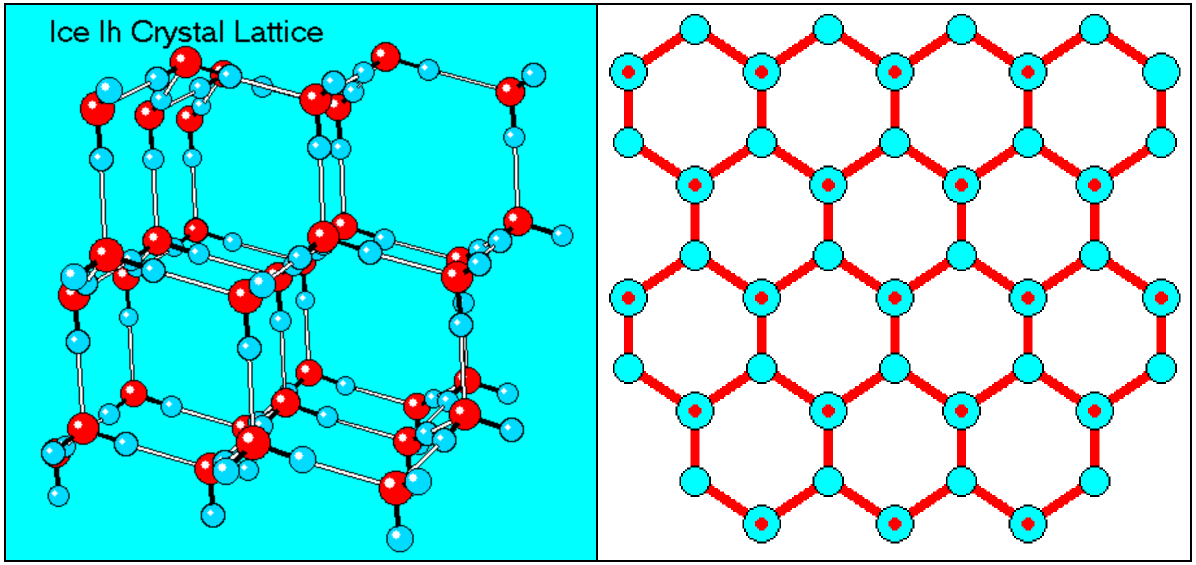
Term	*Wetness index*	*Code*	*Description*	*Approximate range of* $\theta_{\mathrm{w,V}}$ *(volume fraction in %)*[1]		*Graphic symbol*
				range	*mean*	
dry	1	D	Usually T_s is below 0°C, but dry snow can occur at any temperature up to 0°C. Disaggregated snow grains have little tendency to adhere to each other when pressed together, as in making a snowball.	0	0	
moist	2	M	$T_s = 0°C$. The water is not visible even at 10× magnification. When lightly crushed, the snow has a distinct tendency to stick together.	0–3	1.5	|
wet	3	W	$T_s = 0°C$. The water can be recognised at 10× magnification by its meniscus between adjacent snow grains, but water cannot be pressed out by moderately squeezing the snow in the hands (pendular regime).	3–8	5.5	||
very wet	4	V	$T_s = 0°C$. The water can be pressed out by moderately squeezing the snow in the hands, but an appreciable amount of air is confined within the pores (funicular regime).	8–15	11.5	|||
soaked	5	S	$T_s = 0°C$. The snow is soaked with water and contains a volume fraction of air from 20 to 40% (funicular regime).	>15	>15	||||

Phase Diagram of Water and Ice Phases

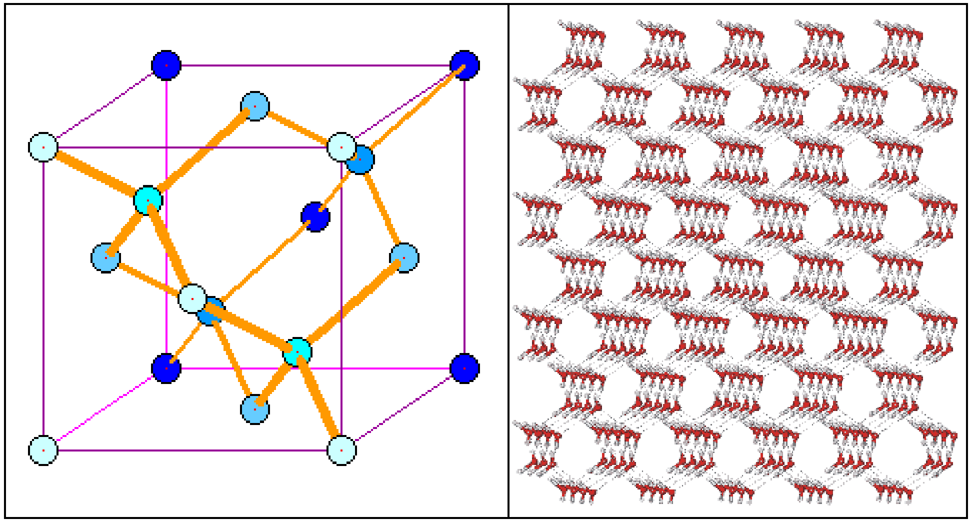


- **Types of Ice**

- Everyday ice and snow has a hexagonal crystal structure (ice Ih).

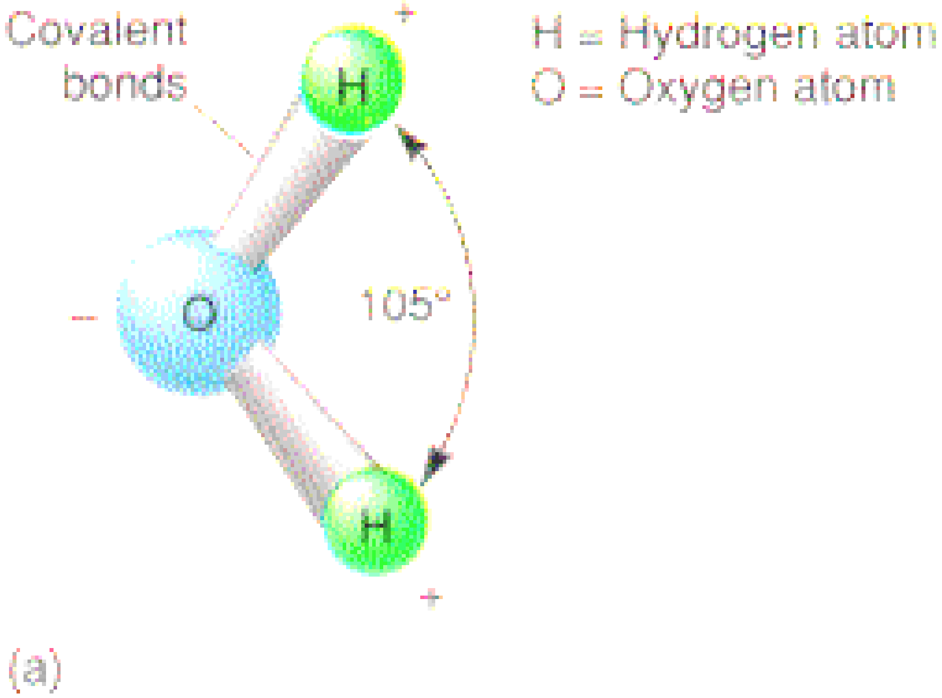


- Only a little less stable (metastable) than Ih is the cubic structure (Ic).

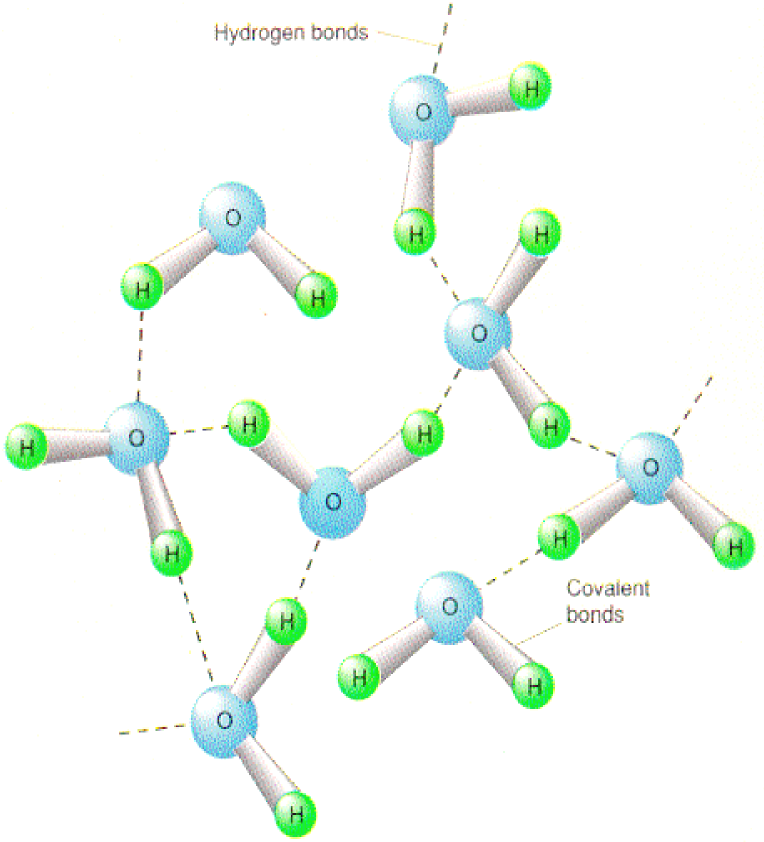


Molecular Structure

- Water molecules
- 1 Oxygen + 2 Hydrogen atoms
- covalent chemical bonds between
- dipolar moment of 105°
- electrical polarity



Hydrogen Bonds



- Electrical polarity causes attraction between molecules
- Weak, but significant “Hydrogen bonds” can form between molecules
- Polarity and hydrogen bonds account for unique properties

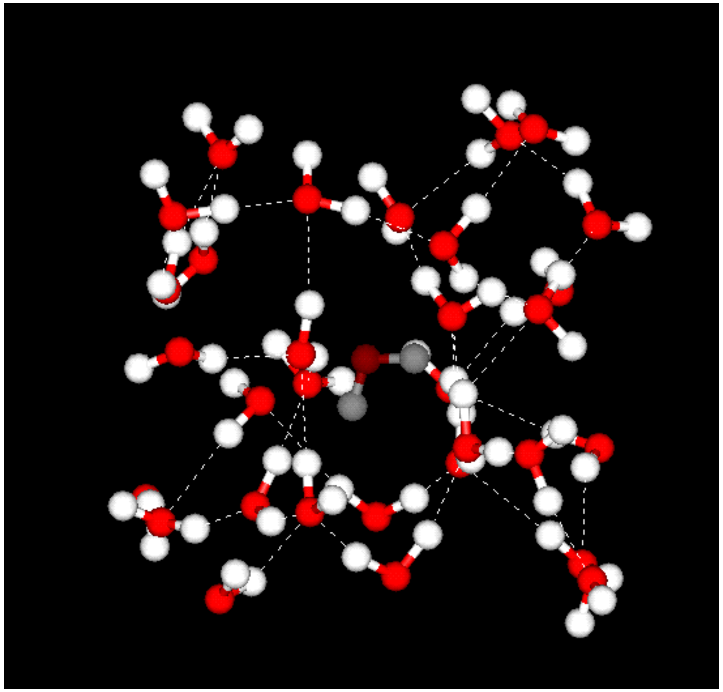
Hydrogen Bond Effects

- Hydrogen bonds cause water to have:
  - High **heat capacity**: can absorb a lot of heat energy with little increase in temperature
    - energy required to break hydrogen bonds
    - highest heat capacity of all solids and liquids, except liquid ammonia
  - High **latent heat of fusion** (energy loss necessary for freezing): highest except ammonia

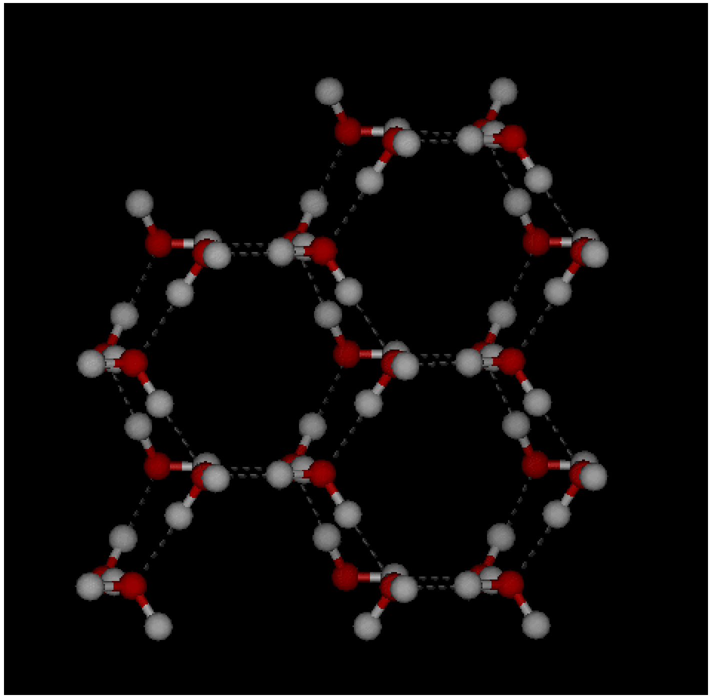
Hydrogen Bond Effects

- Hydrogen bonds cause water to have:
  - High **latent heat of evaporation** (energy necessary to evaporate): highest of all substances
  - High **surface tension**: highest of all liquids; important in formation of droplets and capillary waves

Water and Ice Structure

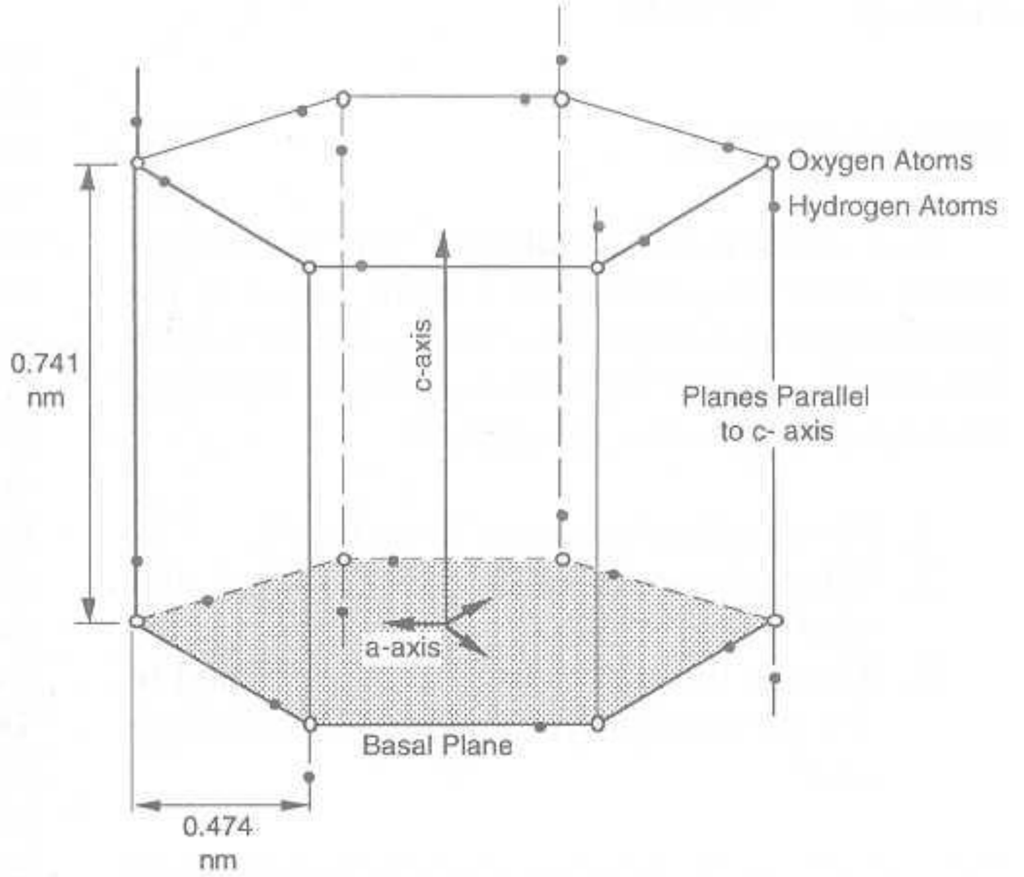


Water has a partially ordered structure where hydrogen bonds are constantly being formed and broken up



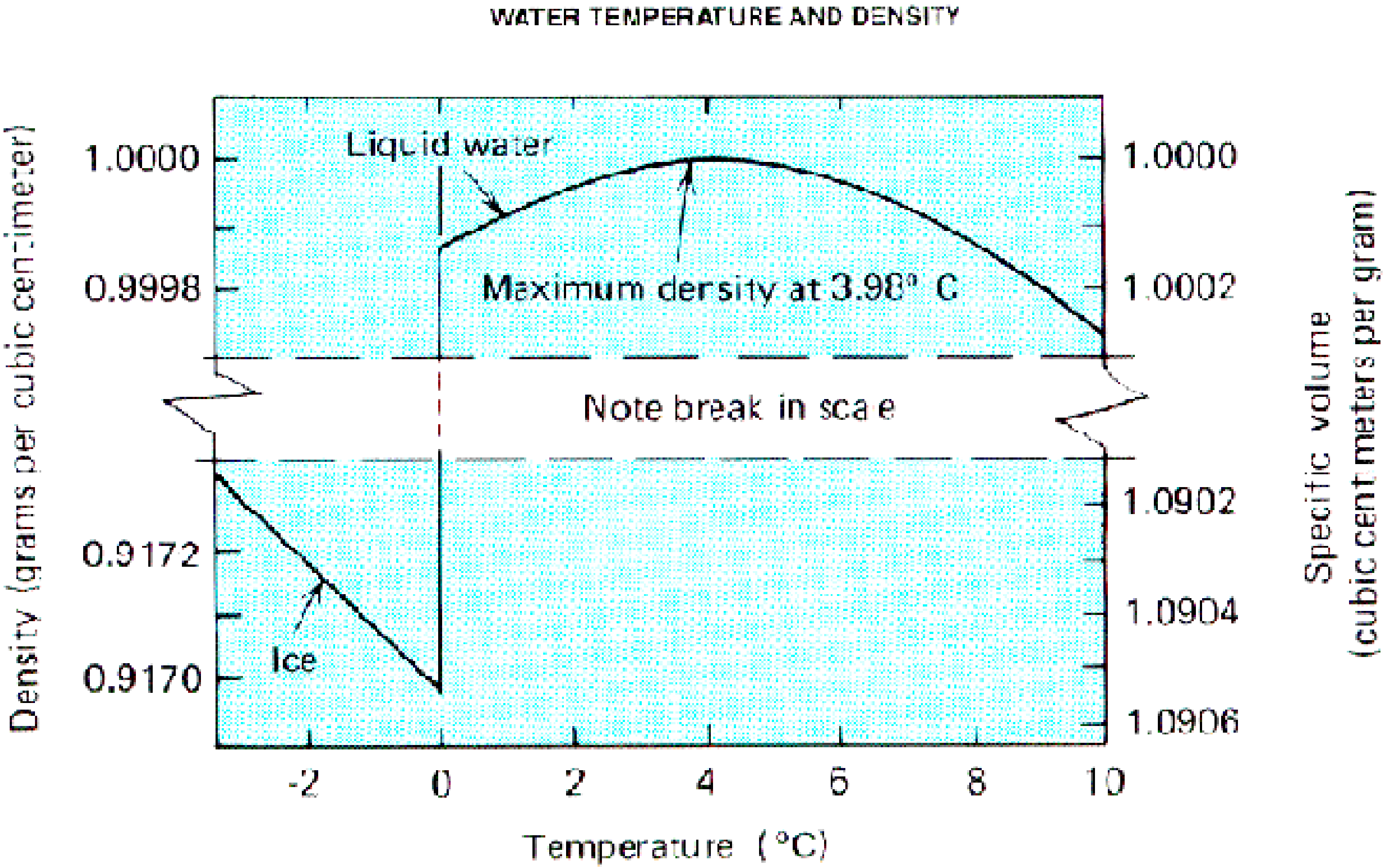
Ice has a rigid lattice structure - each molecule is bonded to 4 other molecules

Hexagonal Structure

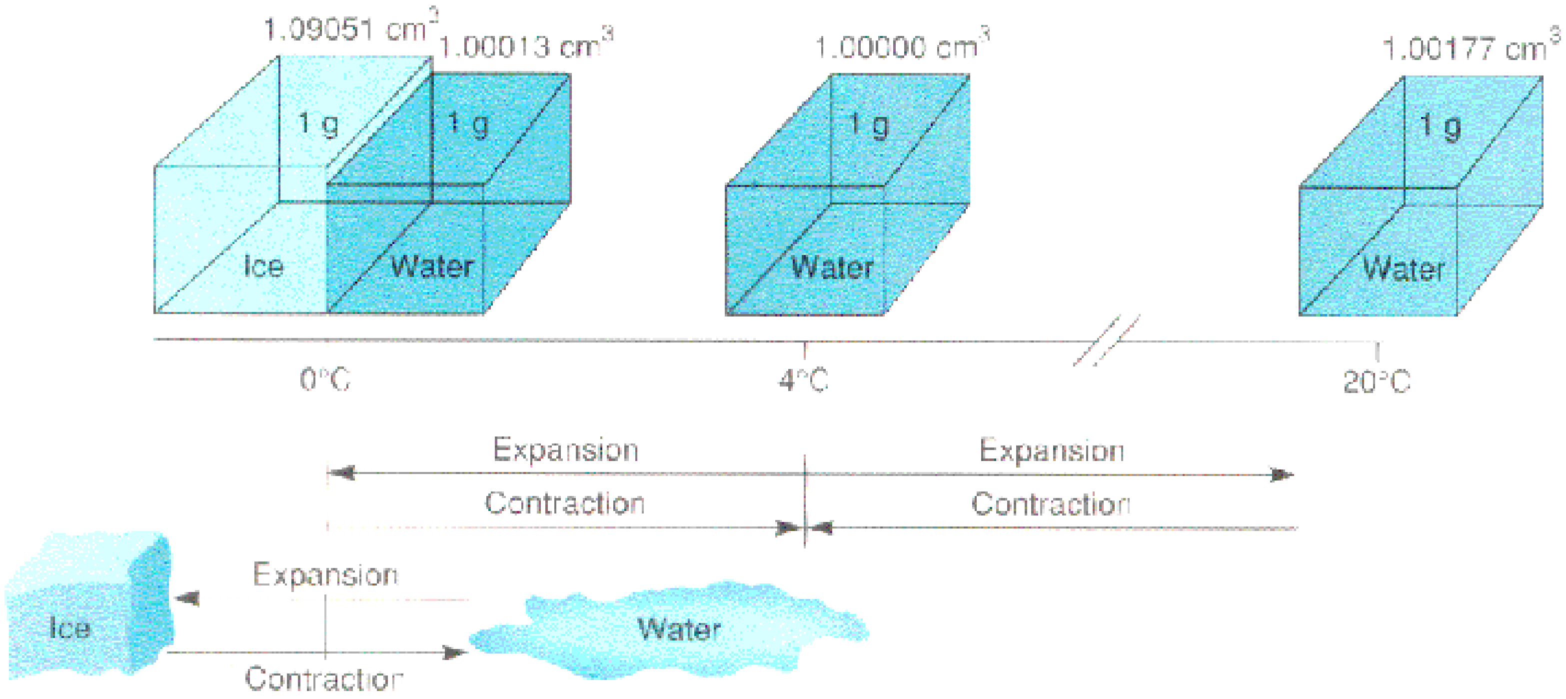


Shape of unit cell for hexagonal ice.

Water Density



Water–Ice Density Change



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1. *Handbook of Snow: Principles, Processes, Management and Use* (Gray & Male, 1981)

2. *The Avalanche Handbook,* (McClung & Schaerer, 2006)

3. *Snow and Climate: Physical Processes, Surface Energy Exchange and Modeling* (Armstrong & Brun, 2008)

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Thank you