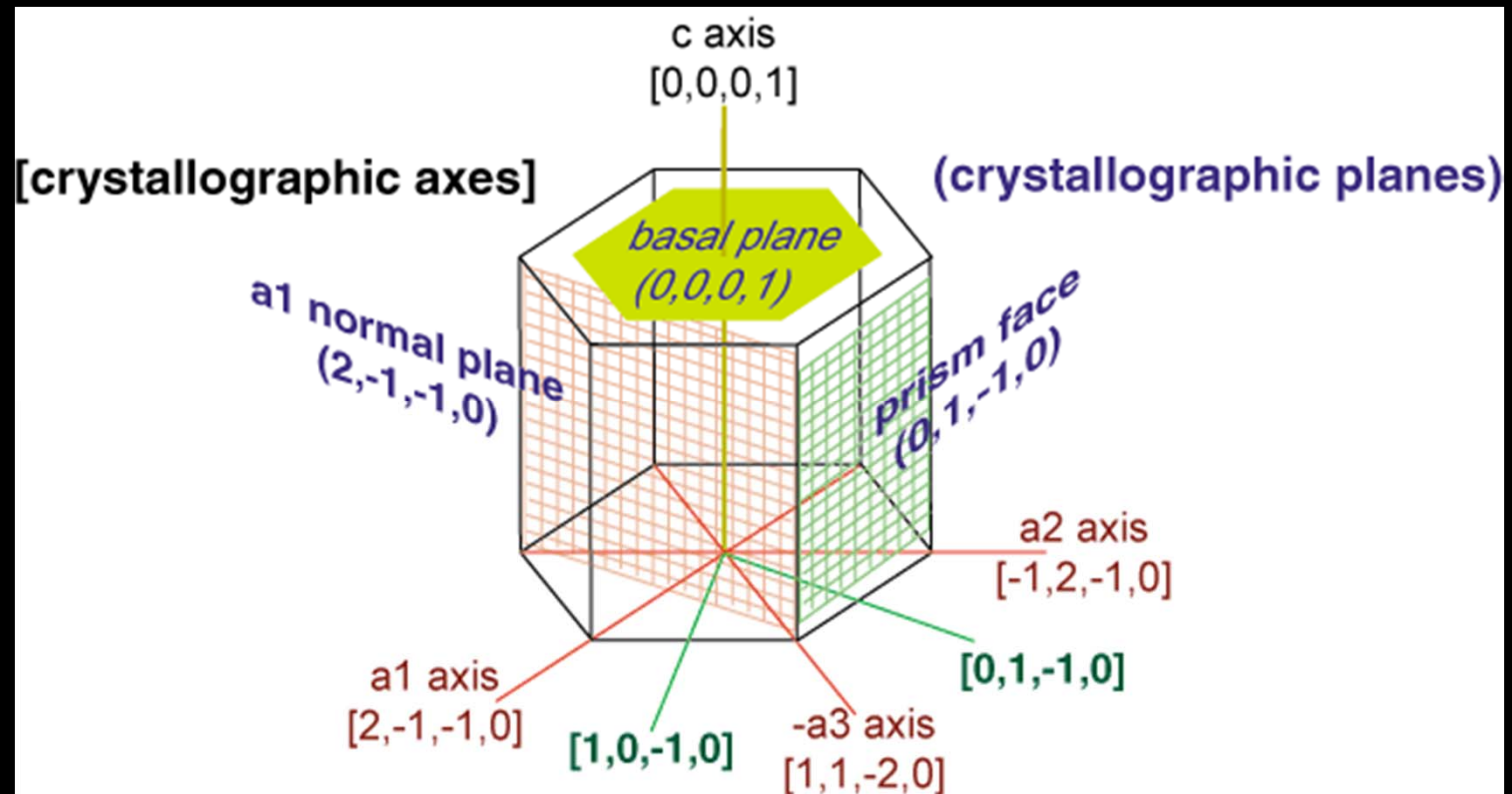
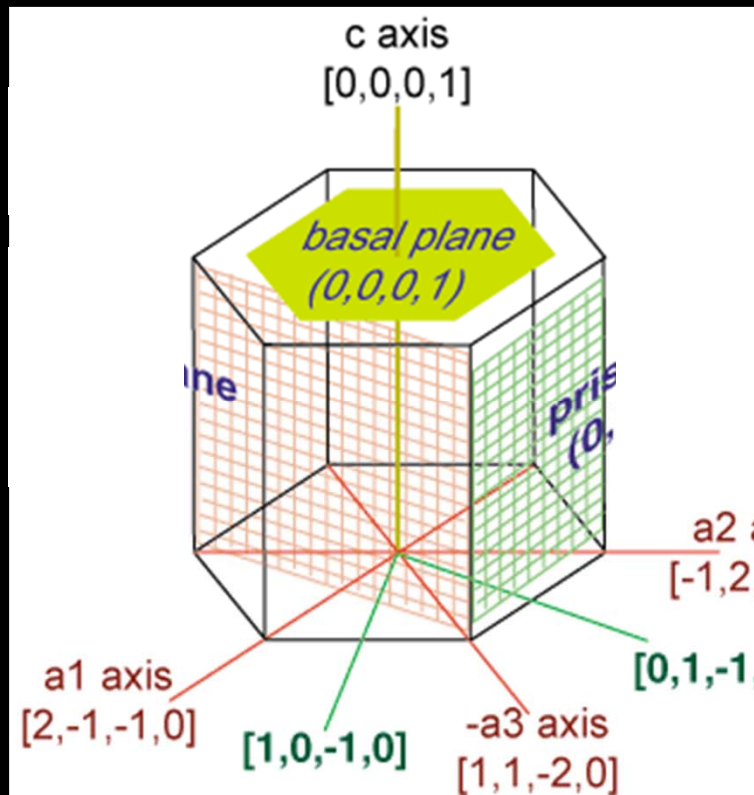
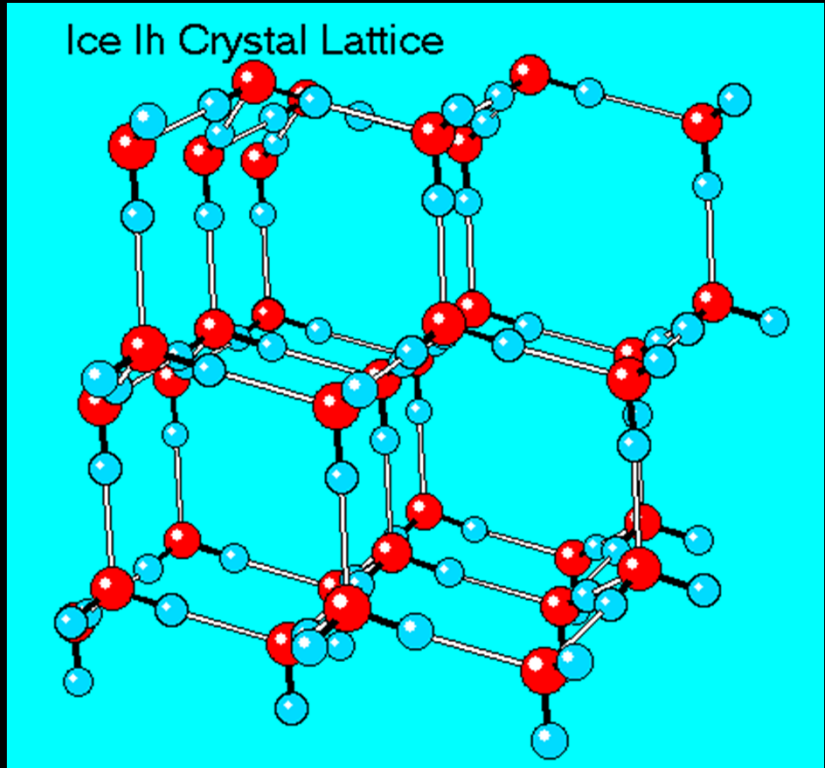
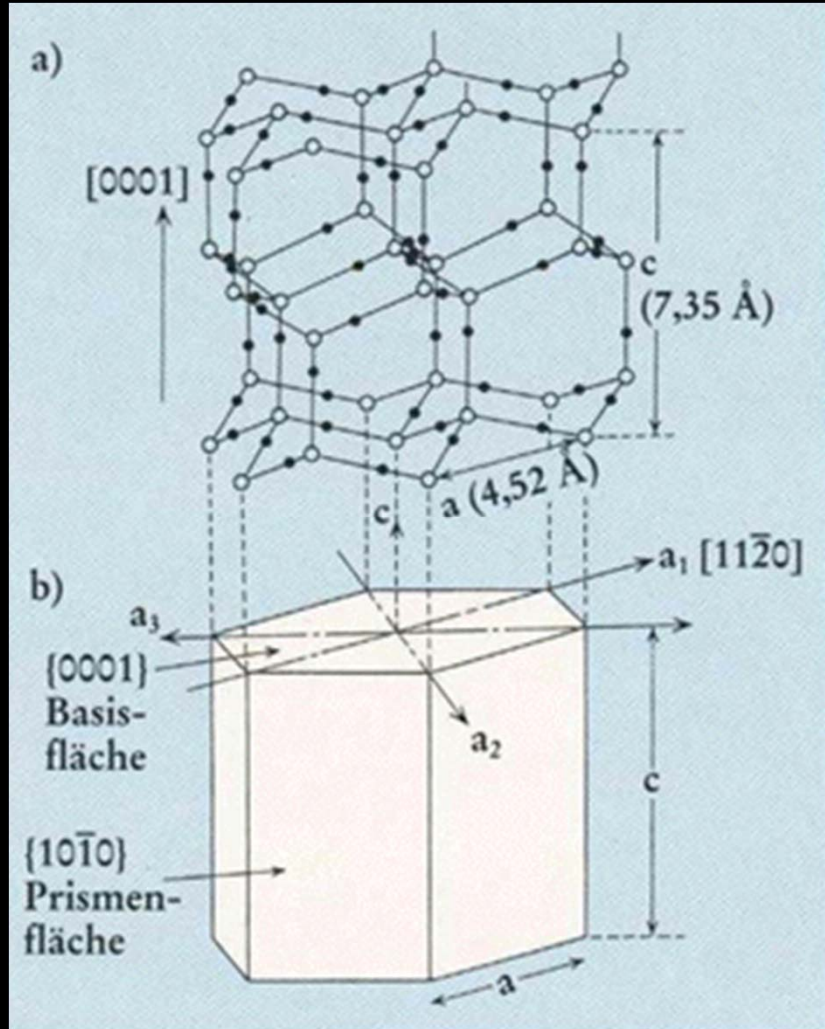
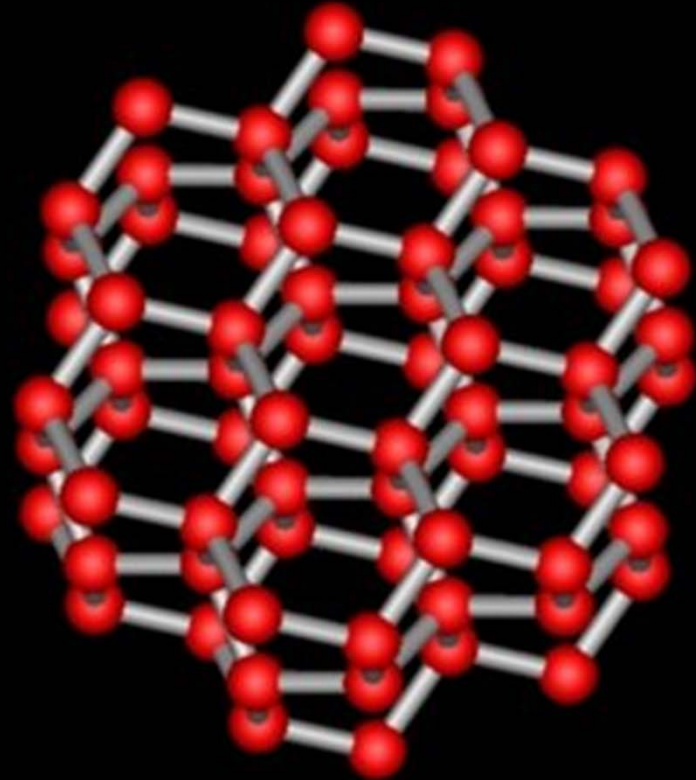
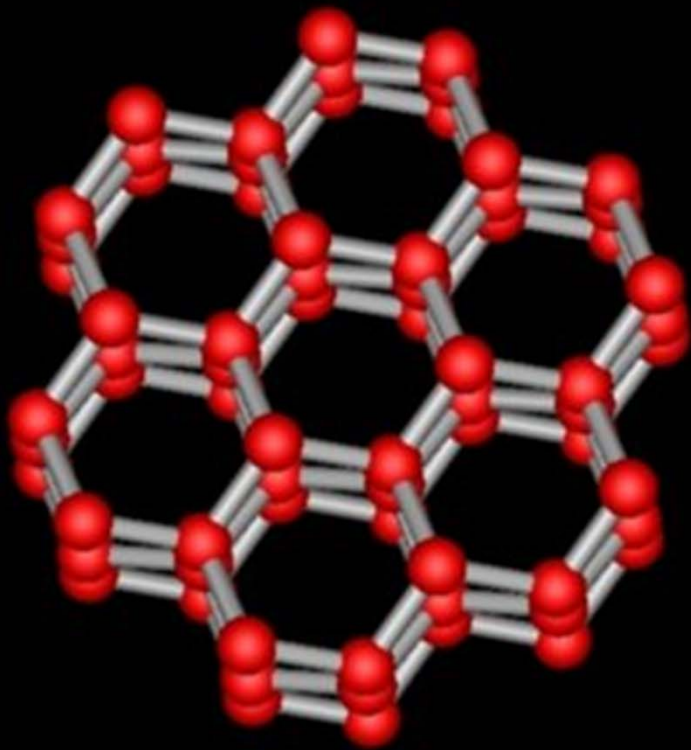


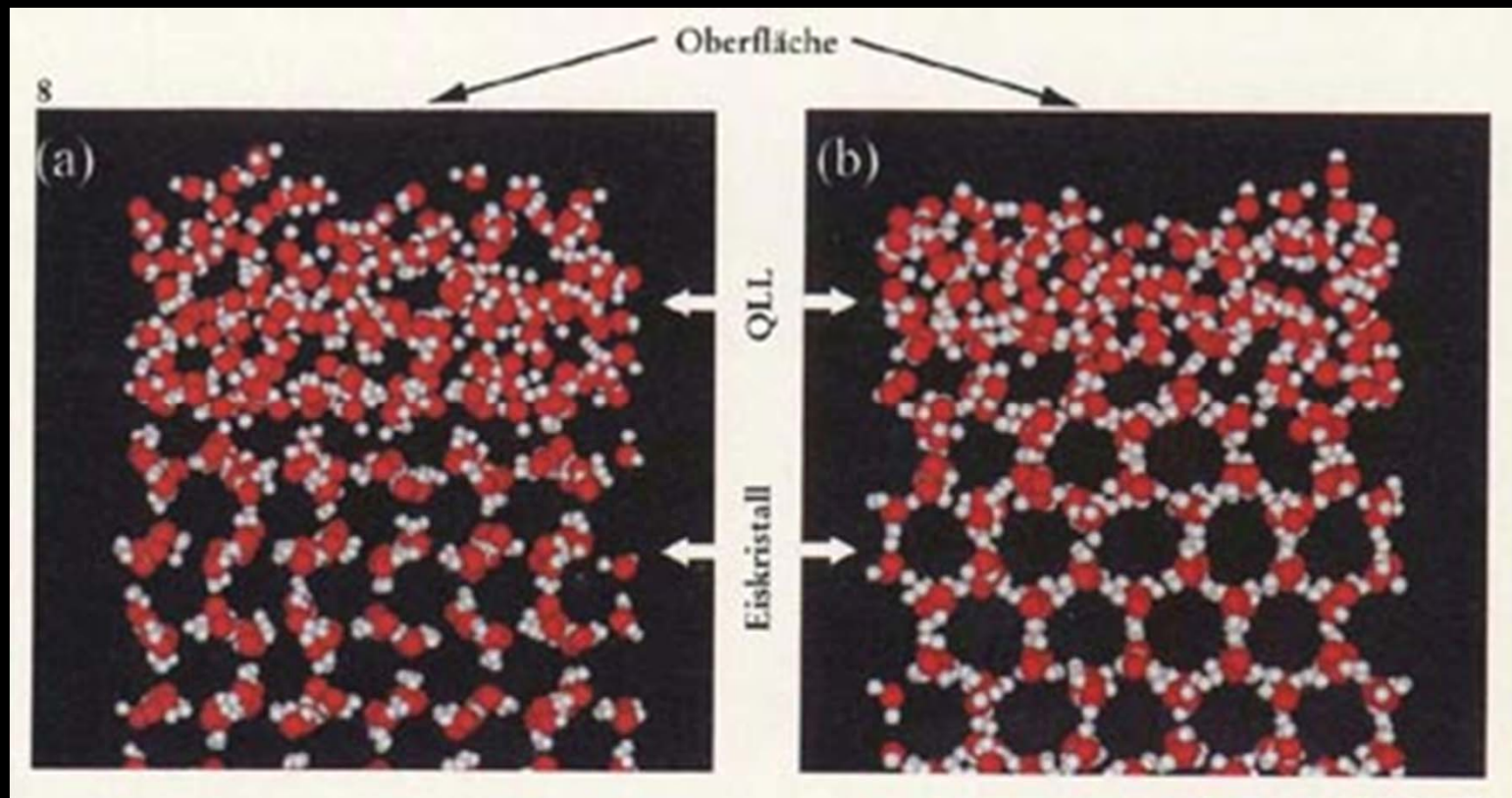
Ice Physics  
and the  
Structure of Glaciers



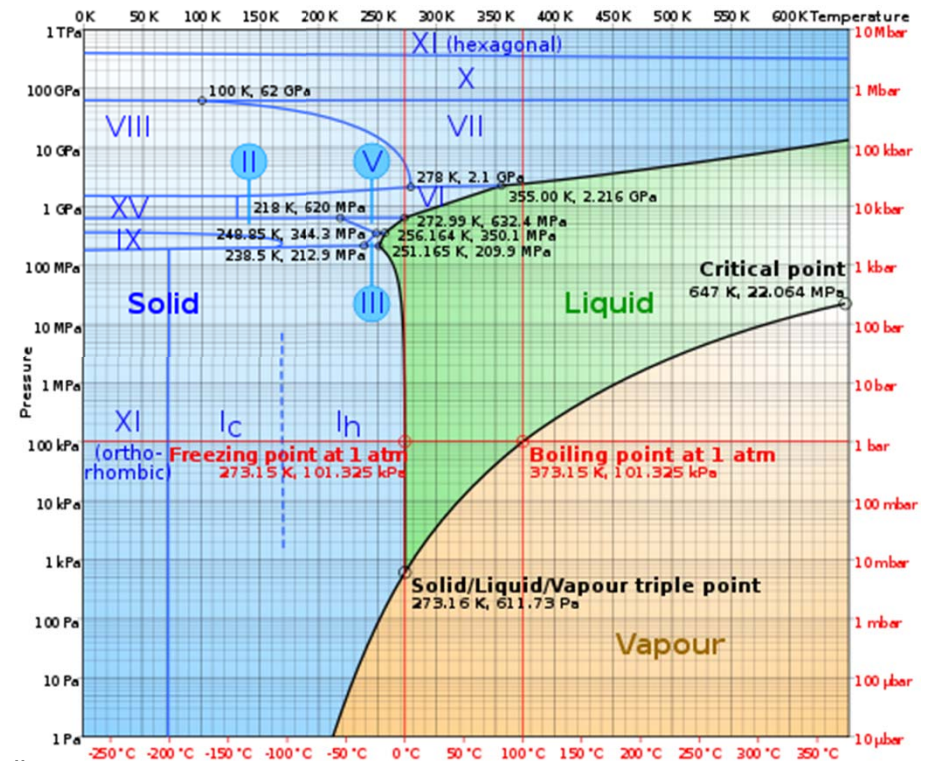
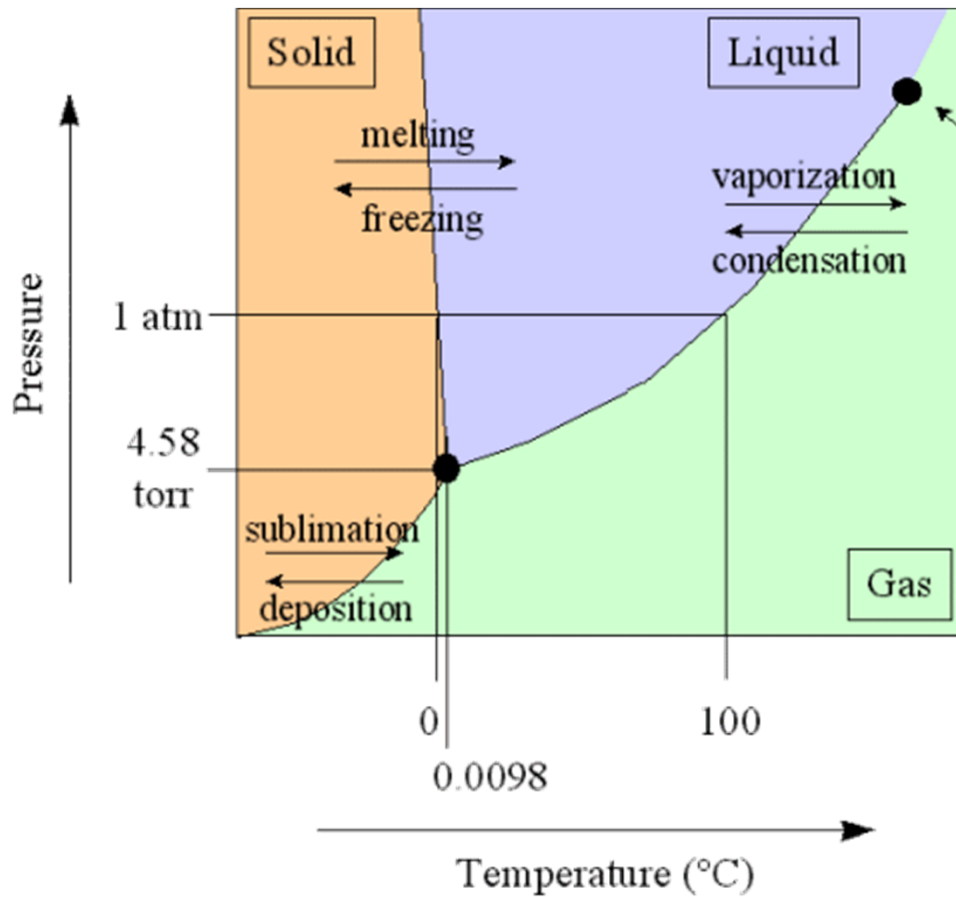








# Solid Liquid Gas Phase Diagram



# Phase Changes
















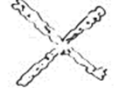
























Solid	→	Liquid	Latent Heat of Fusion Melting	80 cal g <sup>-1</sup> (335 J g <sup>-1</sup> )
Liquid	→	Gas	Latent Heat of Vaporization Evaporation	597 cal g <sup>-1</sup> (2500 J g <sup>-1</sup> )
Solid	→	Gas	Latent Heat of Sublimation Sublimation	677 cal g <sup>-1</sup> (2834 J g <sup>-1</sup> )





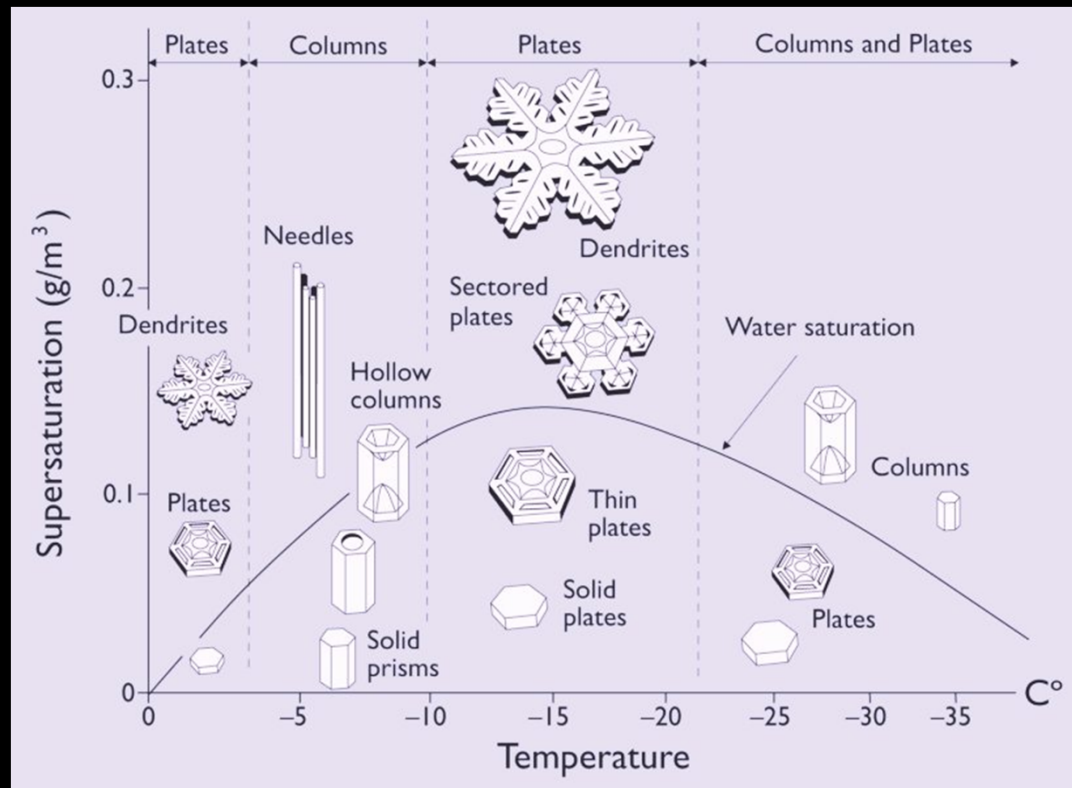
# Hardness

<u>Temperature °C</u>	<u>Equivalent Mineral Hardness</u>
0	Talc/Gypsum
-15	Gypsum-calcite
-40	Fluorite

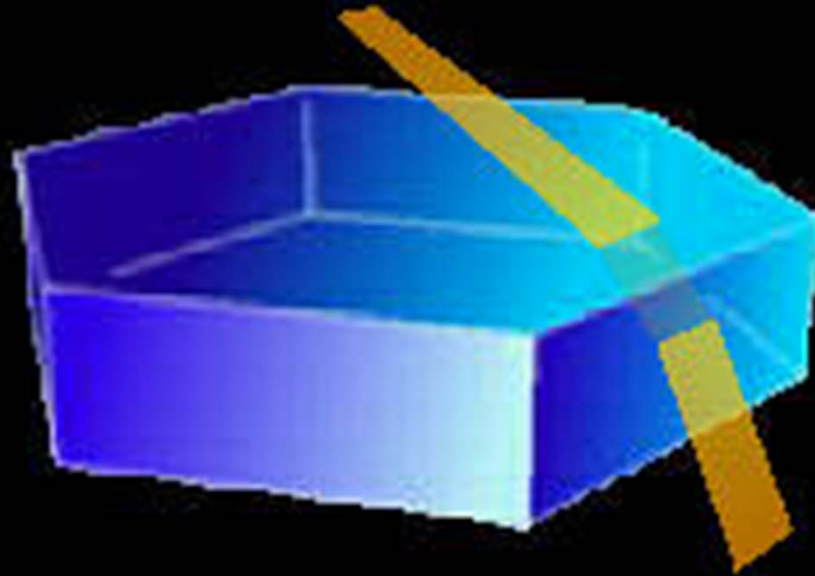
Graphic Symbol	Examples			Symbol	Type of Particle
				F1	Plate
				F2	Stellar crystal
				F3	Column
				F4	Needle
				F5	Spatial dendrite
				F6	Capped column
				F7	Irregular crystal
				F8	Graupel
				F9	Ice pellet
				F0	Hail

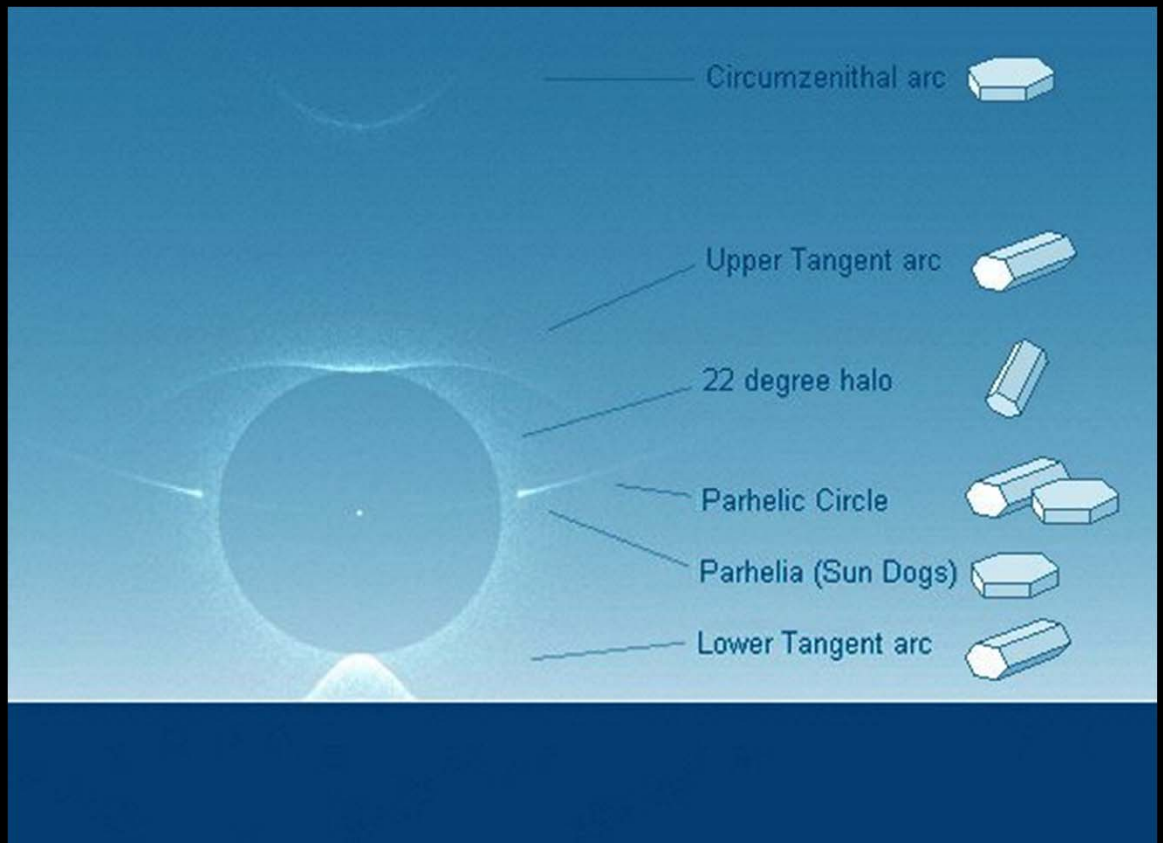
LaChapelle

4. A pictorial summary of the International Snow Classification for solid precipitation. This classification applies to falling snow.



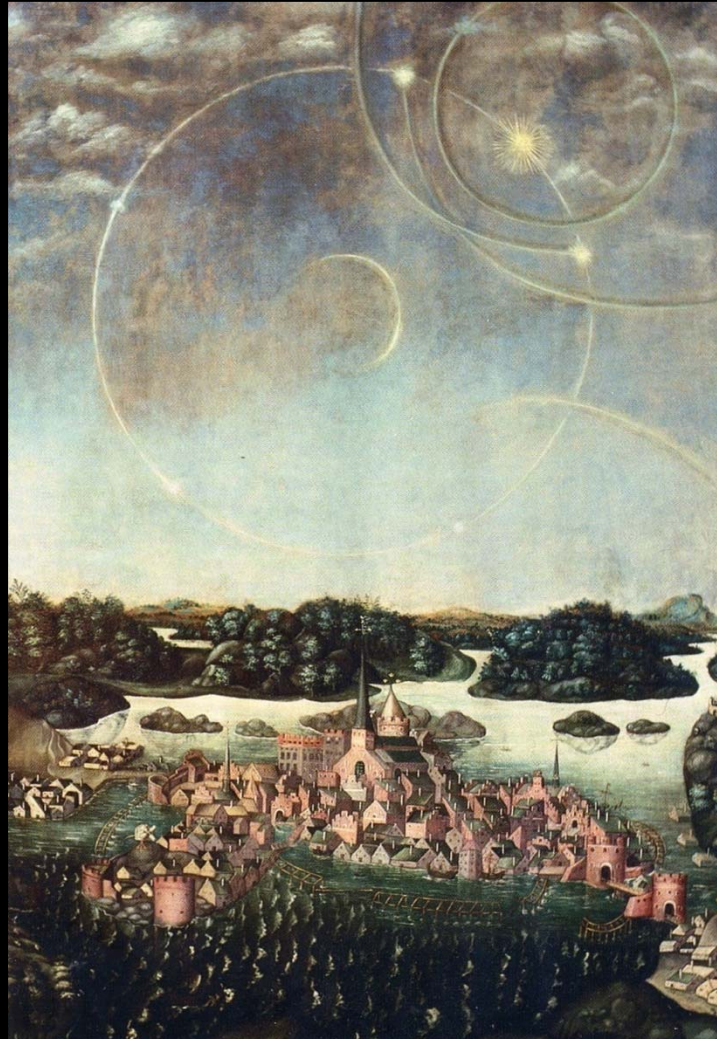
# Light Refraction through an Ice Crystal







Kenneth G. Libbrecht, Caltech



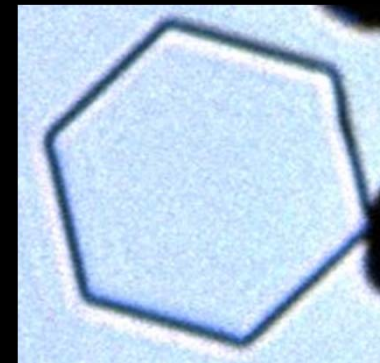
## Stockholm

-J.H. Elbfas 1636

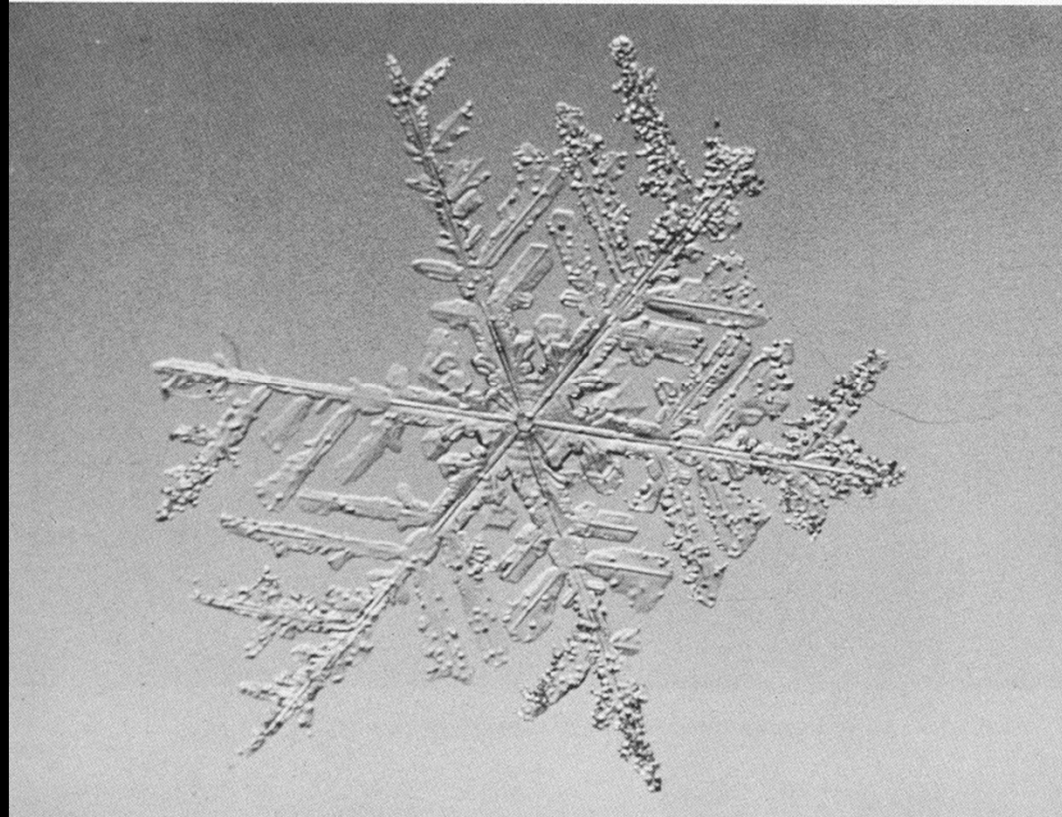
-After an original  
painted in the 1500's.



# From Snowflakes to Glacier Ice



11. Stellar snow crystal with a trace of rime. 30X

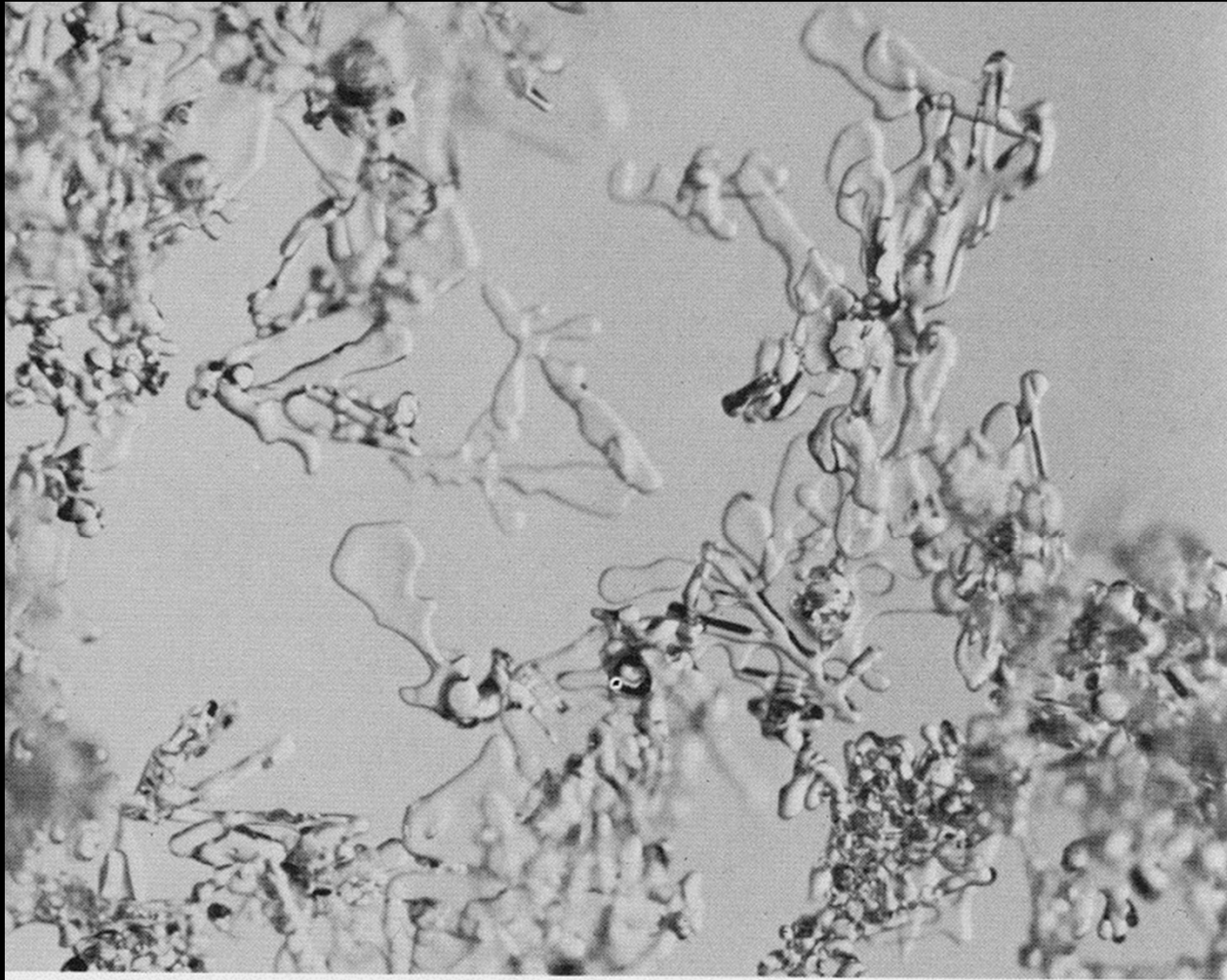


Time: Minutes - Hours



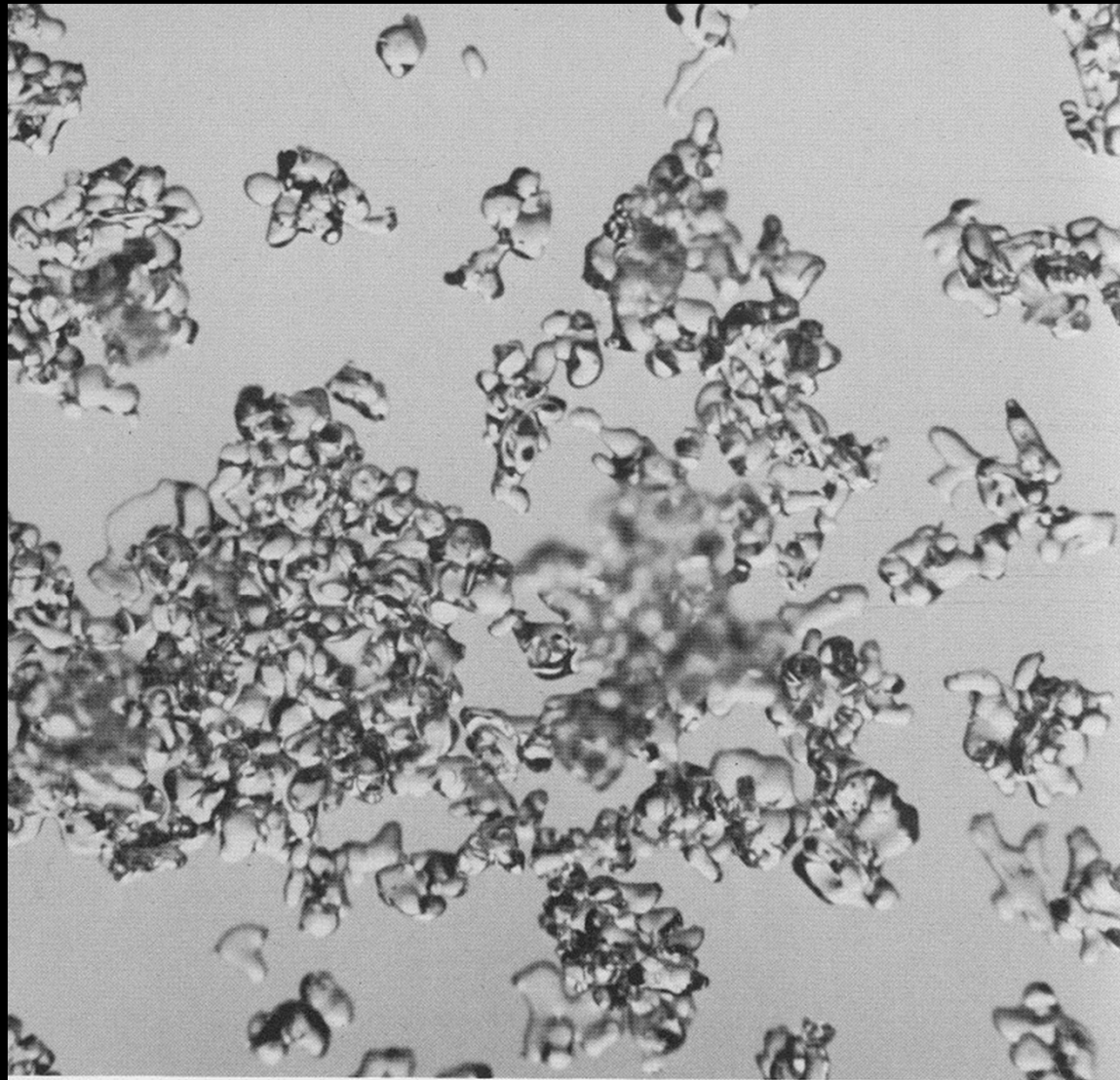
35. Stellar crystals in the first stages of equitemperature metamorphism. 26X

Time: Hours - Day



36. The same snow layer represented in Figure 35, after another 36 hours of metamorphism. 26X

Time: Days



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

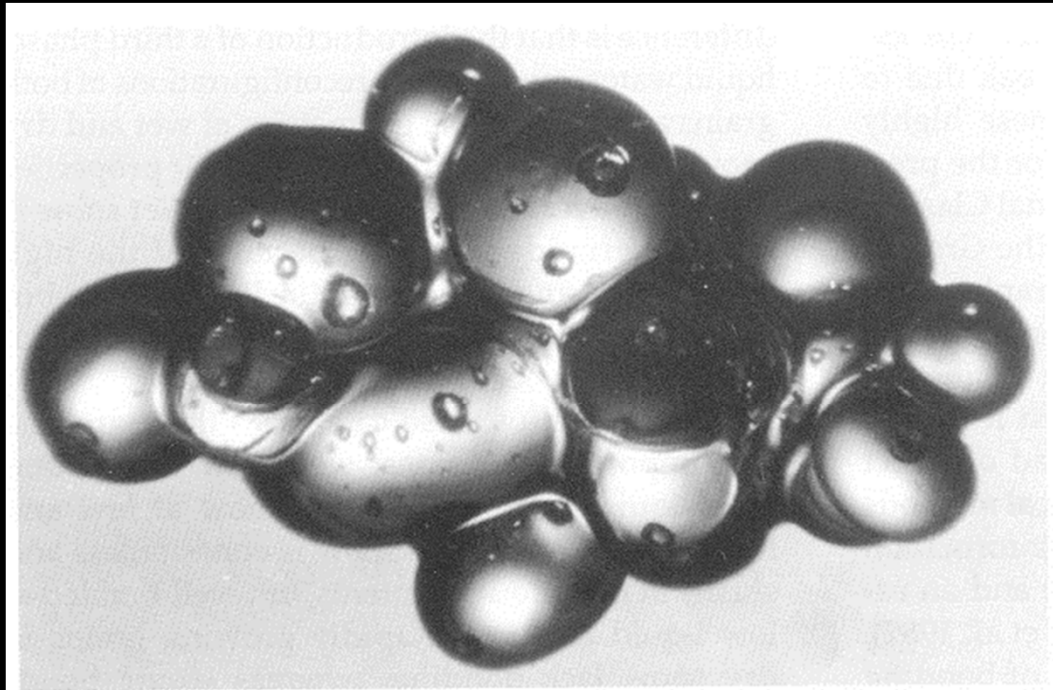
Time: Days - Week

Time: Weeks



43. Fine-grained old snow, 3 weeks old. 26X

Once in the snowpack ...



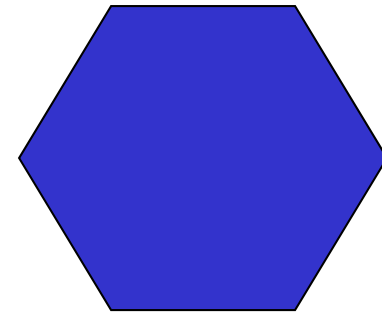
*Figure 1. Cluster of ice grains in wet snow at a low liquid content. The individual ice grains are single crystals, usually 0.5 to 1.0 mm in size.*



# Processes of Snow Metamorphism

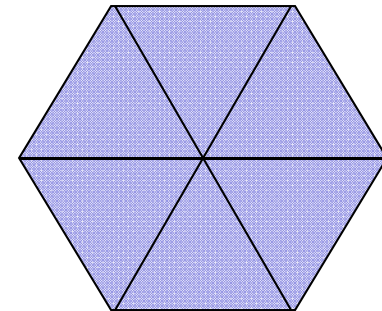
Dry

Vapor Diffusion



Wet

Melt - Refreezing



$$T_m = T_o e^{-c/r}$$

$T_m$  - melting temp,  $T_o$  - equilb melt temp  
 $c$  - constant,  $r$  - radius of curvature

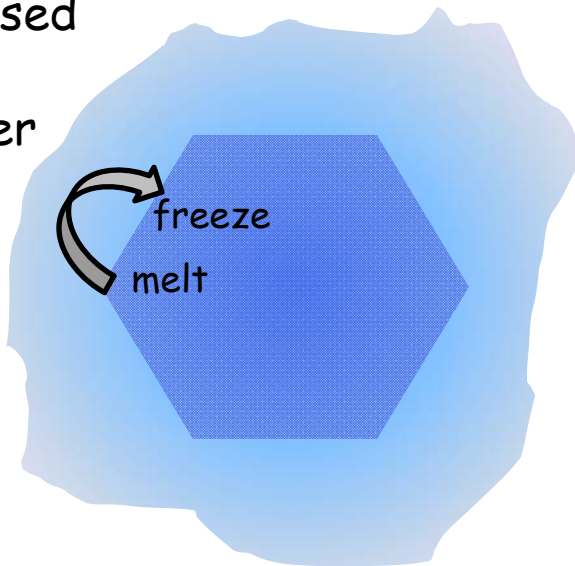
# Processes of Snow Metamorphism

Vapor Diffusion - slow

Melt - Refreezing - faster

$$T_m = T_0 e^{-c/r}$$

Immersed  
In  
Water

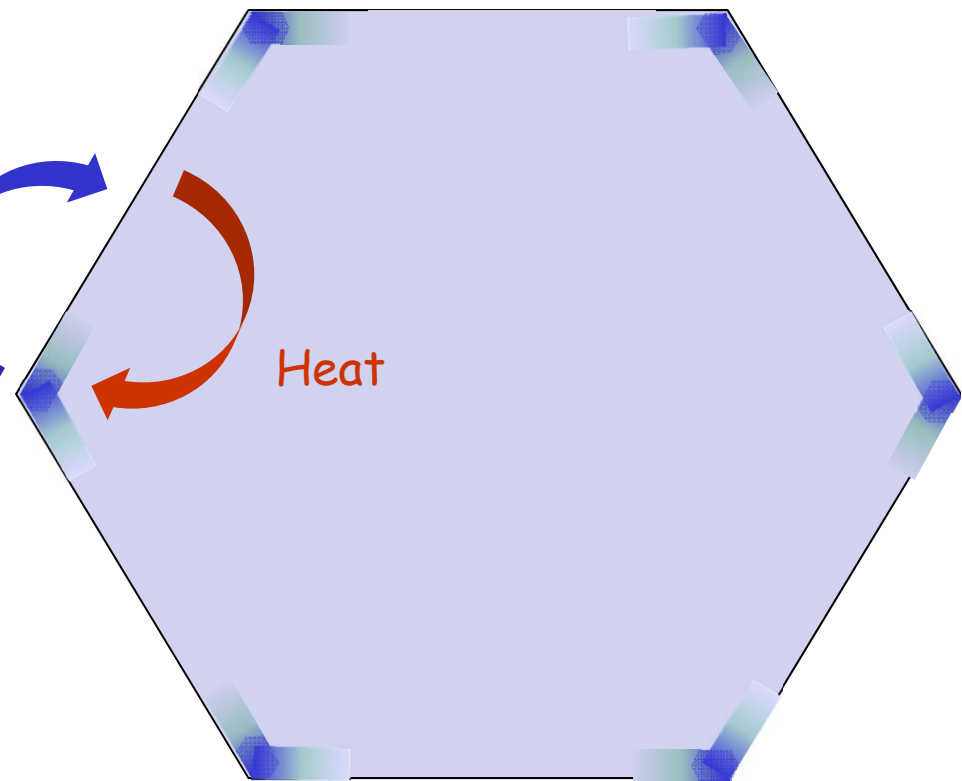


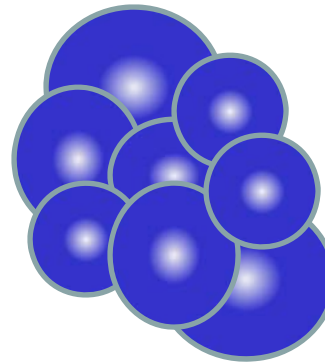
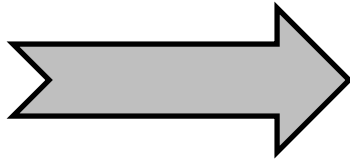
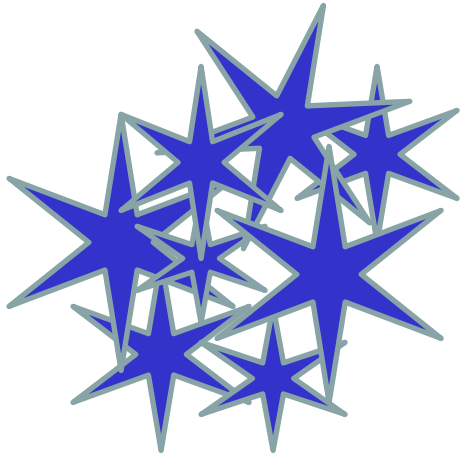
Mass  
Sublimation



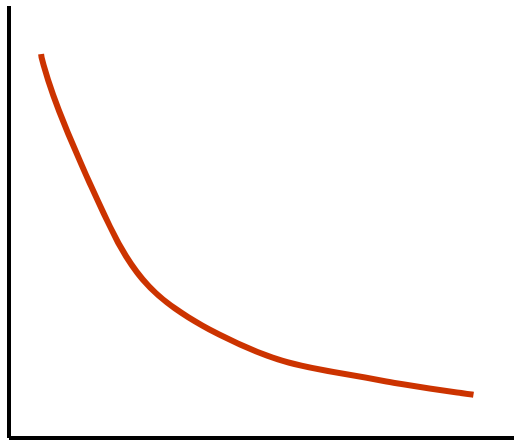
$T_m < T_m$

Vapor Diffusion





rate  
of  
metamorphism



time

The rate is determined  
by temperature and  
water content

## Vapor Diffusion & Avalanches

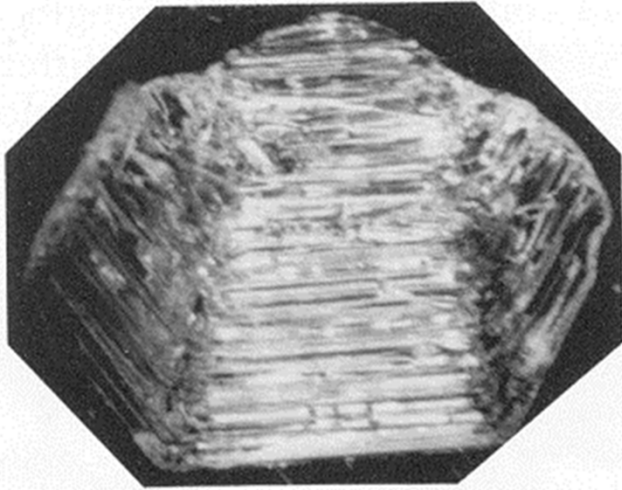
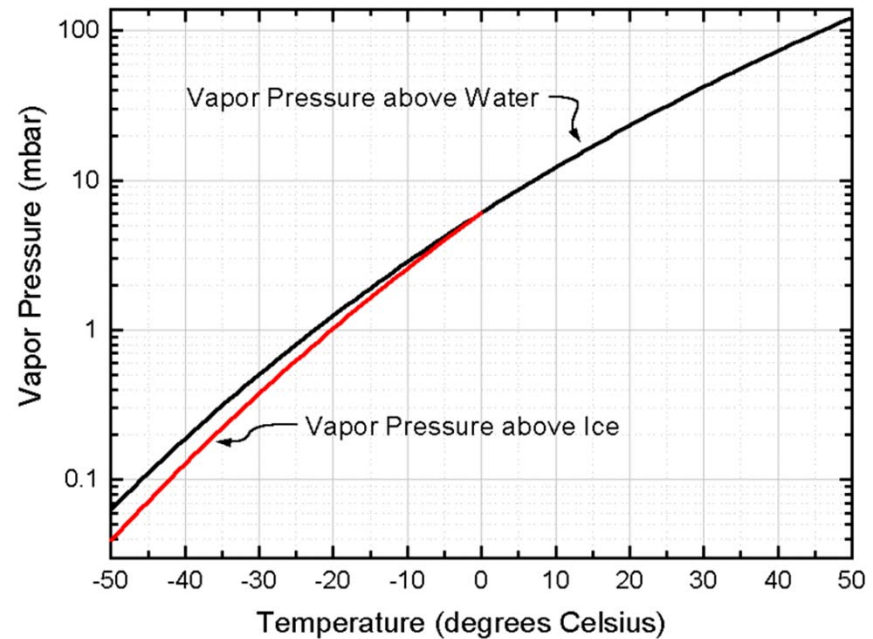
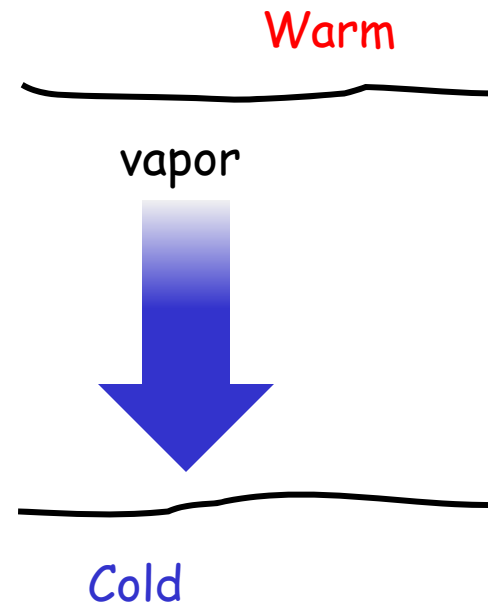
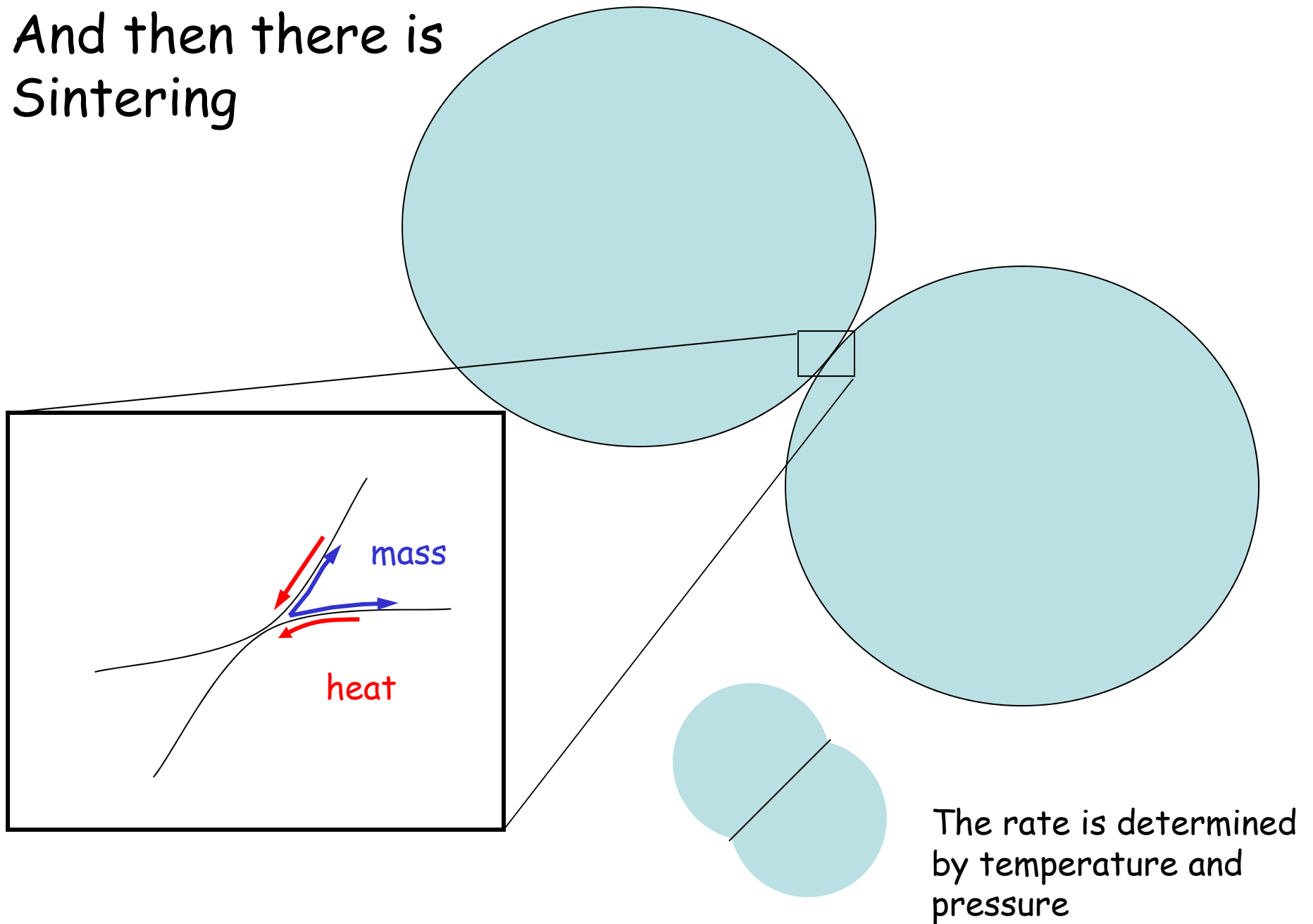


Figure 5. Depth hoar, the extreme case of faceted crystals growing in dry snow at high growth rates due to large temperature gradients. These are poorly sintered because their formation consumes the well-sintered, rounded grains, and large grains sinter slowly.

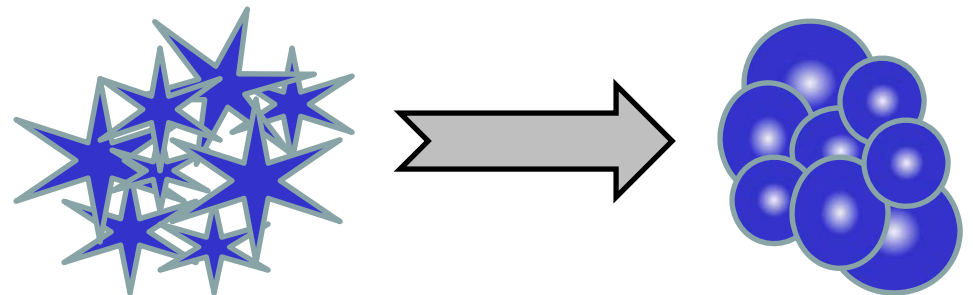


And then there is  
Sintering



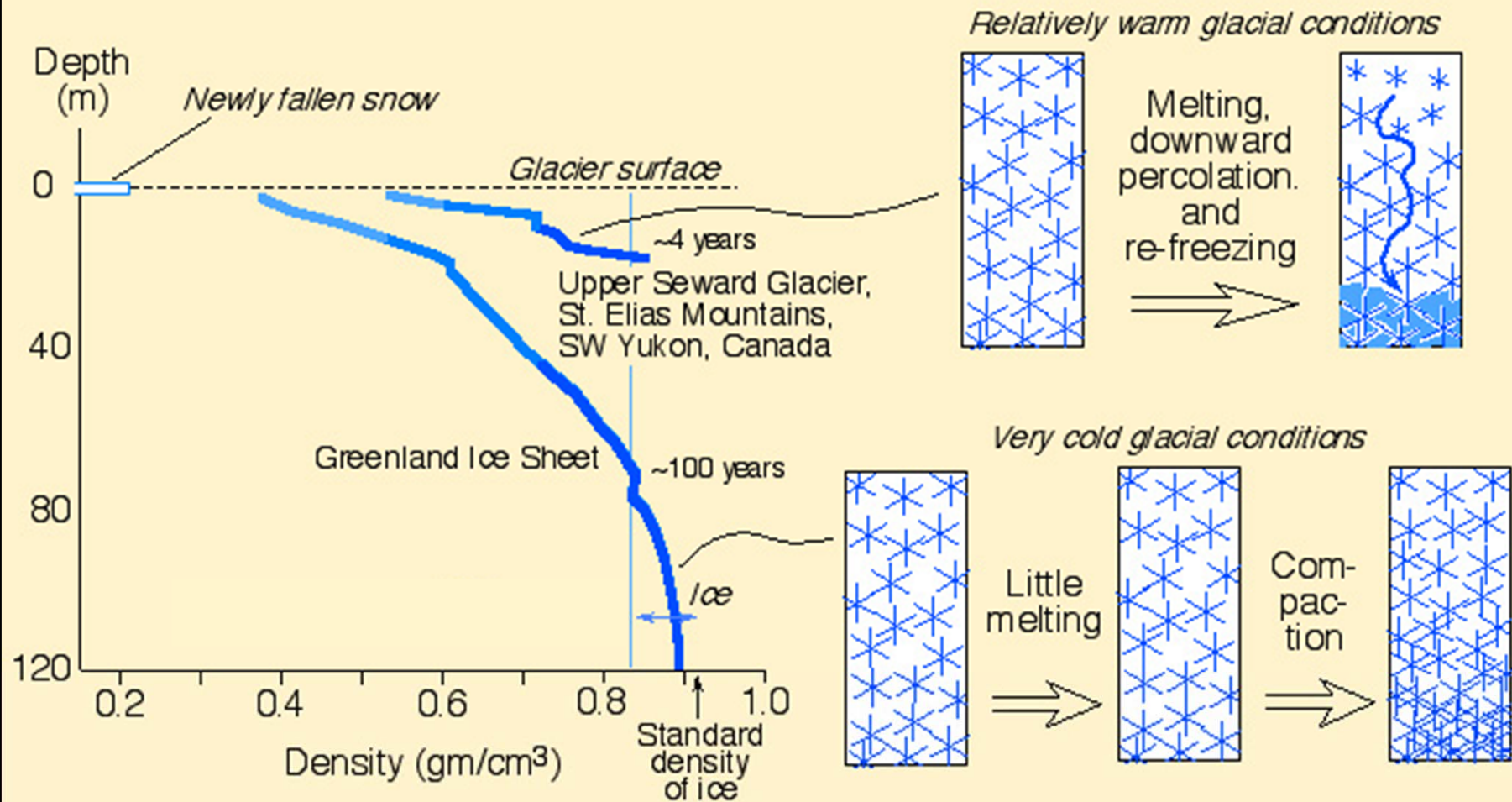
# Snow Compaction and densification

	<u>Cold Snow</u>	<u>Warm Snow</u>
Vapor diffusion	✘	✘
Melt refreezing		✘
Sintering	✘	✘
Bulk refreezing		✘



# Snow pit Greenland





Based on Figure 2.3 of Benn and Evans, *Glaciers and Glaciation*



## Typical Densities

kg m<sup>-3</sup>

New Snow (just fell 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
Glacier Ice	830-923

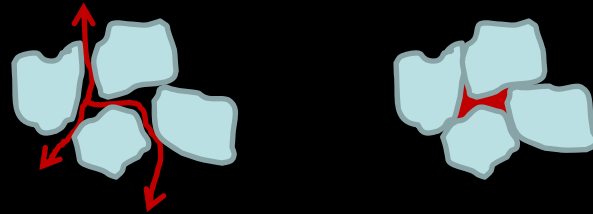
(Table 2.1 Cuffey & Paterson 2010)

what happened to 917?

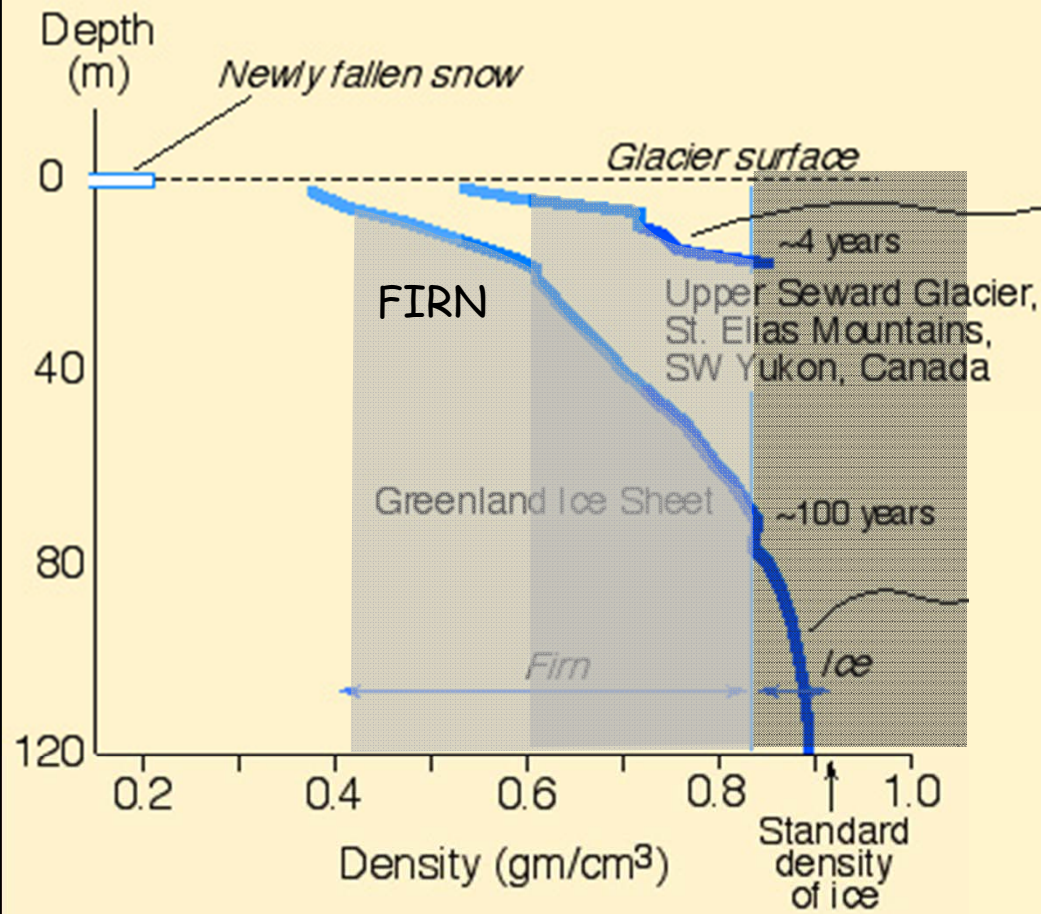


## When is snow ice?

When the interconnecting  
passageways between the  
grains are closed  
~830 kg m<sup>-3</sup>



Snow → Firn → Ice



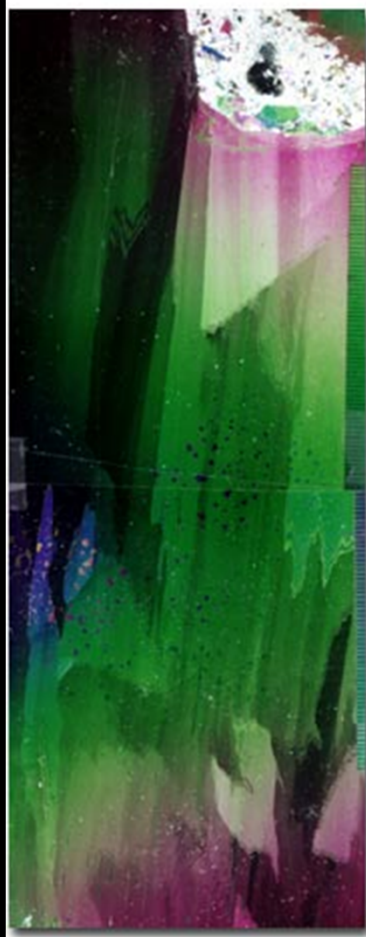
Firn: Snow that has survived one melt season

Based on Figure 2.3 of Benn and Evans, *Glaciers and Glaciation*

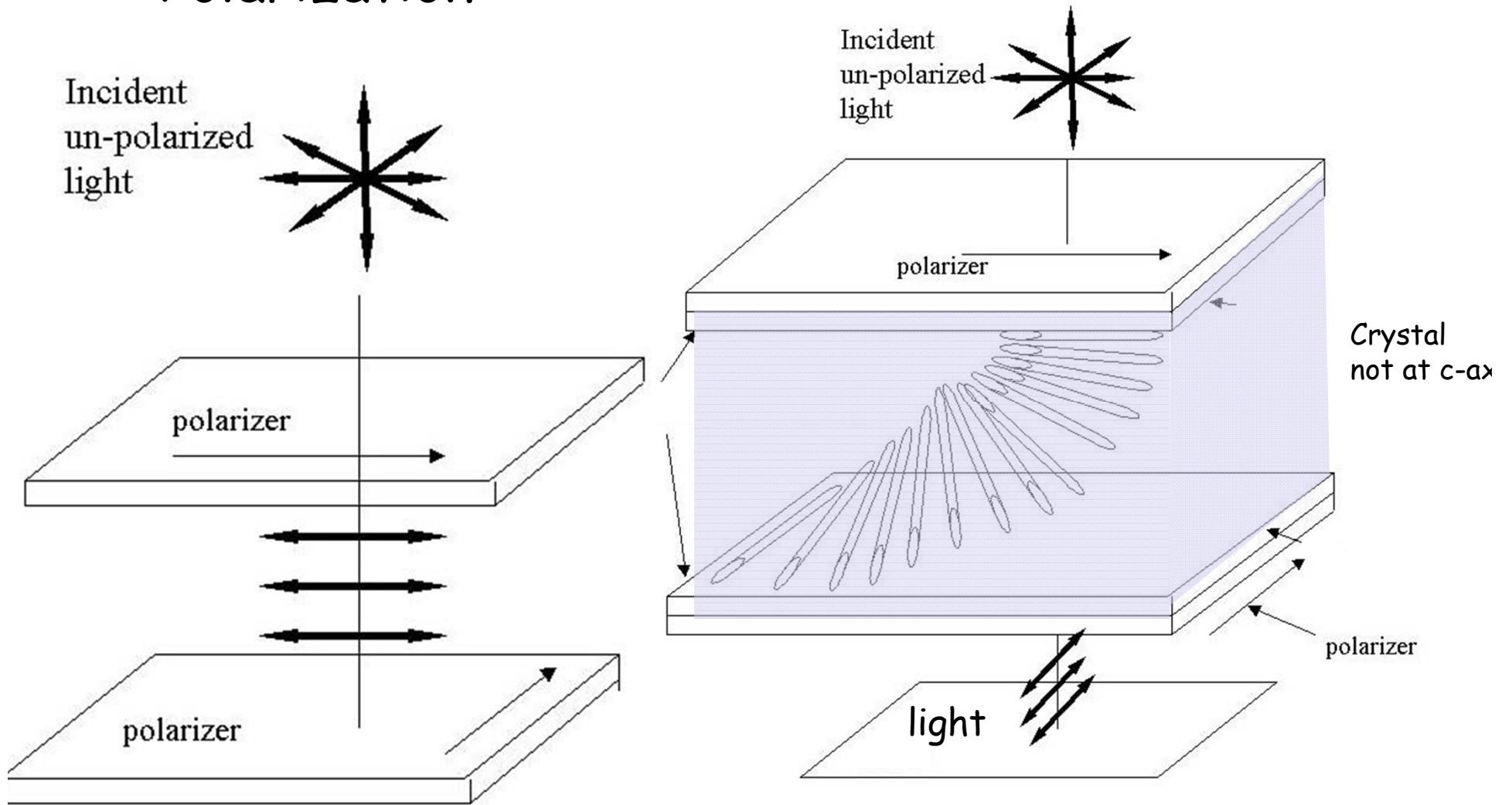
LBR 6/2002

Size of Ice Crystals  
in  
Glaciers and Ice Sheets

# LAKE ICE UNDER POLARIZED LIGHT

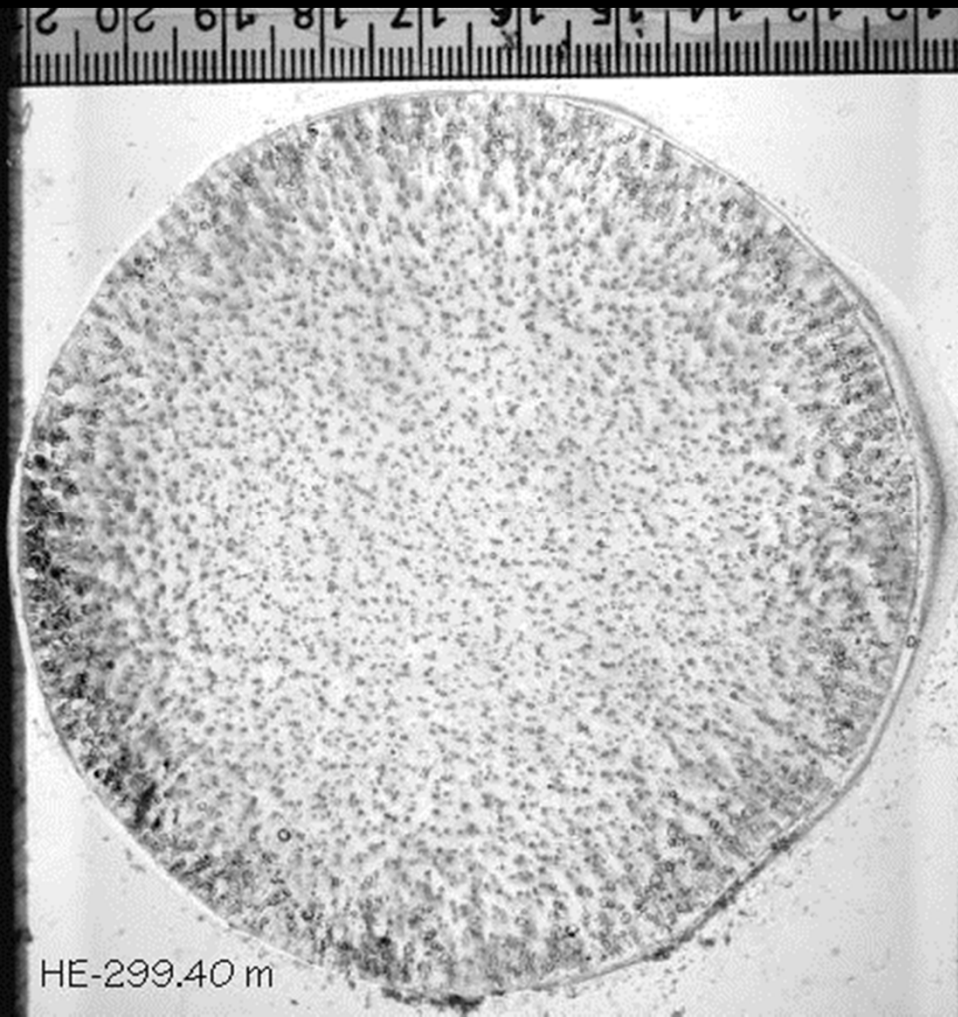


# Polarization

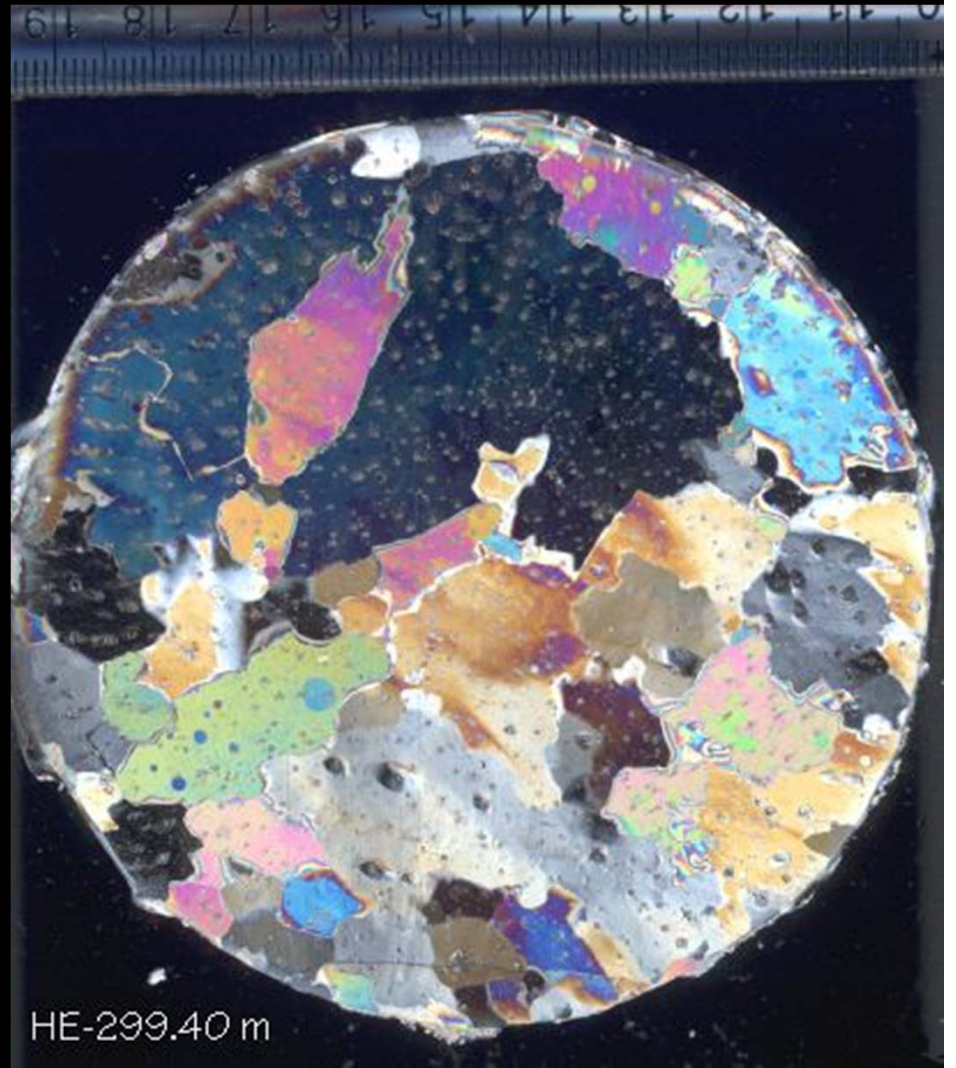


Extinction  
no light



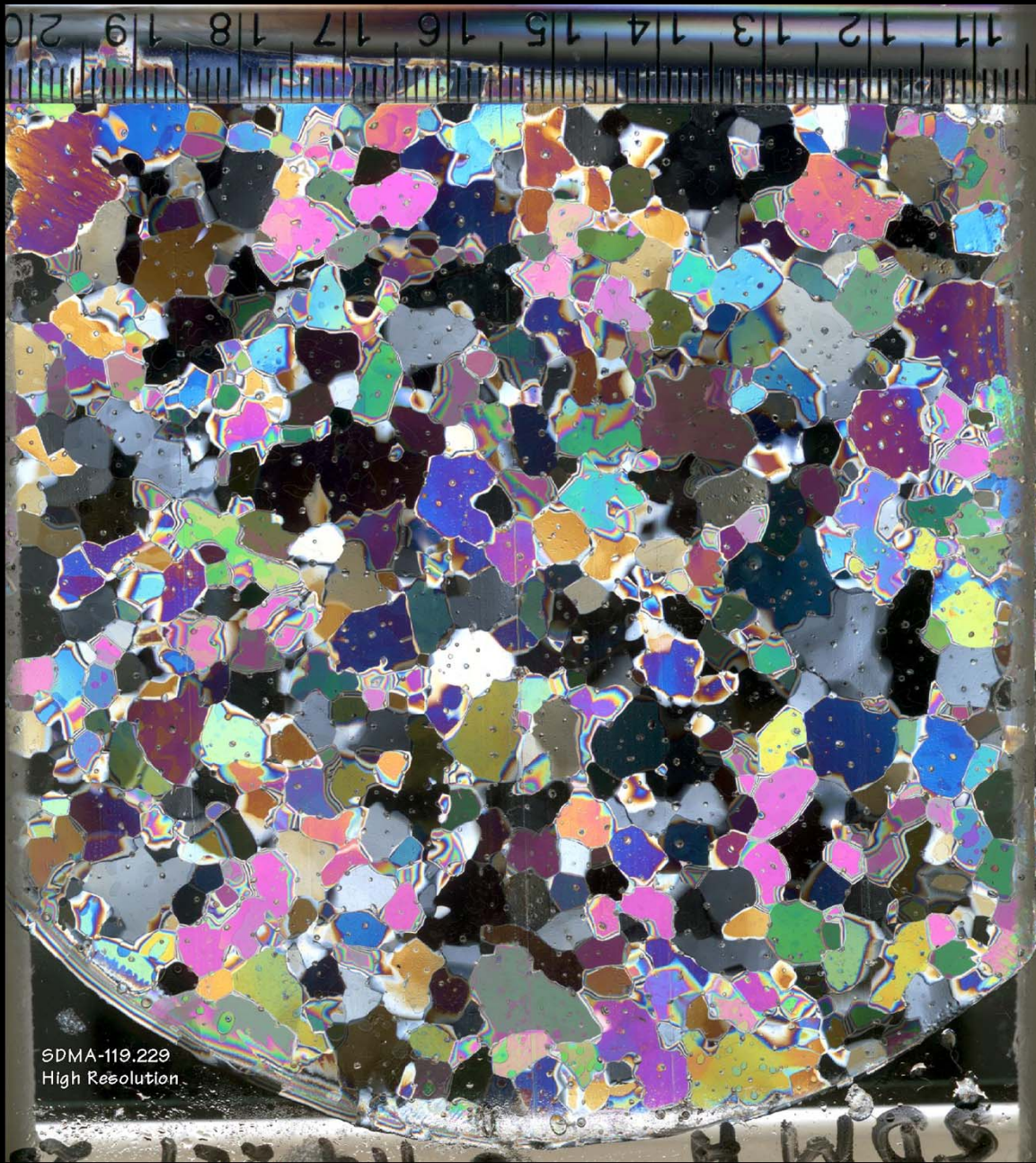


HE-299.40 m



HE-299.40 m

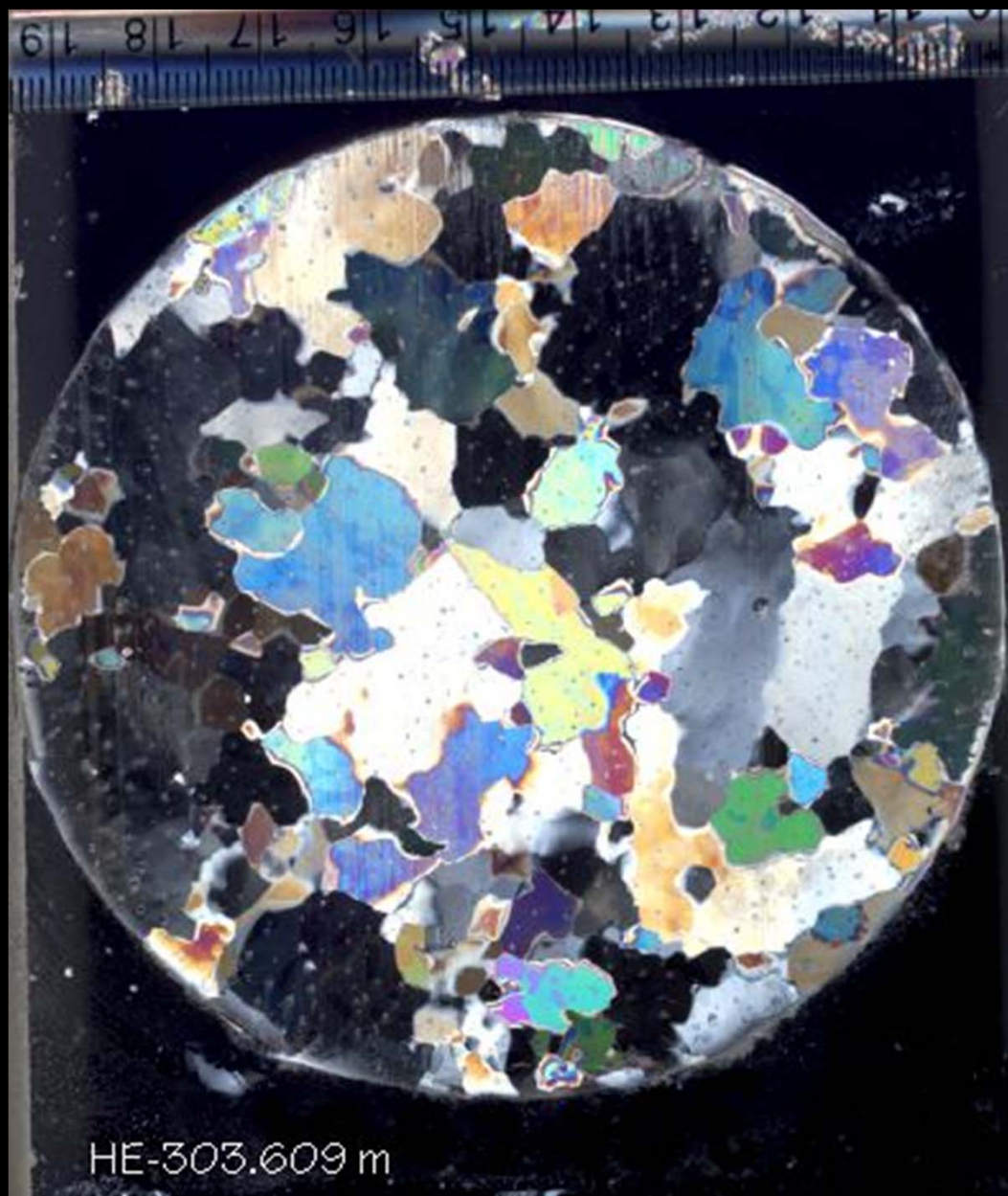
Hermann Engelhardt  
Caltech



SDMA-119.229  
High Resolution

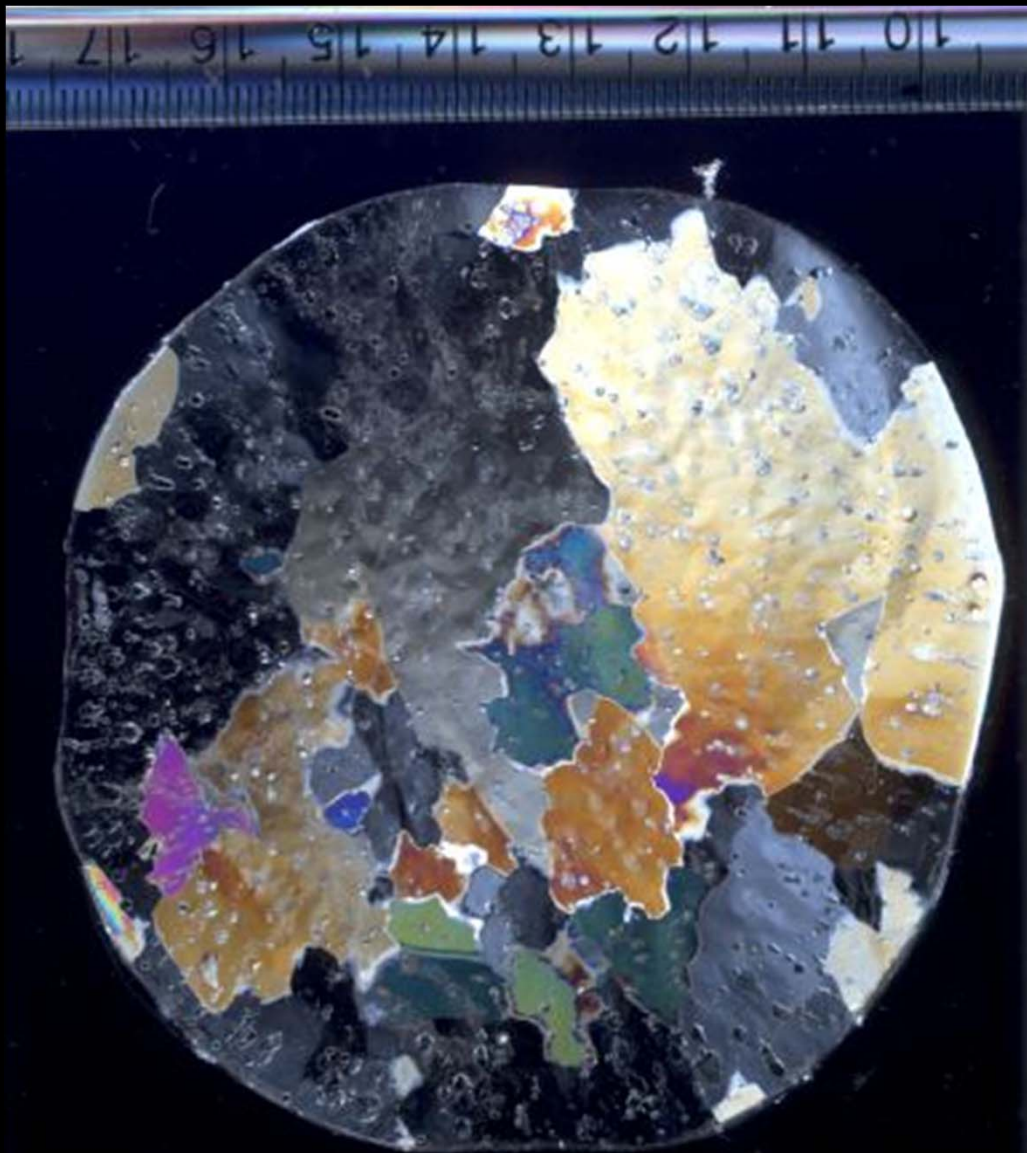
Hermann Engelhardt  
Caltech





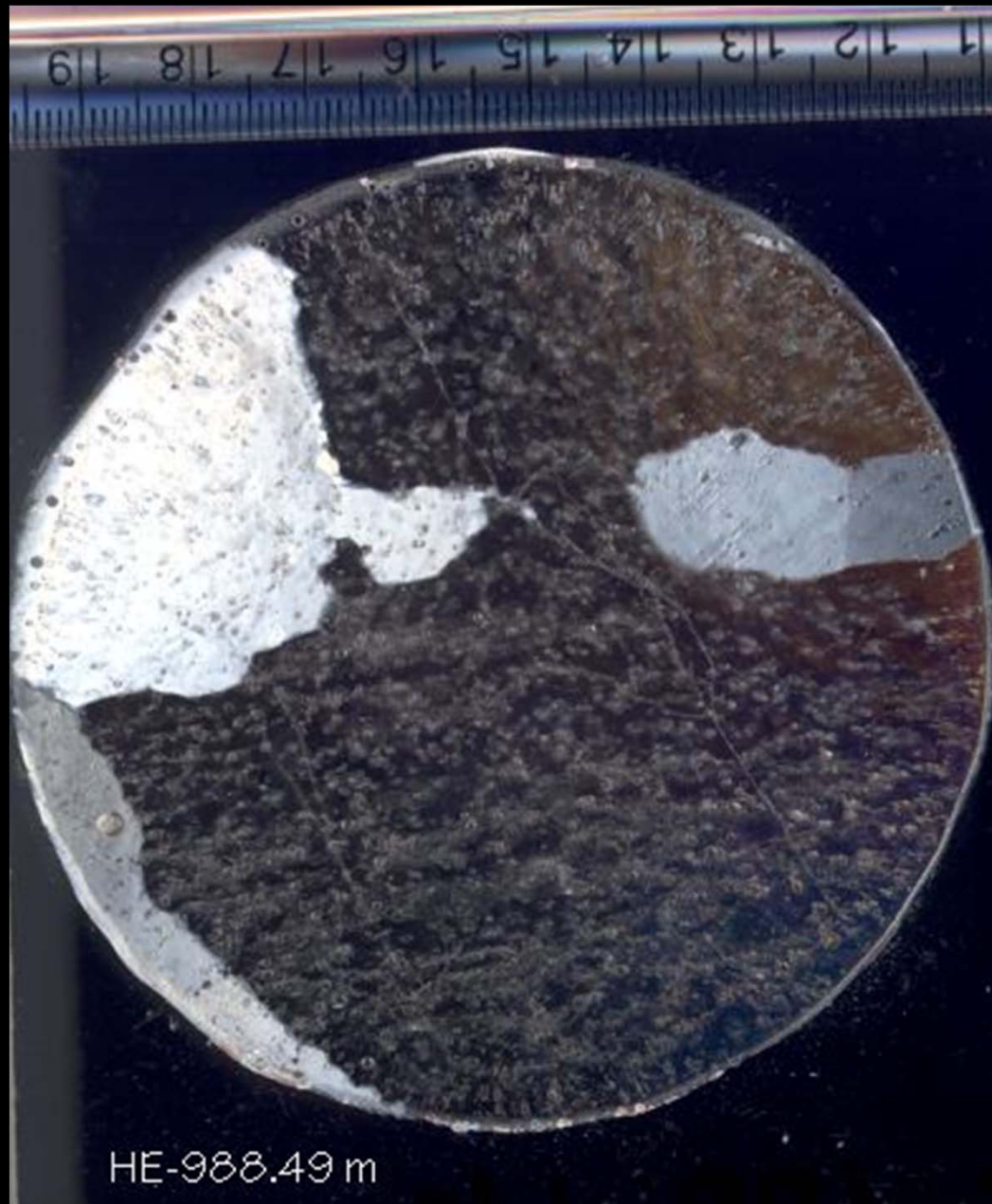
HE-303.609 m

Hermann Engelhardt  
Caltech



HE-676.46 m

Hermann Engelhardt  
Caltech



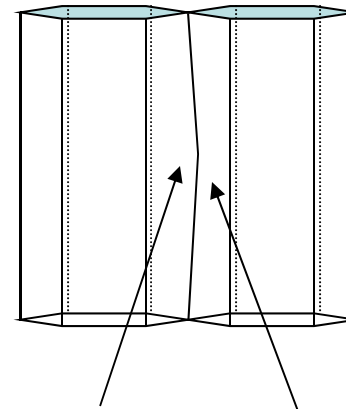
HE-988.49 m

Hermann Engelhardt  
Caltech

# Recrystallization of Glacier Ice

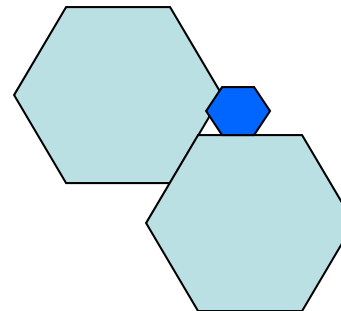
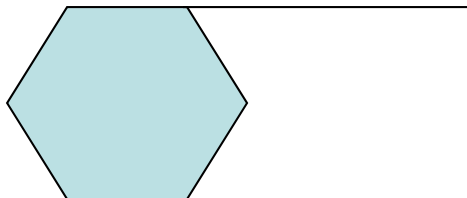
## 1. Grain boundary migration

- curvature



Higher Energy  
Higher pressure

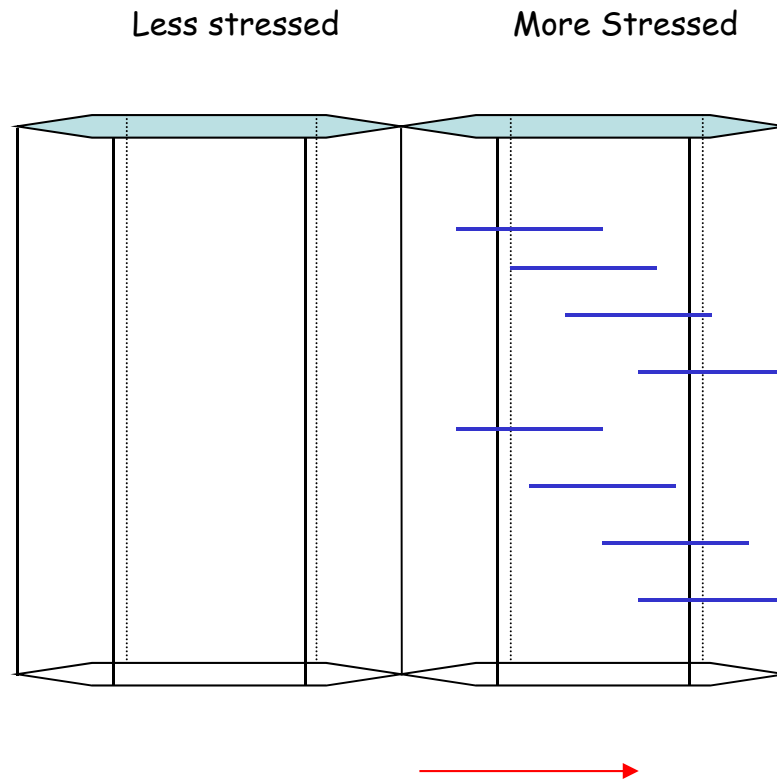
Lower Energy  
Lower pressure



# Recrystallization of Glacier Ice

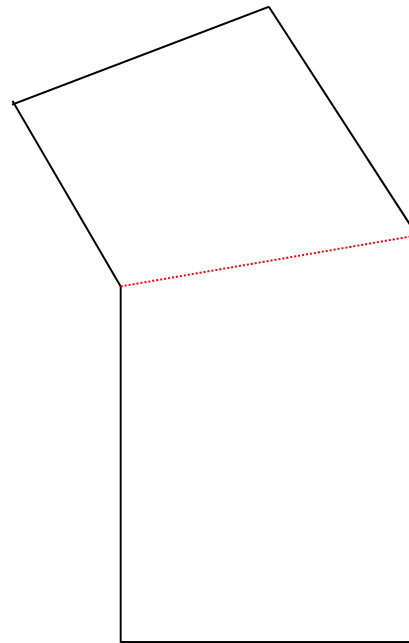
## 1. Grain boundary migration

- stored strain energy



# Recrystallization of Glacier Ice

## 2. Polygonization



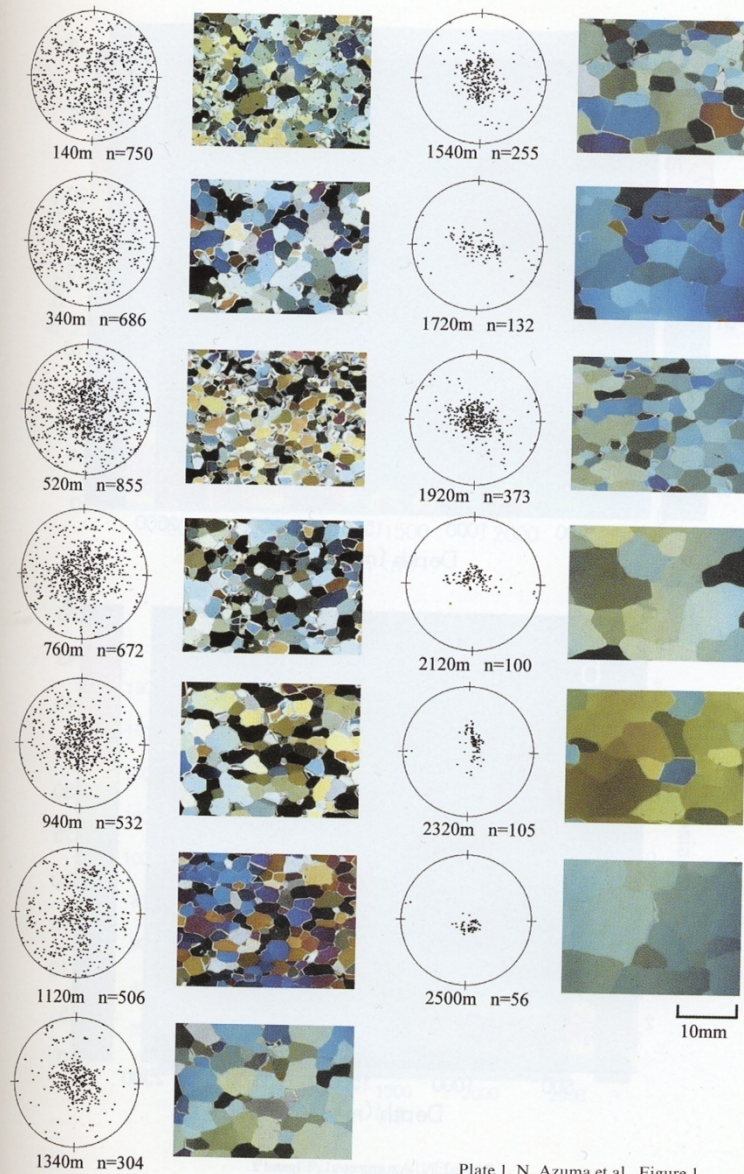
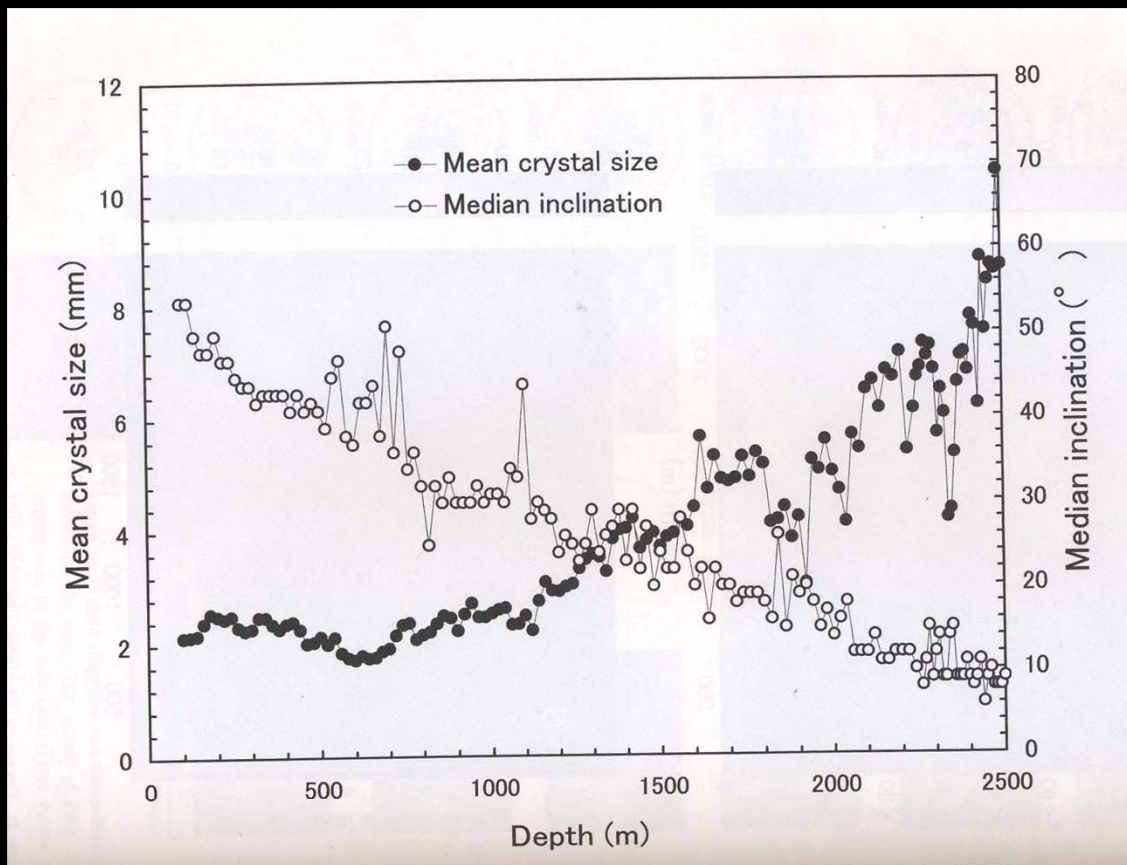


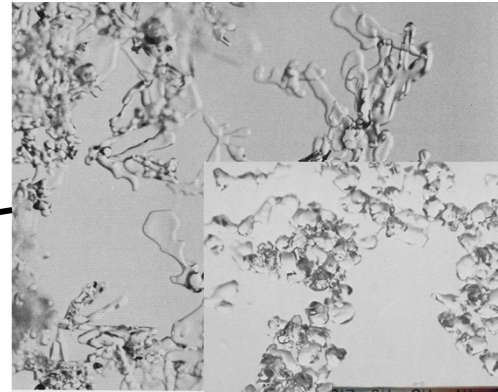
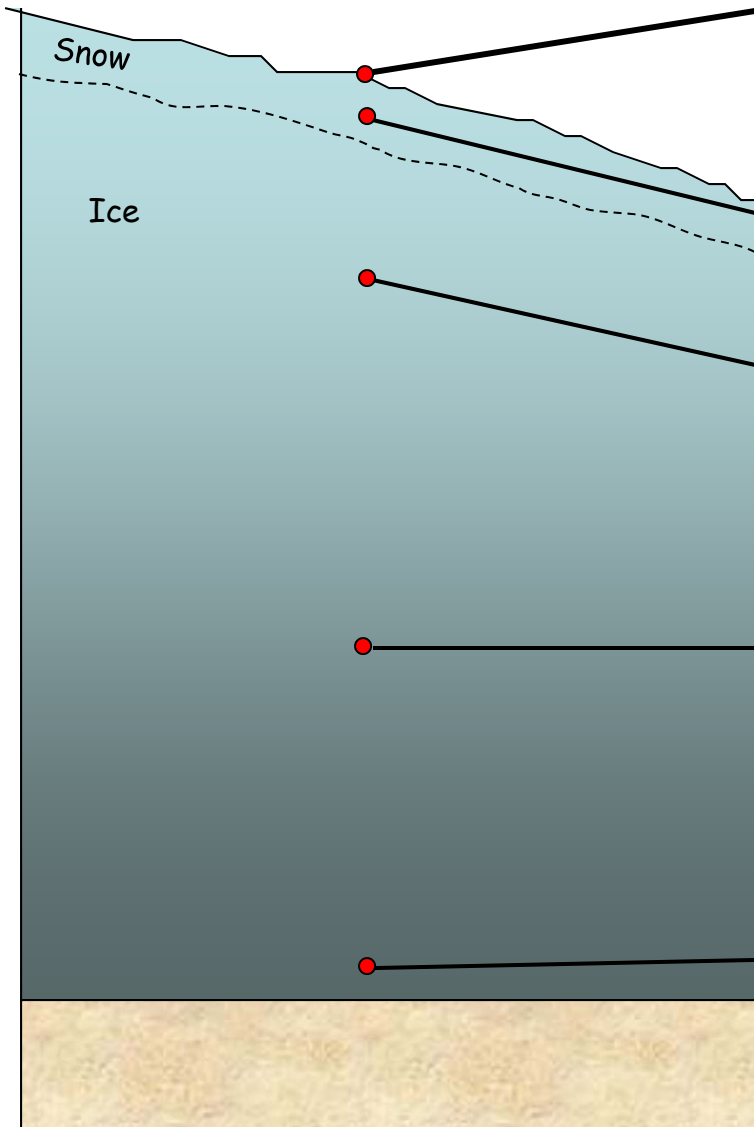
Plate I. N. Azuma et al., Figure 1.

Dome Fuji, Antarctica  
Azuma et al., 2000

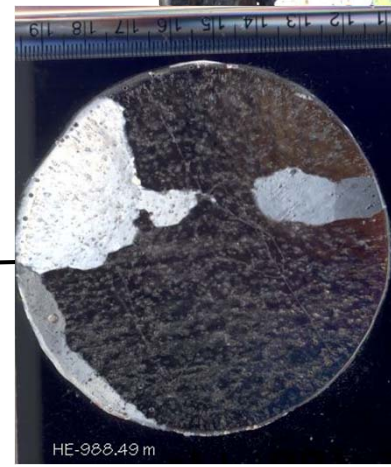
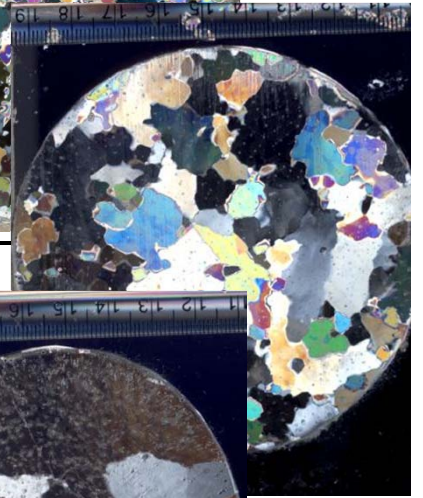
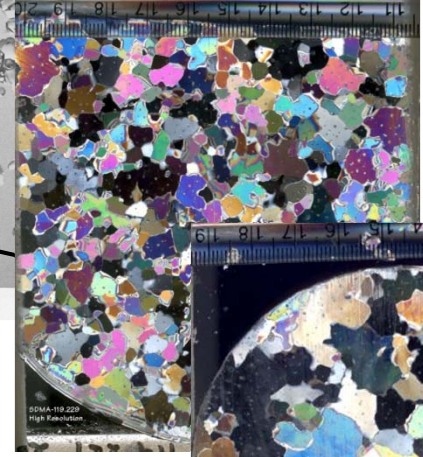
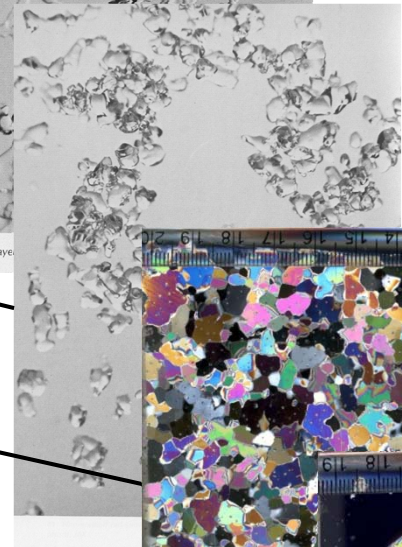


Dome Fuji, Antarctica  
Azuma et al., 2000





36. The same snow layer morphism. 26X



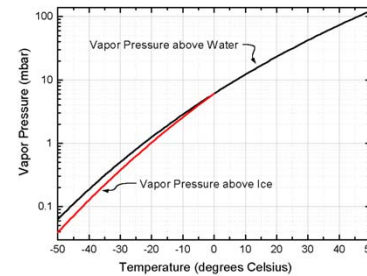
## Snow to Ice Metamorphism

Dry Processes **Cold- SLOW**

vapor diffusion  
compaction and sintering

Wet Processes **Warm-FAST**

vapor diffusion (water to ice)  
compaction and sintering  
melt-refreeze



## Ice Metamorphism (solid state)

dynamic recrystallization

- grain boundary migration - curvature, stored strain energy
- polygonization

End