SNOW STRUCTURE and METAMORPHISM

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I SNOW STRUCTURE

Snow is an interconnected mixture of ice crystals, air pore space, impurities, and sometimes liquid water. The mixture can be described using simple ratios such as:

$$\text{Density} = \frac{\text{Sample mass}}{\text{Sample volume}}$$

$$\text{Porosity} = \frac{\text{Volume of pore space}}{\text{Sample volume}}$$

$$\%\ \text{Liquid Water (by mass)} = \frac{\text{Mass of liquid water} \times 100\%}{\text{Sample mass}}$$

$$\%\ \text{Liquid water (by volume)} = \frac{\text{Volume of liquid water} \times 100\%}{\text{Sample volume}}$$

$$\text{Impurity Content} = \frac{\text{Mass of impurities}}{\text{Sample mass}}$$

Most snow properties vary greatly as these ratios vary. For example, the shear strength of alpine snow can increase by a factor of 1000 as its density increases or porosity decreases (from newly fallen snow to old settled snow). Another example is the tenfold increase in the dielectric constant of snow at high radio frequencies when the pores contain about 10% liquid water.

Many snow properties also vary with snow structure, that is, the spatial distribution of the components (ice, air, and water). By any criterion, snow structure is quite complicated, and quite difficult to describe objectively using simple measures.

The simplest structural observation is to break the sample apart into individual "grains" which can be examined and photographed under a microscope or macroscope. Perhaps it is possible to quickly assign a "size index" to the largest grain in the sample, but an average grain size cannot be assigned easily because of the large range in grain size.

Although broad agreement can be reached on the morphology of individual crystals (plates, prisms, surface hoar, depth hoar, etc.), little can be noted quantitatively on the interconnections that existed before the grains were disaggregated.

Reno,
Nov. 1983

At small supersaturations or small undersaturations, there is a tendency for metamorphism to rearrange the ice skeleton toward minimum free energy, largely by reducing surface area, but also by adjusting prismatic faces relative to their surface energies. The skeleton will also adjust to remove "strain energy" gradients as Nature attempts to equalize stress and/or strain.

The net result is a tendency for individual crystals to approach "equilibrium shapes" -- presumably equisized prisms and ellipsoidal forms.

An important consequence of minimizing surface energy is that saddle shaped necks form in the concavity between neighboring crystals. This so-called "sintering" process interconnects the crystals and increases structural strength.

The consequences of metamorphism toward minimum energy are also:

1. Bigger crystals get ~~smaller~~ bigger

2. Smaller crystals get ~~bigger~~ smaller

3. The mean crystal size increases

4. The number of crystals decreases

5. Crystal boundaries disappear

As long as the snow is dry, snow metamorphism is largely controlled by the transport of water molecules in the vapor phase (vapor diffusion). There is also reason to believe that active transport may occur on the ice surface (surface diffusion), and even to a small degree directly through the crystal (volume diffusion). Perhaps surface diffusion has a significant role when the driving force is a high temperature gradient; in that case, vapor diffusion, possibly amplified by convection is the overwhelmingly dominant mechanism for transport, and hence metamorphism.

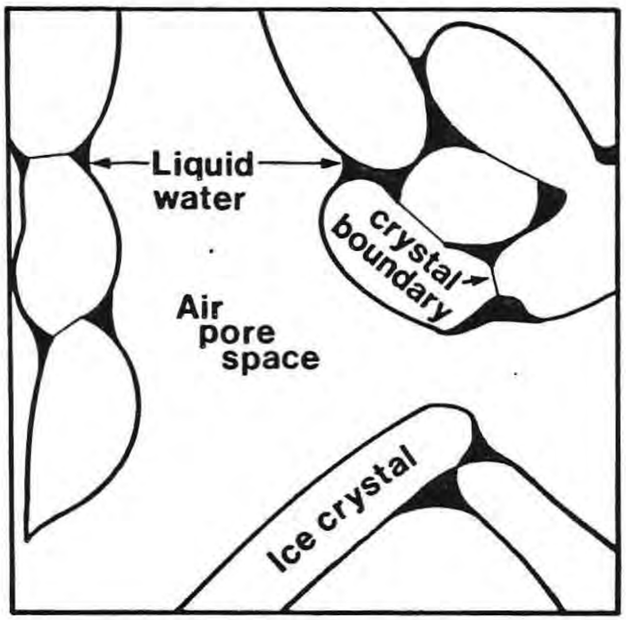
Metamorphism driven by Nature's attempt to minimize free energy occurs more slowly than metamorphism in response to strong temperature gradients, but persists after gradients are removed and can build large crystals over long time periods. An example is the continued growth of crystals in a polar snowpack over periods of 100 to 1000 years. The rate of crystal growth increases exponentially as temperature approaches the melt point (0 degrees C.), and appears to follow a typical rate equation.

Growth rates increase dramatically when free water is present in the snowpack. Here surface energy can drive diffusion over relatively large distances. In a wet snowpack, crystal growth can be measured in minutes and hours, as opposed to days and weeks for dry snow. The interesting problems of wet snow physics are subjects of another lecture.

1

SNOW

Ice crystals
Air pore space
Liquid water (sometimes)
Impurites



2

$$\text{DENSITY} = \frac{\text{SAMPLE MASS}}{\text{SAMPLE VOLUME}}$$

Air....... roughly 1 kg/m³
New snow.......<18 kg/m³
Dry, seasonal..>500 kg/m³
Firn..........>800 kg/m³
Ice...........≥917 kg/m³
Water........ 1000 kg/m³

$$\text{POROSITY} = \frac{\text{VOLUME OF PORE SPACE}}{\text{SAMPLE VOLUME}} \times 100\%$$

Air........... 100%
New snow.......<98%
Dry, seasonal...>50%
Firn...........>10%
Ice............≥ 0%

$$\%\text{LIQUID WATER (by mass)} = \frac{\text{MASS OF LIQUID WATER}}{\text{SAMPLE MASS}} \times 100\%$$

Estimated holding capacity

New snow 20-30% ?
↓ ↓
Older snow 10-15% ?

$$\%\text{LIQUID WATER (by mass)} = \frac{\text{VOLUME OF LIQUID WATER}}{\text{SAMPLE VOLUME}} \times 100\%$$

Estimated holding capacity

2 - 10% ?

$$\text{IMPURITY CONTENT} = \frac{\text{MASS OF IMPURITIES}}{\text{SAMPLE MASS}}$$

Typically less than 3 ppm
NaCl, CaCo₃

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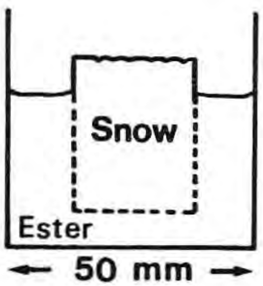
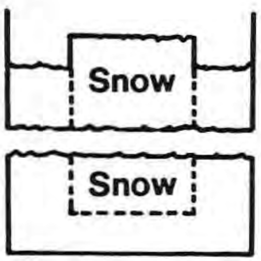


Place snow in small cardboard box.

Add water-insoluble ester. For example:
dimethyl phthalate, mp≈0°C
(supercooled to -5 °C)

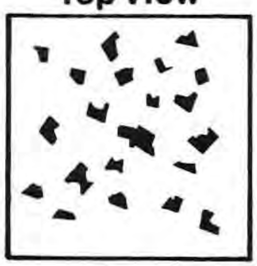


Freeze ester with dry ice.

Saw sample block in half.

Retain lower half as sample.

Top view



Place lower half in microtome, and shave a plane surface. Allow surface to sublimate (etch) for 5 to 10 minutes. Polish lightly with lens tissue and fingerprint powder.

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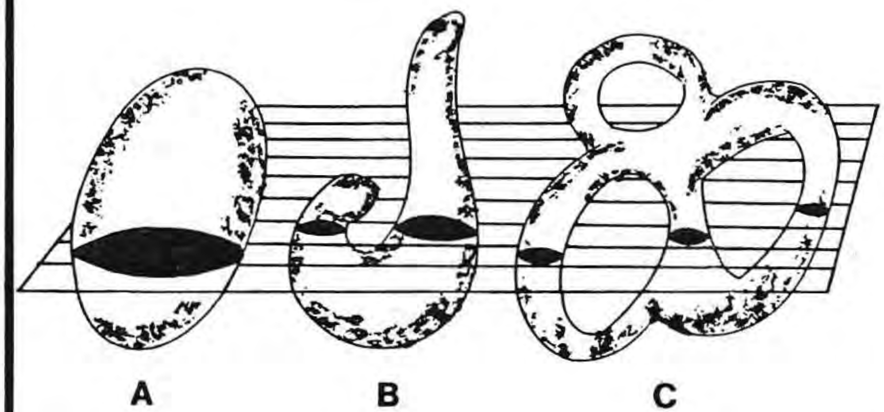

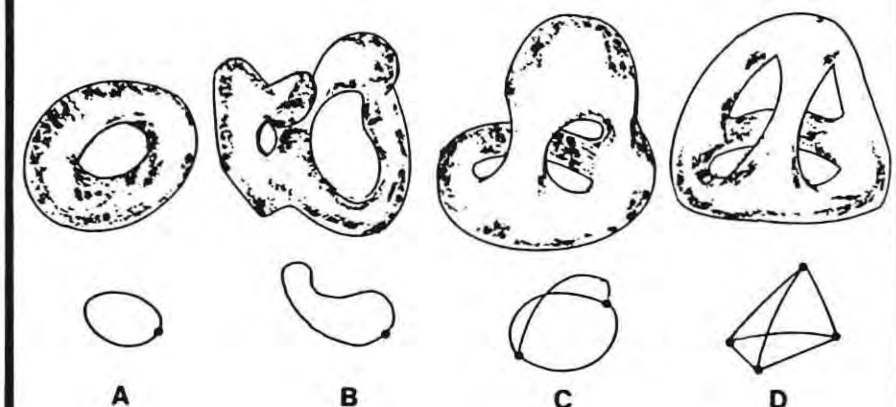

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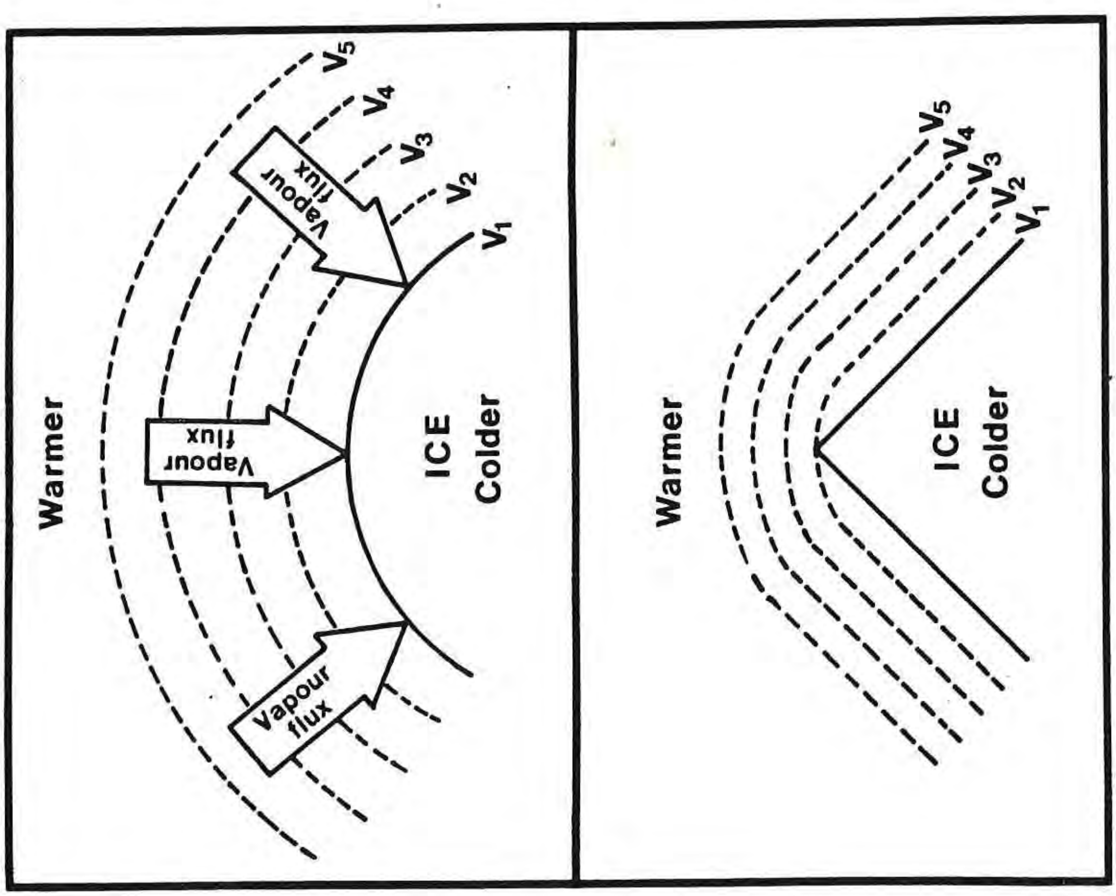
Warmer
Vapour flux
Vapour flux
Vapour flux
ICE
Colder
V_1
V_2
V_3
V_4
V_5
Warmer
ICE
Colder
V_1
V_2
V_3
V_4
V_5

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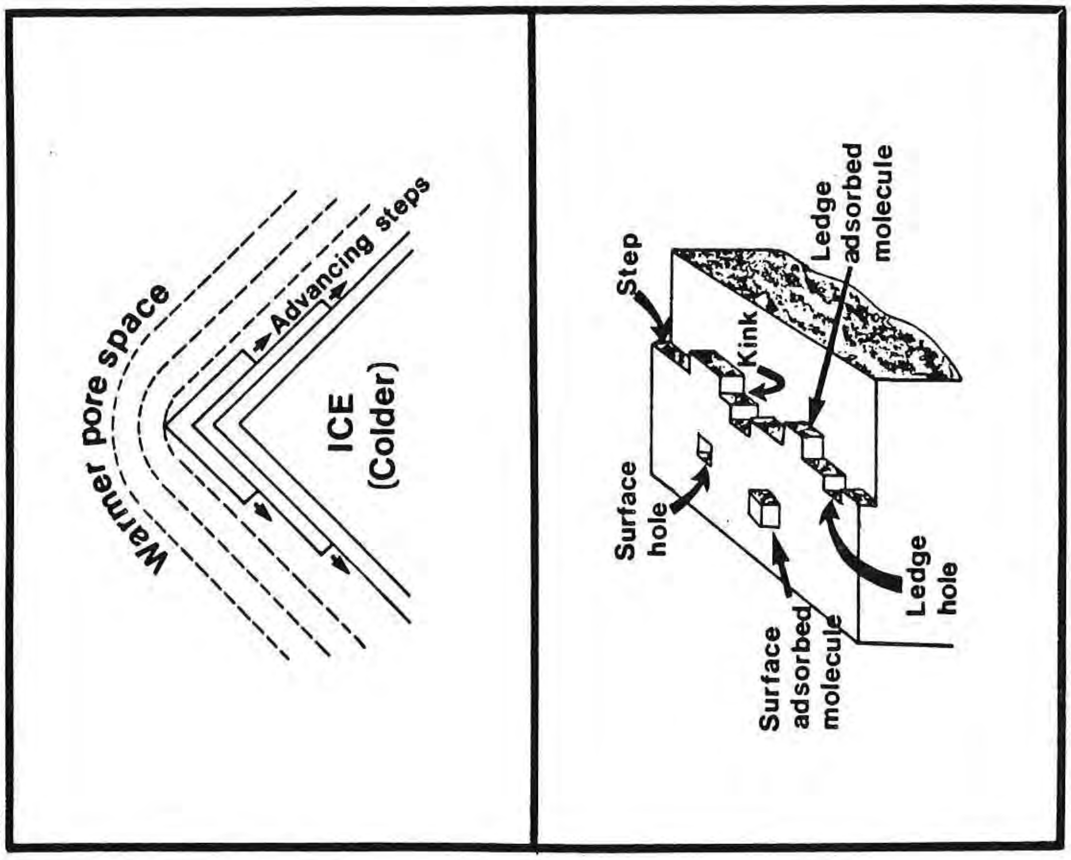
Warmer pore space
Advancing steps
ICE
(Colder)
Step
Kink
Ledge adsorbed molecule
Surface hole
Surface adsorbed molecule
Ledge hole

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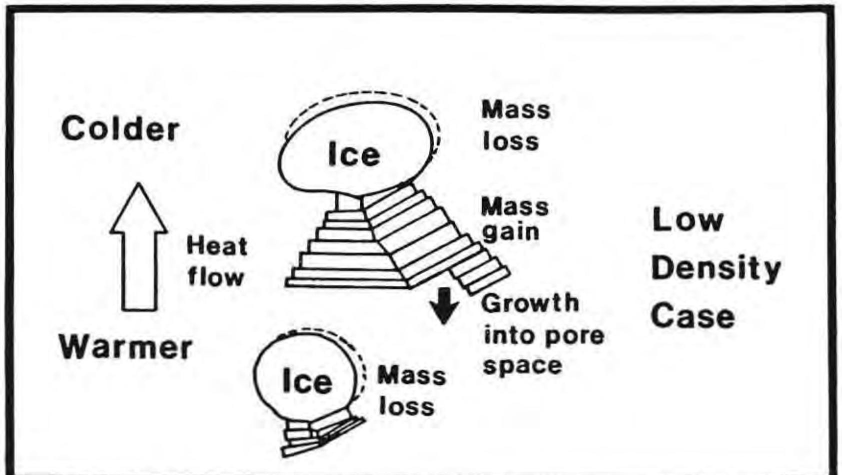

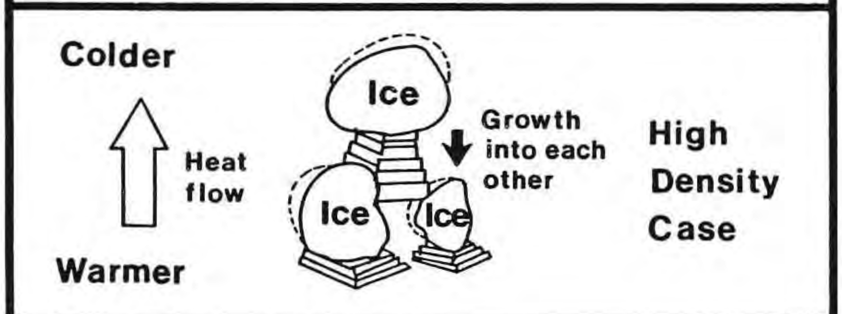

All cases:

Ice spreads out or rearranges.

Ice skeleton becomes better heat conductor.

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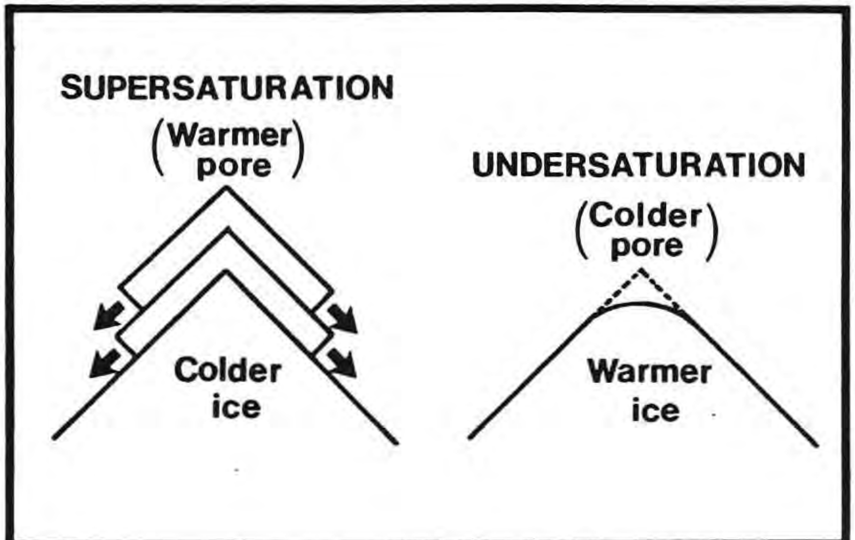

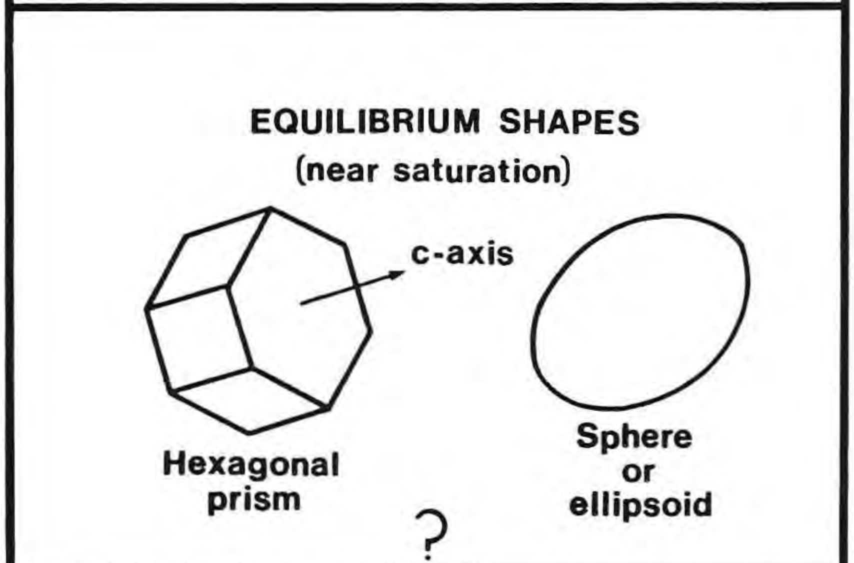

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TOWARD EQUILIBRIUM

(LOWEST SURFACE ENERGY)

BIG GET BIGGER
SMALL GET SMALLER

MEAN CRYSTAL SIZE INCREASES
NUMBER OF CRYSTALS DECREASES

LESS EXAGGERATED SHAPES
MORE EQUISIZED CRYSTALS

SINTERING

CRYSTAL BOUNDARIES DISAPPEAR

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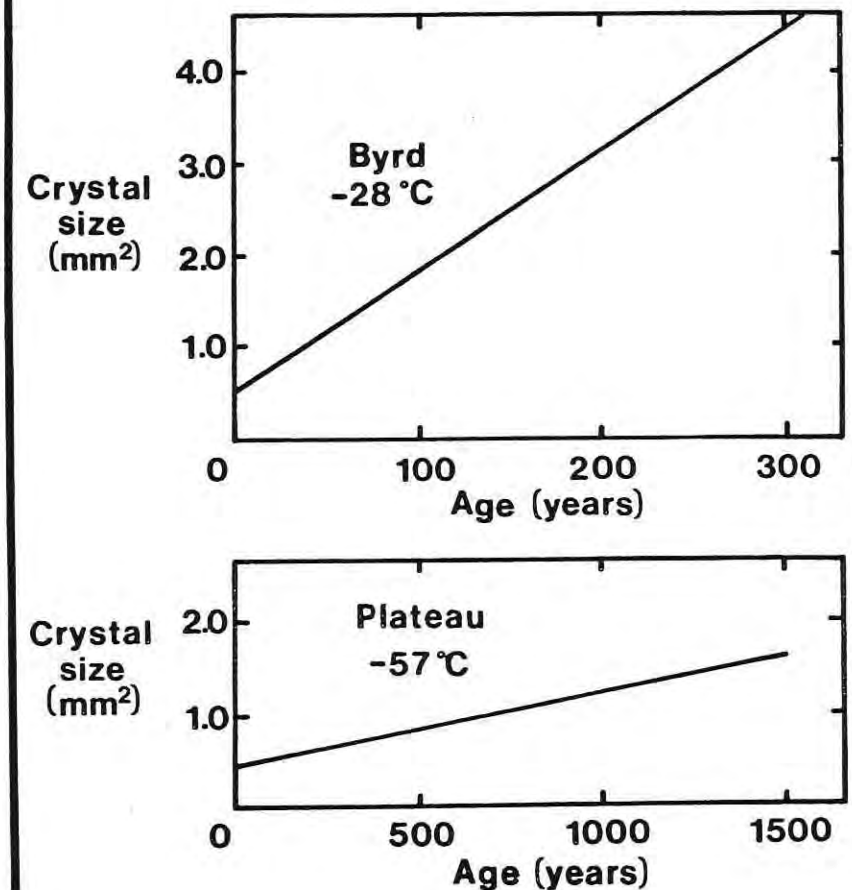
CRYSTAL GROWTH IN ANTARCTICA



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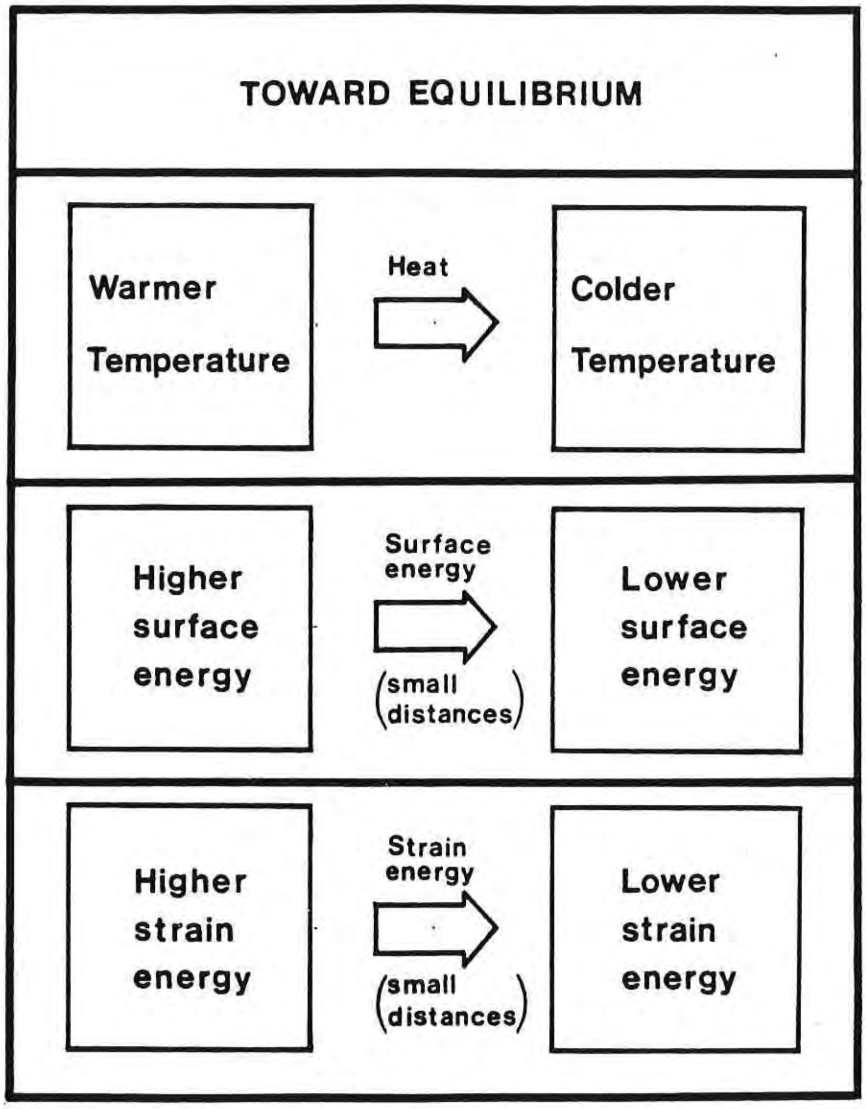
TOWARD EQUILIBRIUM
Warmer Temperature
Heat
Colder Temperature
Higher surface energy
Surface energy
(small distances)
Lower surface energy
Higher strain energy
Strain energy
(small distances)
Lower strain energy