

# Neige et Glace

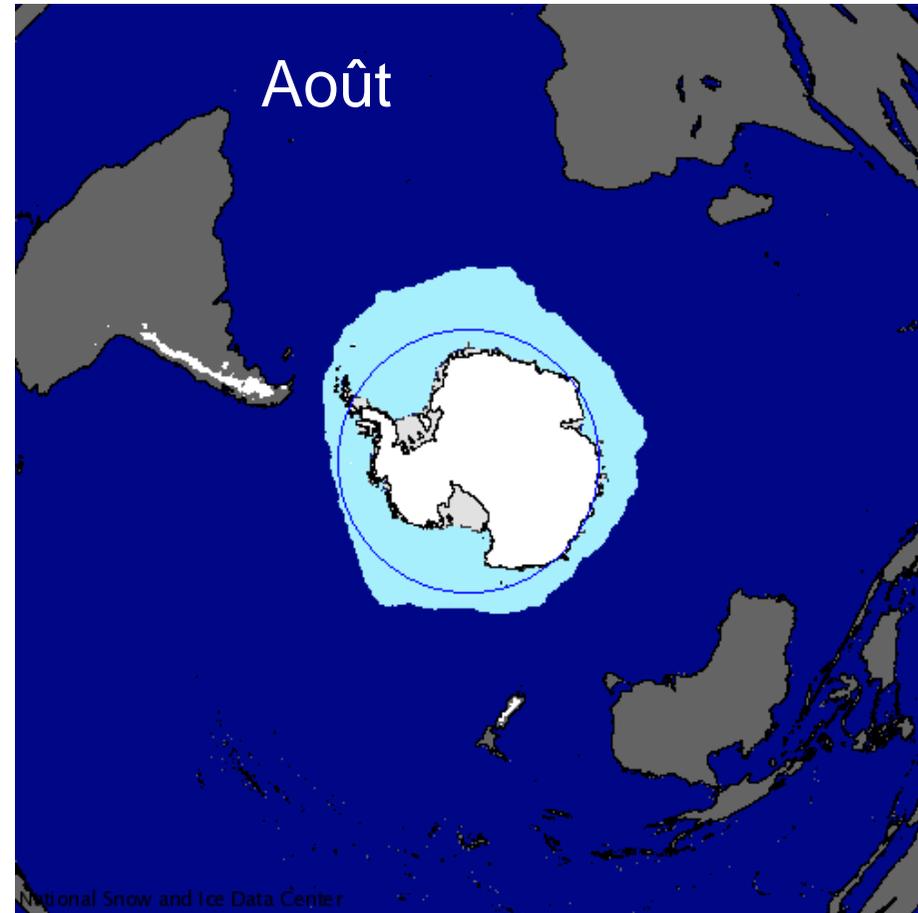
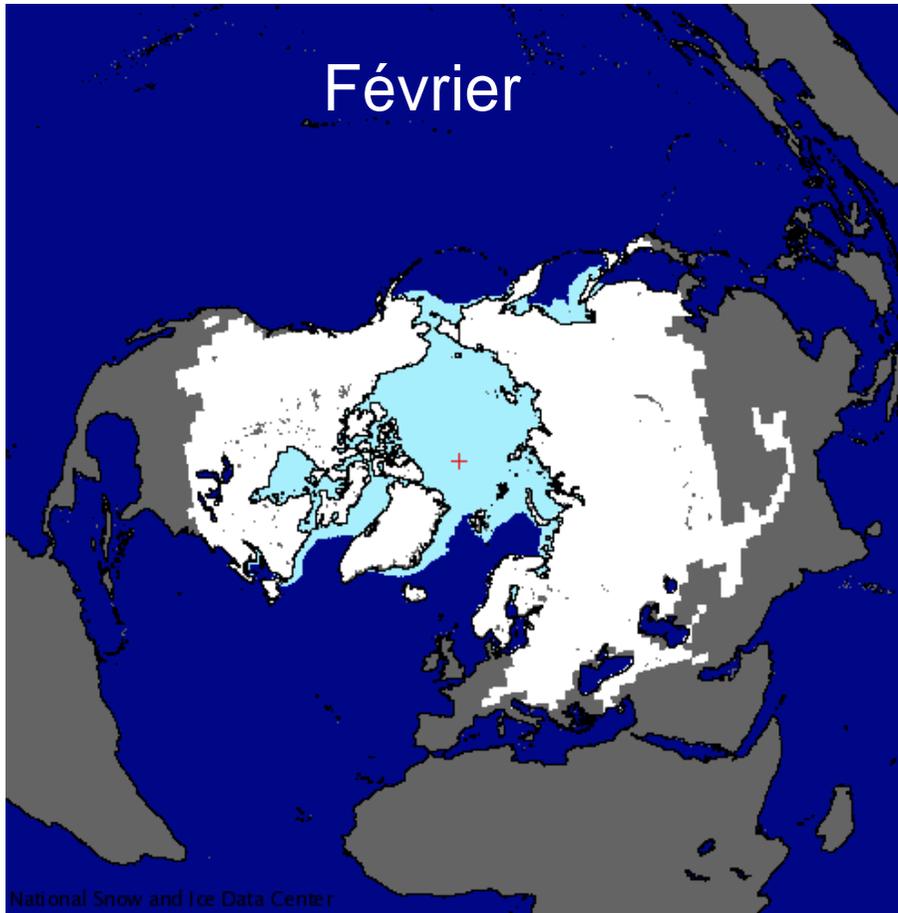
**FTUE 533 O**

**Neige : Florent Domine**

**Glaciers : Emmanuel Lemeur**

**Calottes polaires : Frédéric Parrenin**

**Florent Domine  
CNRS-Laboratoire de Glaciologie  
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florent@lgge.obs.ujf-grenoble.fr**

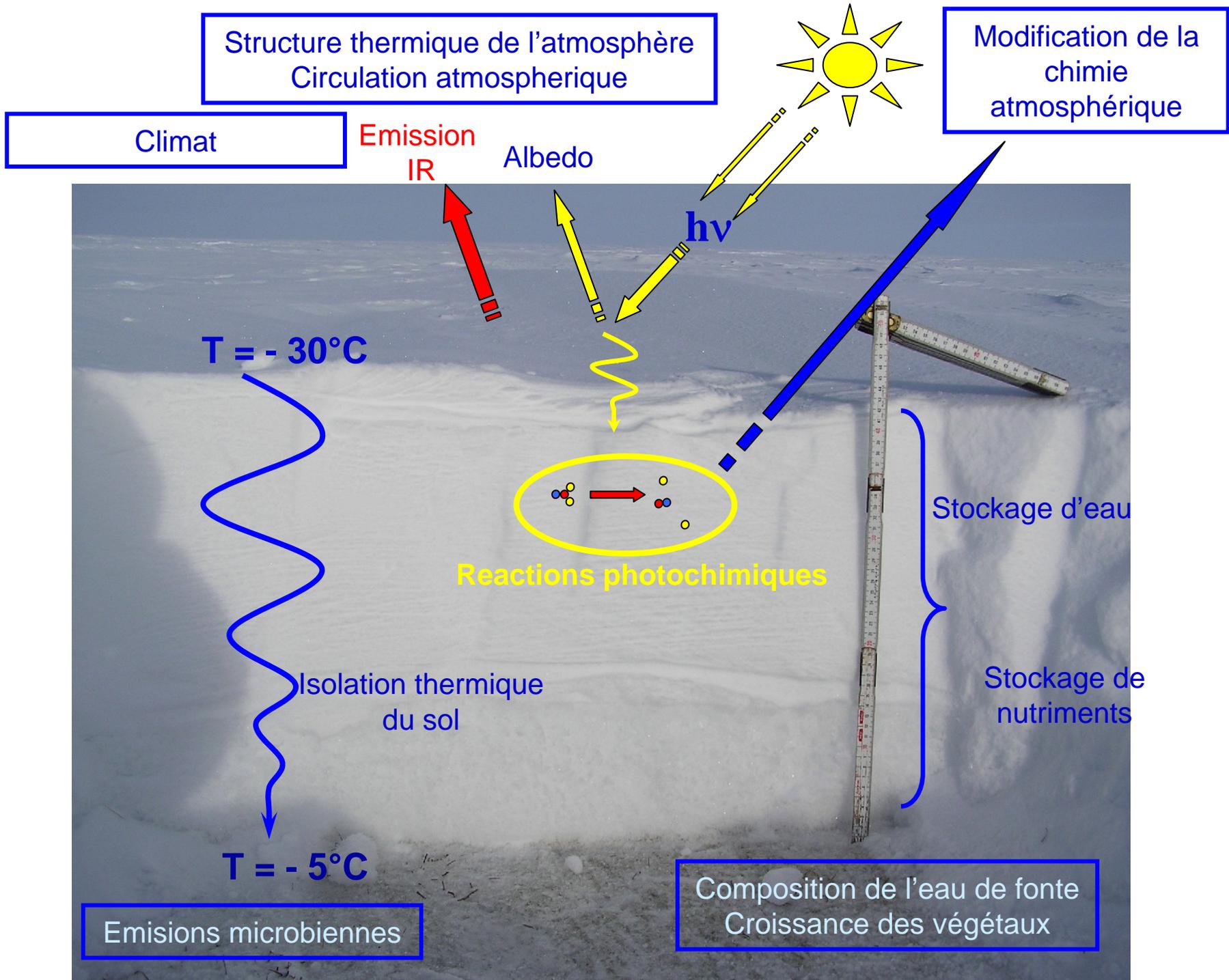


Hémisphère Nord :  $254 \cdot 10^6 \text{ km}^2$

Continents :  $\approx 100 \cdot 10^6 \text{ km}^2$

Conversion neigee continentale, février :  $42 \cdot 10^6 \text{ km}^2$

Terre, février : la neige couvre 14% de la surface du globe



# Neige

**I - La neige dans l'atmosphère**

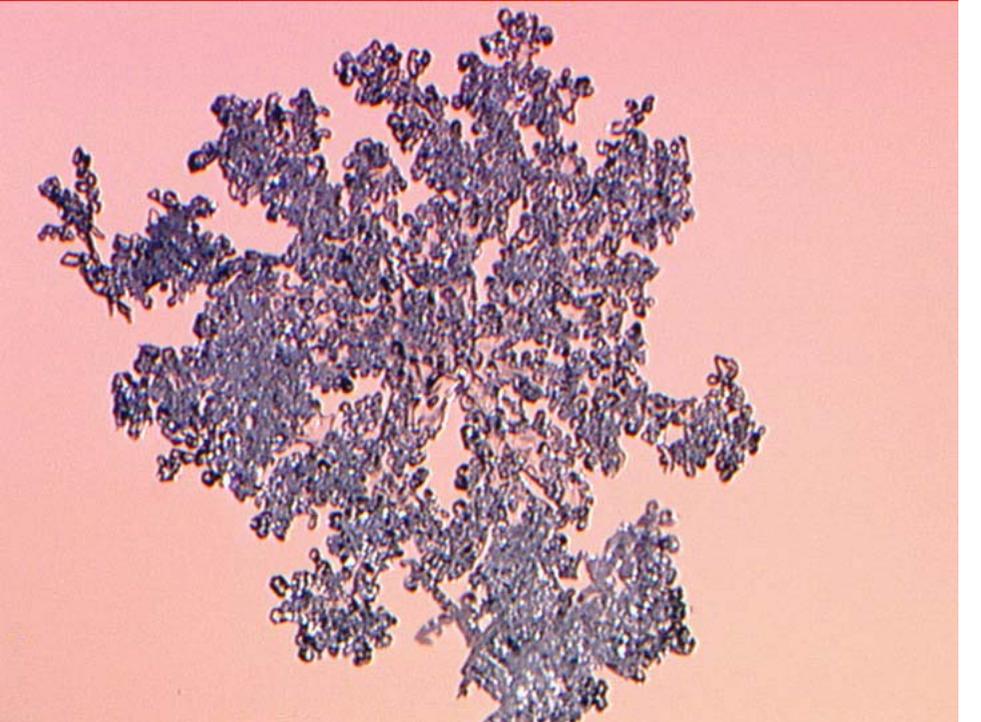
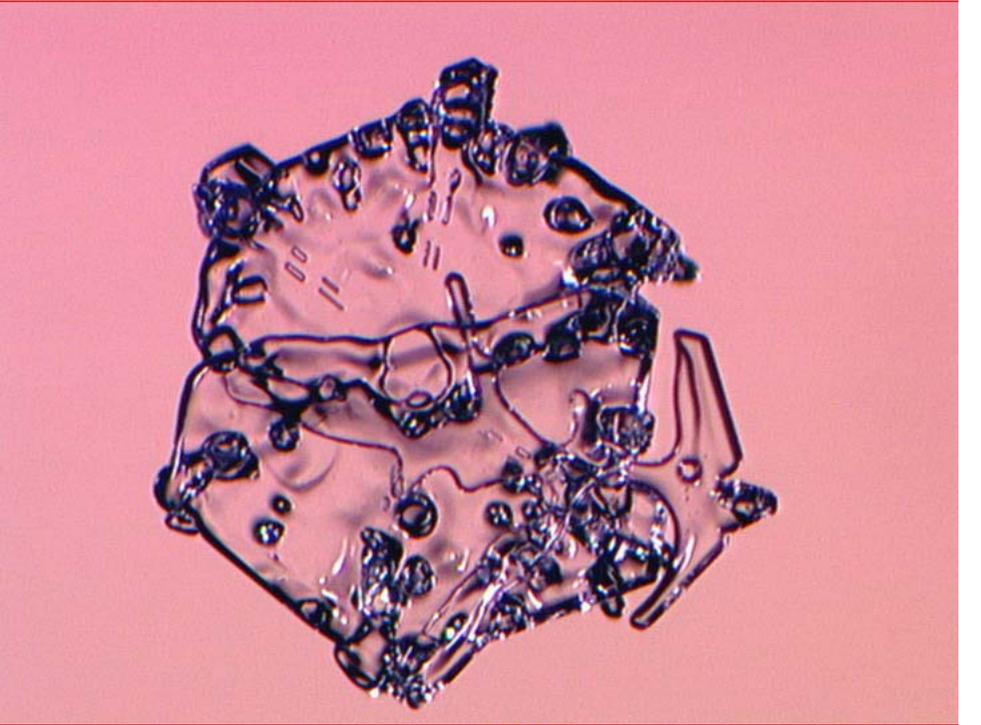
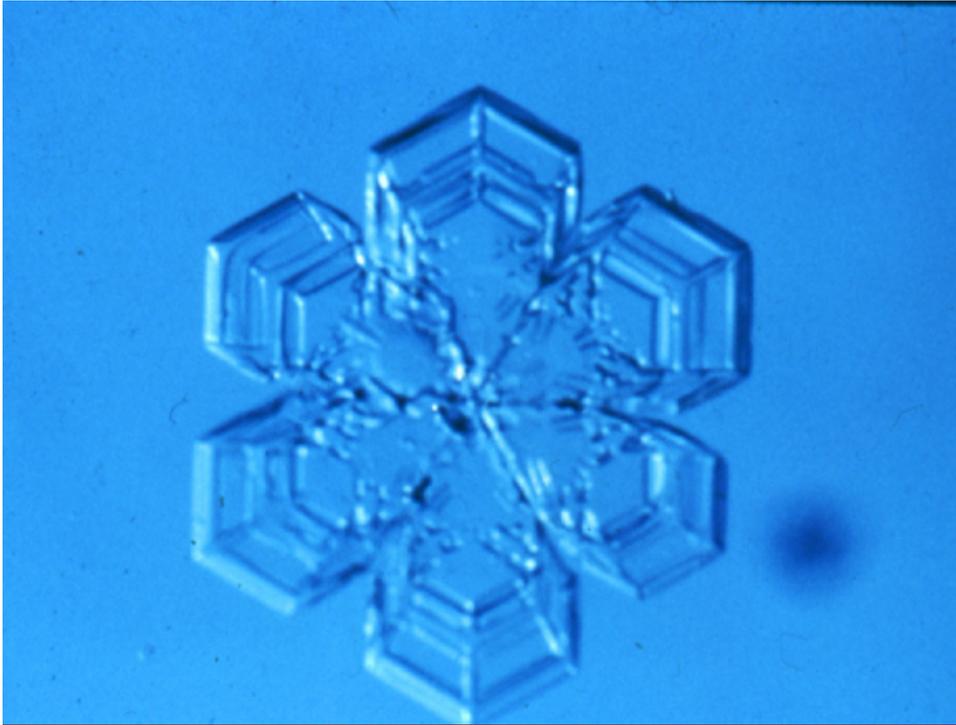
**II – Le métamorphisme de la neige : formation et évolution du manteau neigeux**

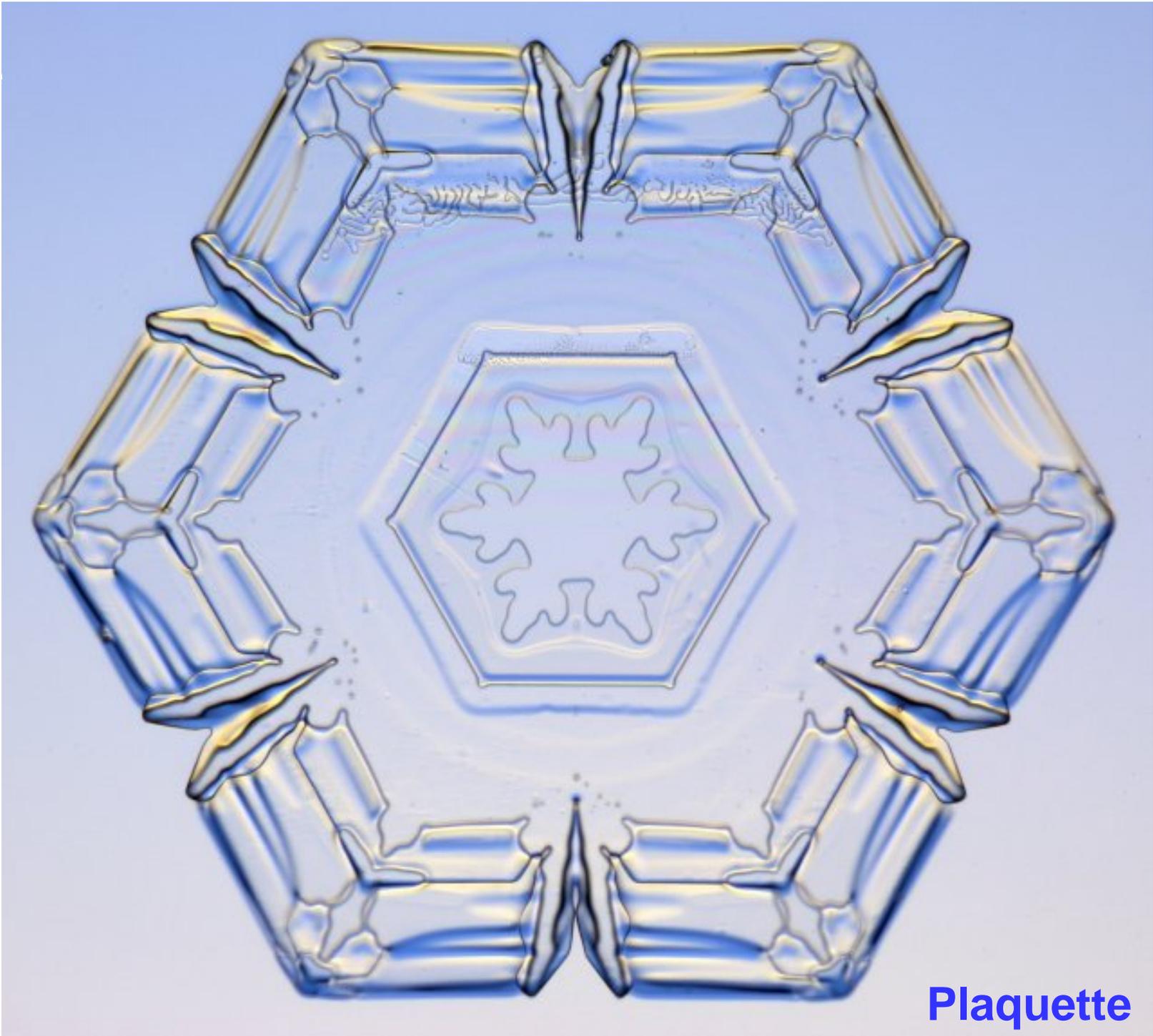
**III – La composition chimique de la neige**

**IV – Changements de la composition chimique de la neige lors du métamorphisme**

**V – Evolution des propriétés physiques de la neige lors du métamorphisme**

**VI – Composition chimique des carottes de glace**

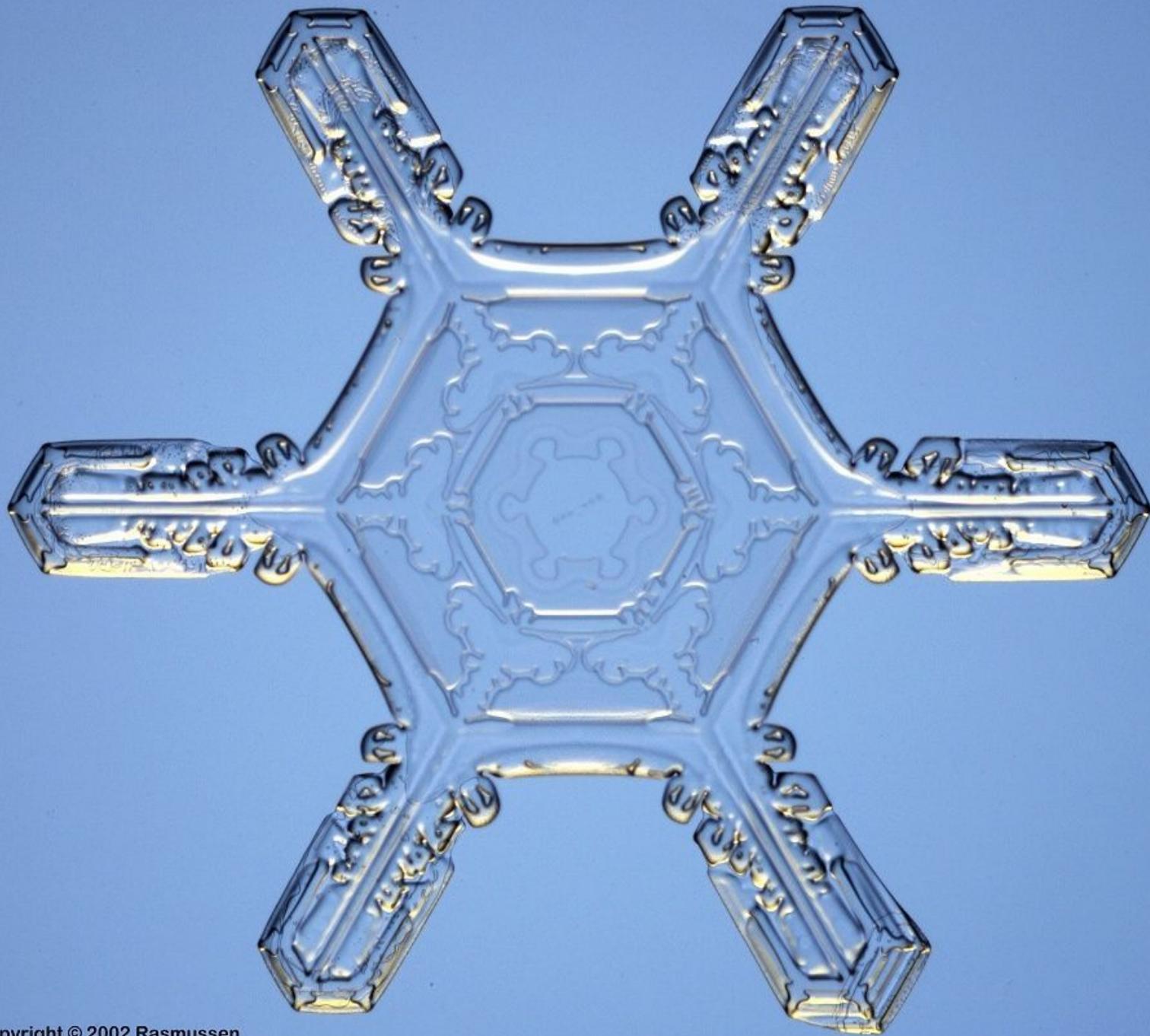




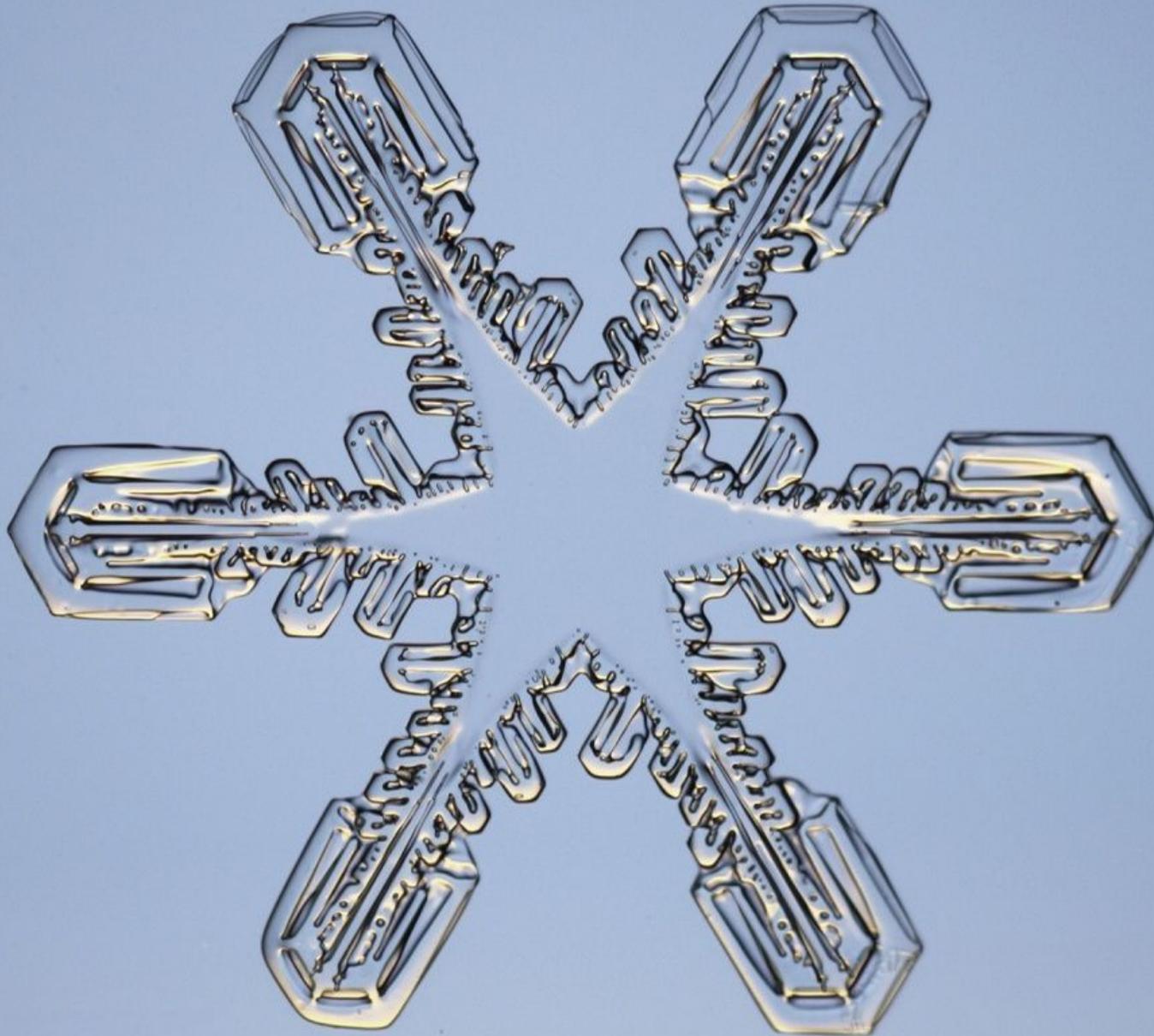
Plaque



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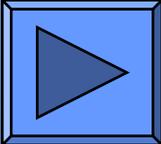
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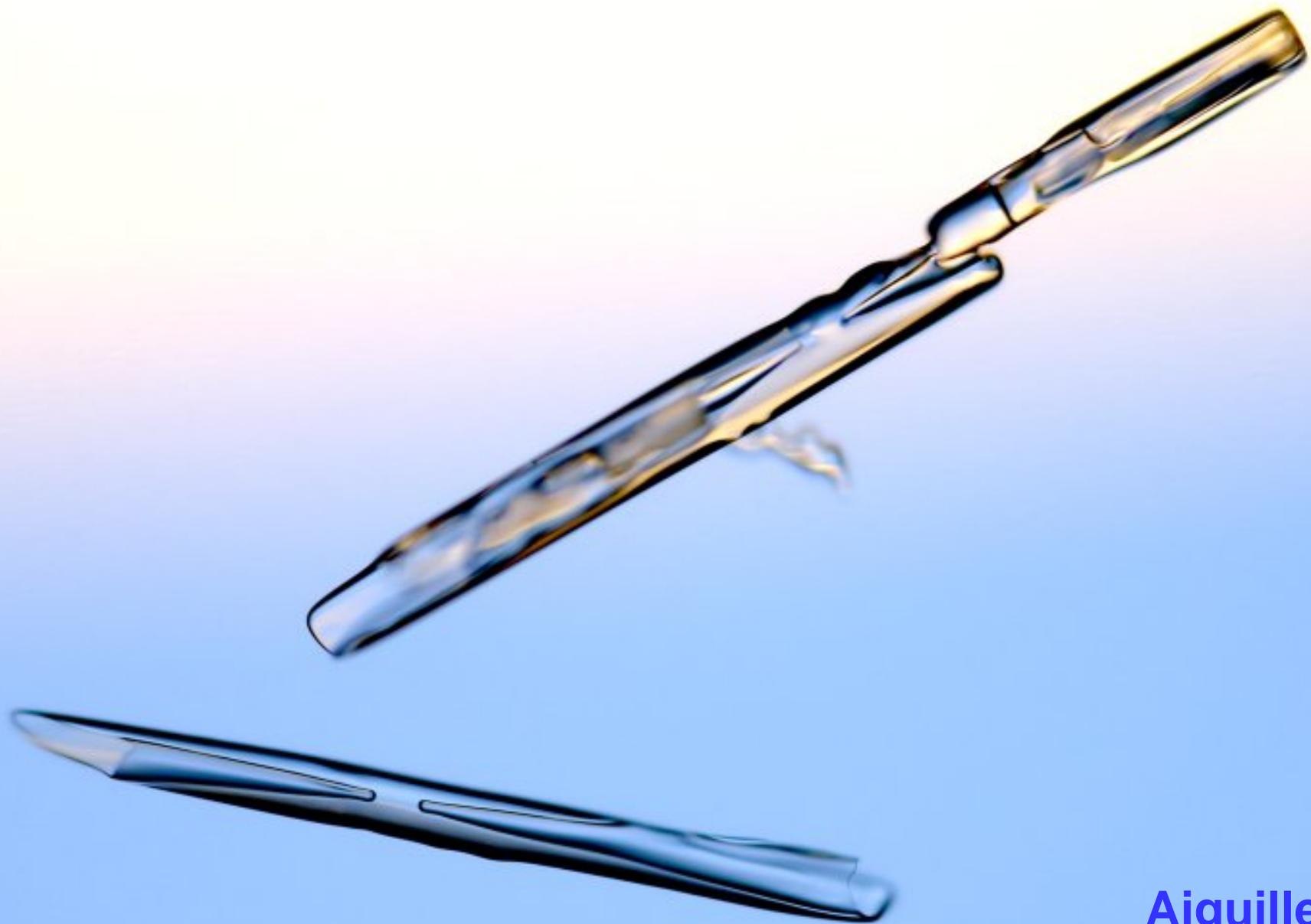


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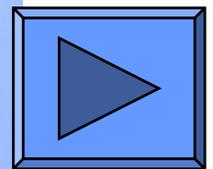


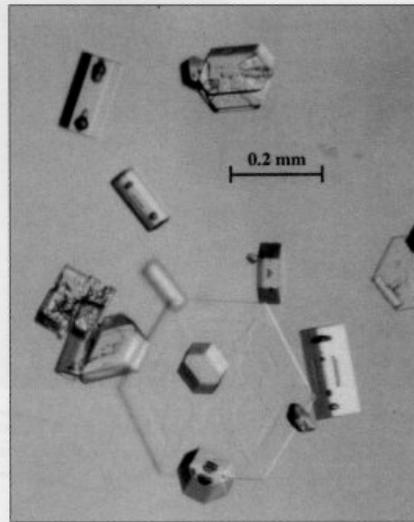
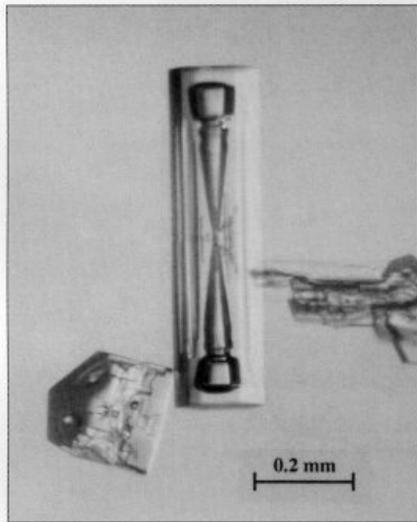
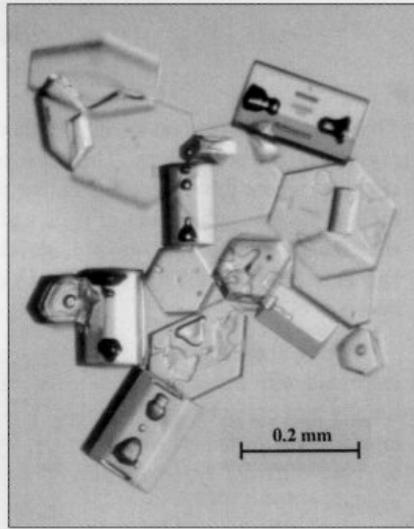
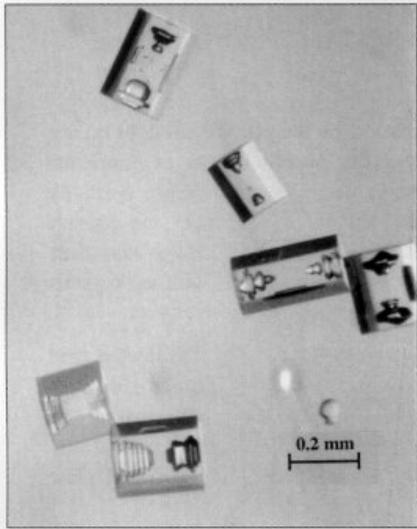


**Colonne**

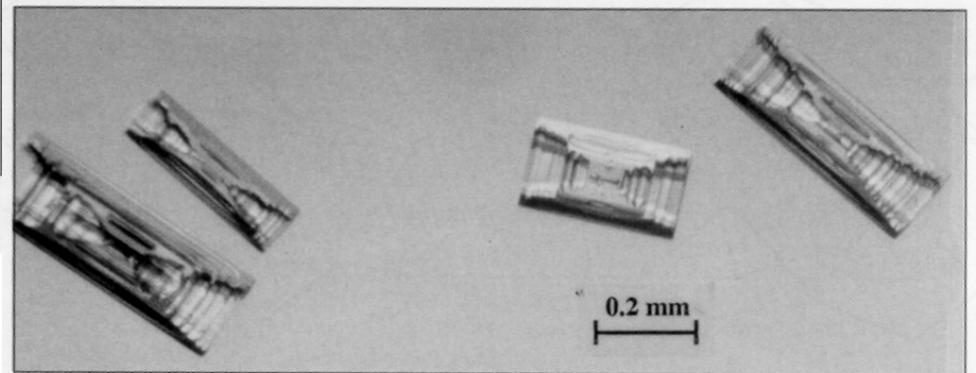


**Aiguilles**

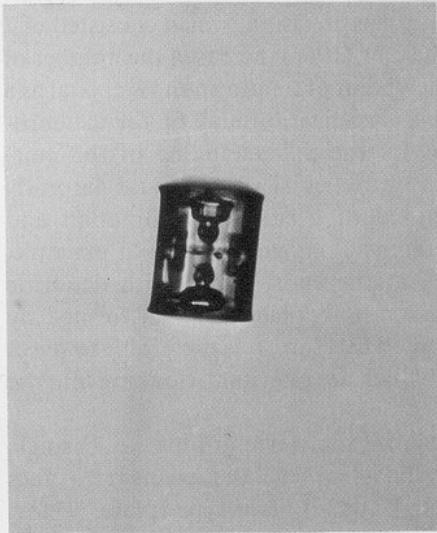




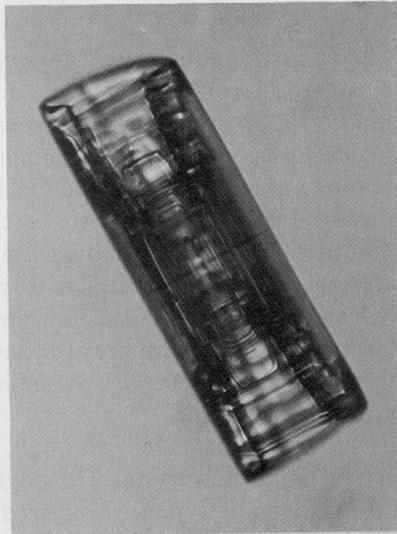
**Figure 1-3.** Some ice crystals that fell during halo displays. (Top left) Stubby columns. (Top right) Columns and plates. (Bottom left) Large column with beautiful internal structure. (Bottom right) Columns and plates.



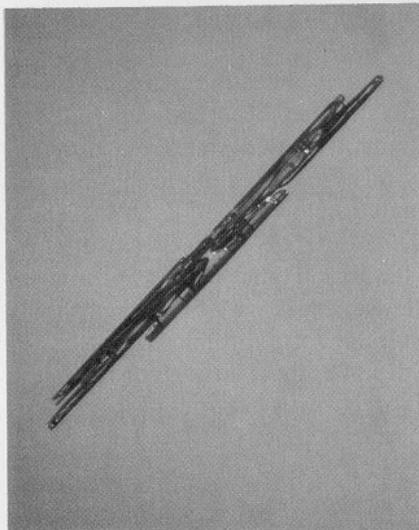
**Figure 2-5.** Some crystals collected during another halo display, similar to Display 2-1. South Pole, January 21, 1990.



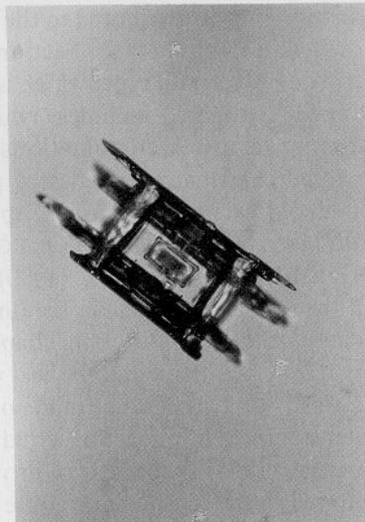
(a)



(b)



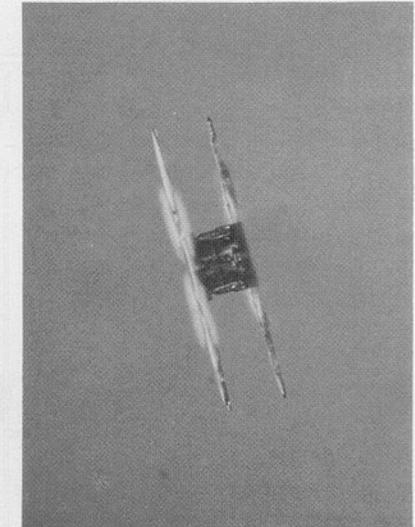
(c-i)



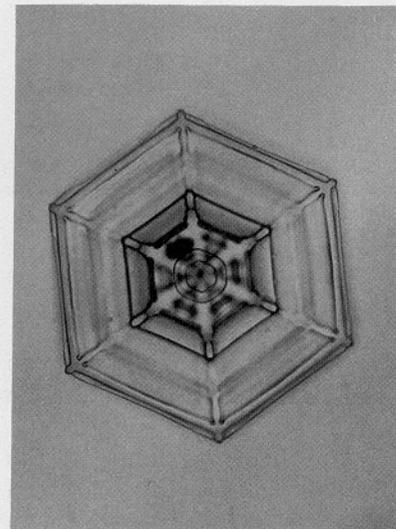
(c-ii)



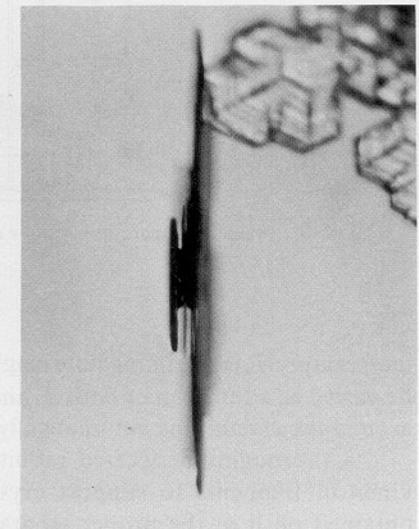
(i-i)



(i-ii)

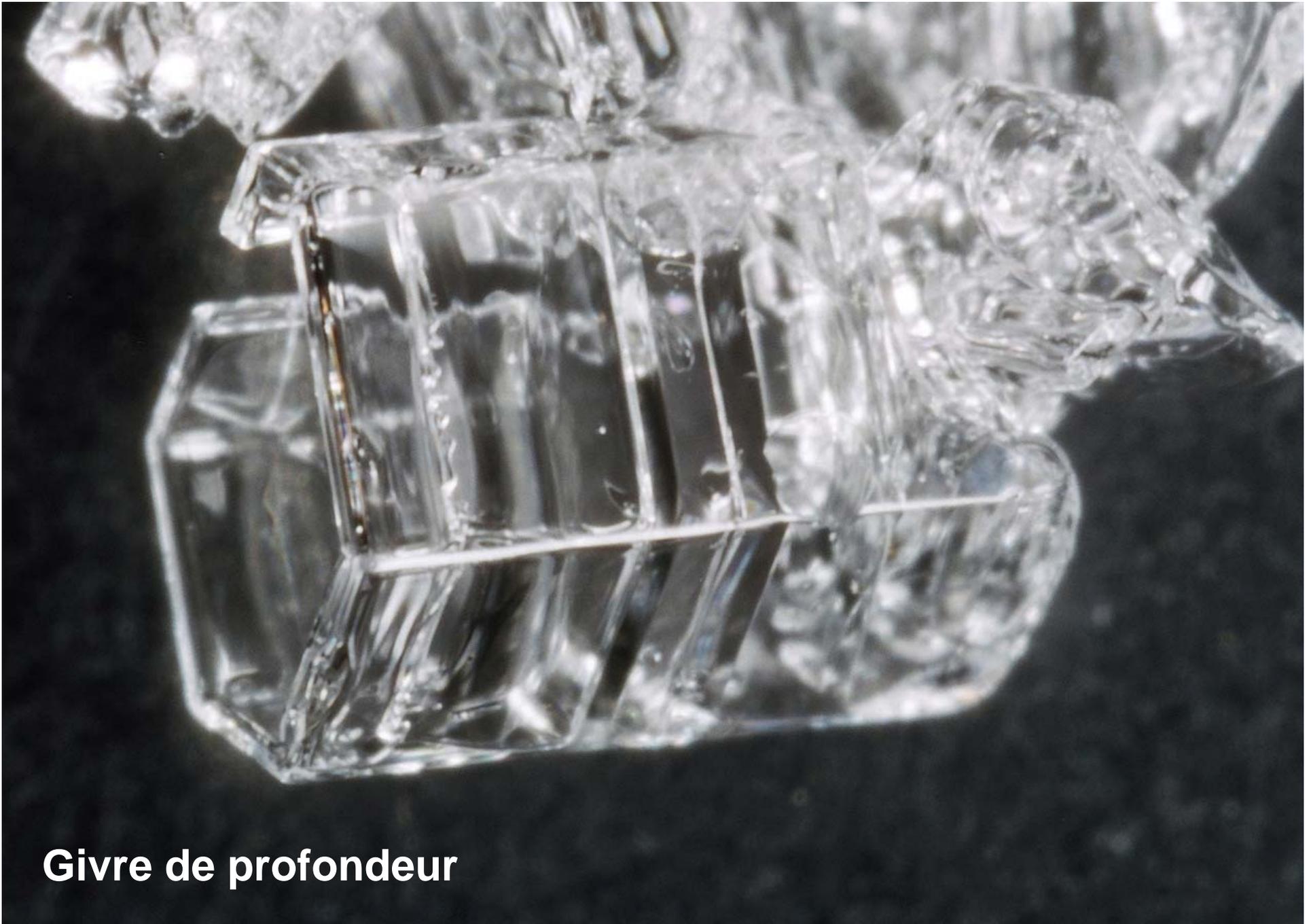


(j)



(k)

FIG. 2. Photomicrographs of snow single crystals: (a) Prism, (b) Skeletal prism, (c) Needle, (d) Plate, (e) Sector, (f) Dendrite, (g) Dendrite with plates at ends, (h) Plate with dendritic extensions, (i) "Tsumuzumi" (prism with plates), (j) Double plate, (k) its side view.

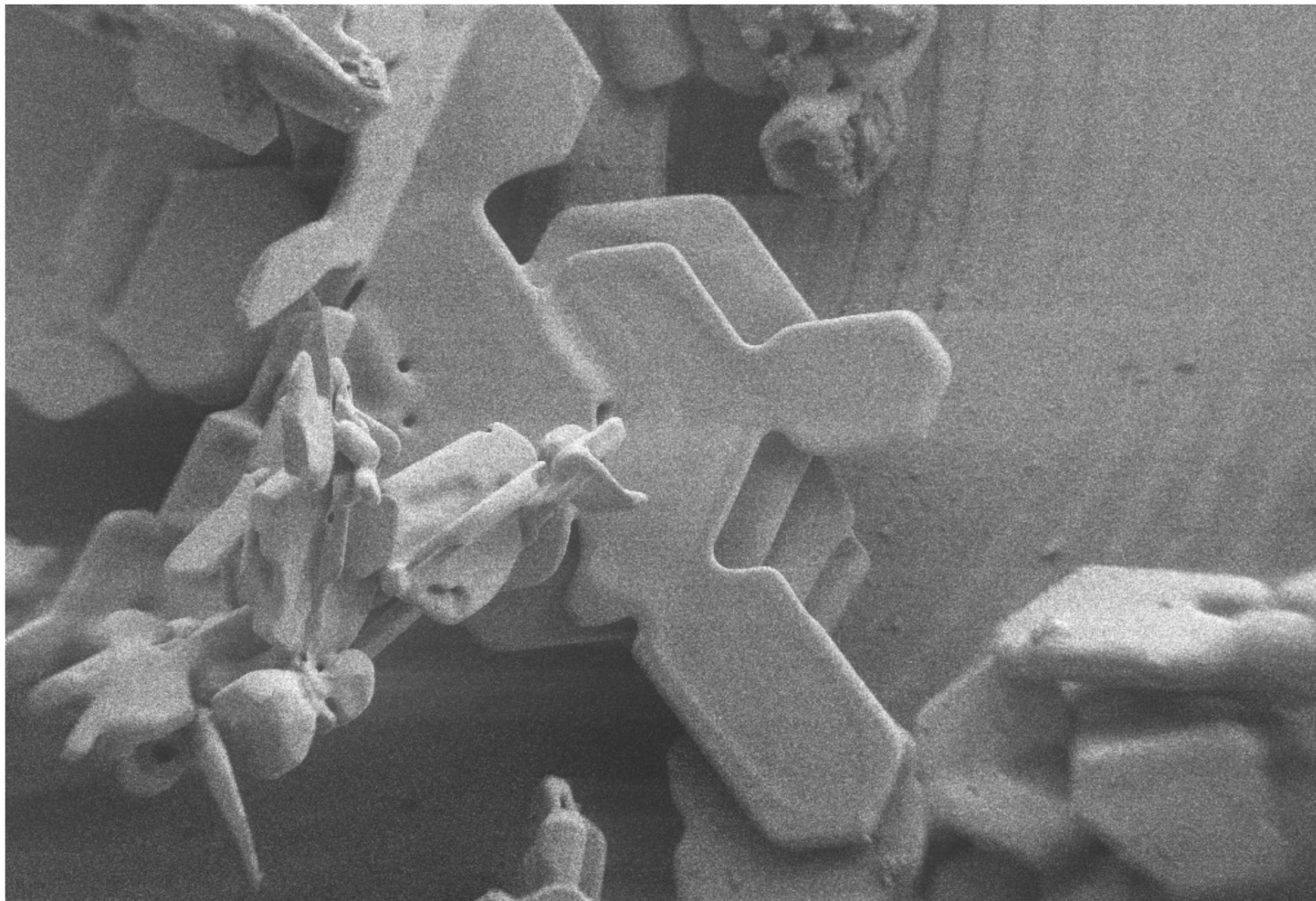


**Givre de profondeur**







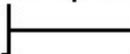


FE-REM Lab GeoZentrum-GÖ

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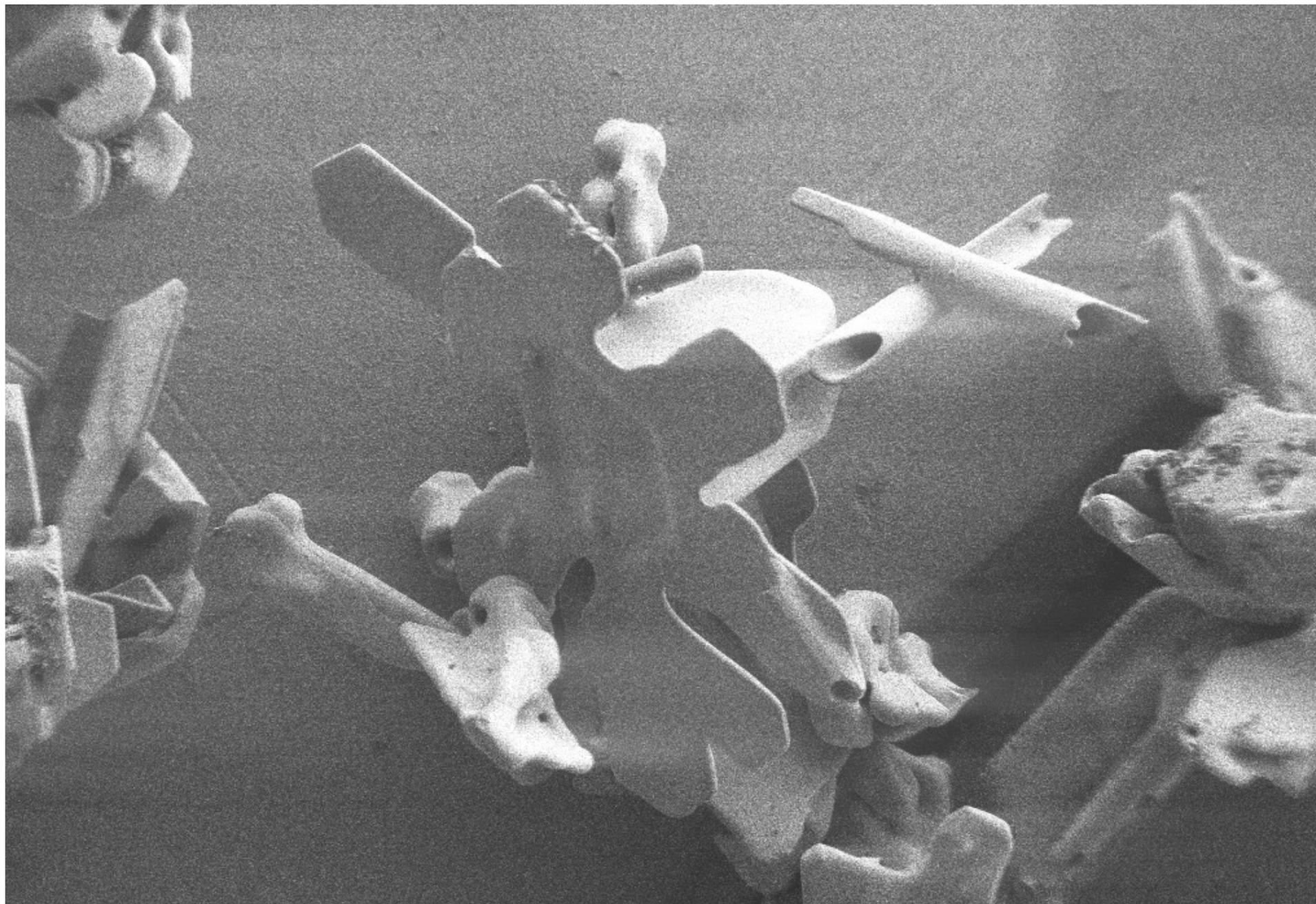
100µm



EHT = 1.20 kV  
WD = 9 mm

Signal A = SE2  
Photo No. = 1617

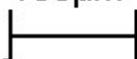
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FE-REM Lab GeoZentrum-GÖ

100µm

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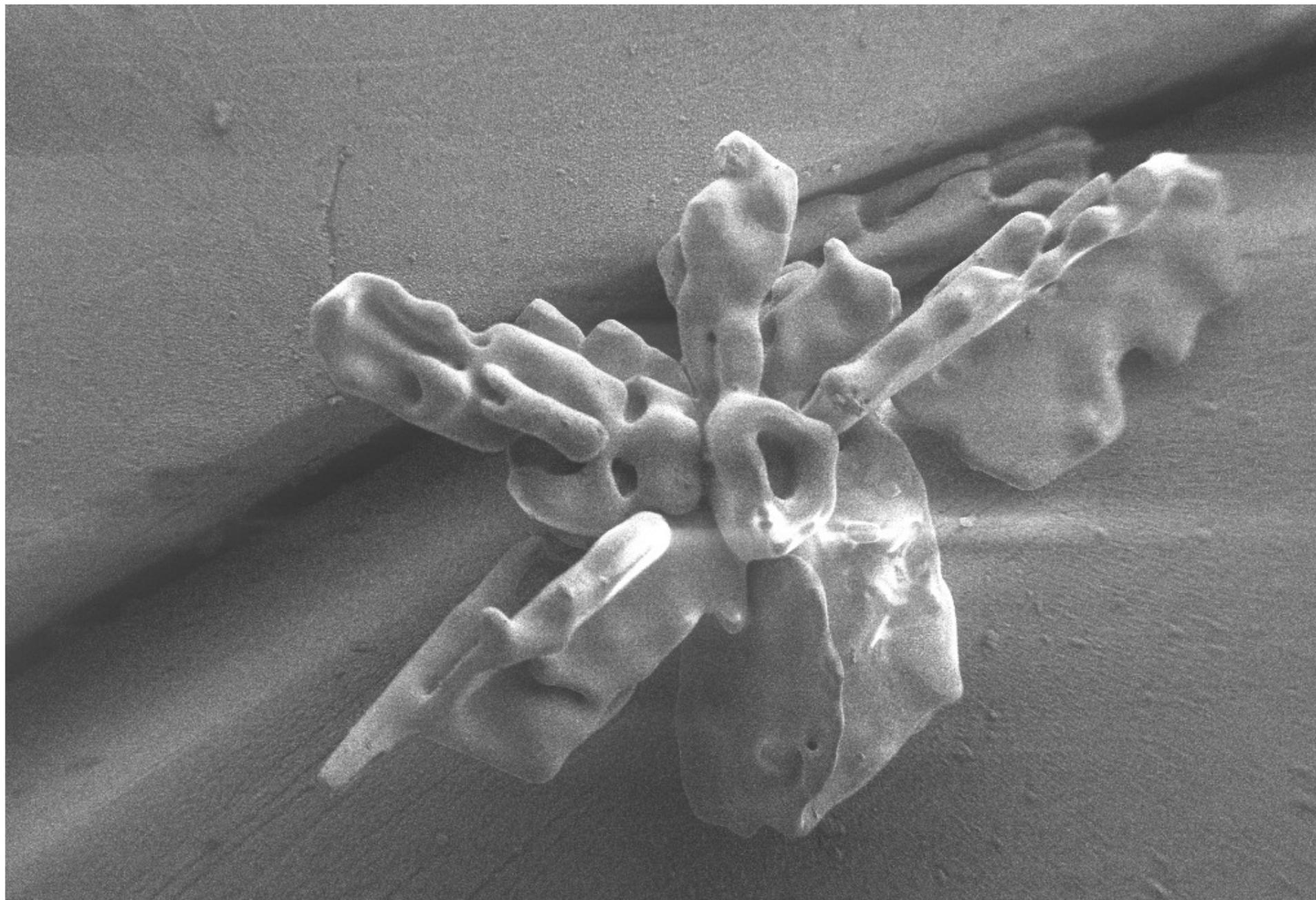


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WD = 7 mm

Signal A = SE2  
Photo No. = 1630

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Time :16:36

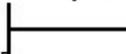


FE-REM Lab GeoZentrum-GÖ

MAG = 173 X

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100µm



EHT = 1.20 kV  
WD = 9 mm

Signal A = SE2  
Photo No. = 1666

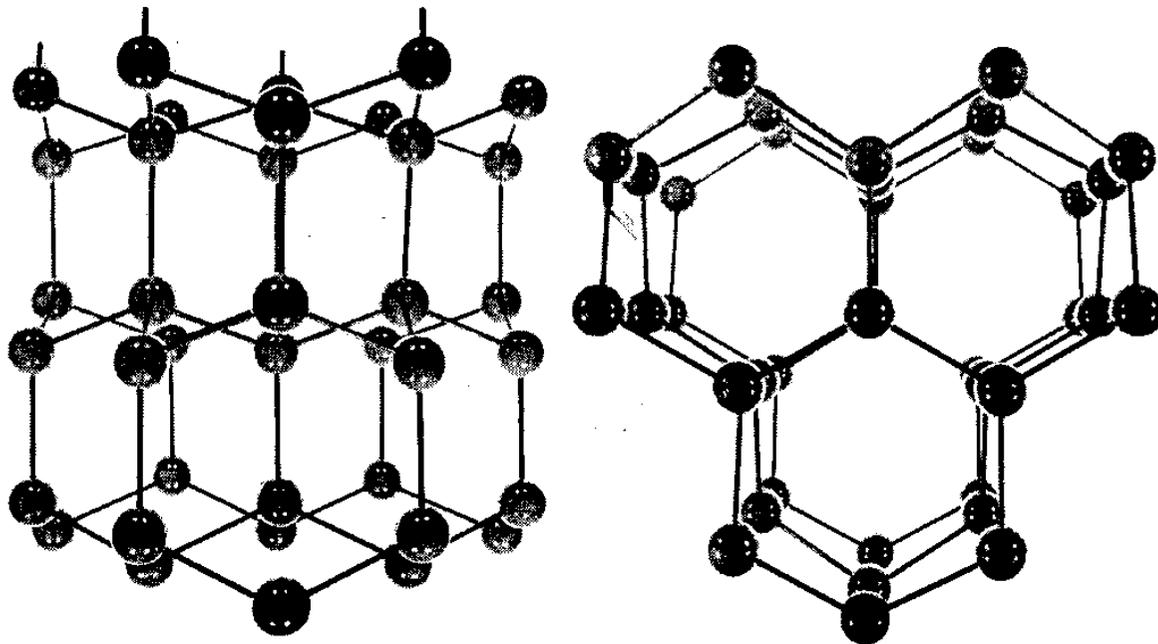
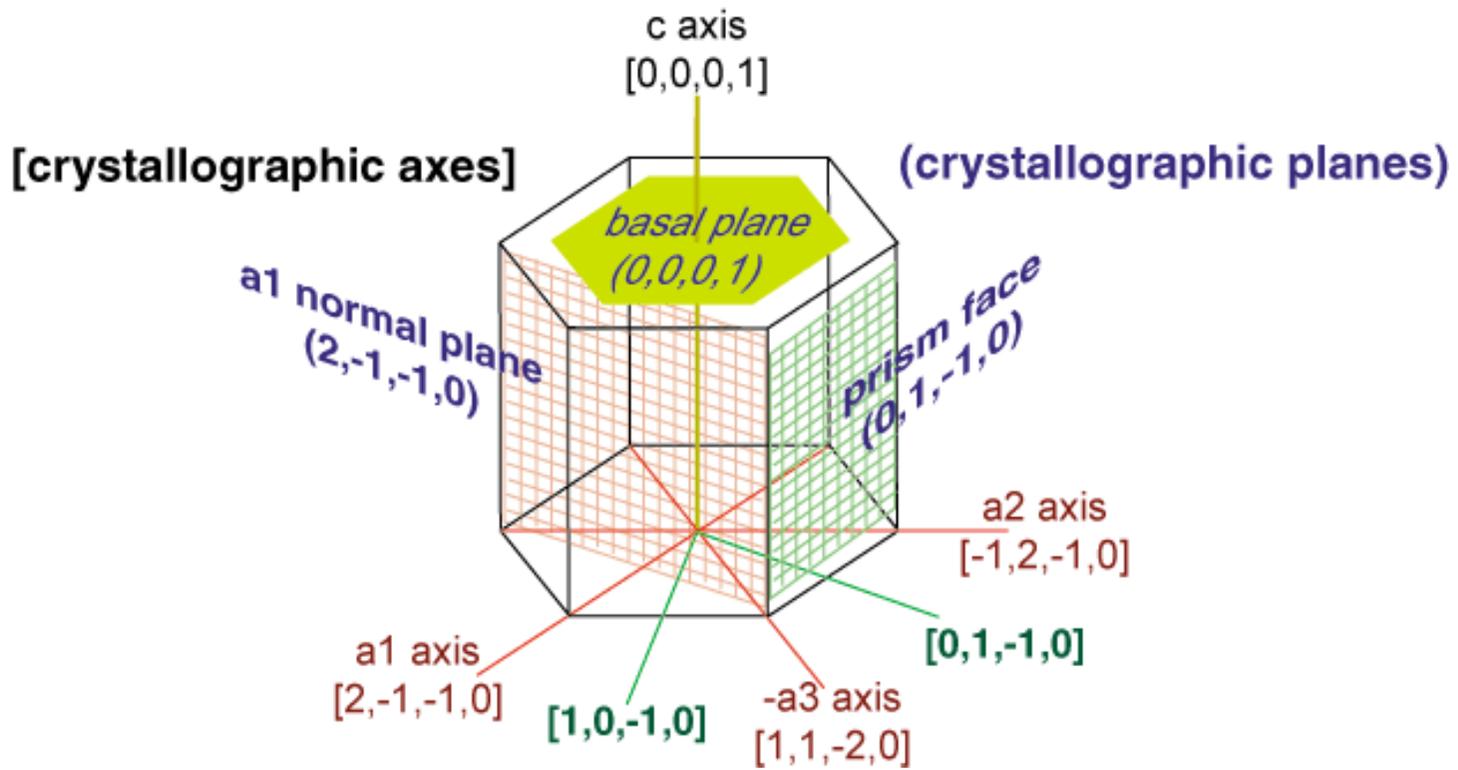
Date :14 Mar 2002  
Time :17:38

<http://www.its.caltech.edu/~atomic/snowcrystals/>

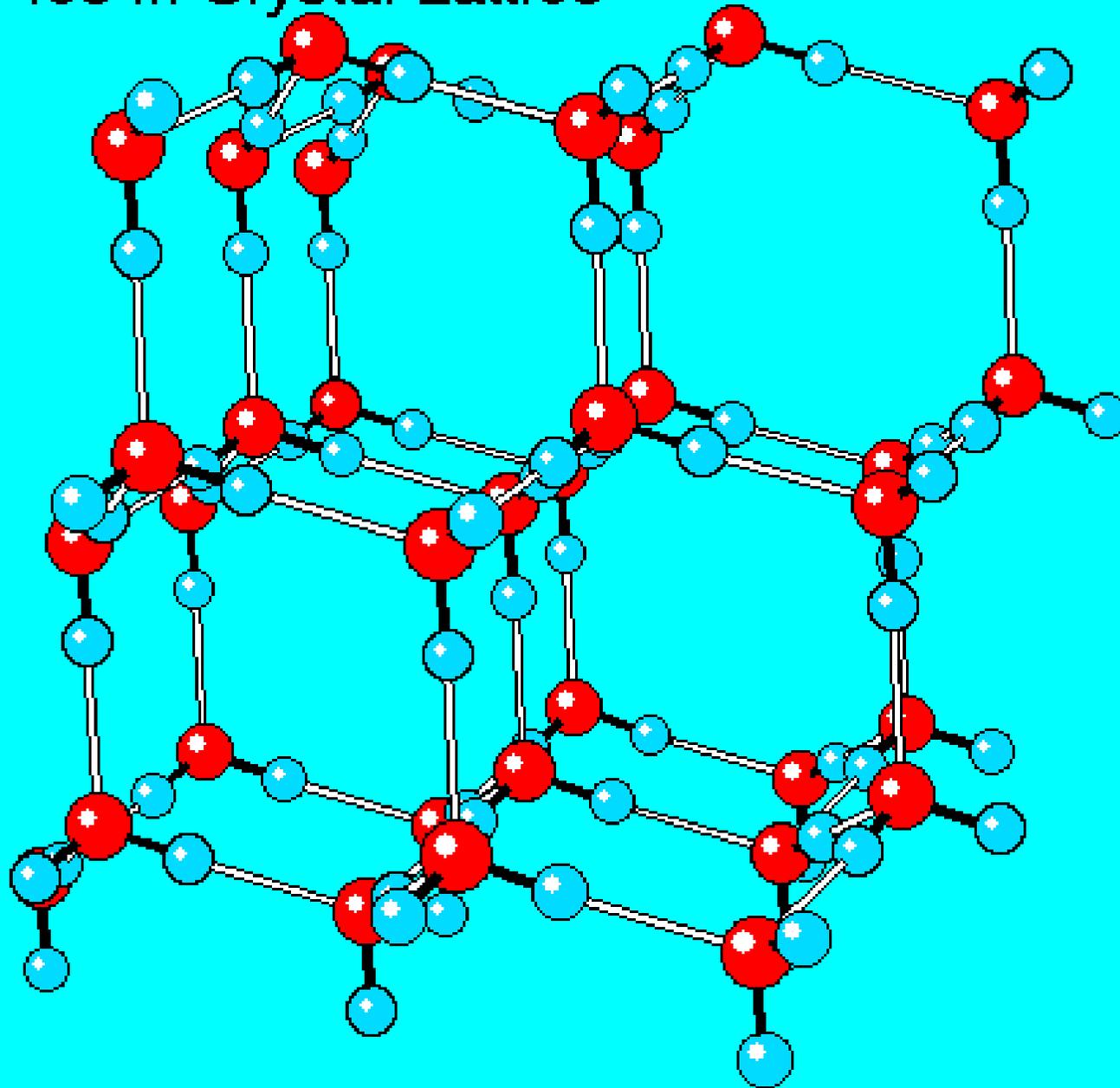
<http://emu.arsusda.gov/snowsite/default.html>

## **Objectifs de la première partie de ce cours :**

- Apporter des éléments permettant d'expliquer la forme des cristaux de neige précipitants
- Décrire les transformations des cristaux de neige après la précipitation : le métamorphisme



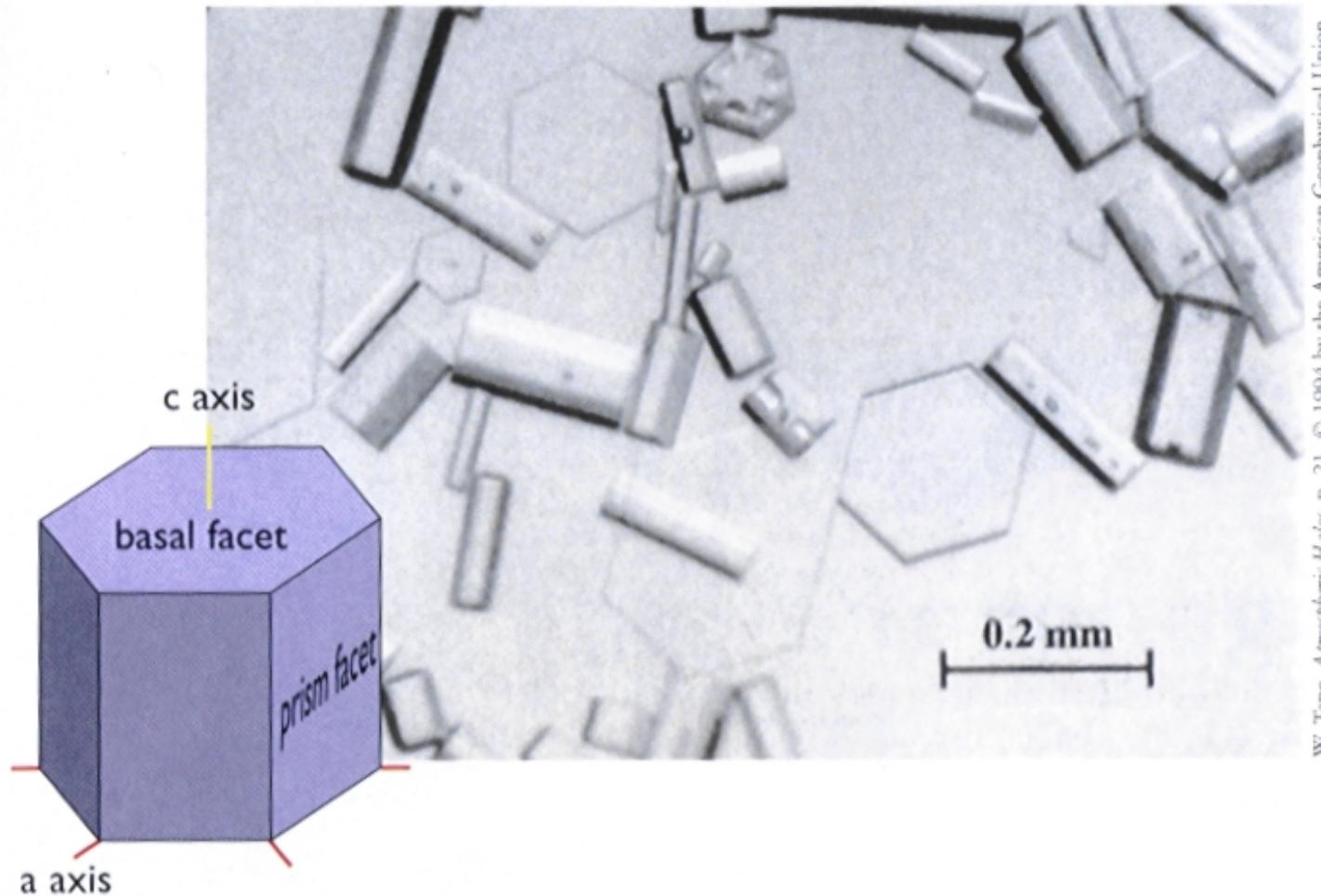
# Ice Ih Crystal Lattice

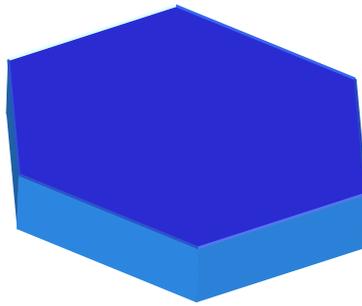


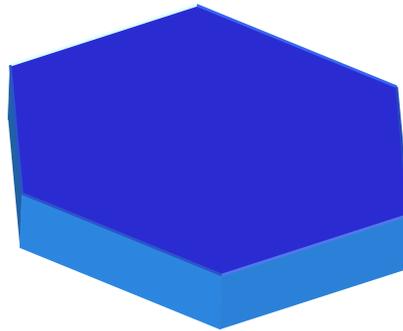
# Croissance des cristaux

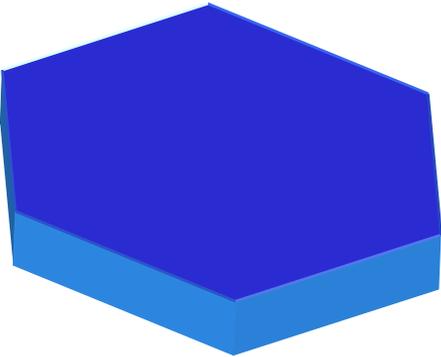
La forme dépend de la face dont la croissance est favorisée

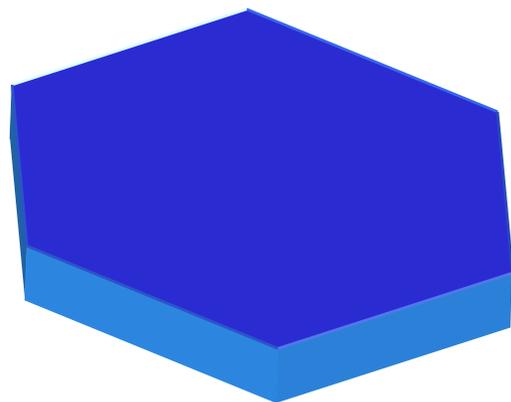
- Face prismatique : plaquettes, étoiles, dendrites
- Face basale : colonnes, aiguilles

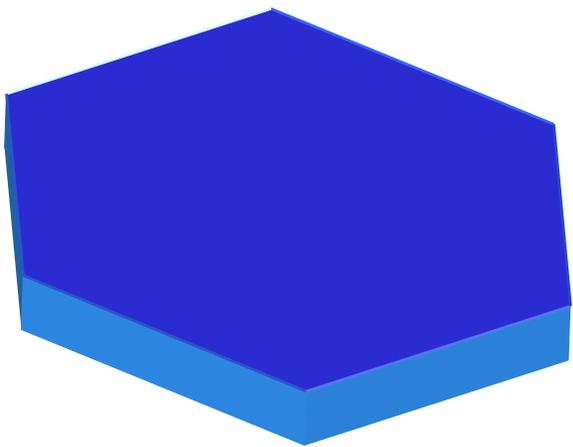


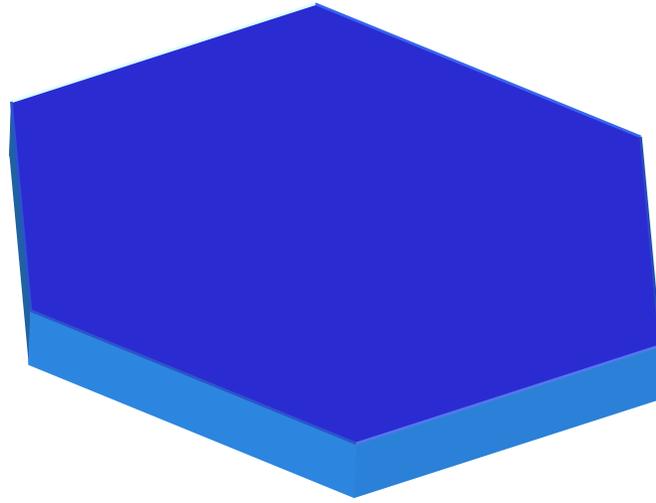


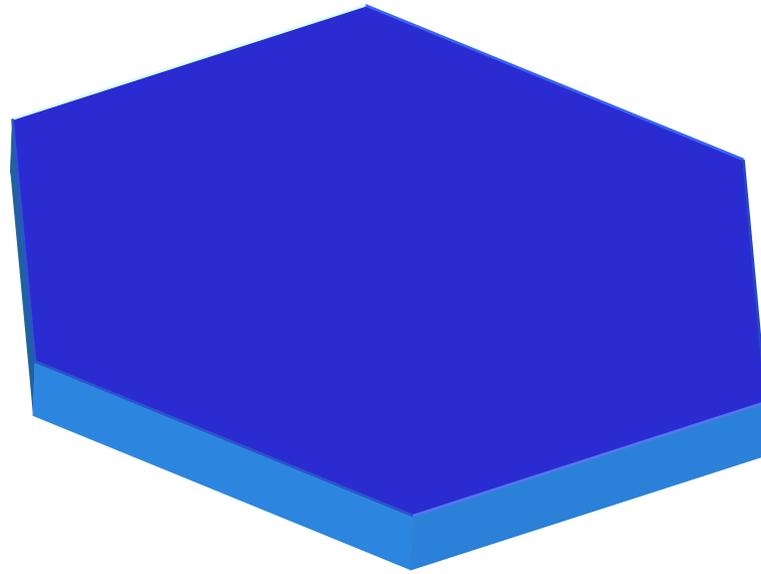


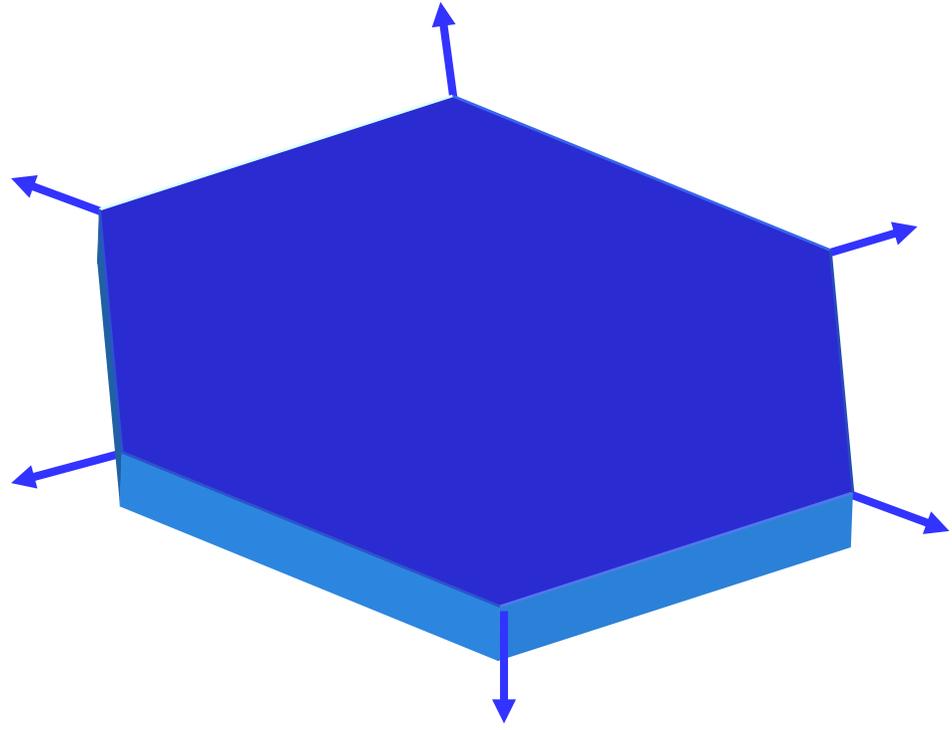


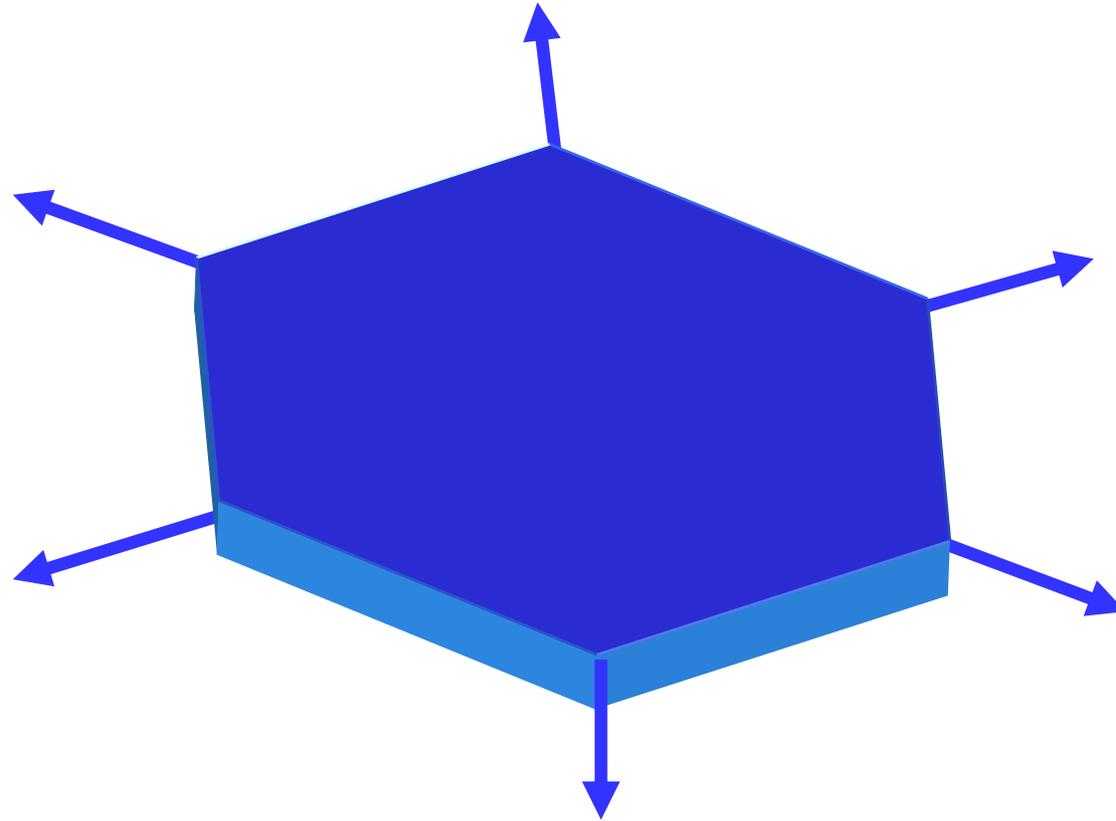


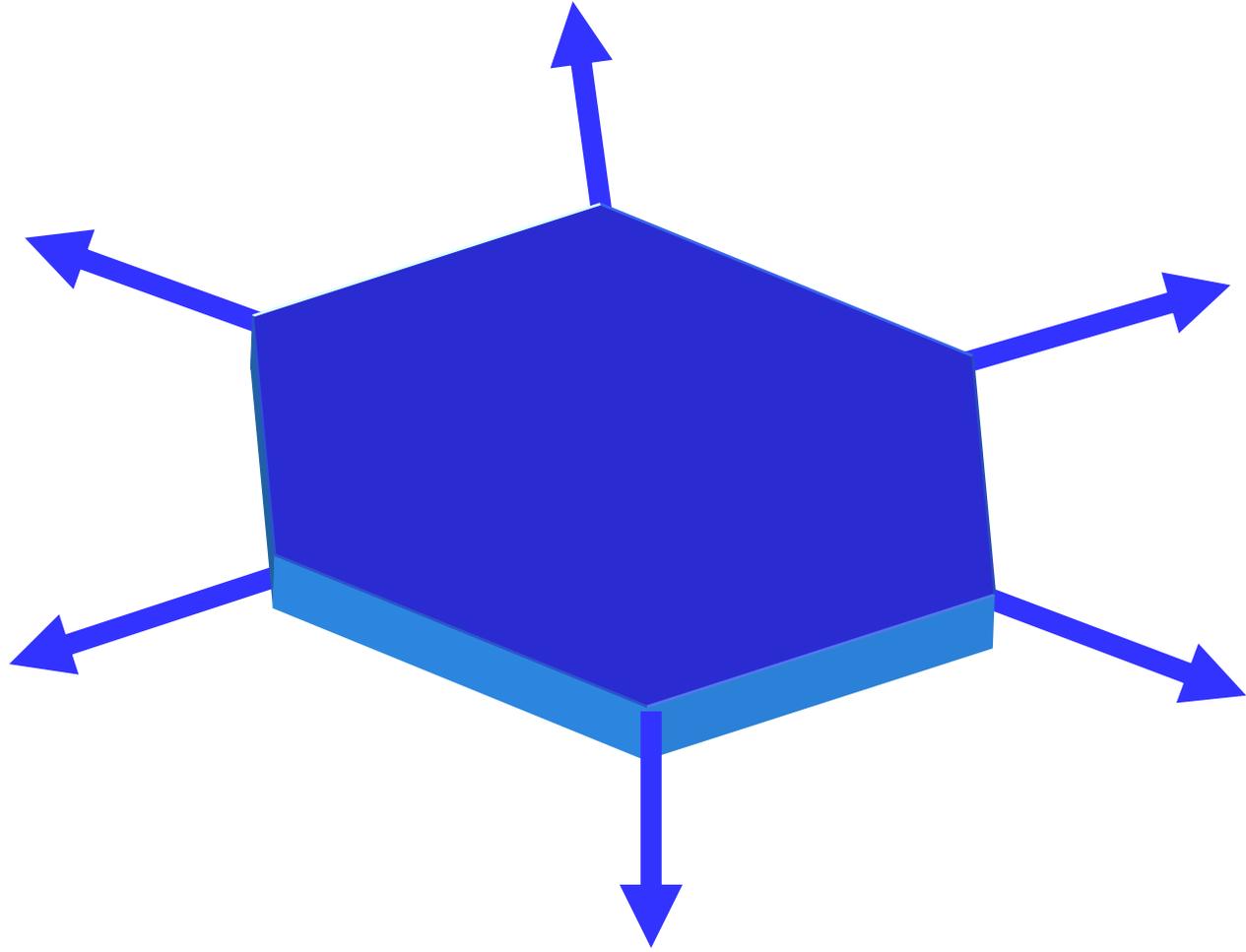


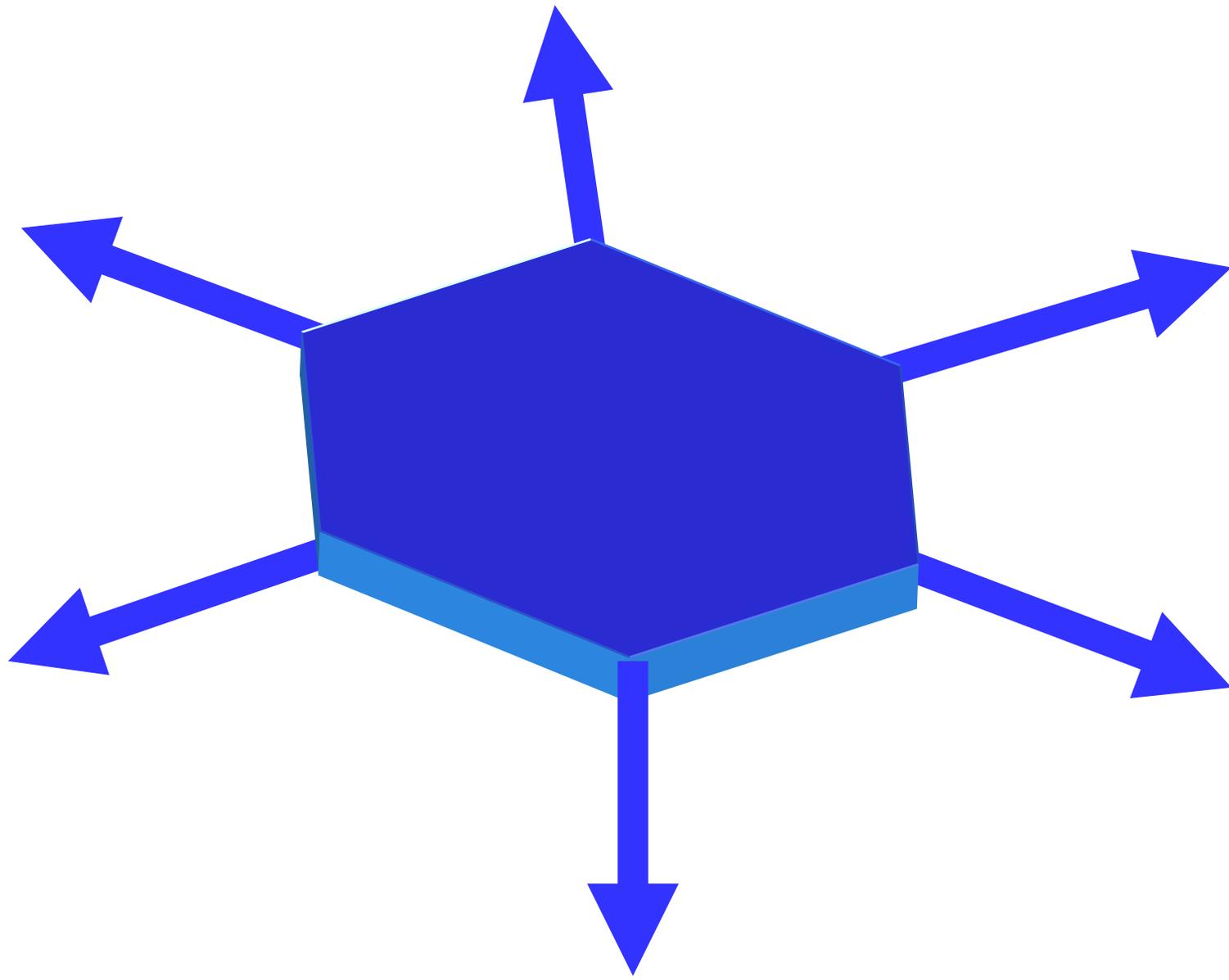


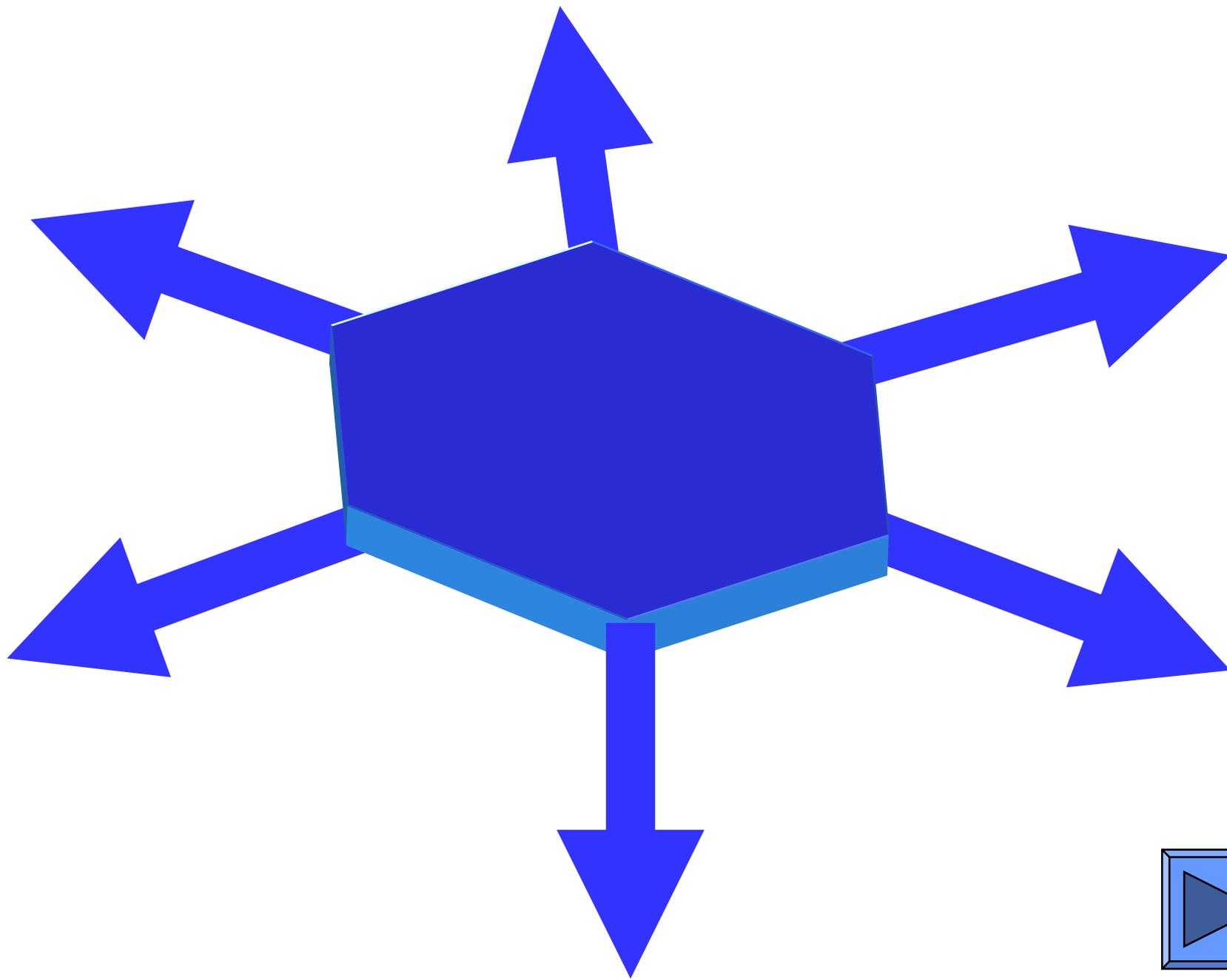




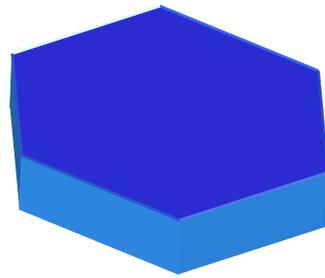


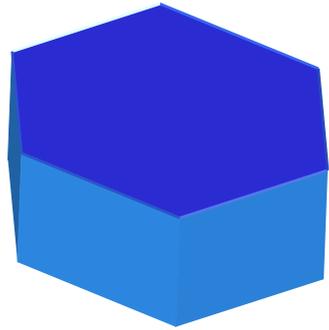


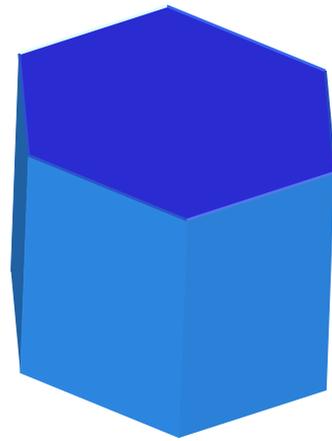


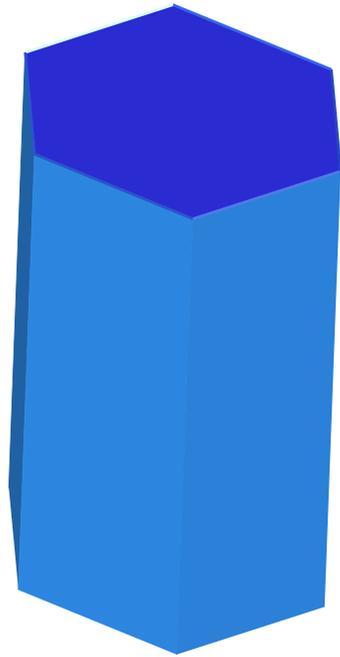


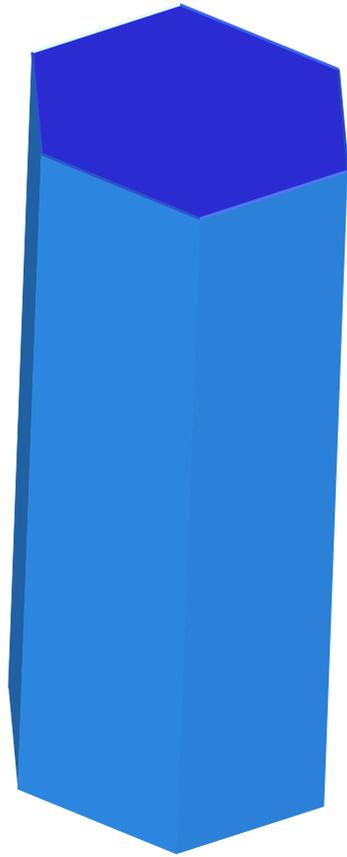


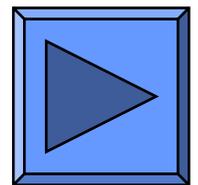
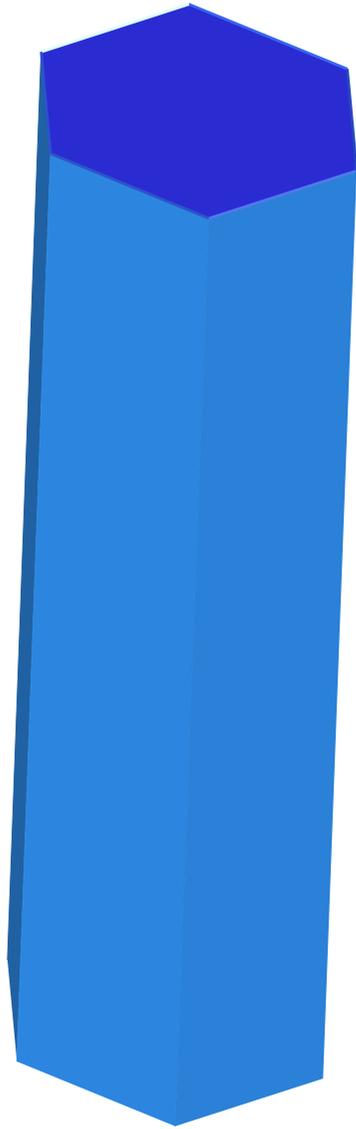




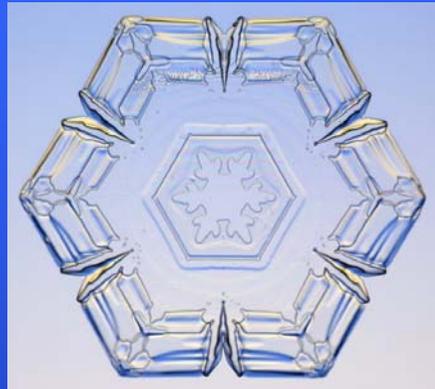




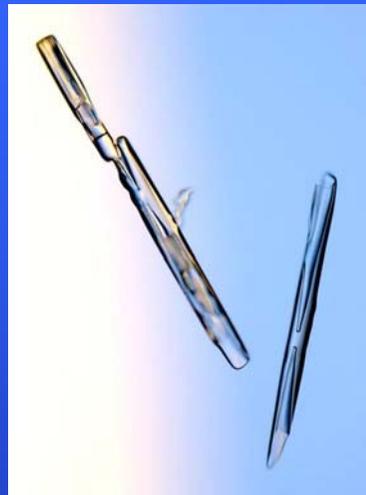




**Plaquettes**



**Colonnes  
ou  
aiguilles**



**Cristaux  
dendritiques**



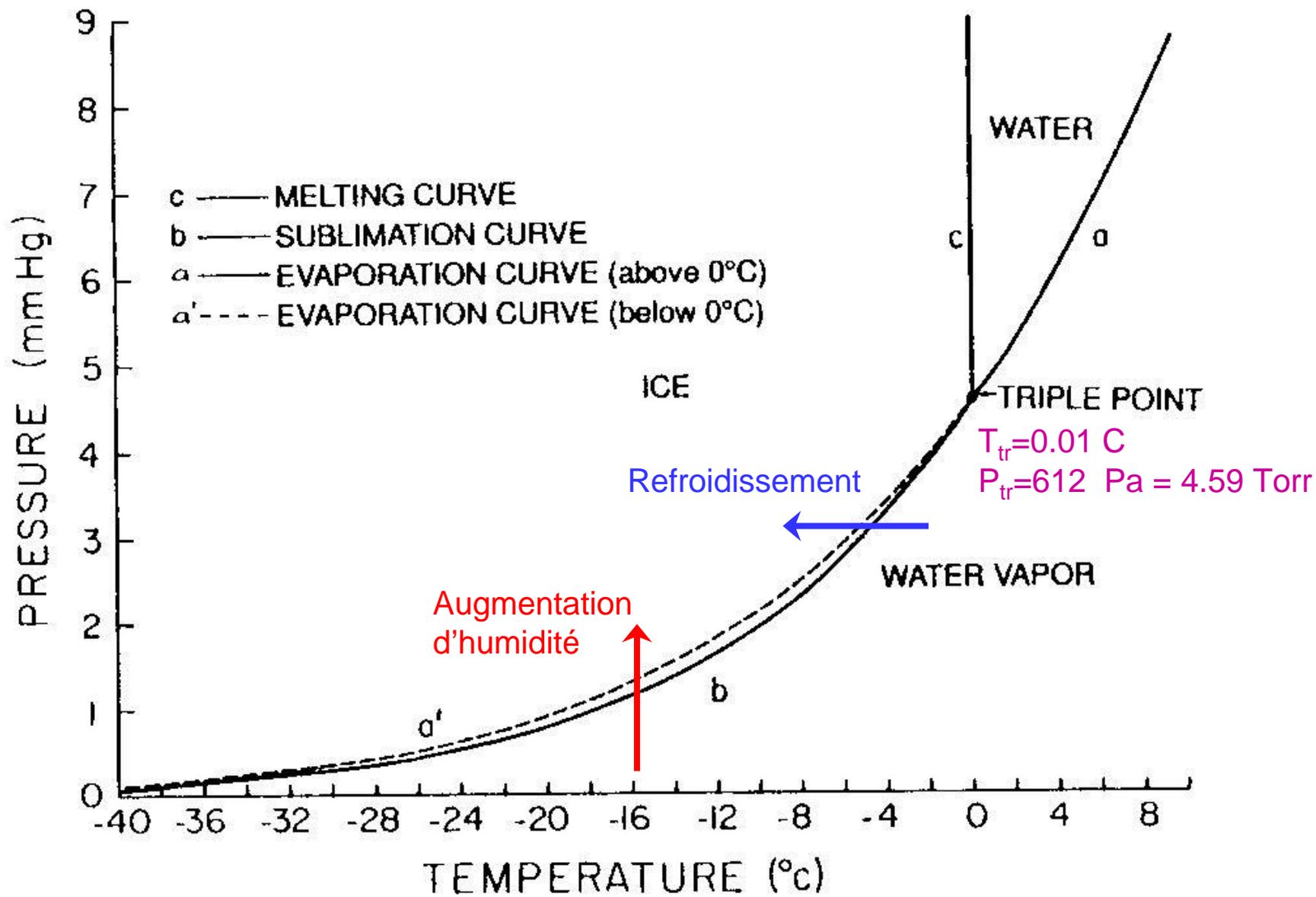
**Balles de  
fusil**

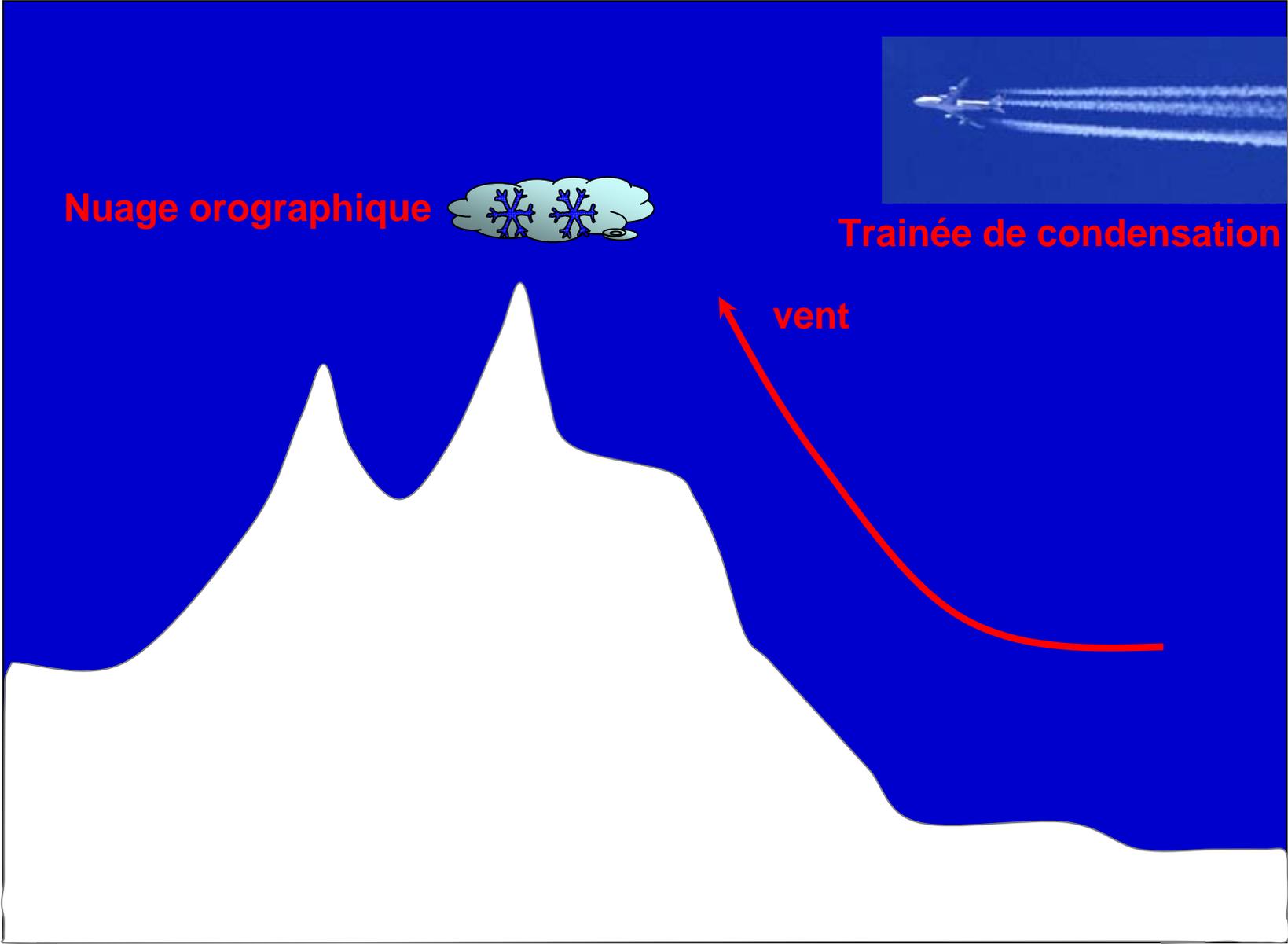


**Doux**

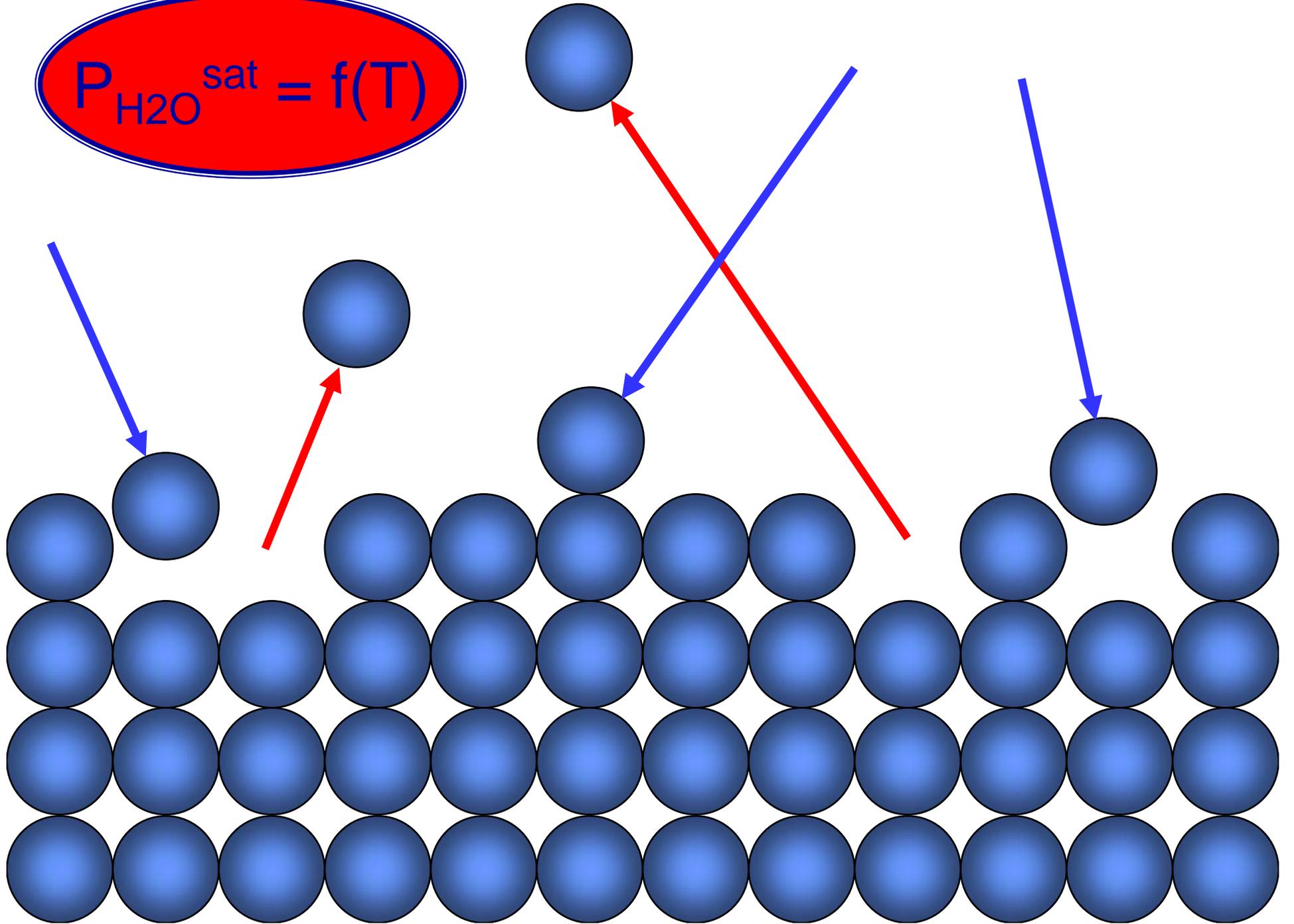
**Froid**

**Très froid**

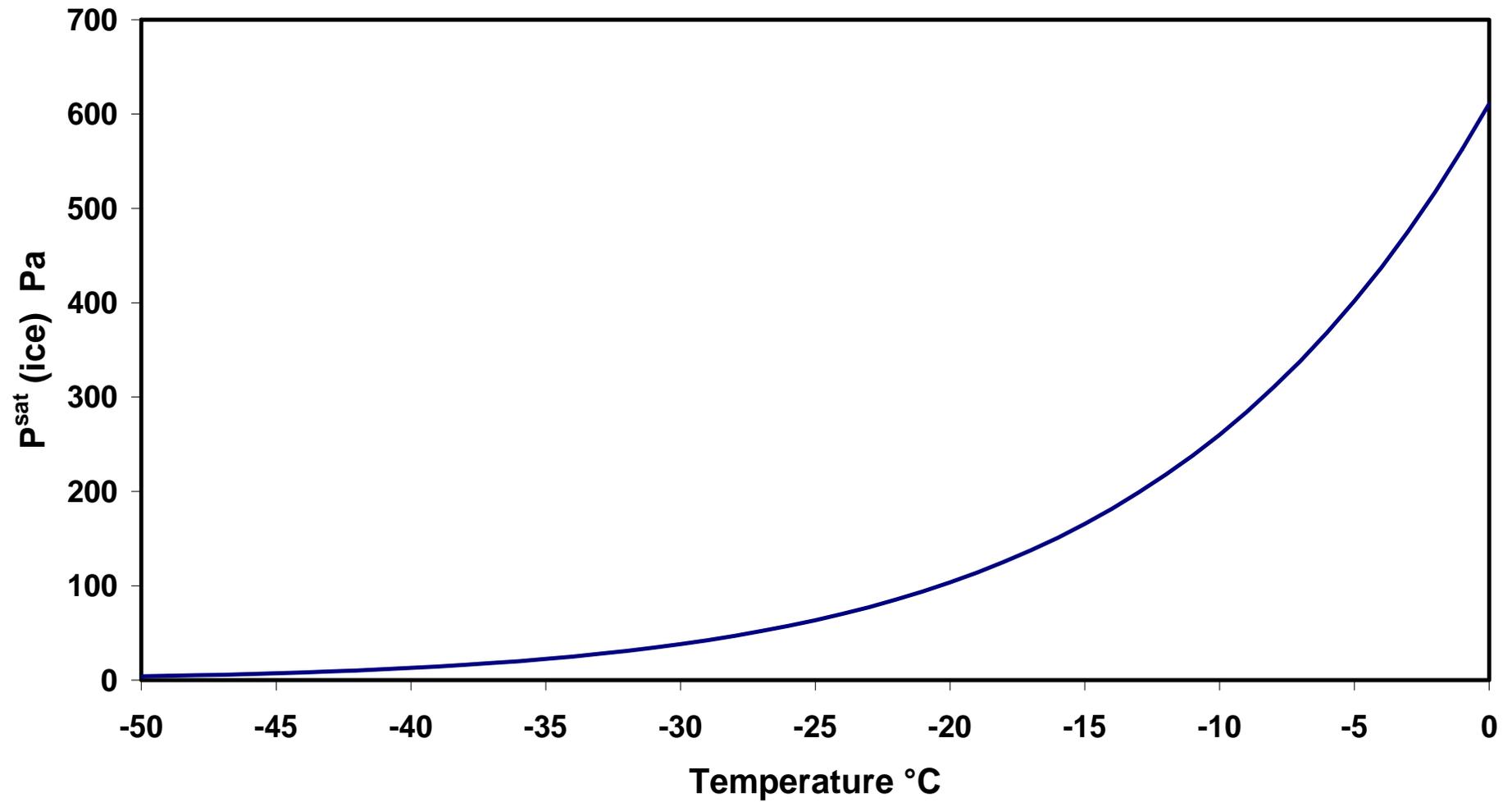




$$P_{\text{H}_2\text{O}}^{\text{sat}} = f(T)$$

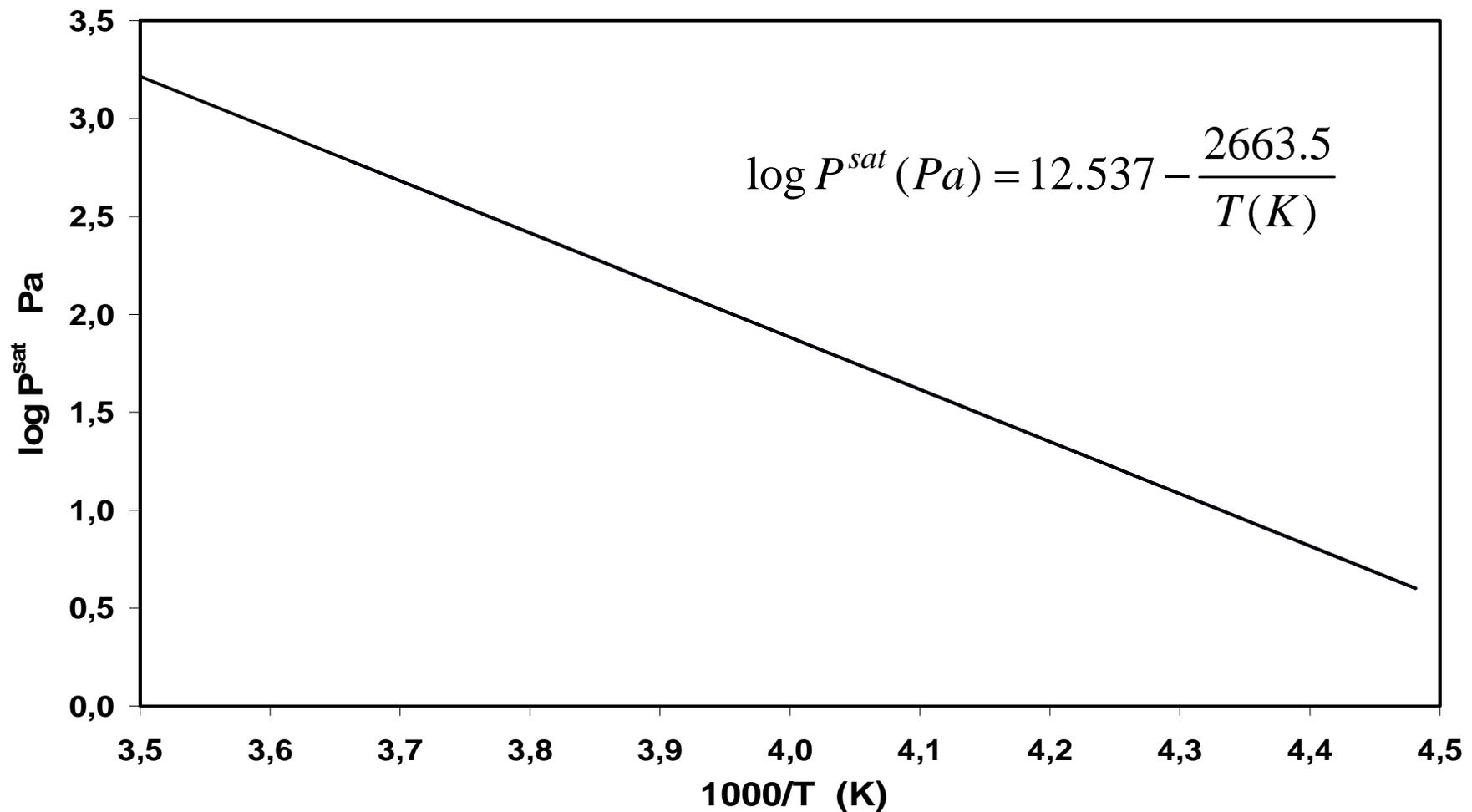


# Pression de vapeur saturante au dessus de la glace

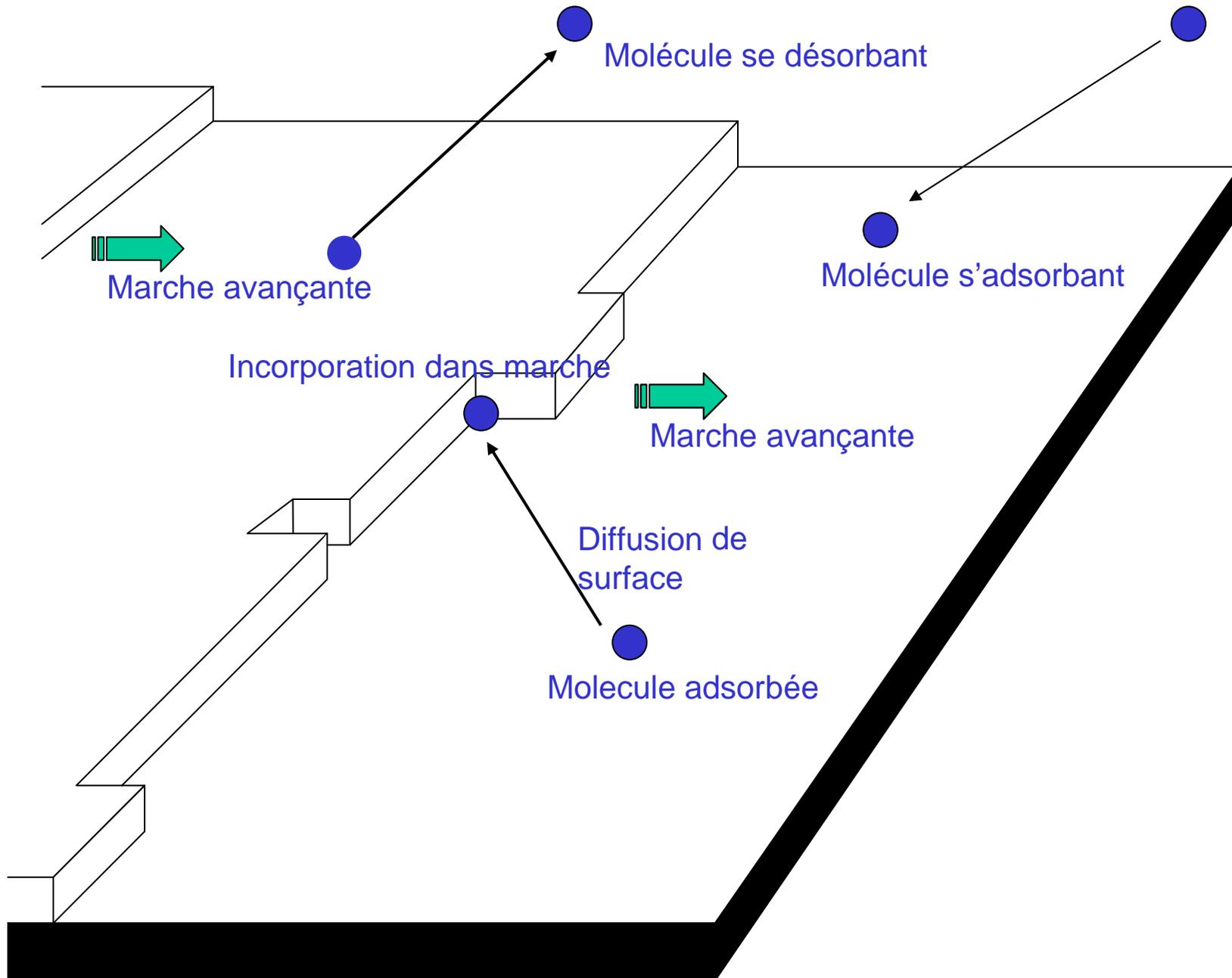


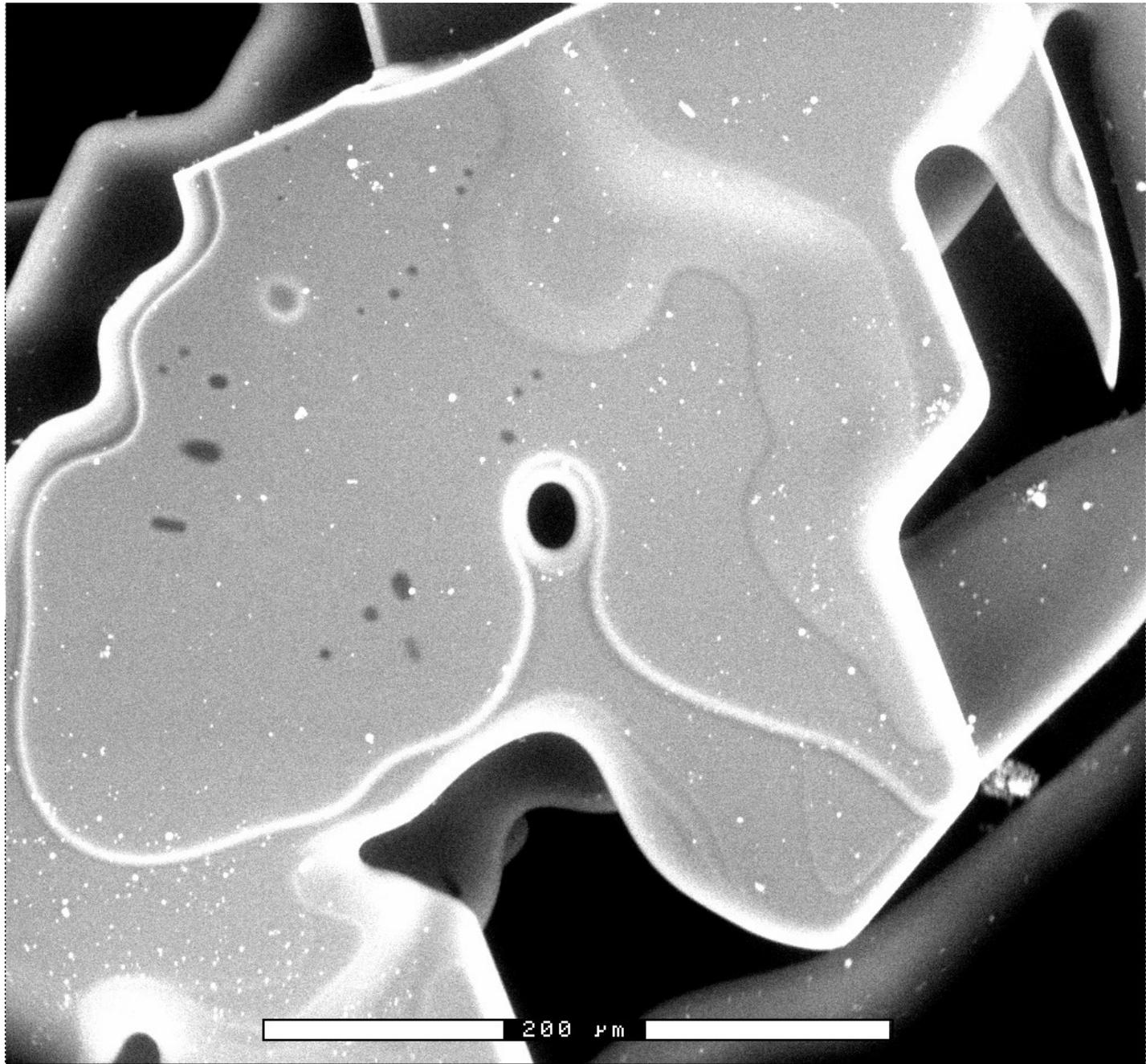
# Pression de vapeur saturante au dessus de la glace

Loi de Clapeyron :  $\frac{d \ln P^{sat}}{d(1/T)} = -\frac{\Delta H_{sub}}{R}$        $\Delta H_{sub} = -50973 \text{ J/mol}$



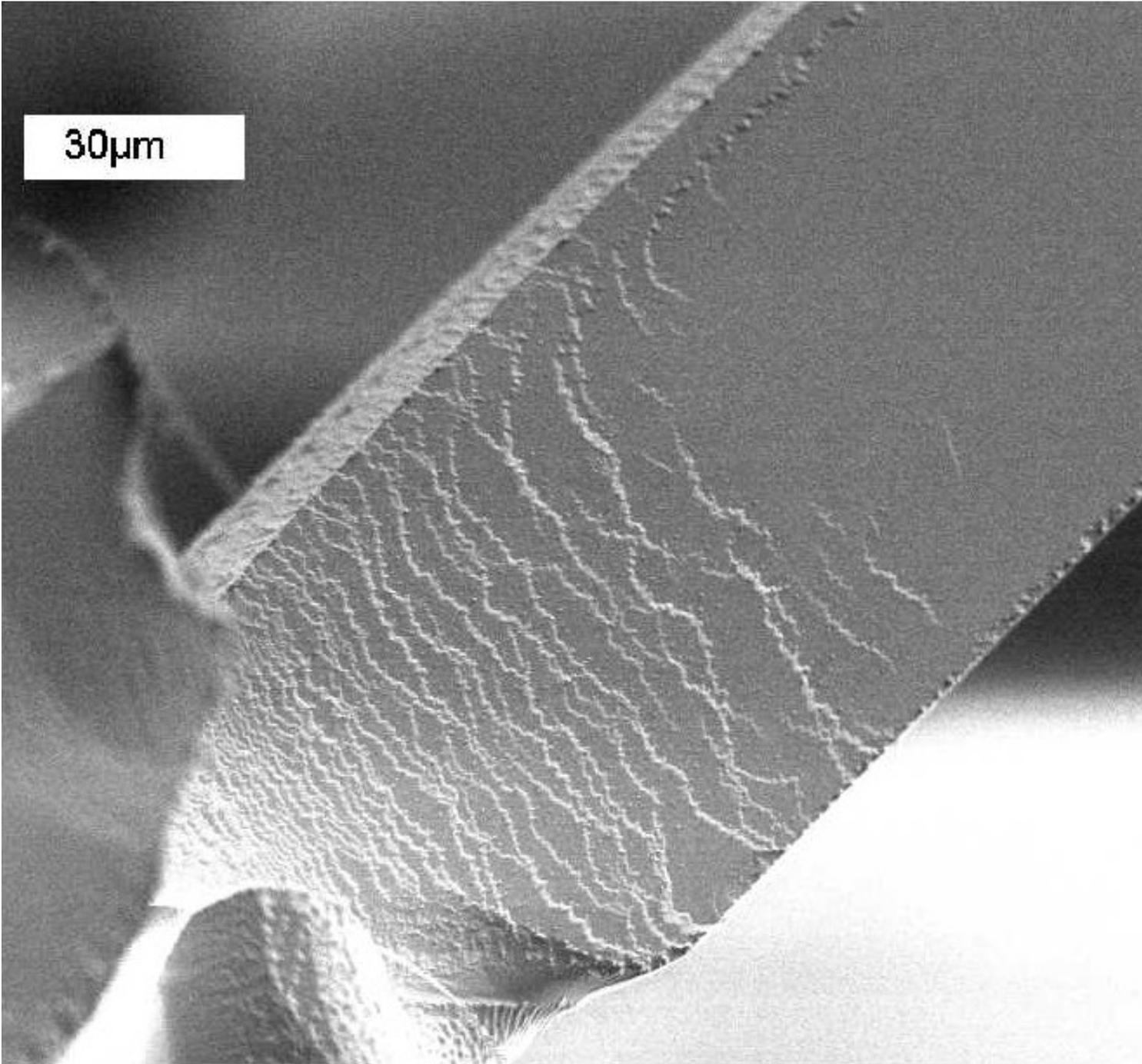
# Mécanisme de croissance d'un cristal par condensation de gaz



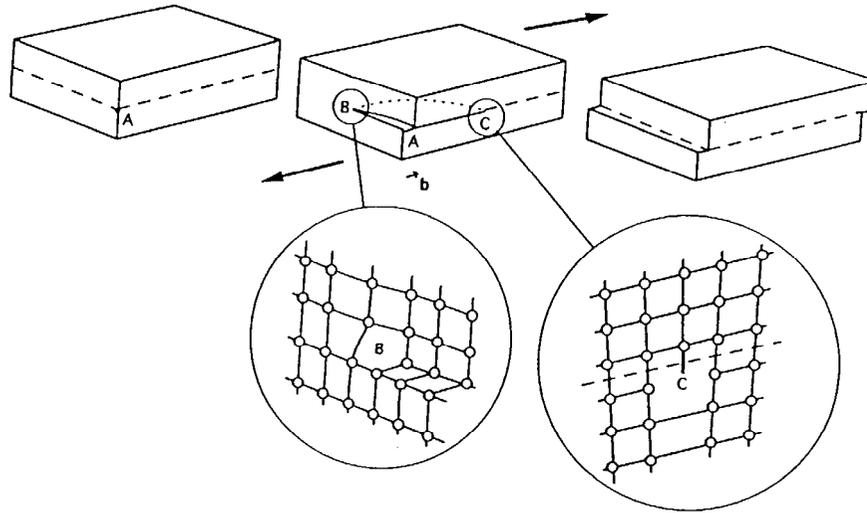


15.kV 250x GSED  
AIL ESEM U Alaska Fairbanks

18.0mm 2.9T  
04/02/05 10:55

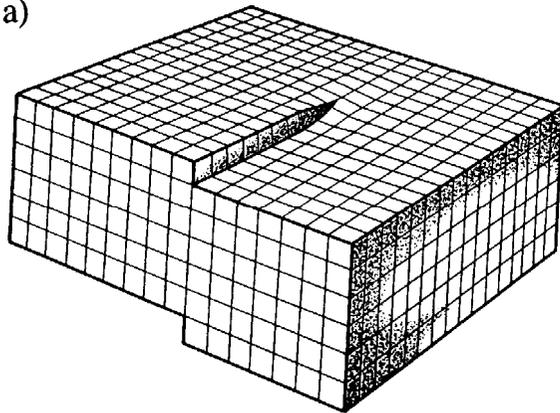


## Mécanisme possible de croissance cristalline



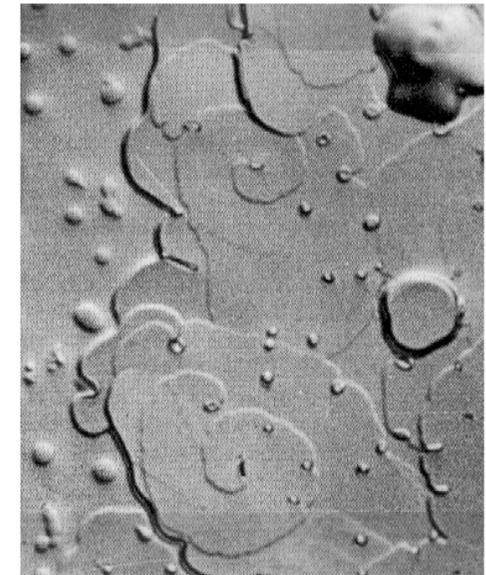
Les dislocations sont des défauts linéaires fréquents dans les solides cristallins

a)

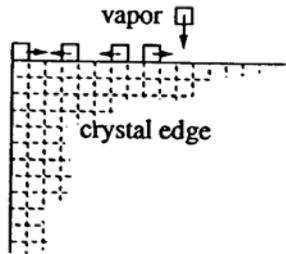


L'émergence de dislocations à la surface peut être un site de croissance cristalline, produisant une croissance en spirale

Croissance possible pour une sursaturation  $\sigma = (P_{\text{H}_2\text{O}} - P_{\text{sat}}) / P_{\text{sat}} = \varepsilon$



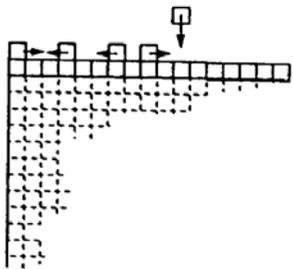
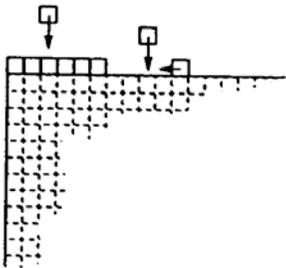
## Formation de nouvelles marches sur des cristaux croissant dans l'atmosphère



Croissance de la glace dans l'atmosphère :  
Par la nucleation homogène de nouvelles marches aux angles

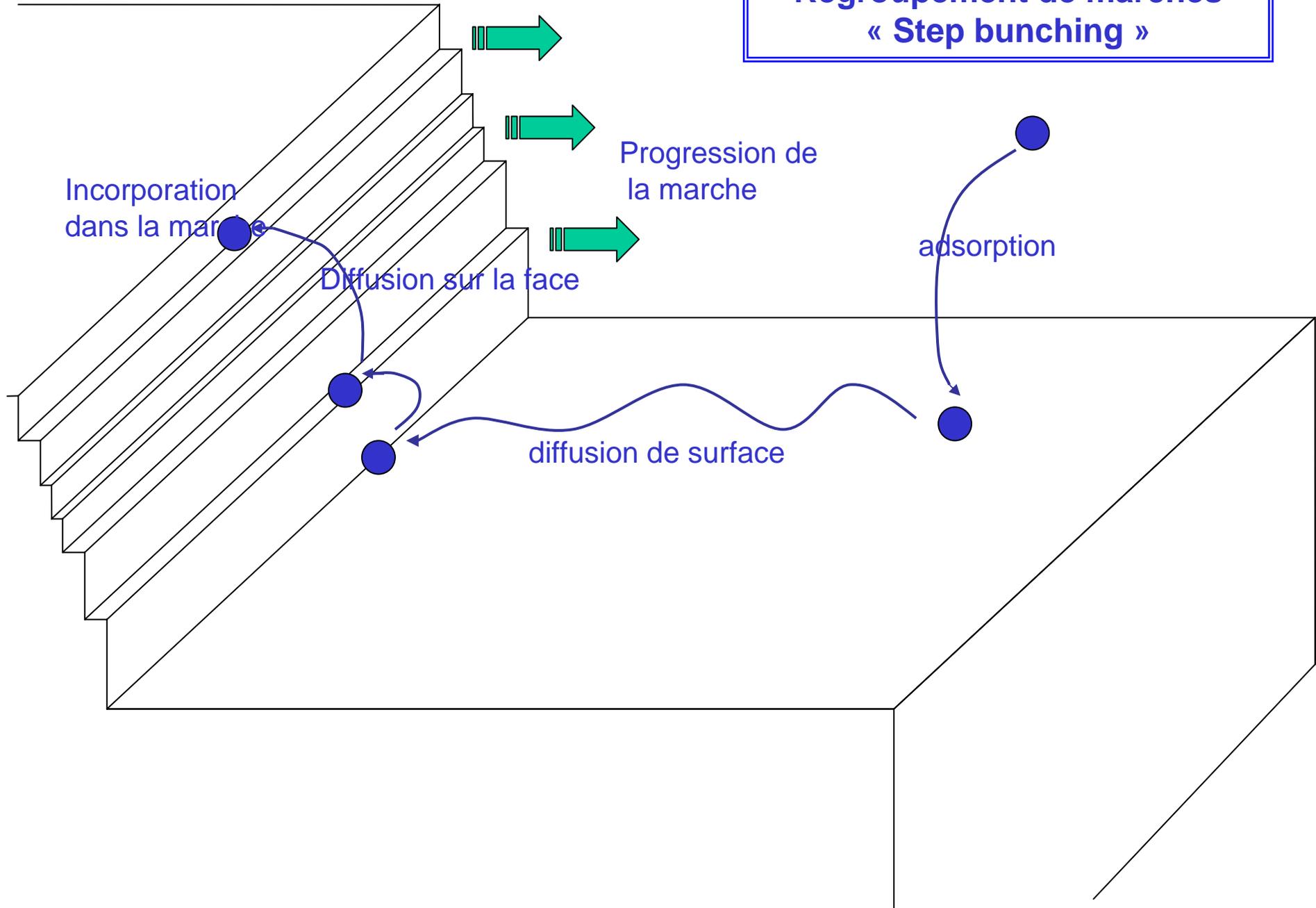
Croissance nécessite  $\sigma > \sigma_{\text{crit}}$

Glace :  $\sigma_{\text{crit}} \approx 0.4 \%$



La nucleation de nouvelles marches est un phénomène aléatoire  $\Rightarrow$   
Les terrasses auront des surfaces différentes  $\Rightarrow ??$

# Regroupement de marches « Step bunching »



## Vitesse de croissance d'un cristal par condensation de gaz

Etapes conduisant à l'incorporation d'une molécule d'eau en phase gaz

- Diffusion de la molécule d'eau (en phase gaz) vers la surface de glace
- Collision de la molécule d'eau avec la surface de glace
- Collage de la molécule d'eau sur la surface de glace et incorporation dans le réseau cristallin de la glace

Autres processus à prendre en compte pour quantifier la croissance d'un cristal:

- Sublimation du cristal (ré-émission de molécules d'eau depuis le cristal de glace vers la phase gazeuse)

La diffusion en phase gazeuse et les phénomènes de surface ont leurs limitations cinétiques

Intéressons nous aux phénomènes de surface

Théorie cinétique des gaz  $\Rightarrow$

Nombre de molécules d'eau incorporées à la surface =

$$C_{cond} = \frac{\alpha_{cond} P_{H_2O}}{\sqrt{2\pi m k T_g}}$$

m: masse d'une molécule

k: constante de Boltzmann =  $1.38 \times 10^{-23} \text{ J K}^{-1}$

$\alpha_{cond}$  : coefficient de condensation  $\alpha_{cond} = \frac{\text{nombre de collisions qui collent}}{\text{nombre de collisions total}}$

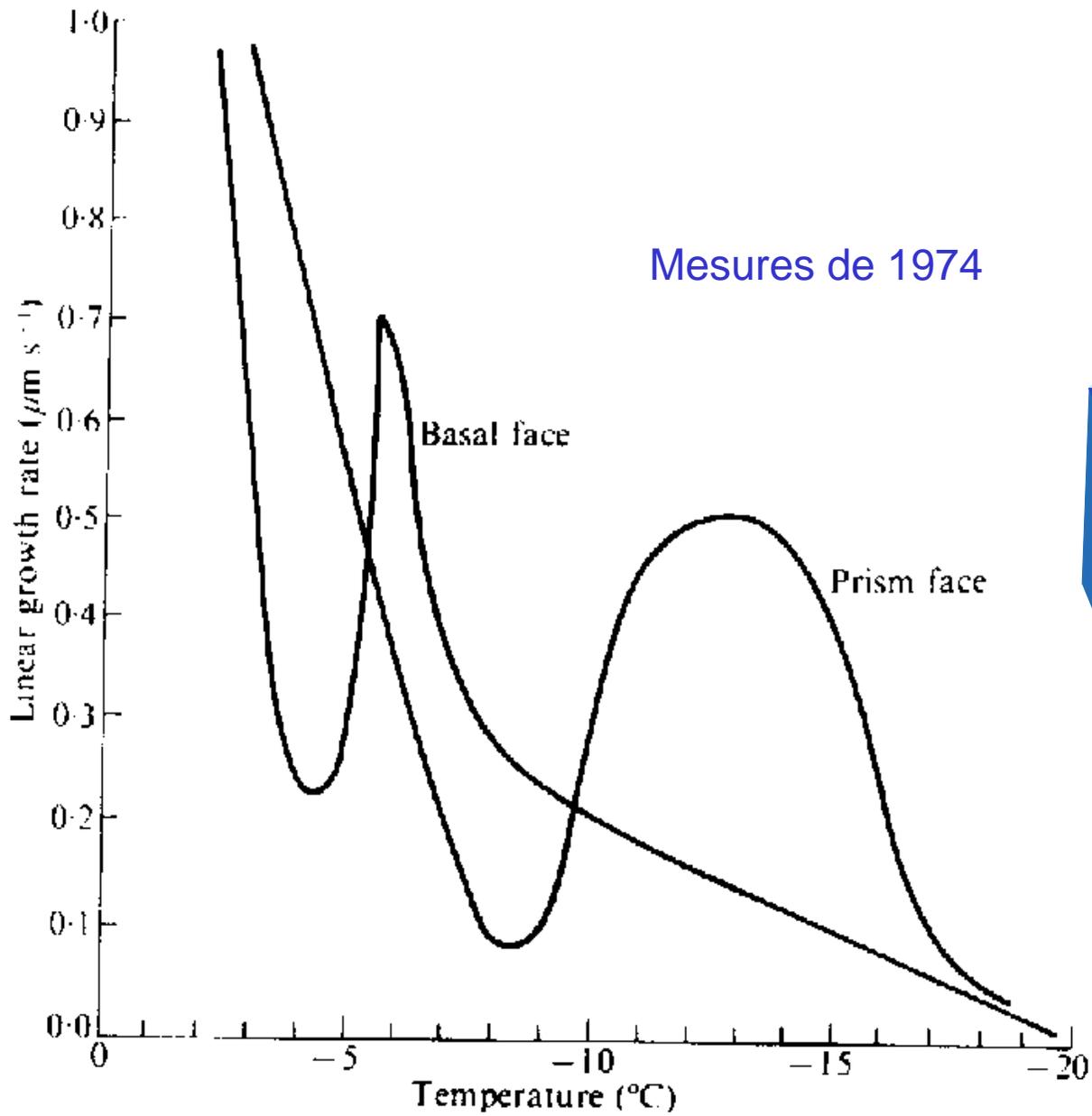
Nombre de molécules d'eau se sublimant =  $C_{sub} = \frac{\alpha_{sub} P_{sat}}{\sqrt{2\pi m k T_s}}$

En général :  $\alpha_{cond} = \alpha_{sub} = \alpha$  et  $T_g = T_s$ , le flux net à la surface est donc :

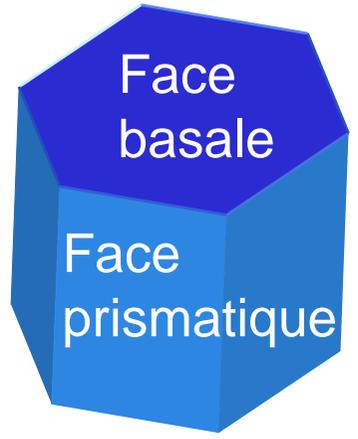
$$\varphi = \frac{\alpha (P_{H_2O} - P_{sat})}{\sqrt{2\pi m k T}}$$

$\alpha$  est donc un paramètre clé, qui détermine la vitesse de croissance:

Mesures de  $\alpha$ : de nombreux chercheurs y ont consacré (presque) toute leur vie.  
Méthode : mesure de vitesse de croissance



Mesures de 1974



Autres mesures de 1974

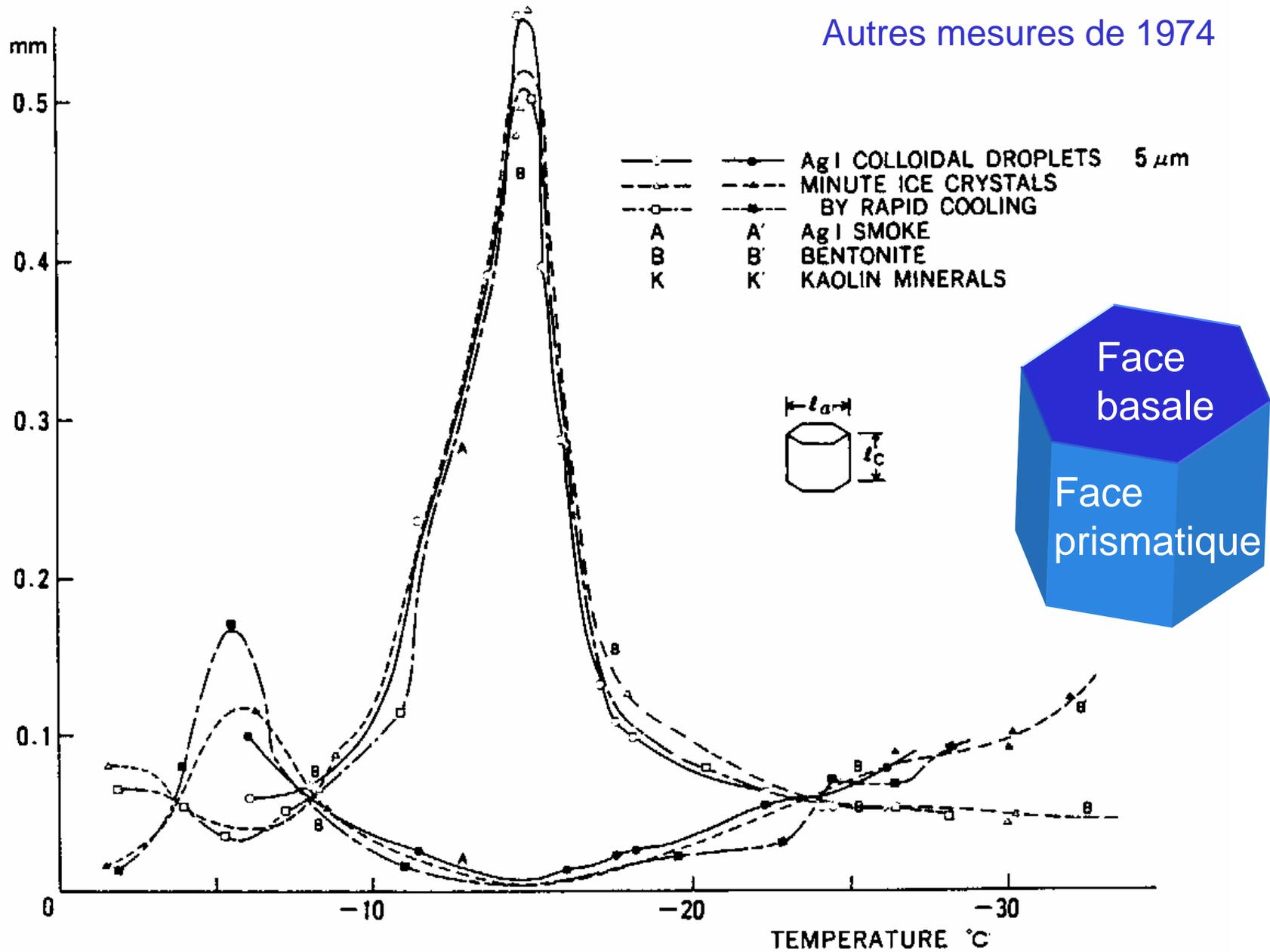
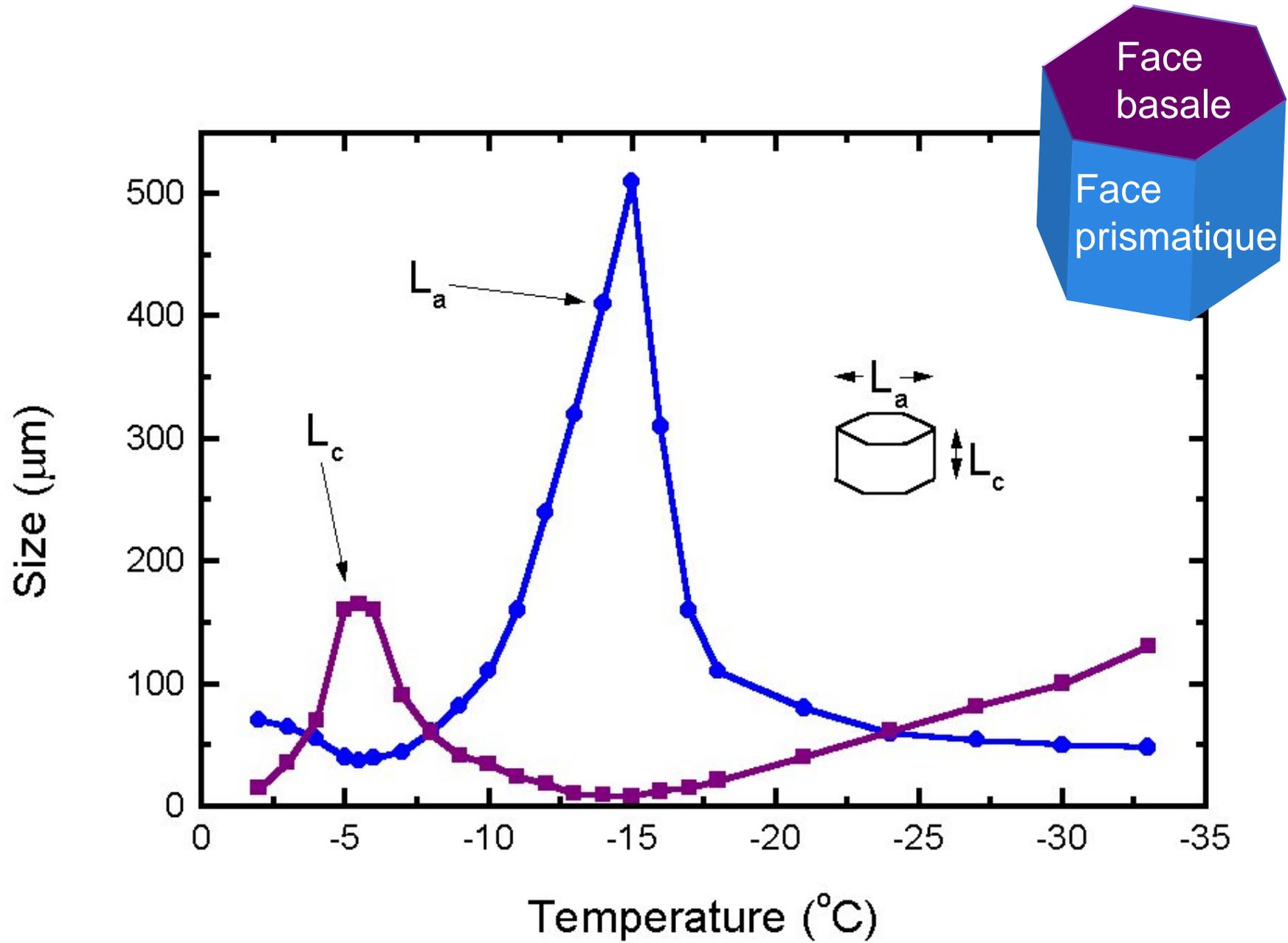
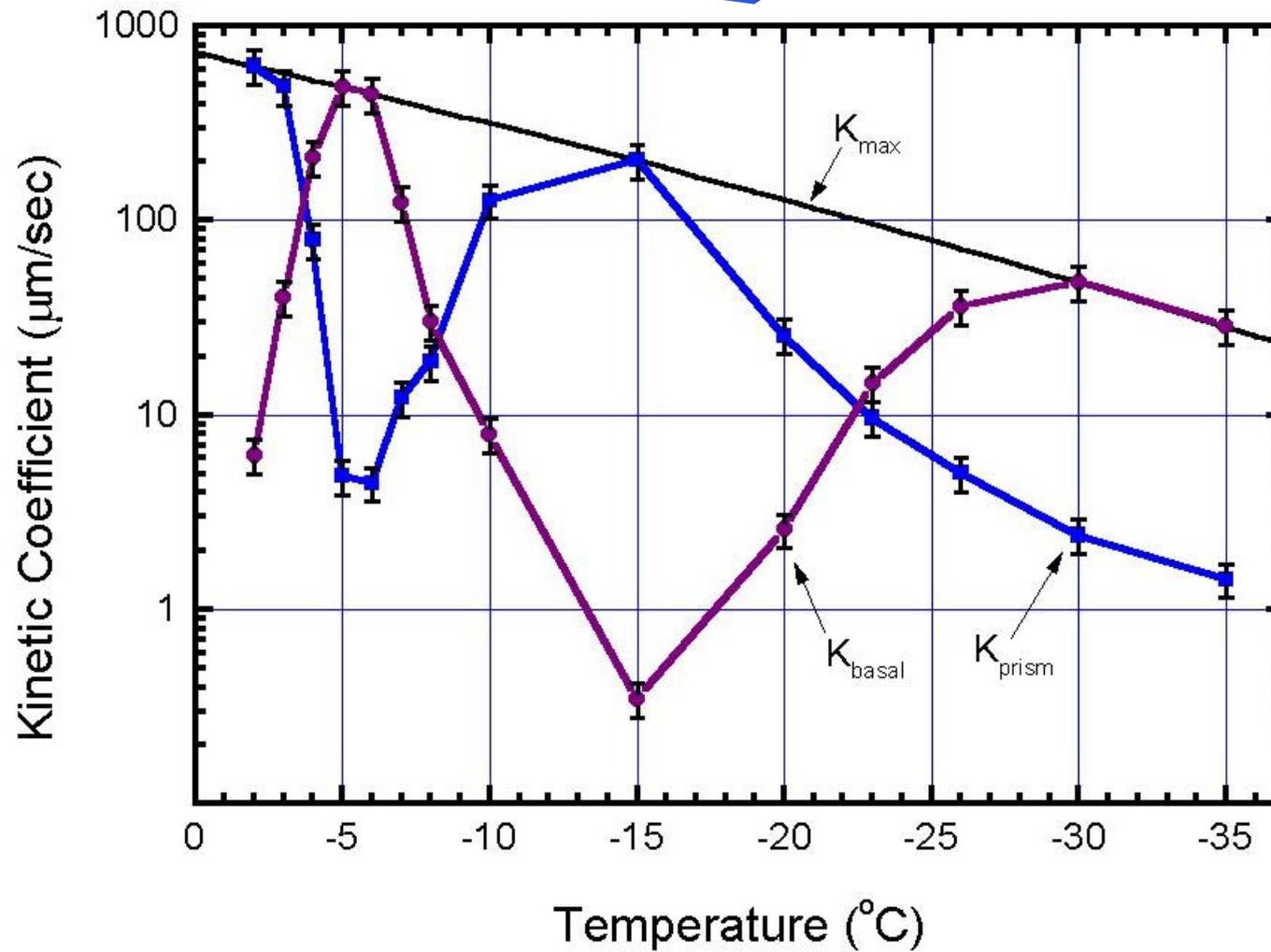
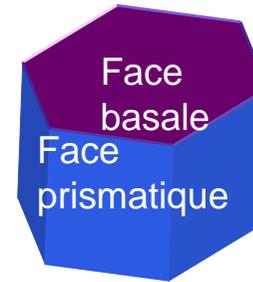


FIG. 11. Temperature dependence of the lengths of  $c$ - and  $a$ -axis of a falling ice crystal 200 s after seeding. After YAMASHITA (1974).

Mesures de 2002



Déduction de  $\alpha$  à partir des mesures de vitesses de croissance : tâche complexe....



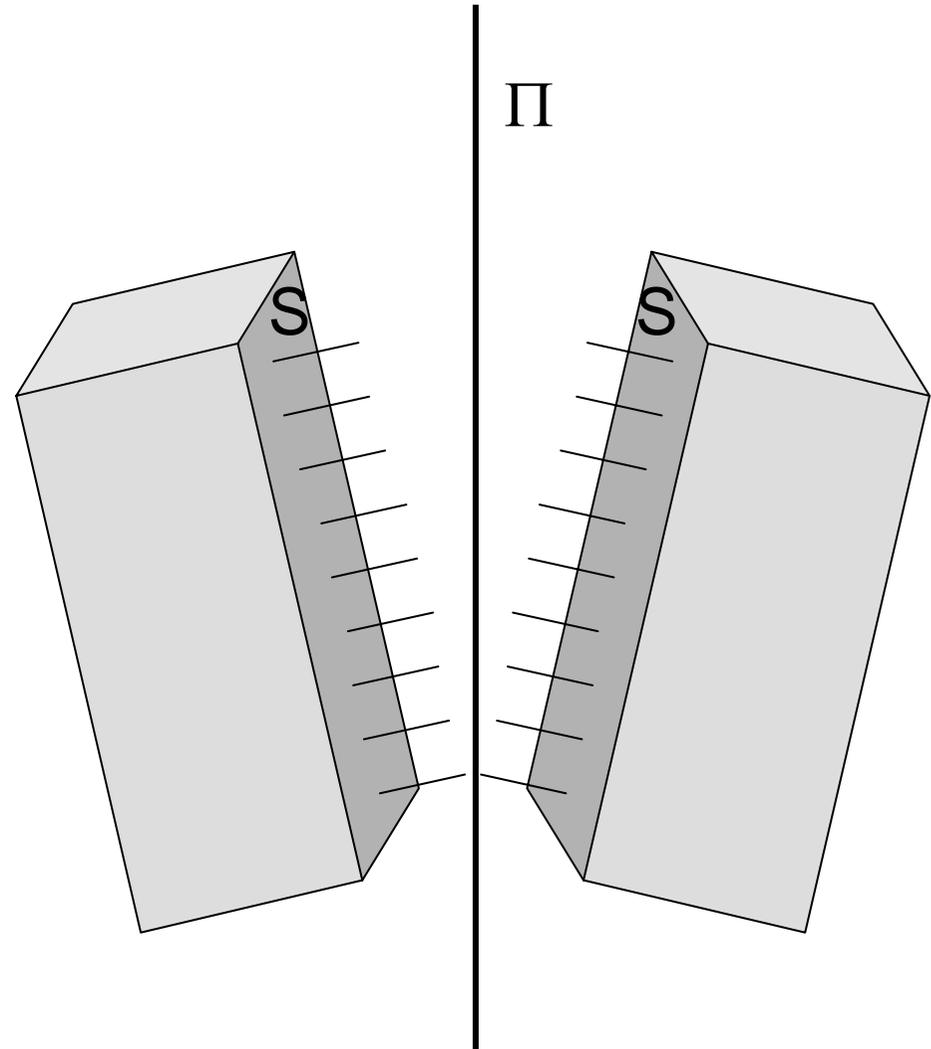
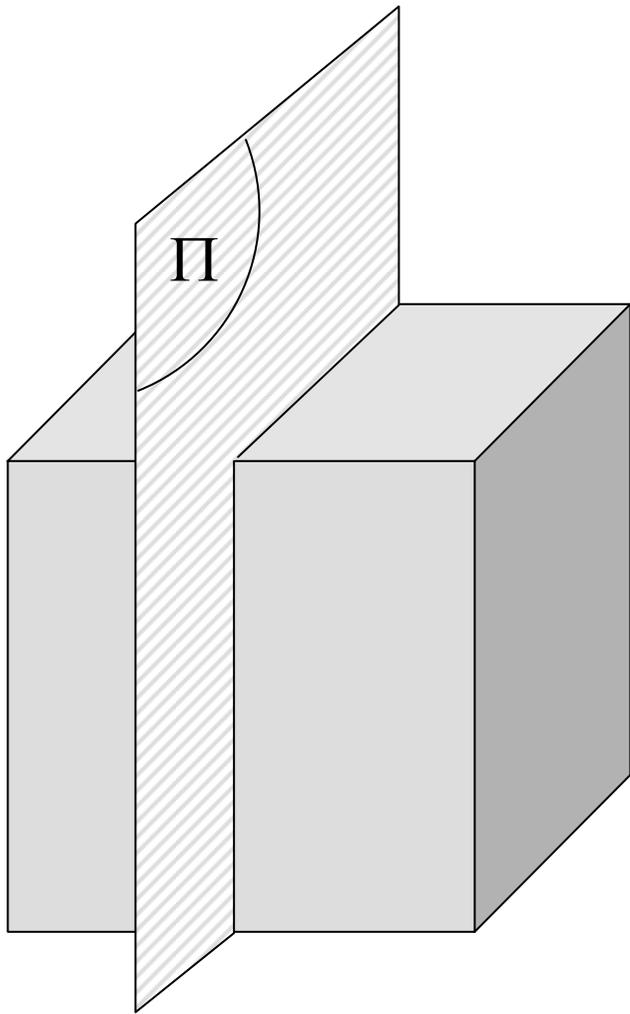
Pourquoi cette dépendance complexe de  $\alpha$  avec la température ?

« At present we do not have even a satisfactory *qualitative* picture of the mechanisms that produce such dramatic changes in morphology with temperature »

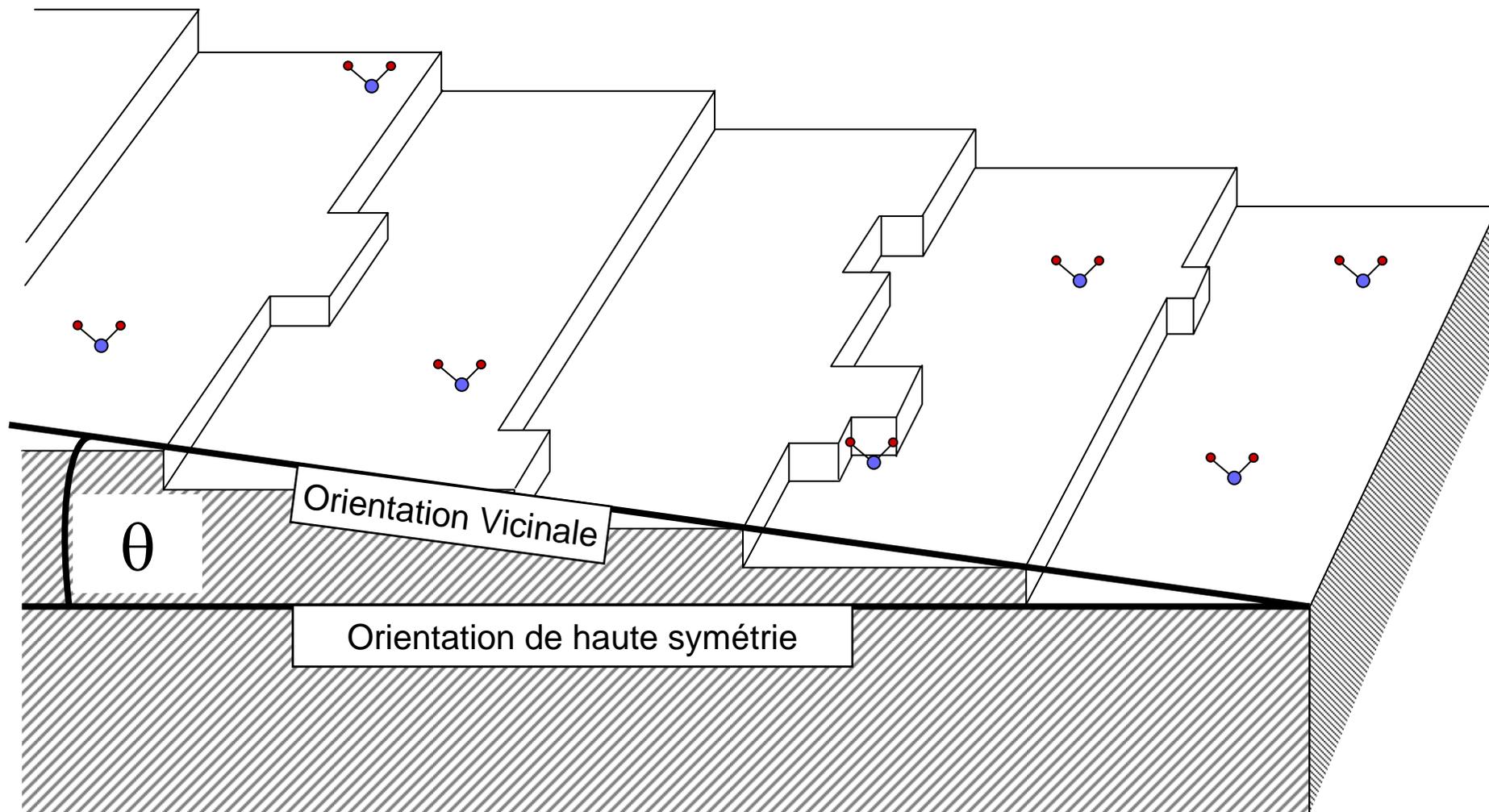
K.G. Libbrecht (2005) The physics of snow crystals, *Reports on Progress in Physics*, vol. 68, 855-895.

Energie de surface = tension de surface  $\gamma$  (joule m<sup>-2</sup>)

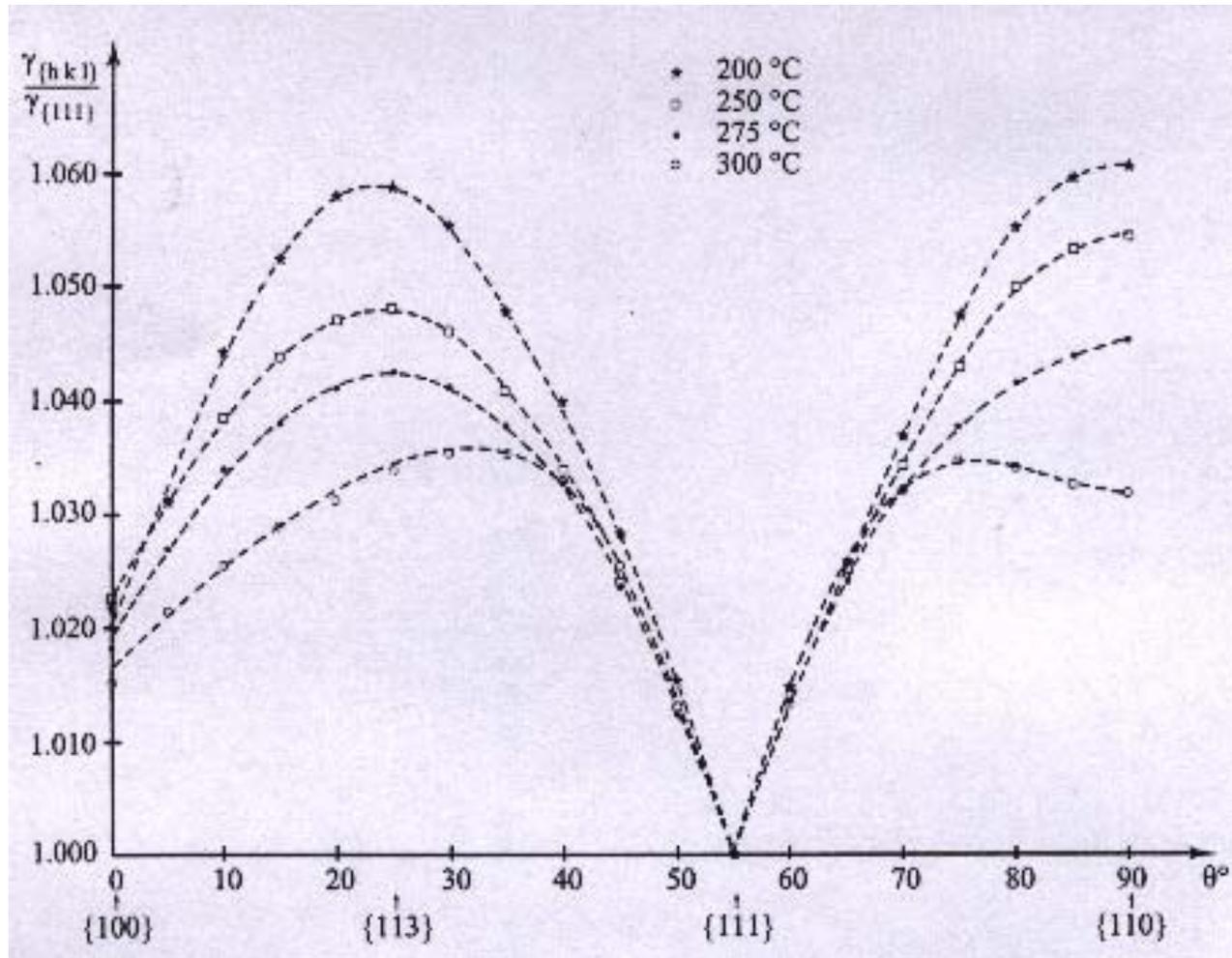
$$\gamma = \frac{\Delta G}{2S}$$



$$\gamma = f(\text{orientation cristallographique})$$



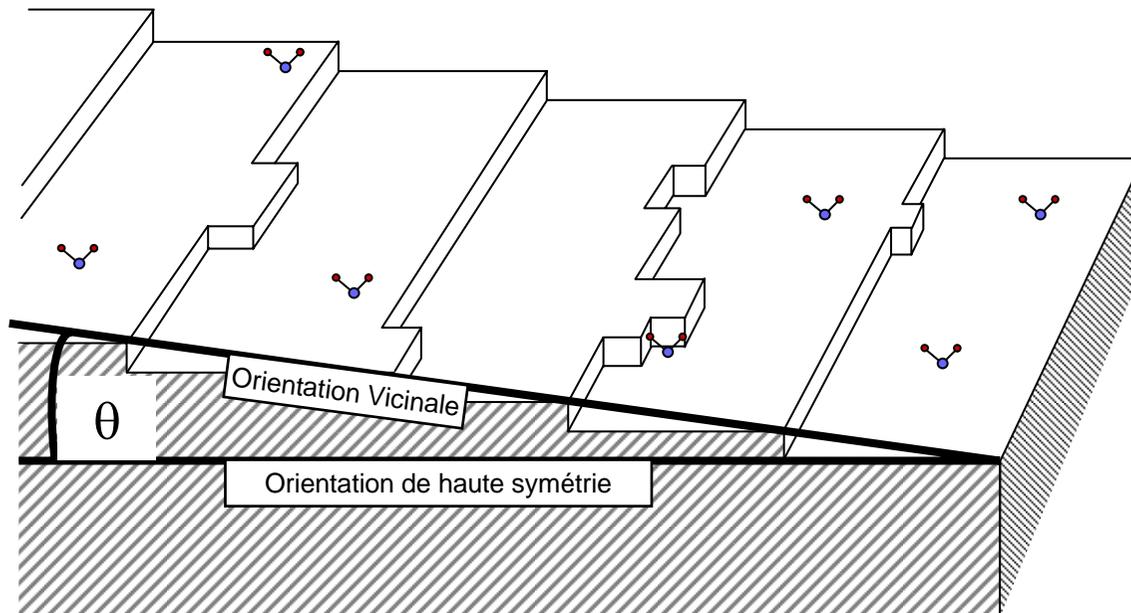
Tension de surface  $\gamma$  de l'indium =  $f(T, \theta)$



## Structure et énergie de surface

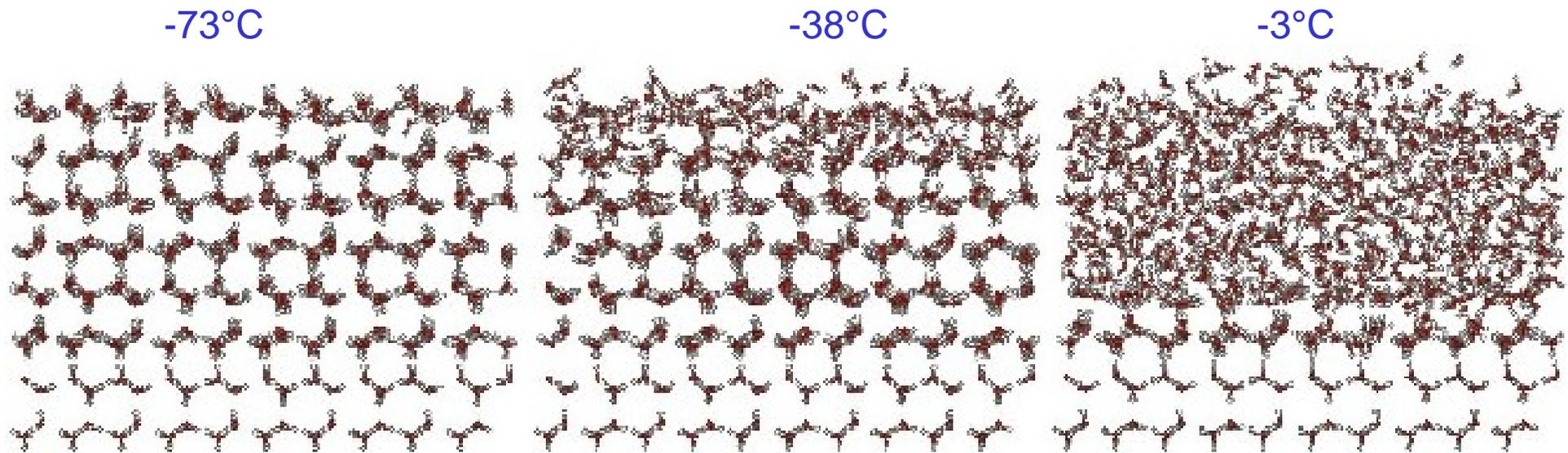
$$\gamma(\theta) = \gamma_0 + \phi |\tan \theta| \quad \phi = \text{energie libre de formation d'une marche}$$

$$G(\theta) = H(\theta) - TS(\theta) \quad \Rightarrow \quad \phi = 0 \text{ pour } T = T_R = \text{température de transition rugueuse}$$

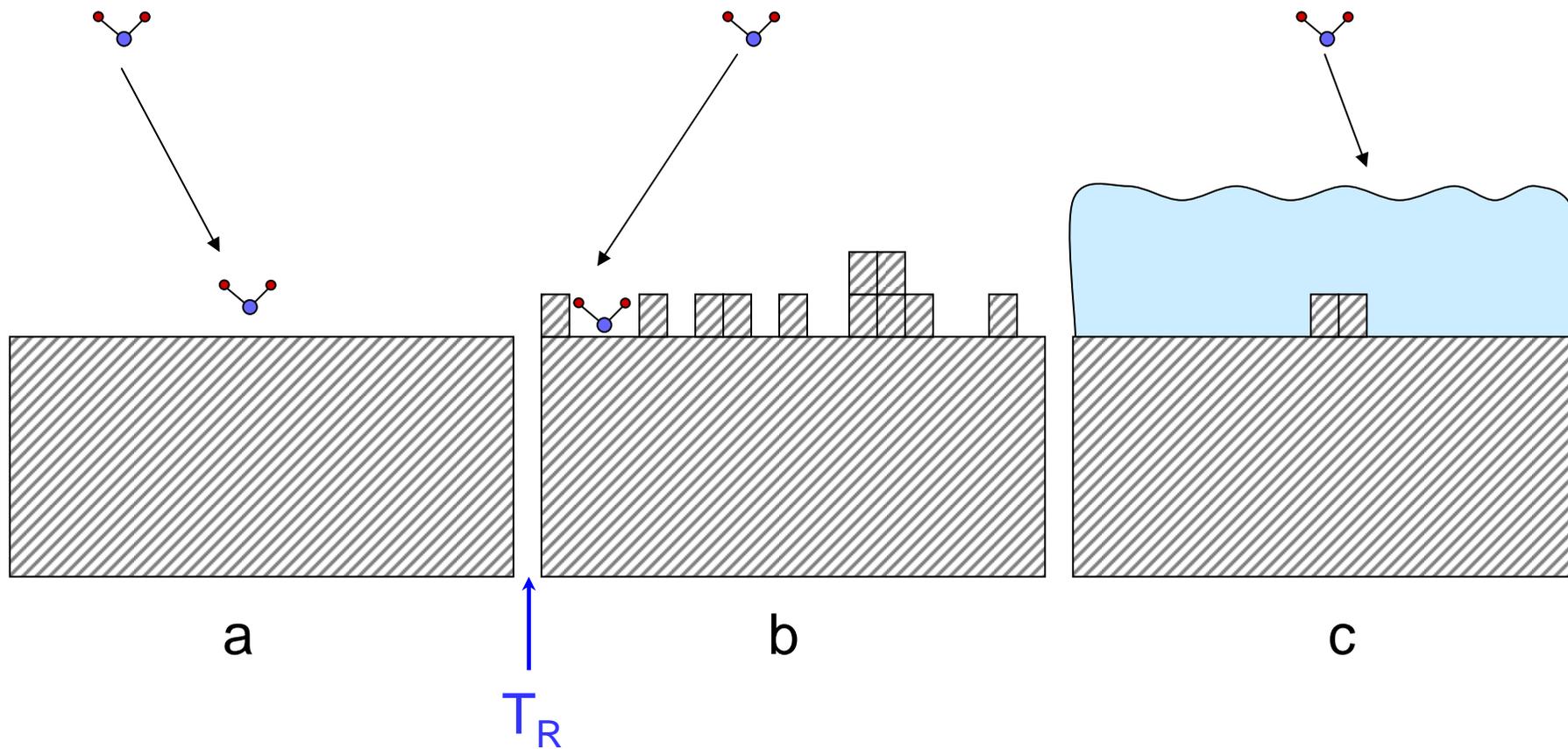


## Phénomène supplémentaire à la surface de la glace

Le désordre de surface de la glace : couche quasi-liquide



Anisotropie de la glace (face basale  $\neq$  face prismatique)  $\Rightarrow$  transition CQL-solide a lieu a une température différente sur chaque face.



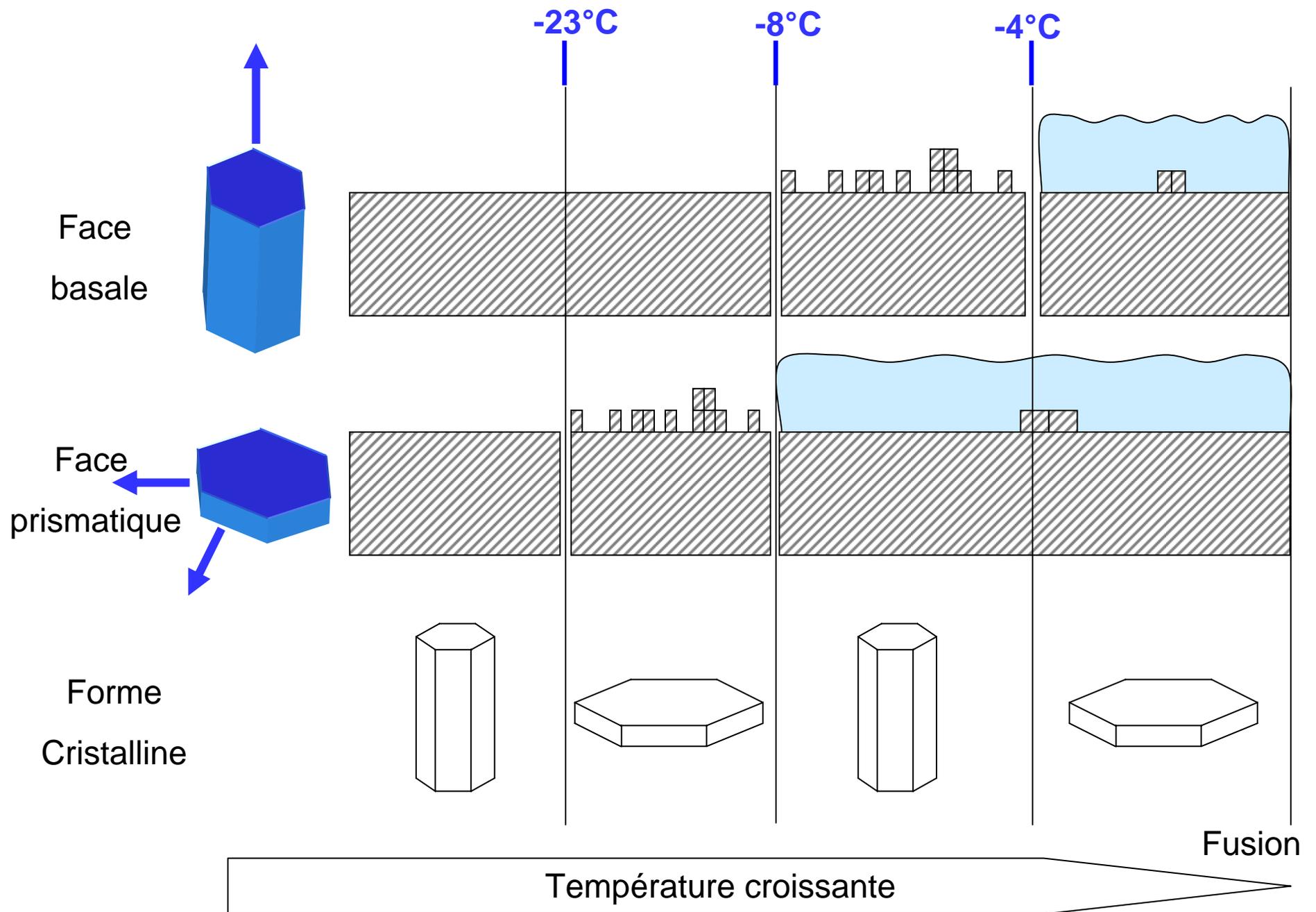
a

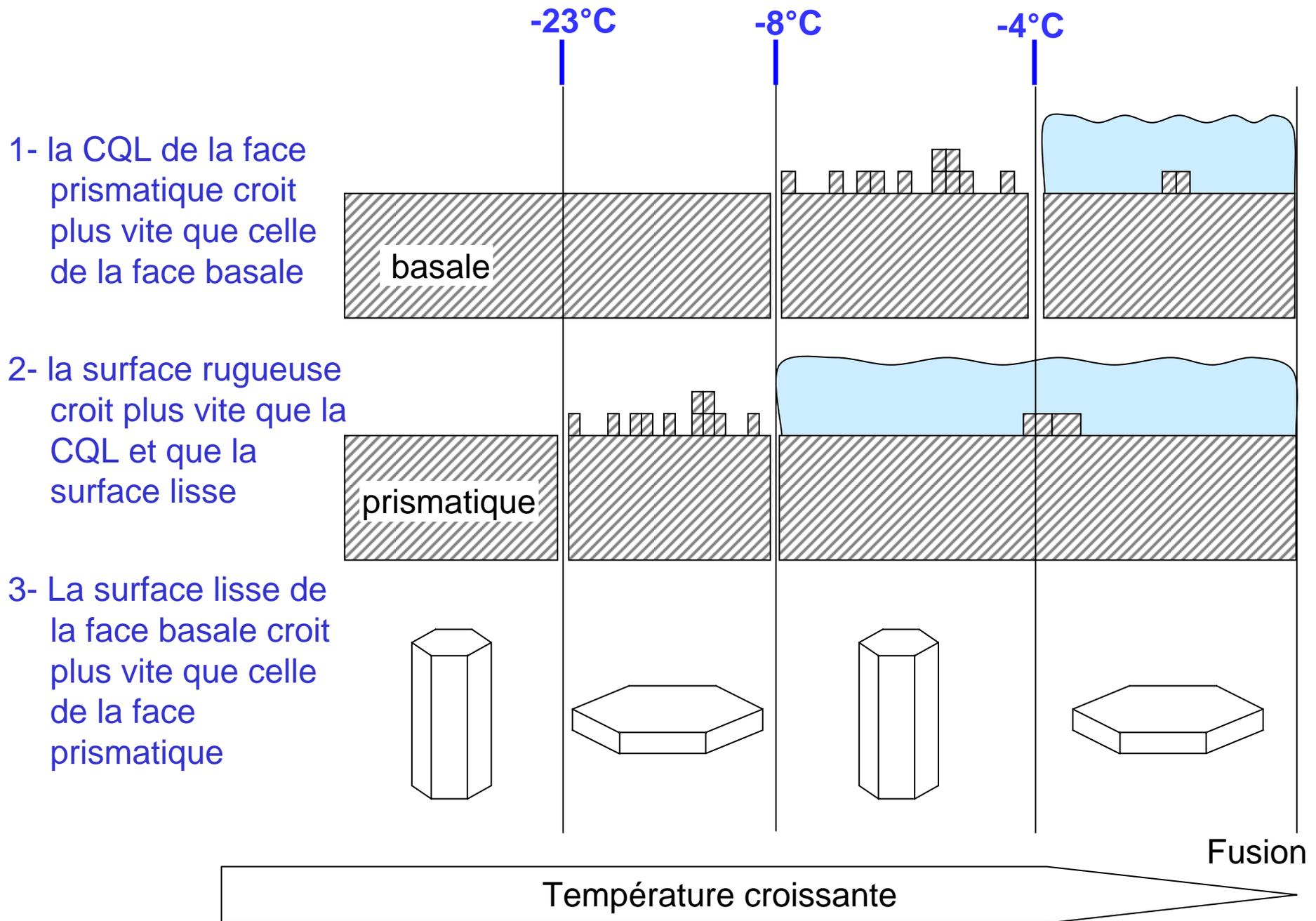
b

c

$T_R$

Température croissante





Ces considérations de l'état de surface rendent compte des transitions suivantes

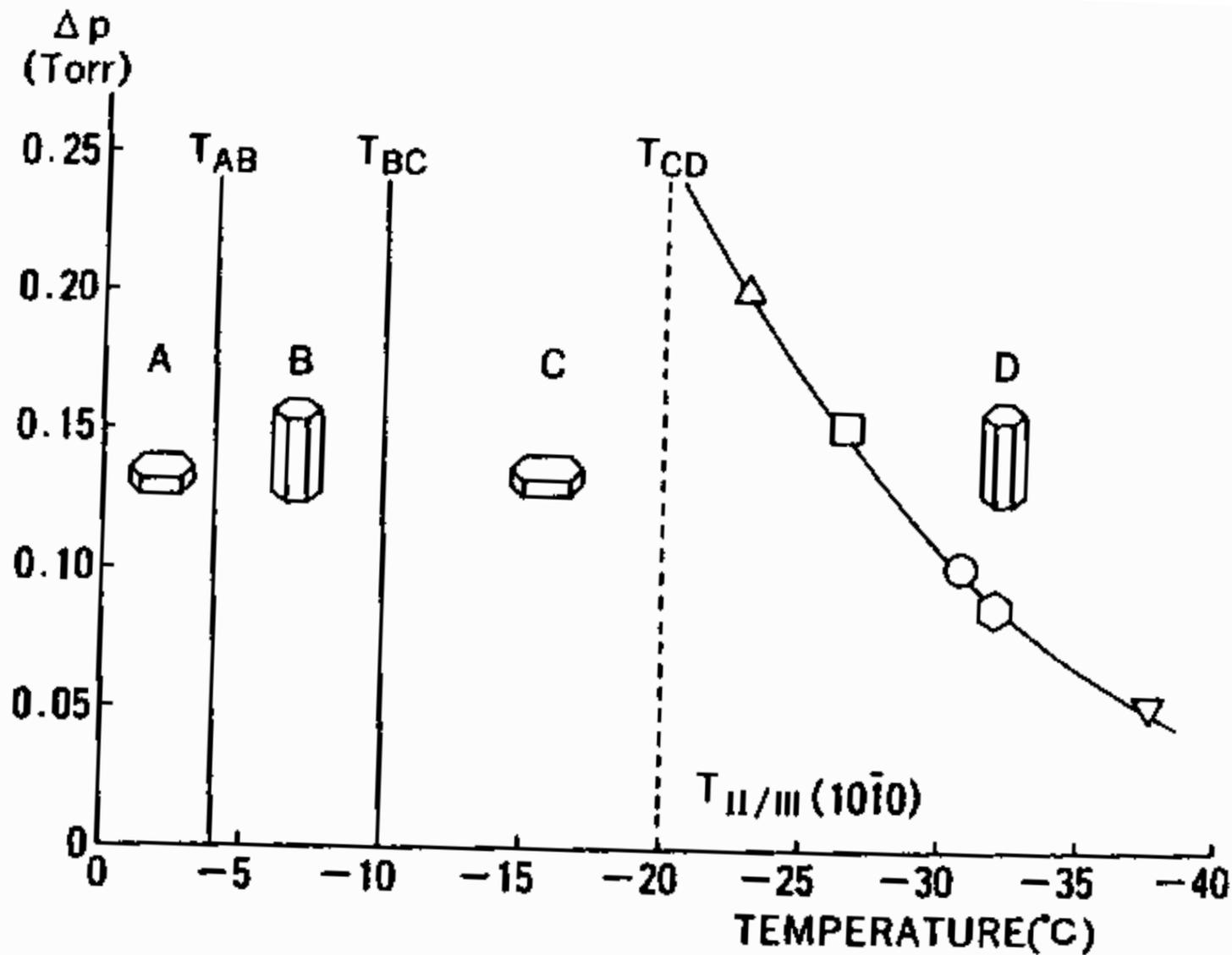
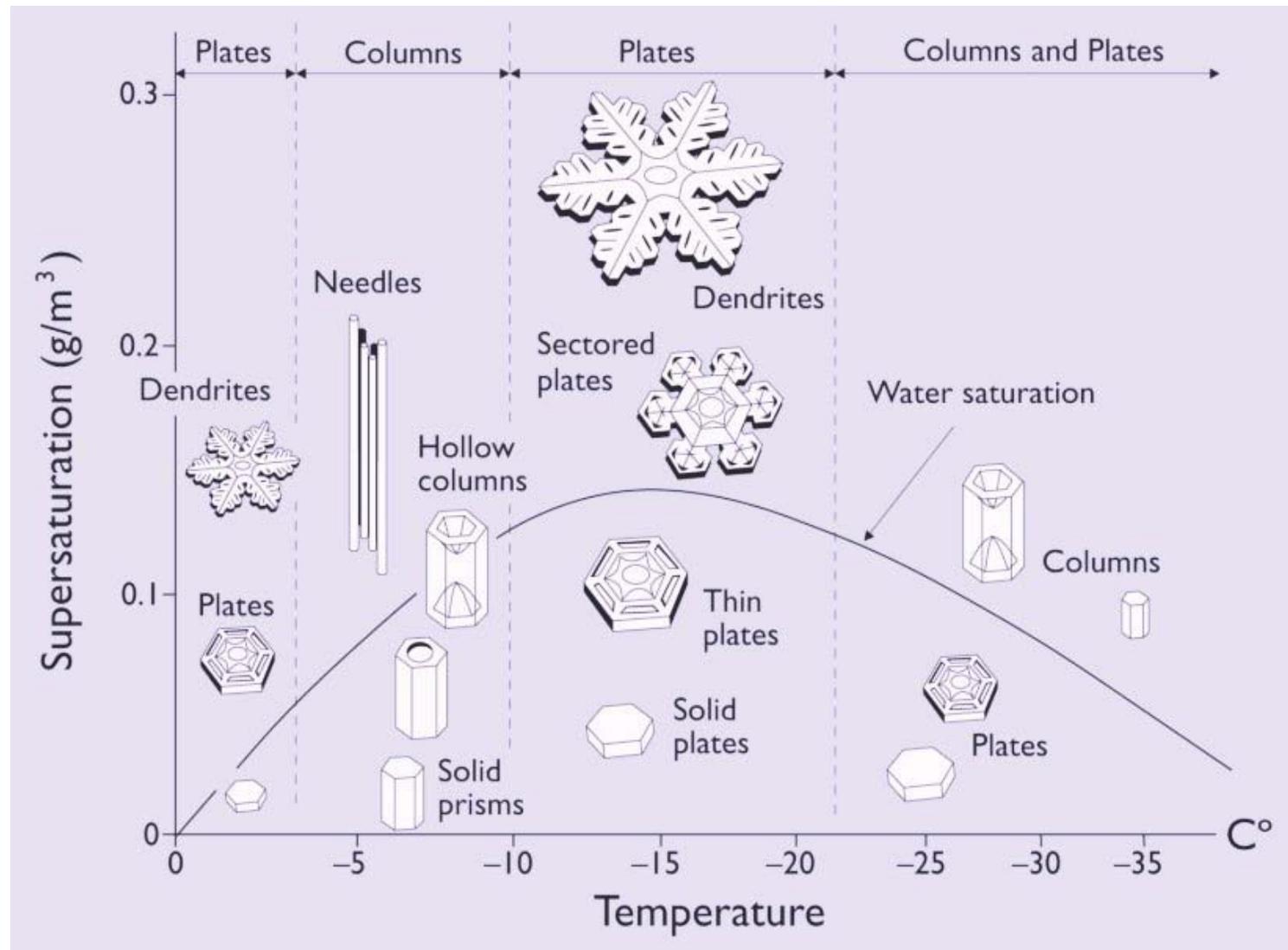


FIG. 23. Theoretical diagram showing the relation between the basic habit of ice crystals and growth conditions. After KURODA and LACMANN (1982).

Mais les variétés de forme à expliquer sont beaucoup plus grandes .....



## Croissance : le rôle limitant de la diffusion

Si la diffusion n'est pas limitante, le flux de molécules à la surface est :

$$\varphi = \frac{\alpha (P_{H_2O} - P_{sat})}{\sqrt{2\pi m kT}}$$

En tenant compte de la diffusion, le flux de molécules à la surface est :

$$\varphi = \frac{(P_{H_2O} - P_{sat}) \left( \frac{1}{\sqrt{2\pi m kT}} \right)}{\frac{1}{\alpha} + \frac{r_c}{D_g} \sqrt{\frac{kT}{2\pi m}}}$$

$D_g$  et  $r_c$  interviennent dans cette équation : des gradients de concentration vont s'établir autour du cristal

# Lignes d'isoconcentrations autour d'un cristal

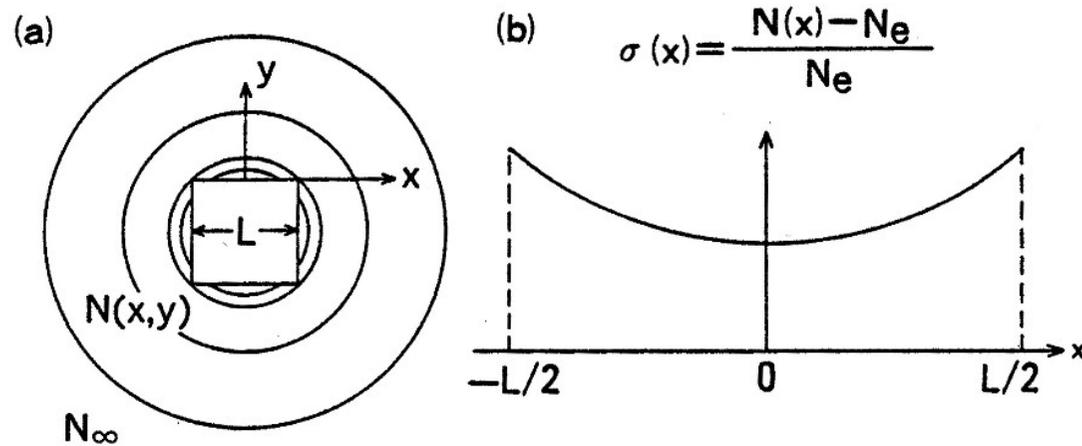


FIG. 24. Schematic representation of (a) equi-concentration surfaces of a growth unit and (b) inhomogeneity in supersaturation  $\sigma(x)$  over the crystal surface.

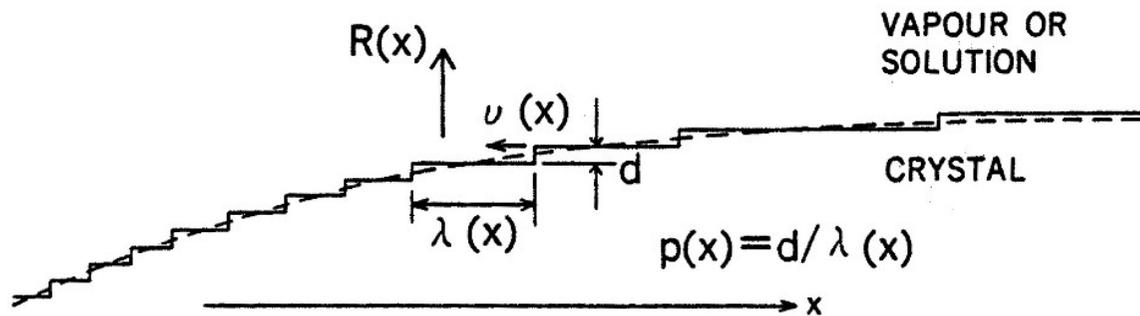
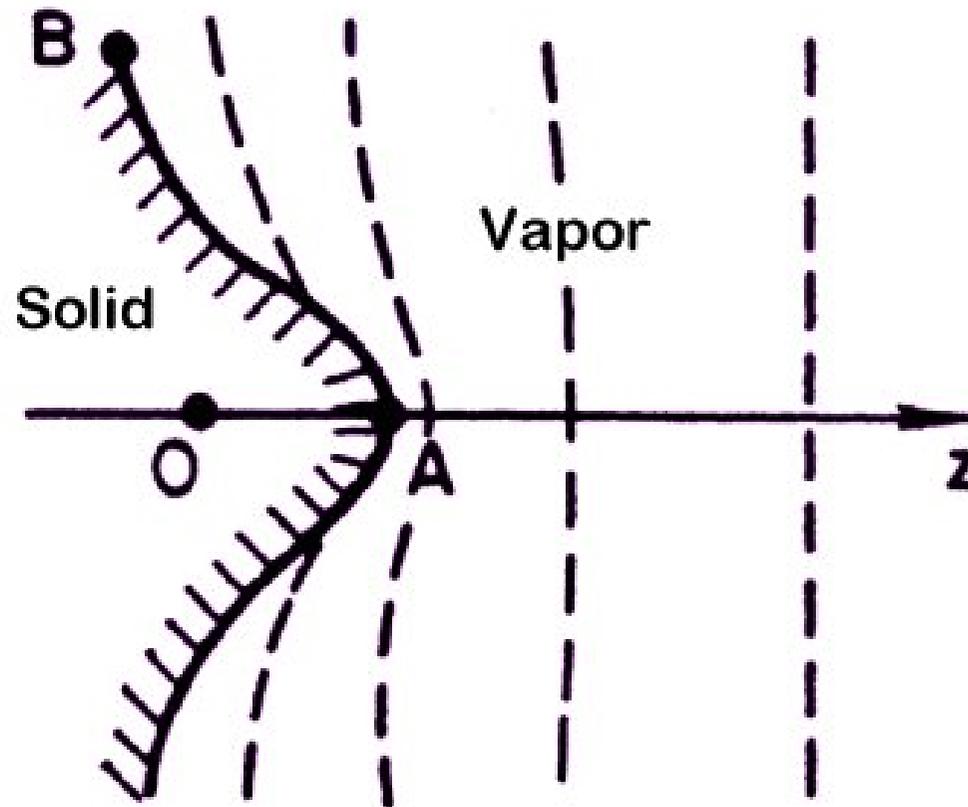


FIG. 25. Schematic representation of step distribution for compensation of inhomogeneity in supersaturation.

# Les instabilités de croissance

## I - Instabilité de Mullins – Sekerka



Un point de croissance plus rapide va générer une croissance encore plus rapide

⇒ Formation de dendrites

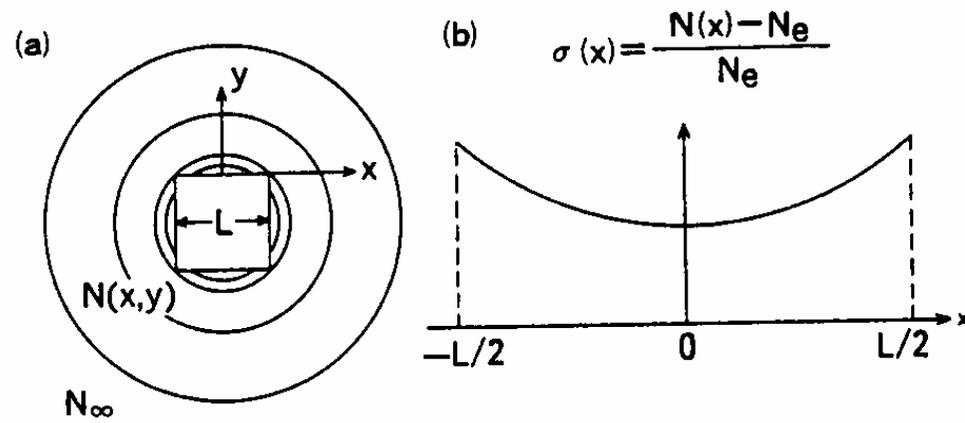
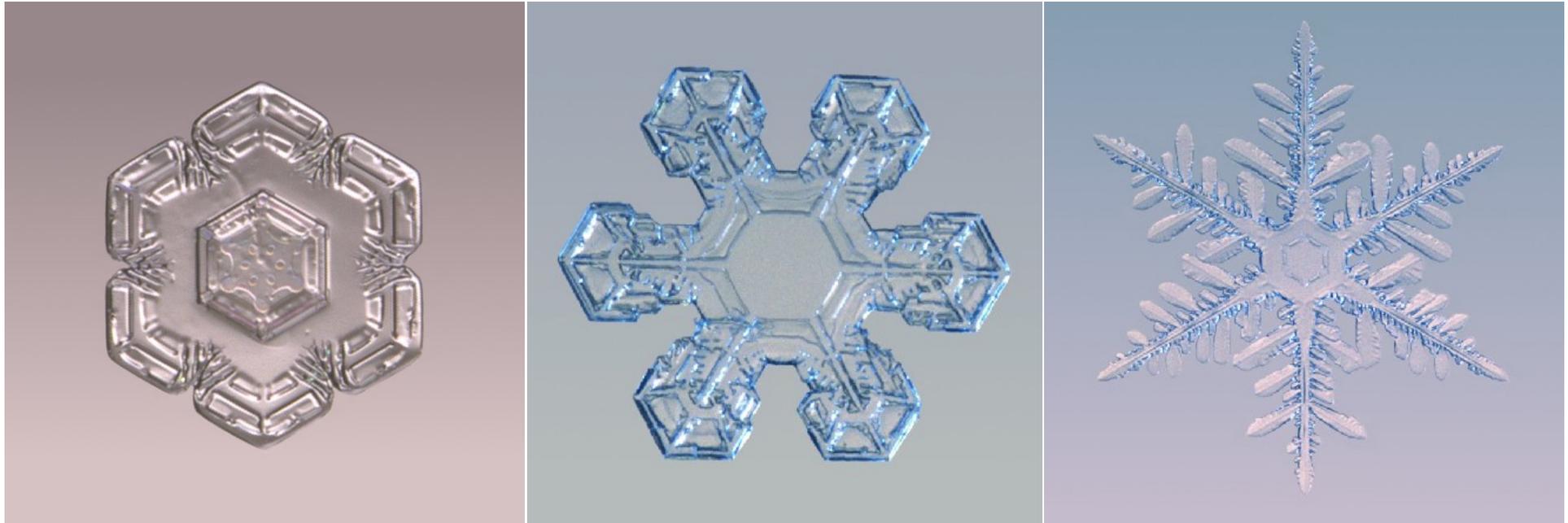


FIG. 24. Schematic representation of (a) equi-concentration surfaces of a growth unit and (b) inhomogeneity in supersaturation  $\sigma(x)$  over the crystal surface.



# Les instabilités de croissance

## II - Instabilité de Hopper

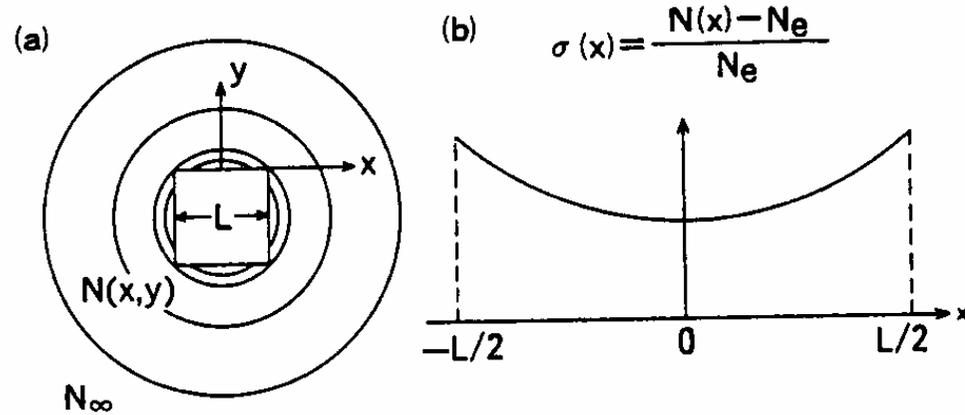
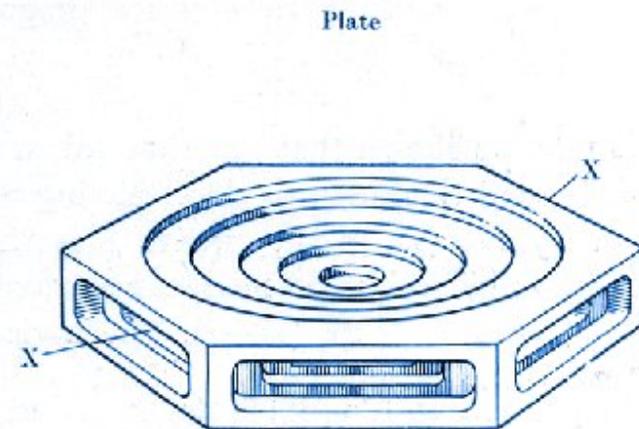
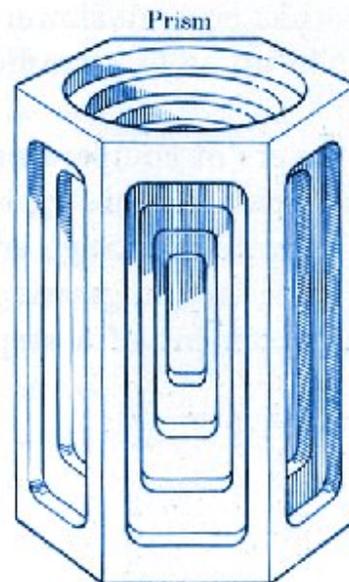
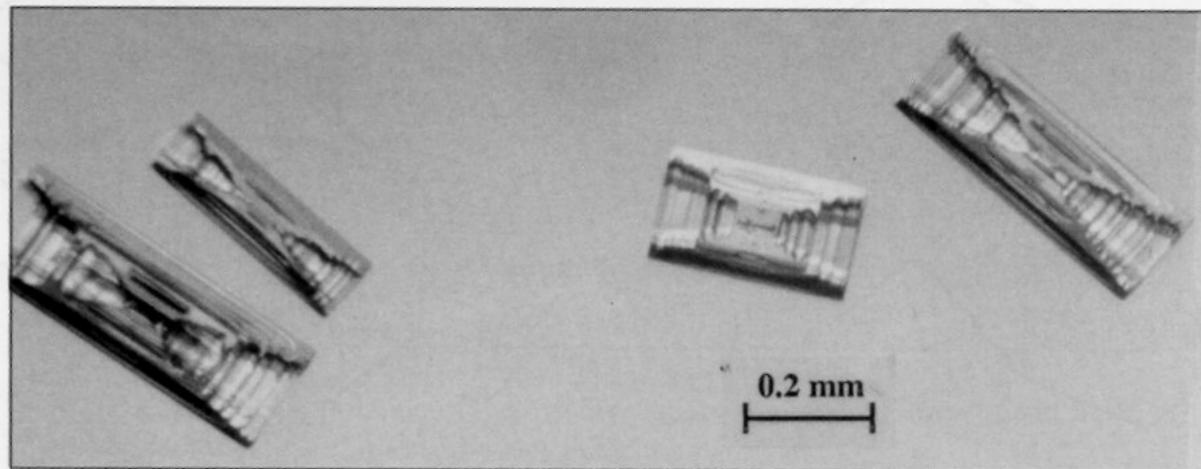


FIG. 24. Schematic representation of (a) equi-concentration surfaces of a growth unit and (b) inhomogeneity in supersaturation  $\sigma(x)$  over the crystal surface.

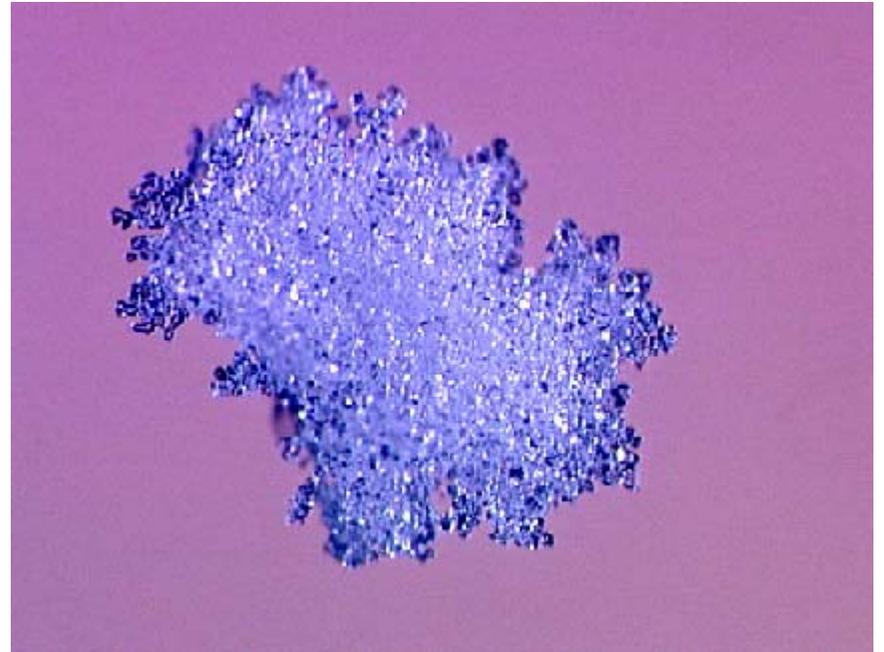
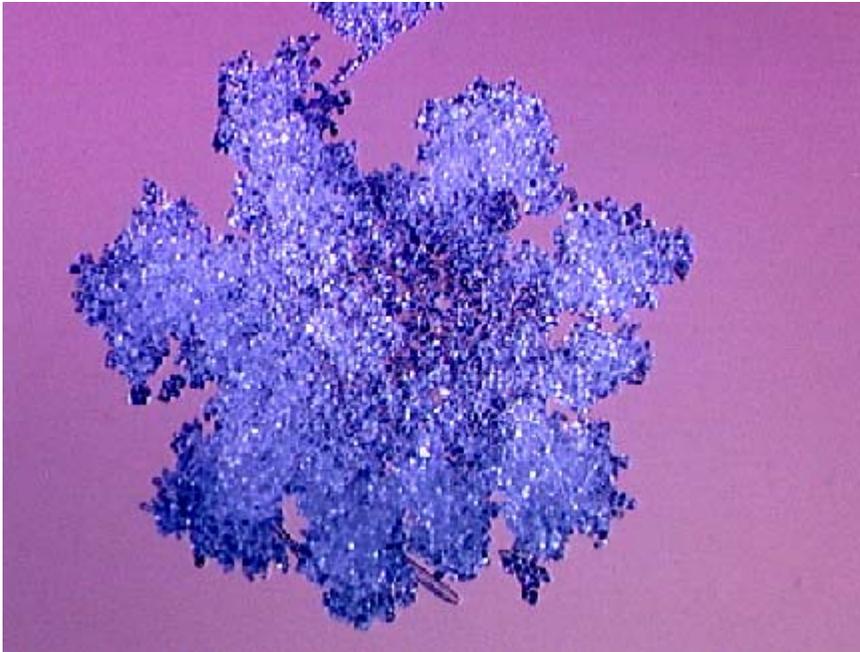
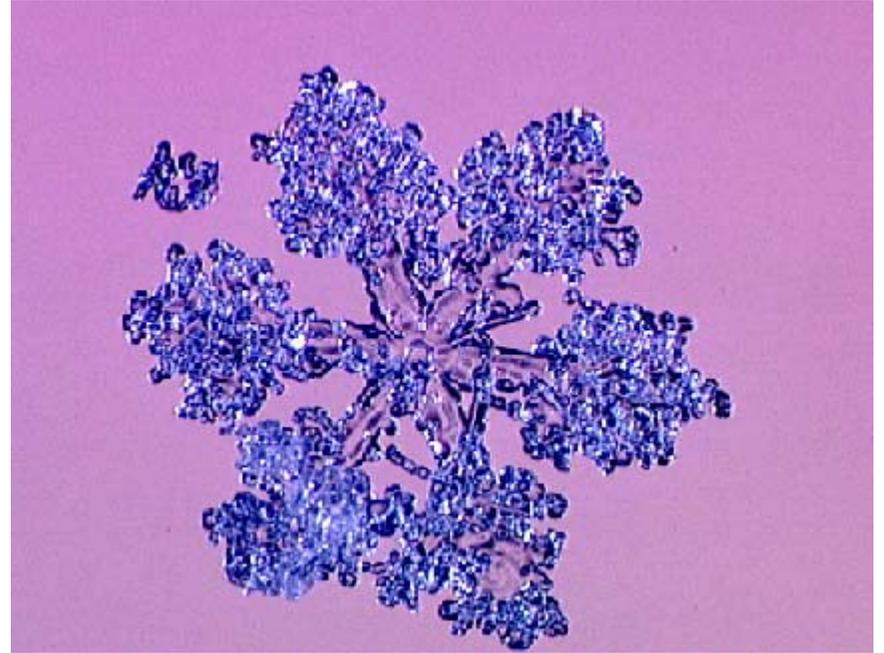
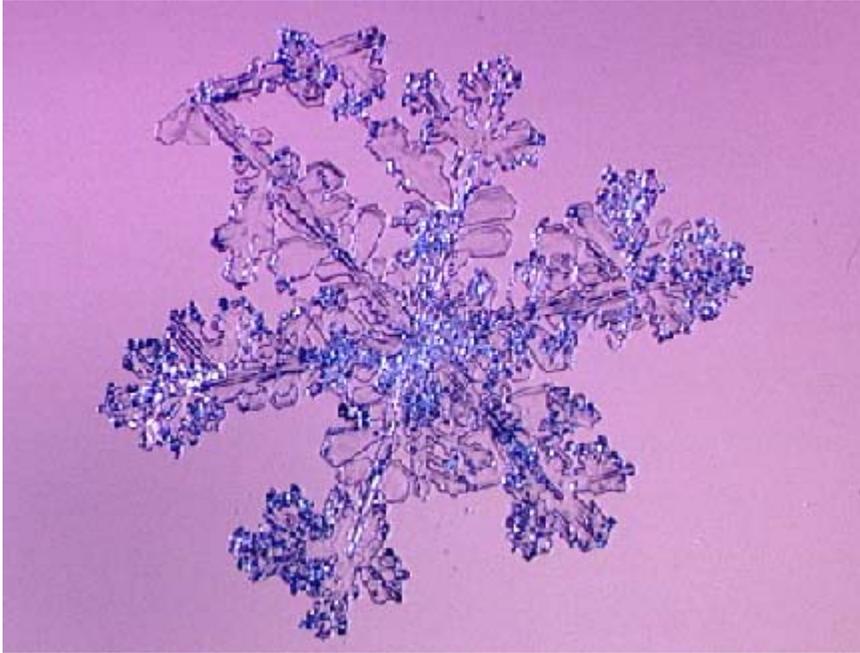
Formation de cristaux creux





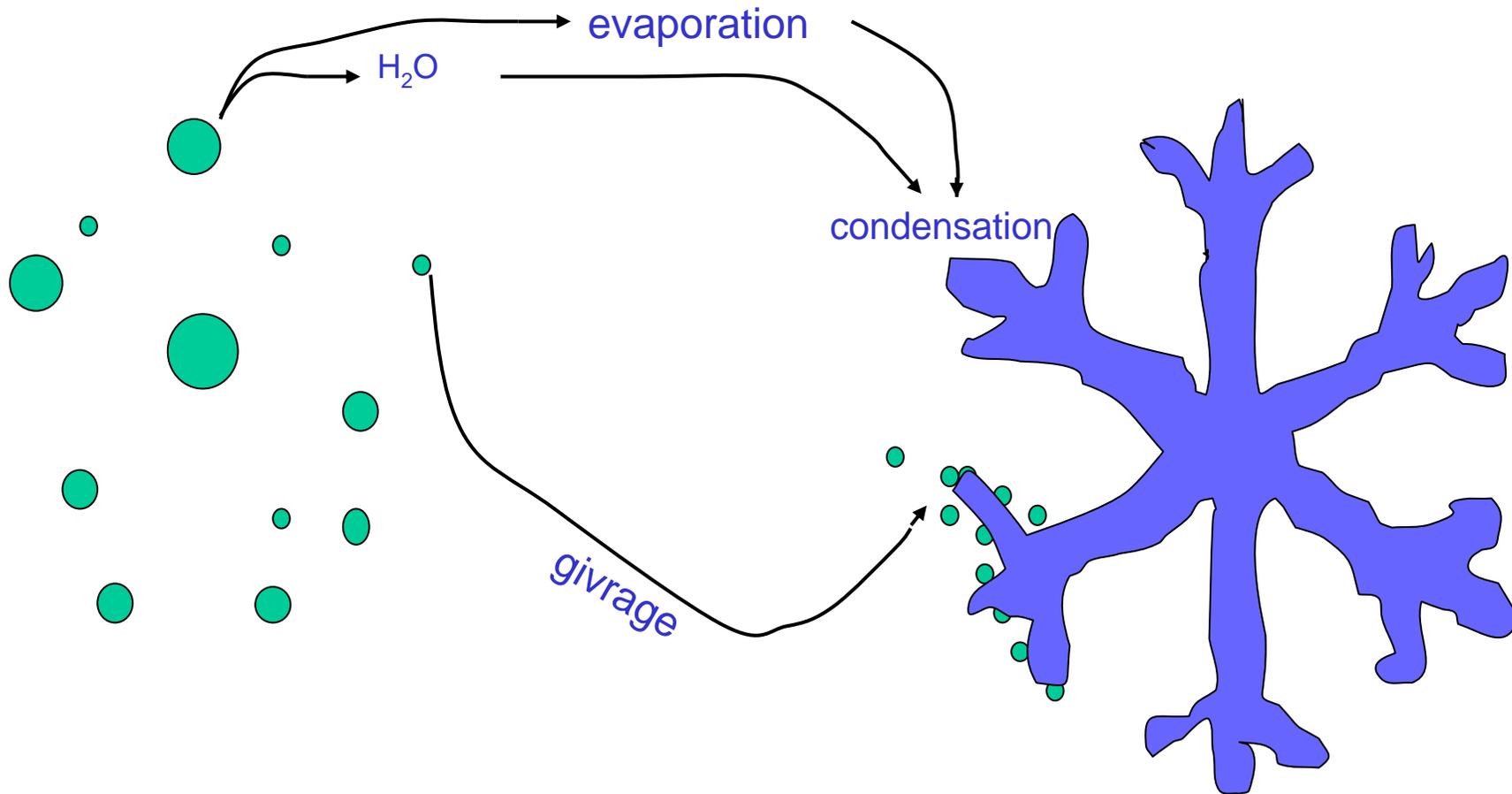
**Figure 2-5.** Some crystals collected during another halo display, similar to Display 2-1. South Pole, January 21, 1990.

Et ça ???



# La plupart des nuages : nuages mixtes

- Eau
- Glace

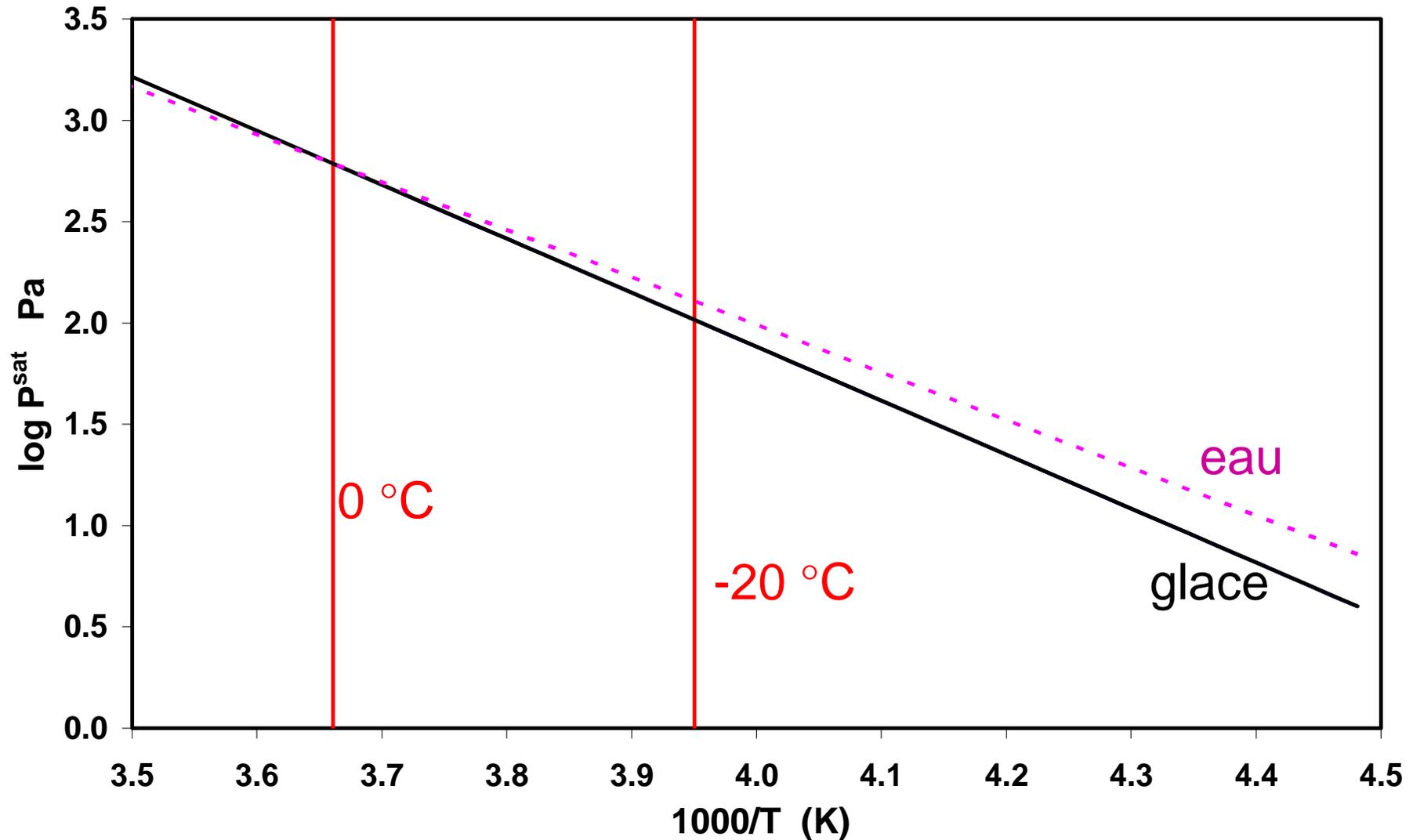


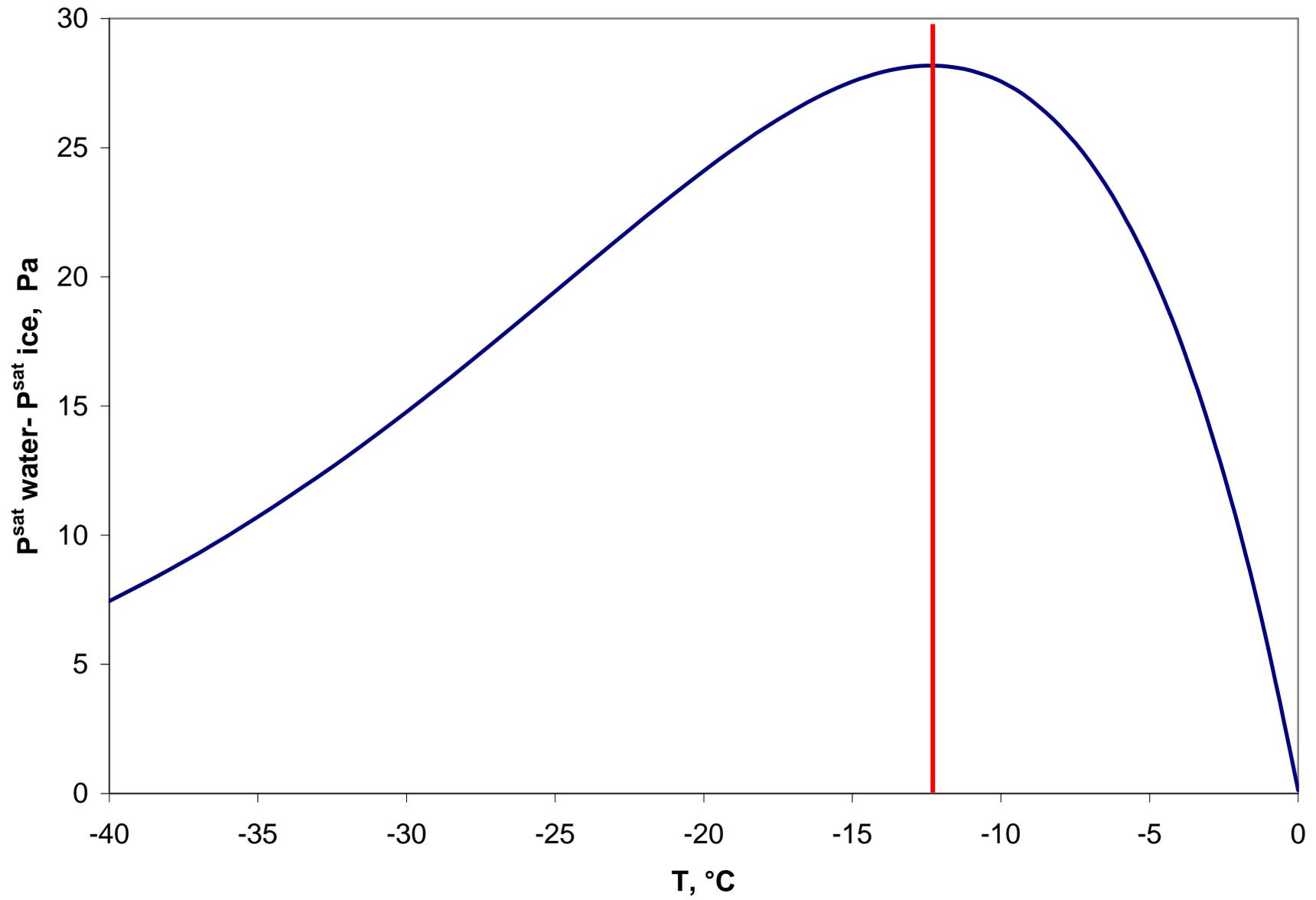
**Givrage = congélation de microgouttellettes surfondues par impaction sur un cristal de glace**

Clapeyron:

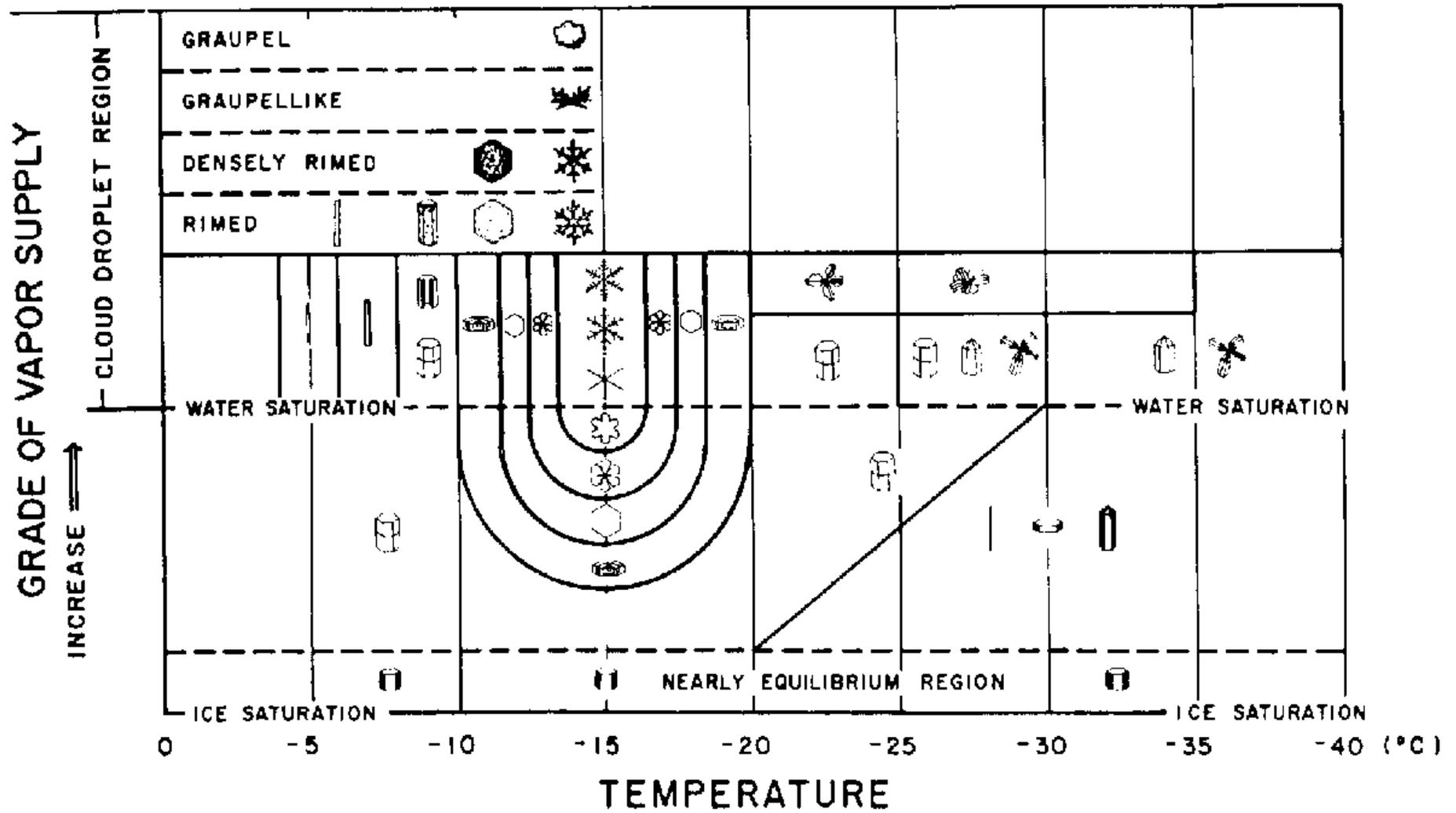
$$\frac{d \ln P^{sat}}{d(1/T)} = - \frac{\Delta H_{sub}}{R}$$

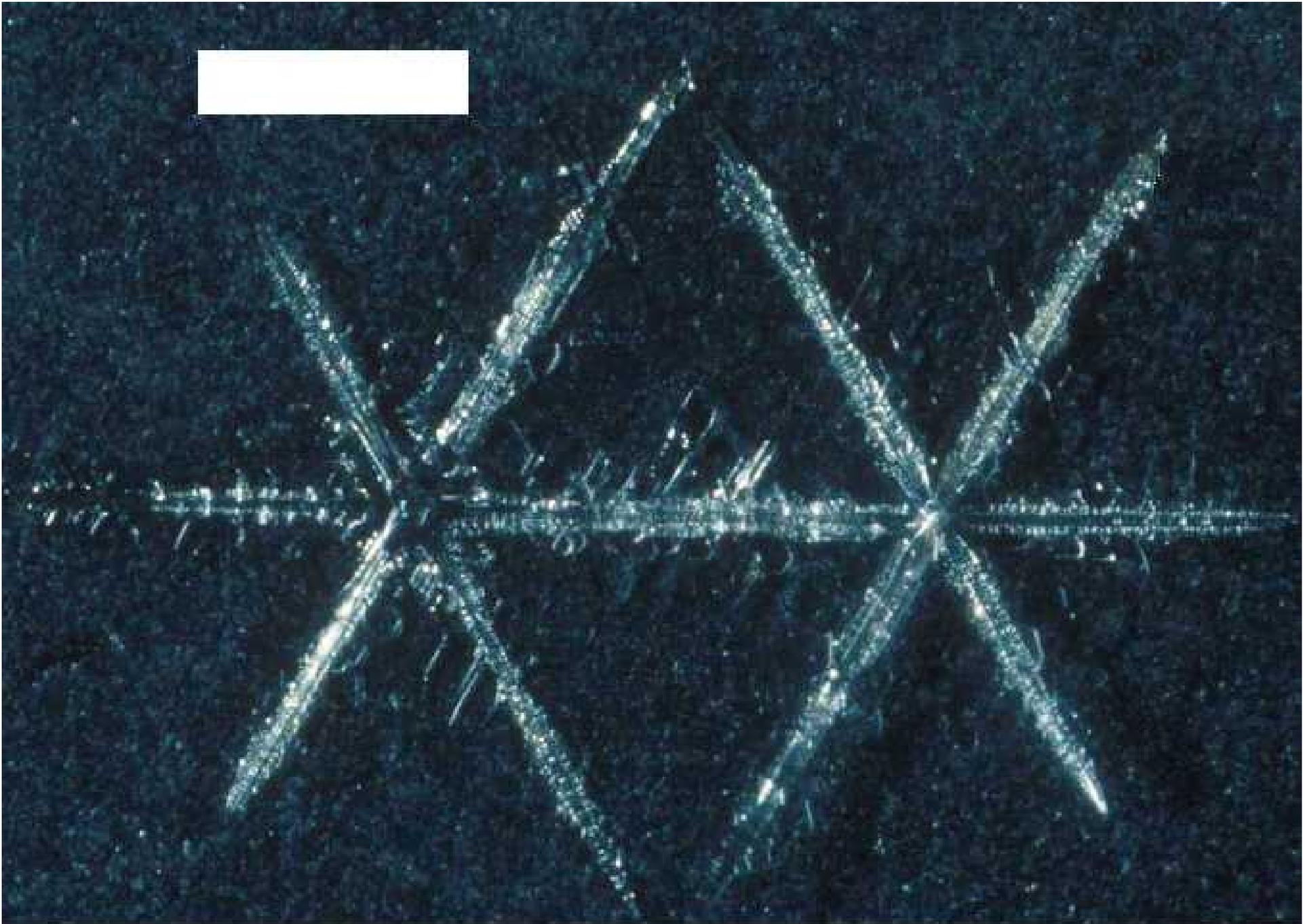
$\Delta H_{sub}$  glace = -50973 J/mol  
 $\Delta H_{evap}$  eau = -44989 J/mol

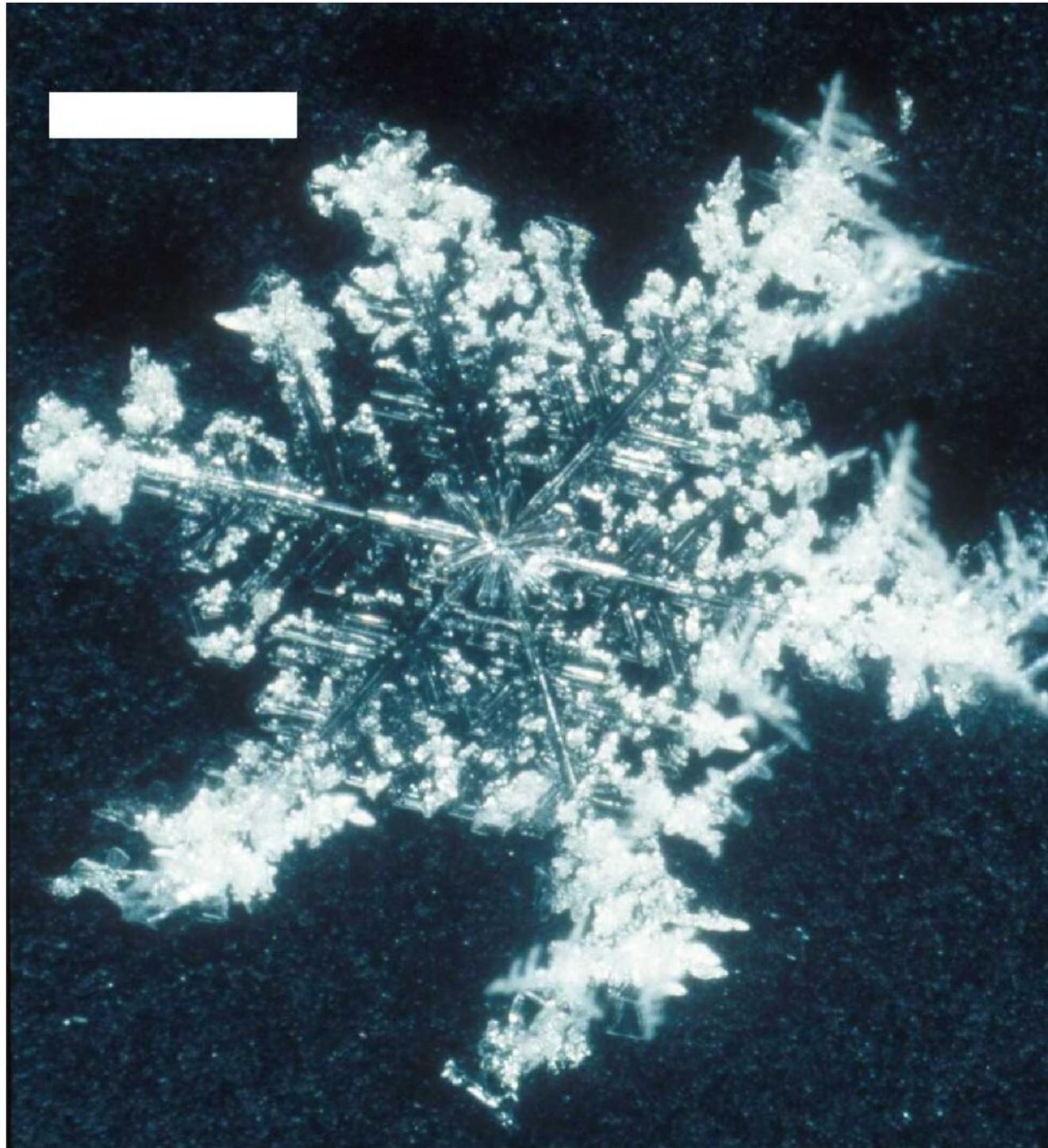


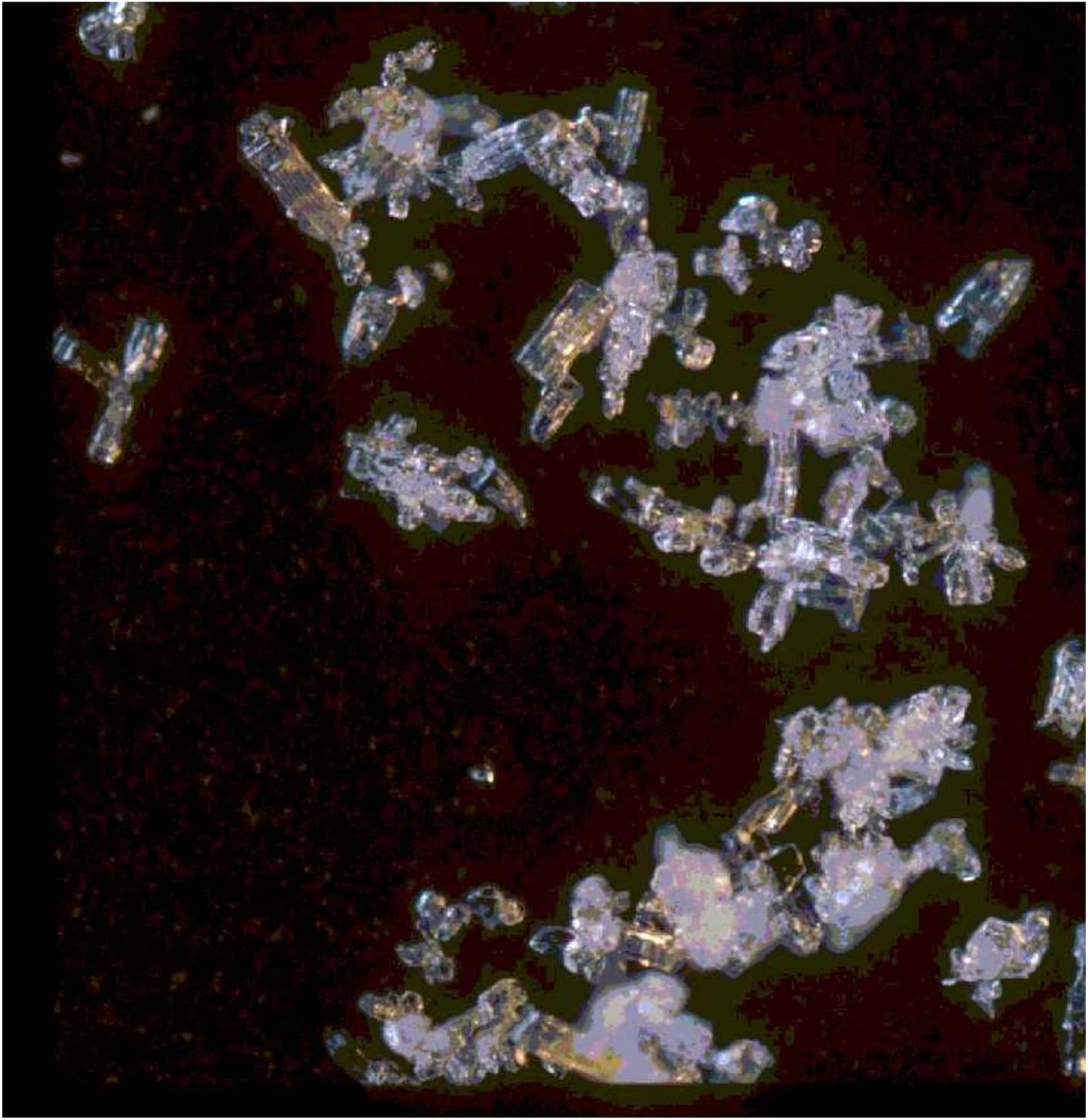


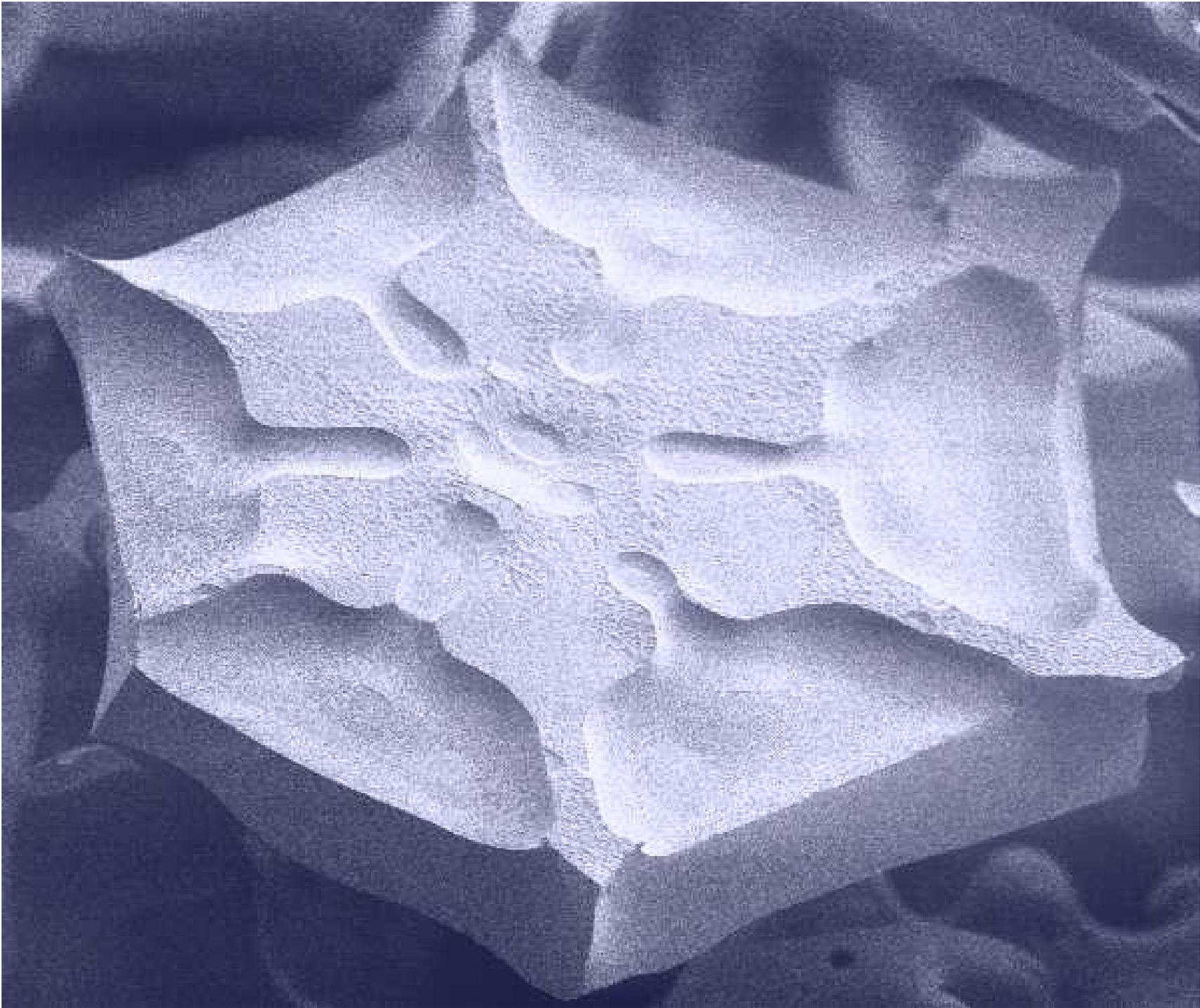
# Conclusion sur la formation des cristaux de neige dans les nuages

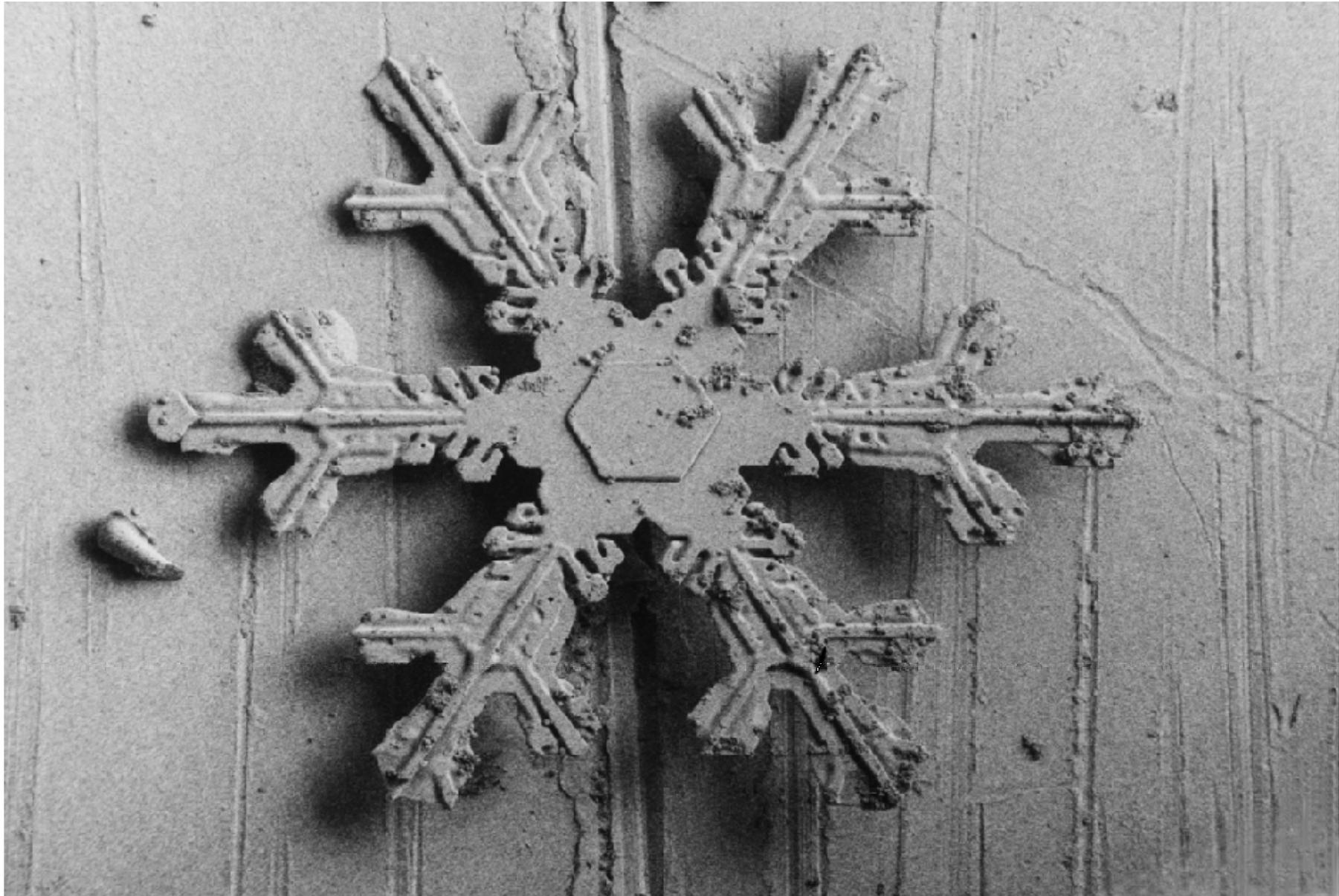


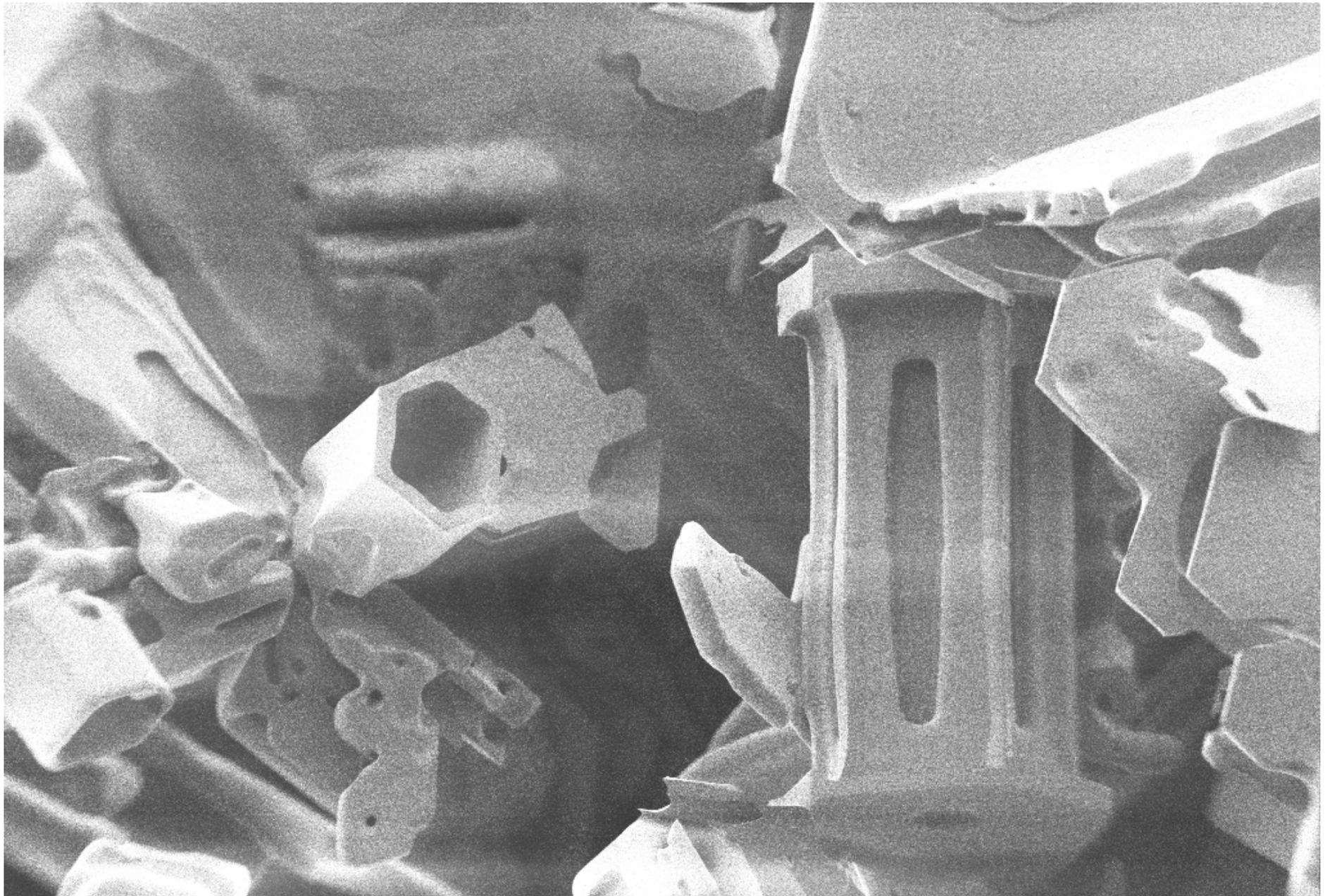












FE-REM Lab GeoZentrum-GÖ

100µm

MAG = 204 X

File Name = Cham-4-35b-08.tif

EHT = 1.20 kV

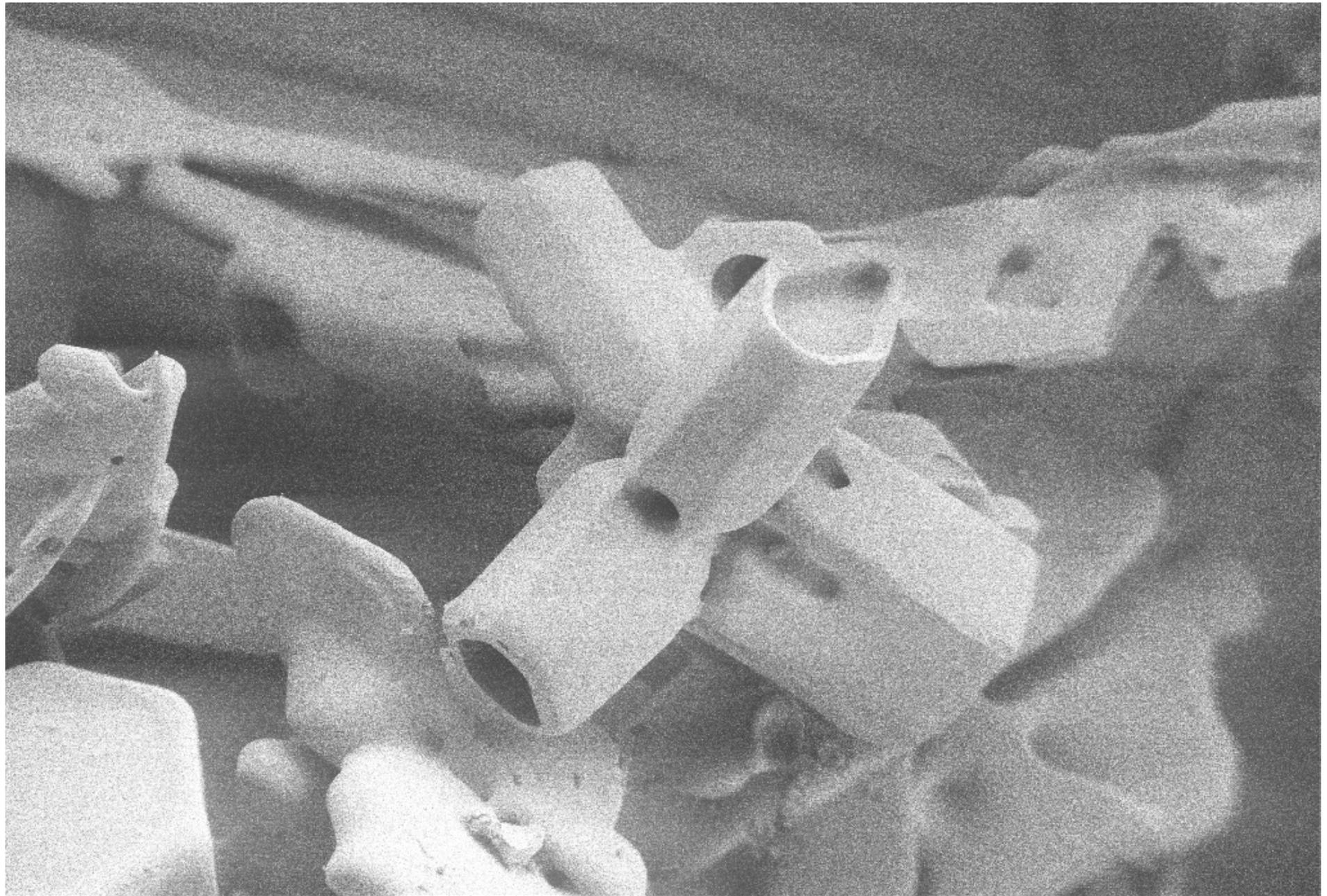
WD = 9 mm

Signal A = SE2

Photo No. = 1642

Date :14 Mar 2002

Time :17:07

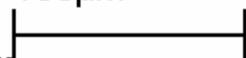


FE-REM Lab GeoZentrum-GÖ

MAG = 333 X

File Name = Cham-4-35a-30.tif

100µm



EHT = 1.20 kV

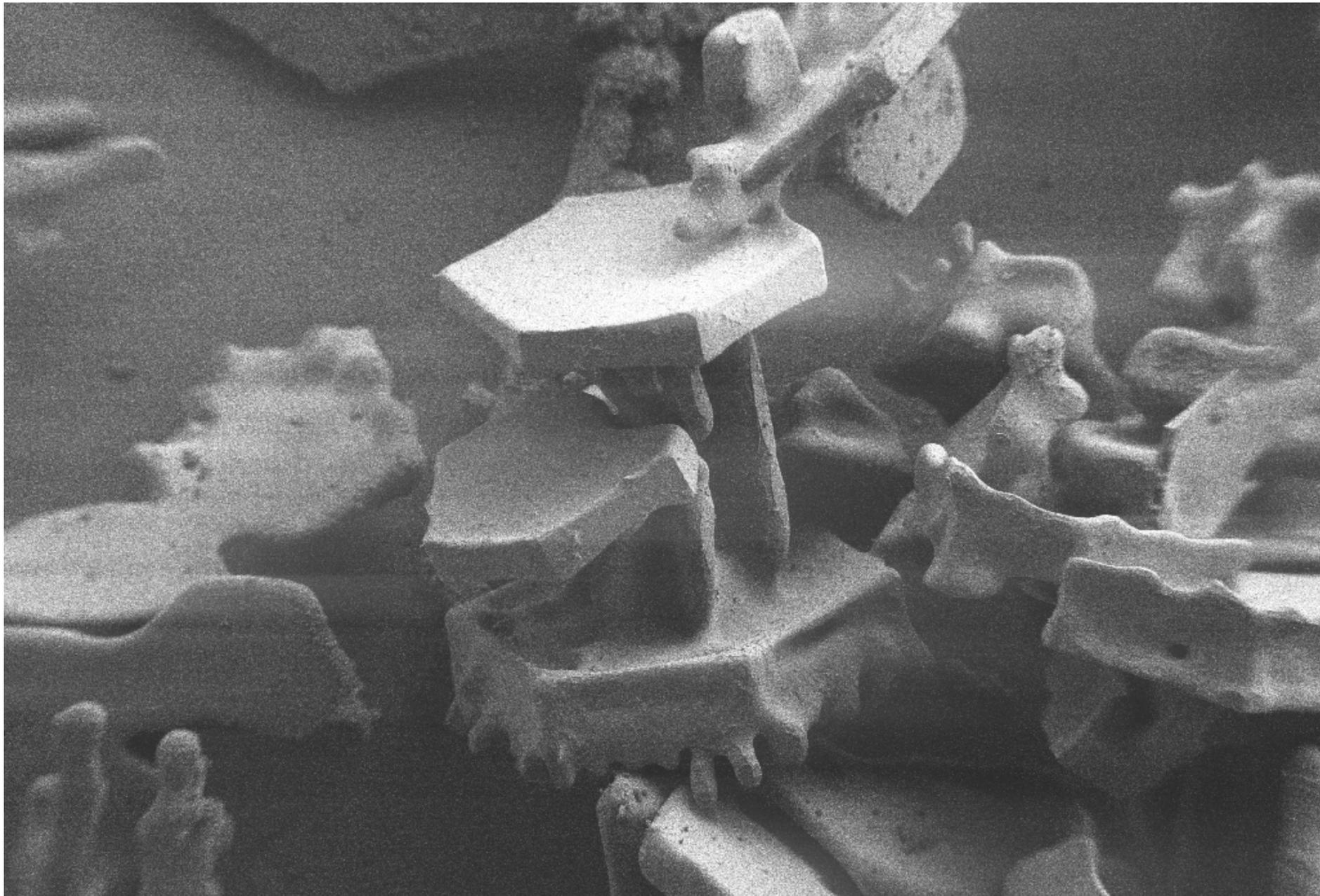
WD = 9 mm

Signal A = SE2

Photo No. = 1622

Date :14 Mar 2002

Time :16:26

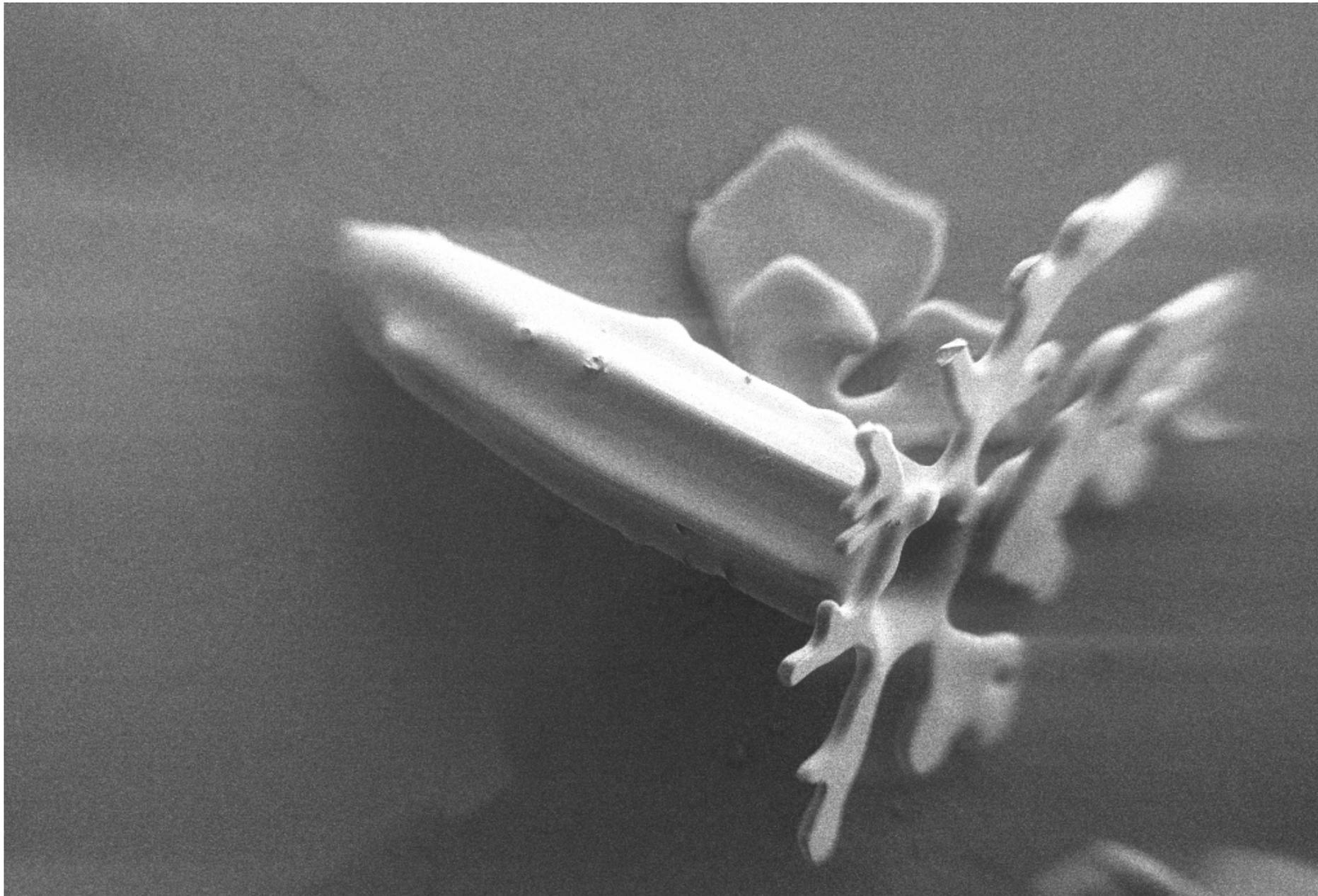


FE-REM Lab GeoZentrum-GÖ 100µm  
MAG = 156 X  
File Name = CdP-15-47b-18.tif

EHT = 1.10 kV  
WD = 7 mm

Signal A = SE2  
Photo No. = 1163

Date :12 Mar 2002  
Time :11:49

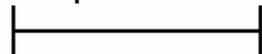


FE-REM Lab GeoZentrum-GÖ

**MAG = 121 X**

*File Name = Ch-4-20-30.tif*

300µm



EHT = 1.00 kV

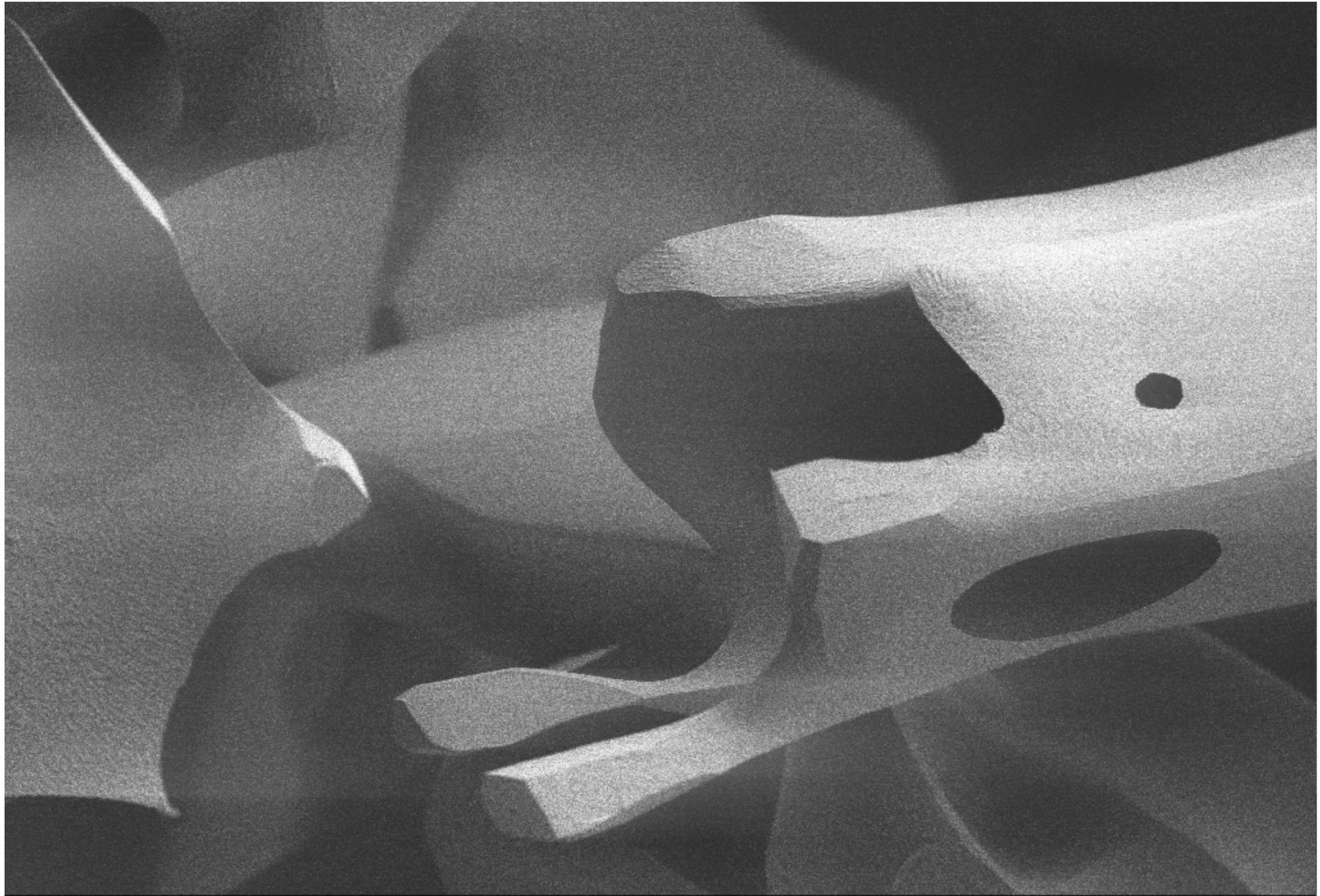
WD = 6 mm

Signal A = SE2

Photo No. = 1029

Date :11 Mar 2002

Time :13:21

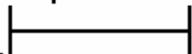


FE-REM Lab GeoZentrum-GÖ

MAG = 880 X

File Name = CdP-15-47a-23.tif

30µm



EHT = 1.20 kV

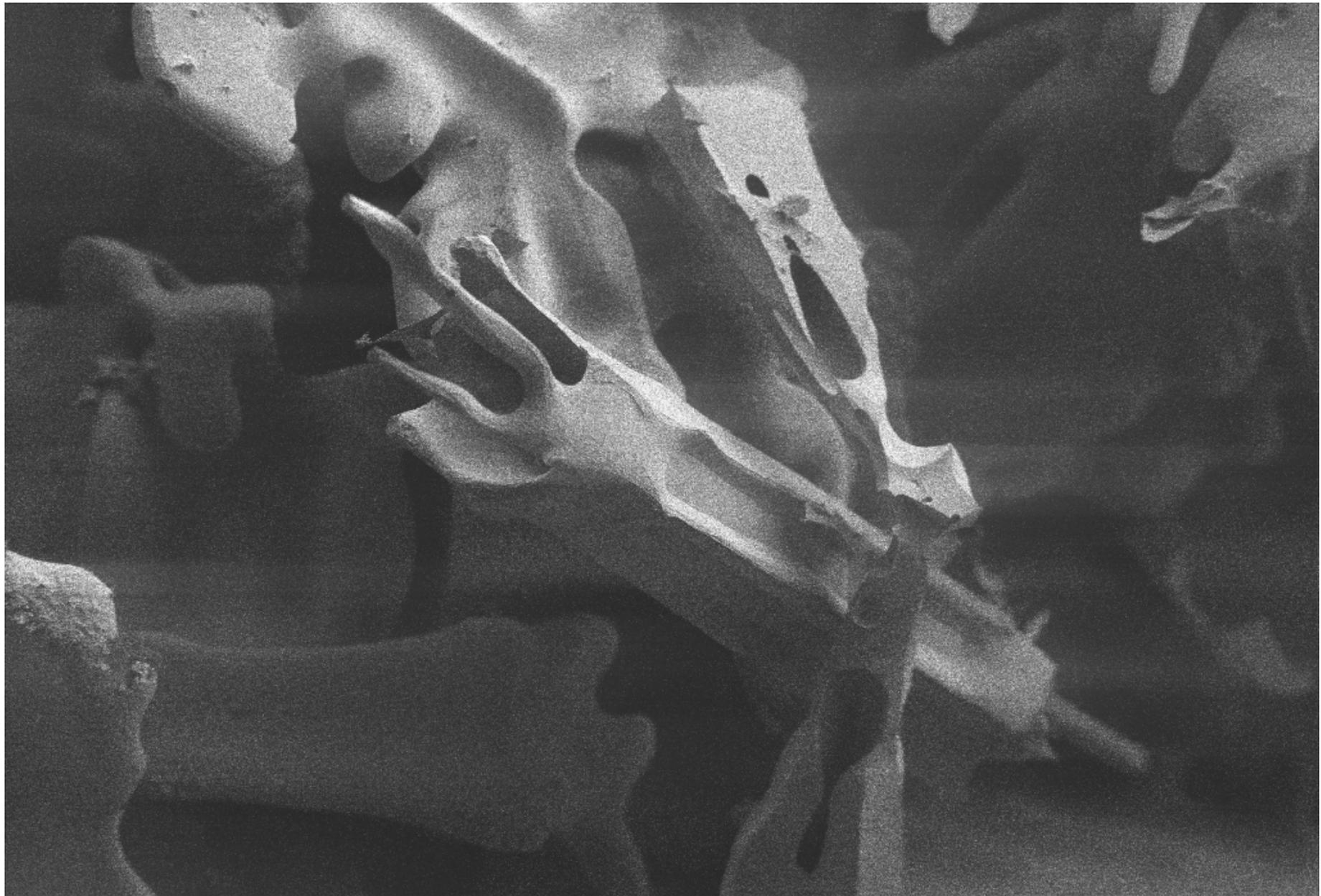
WD = 5 mm

Signal A = SE2

Photo No. = 1127

Date :12 Mar 2002

Time :10:35

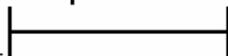


FE-REM Lab GeoZentrum-GÖ

**MAG = 323 X**

File Name = CdP-15-47b-20.tif

100µm



EHT = 1.10 kV

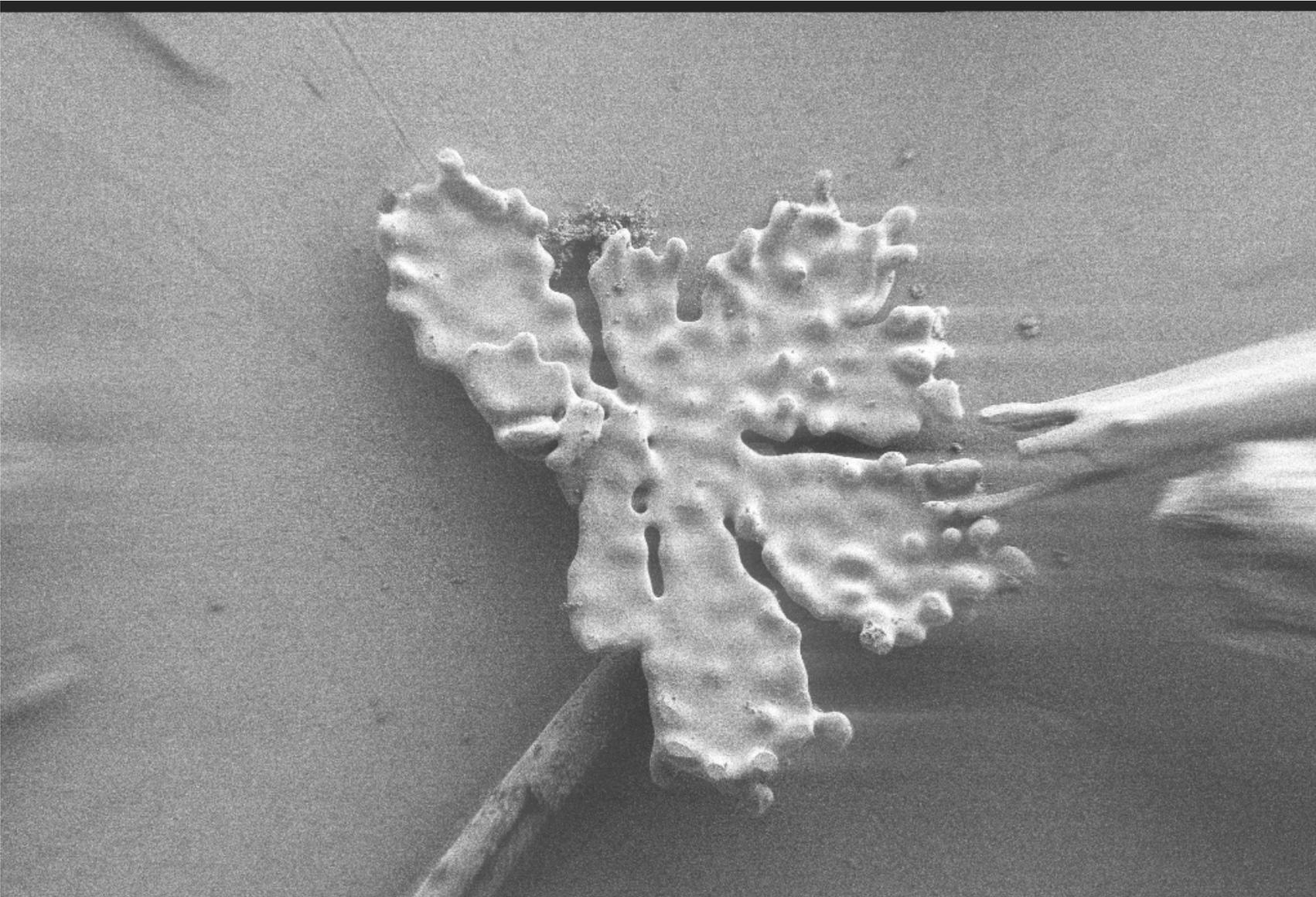
WD = 6 mm

Signal A = SE2

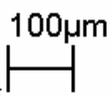
Photo No. = 1165

Date :12 Mar 2002

Time :11:51



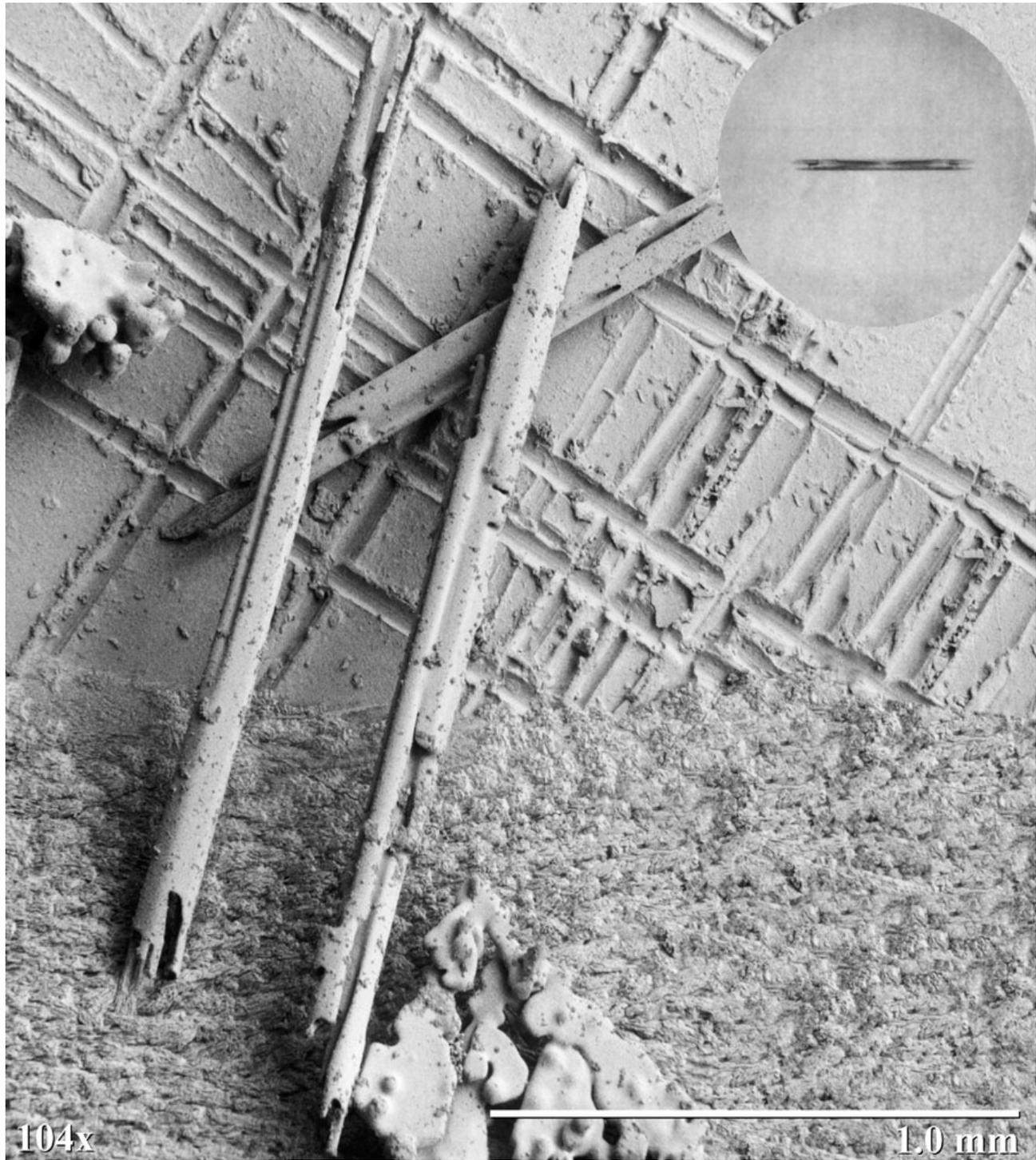
FE-REM Lab GeoZentrum-GÖ  
**MAG = 105 X**  
File Name = CdP-15-47b-27.tif

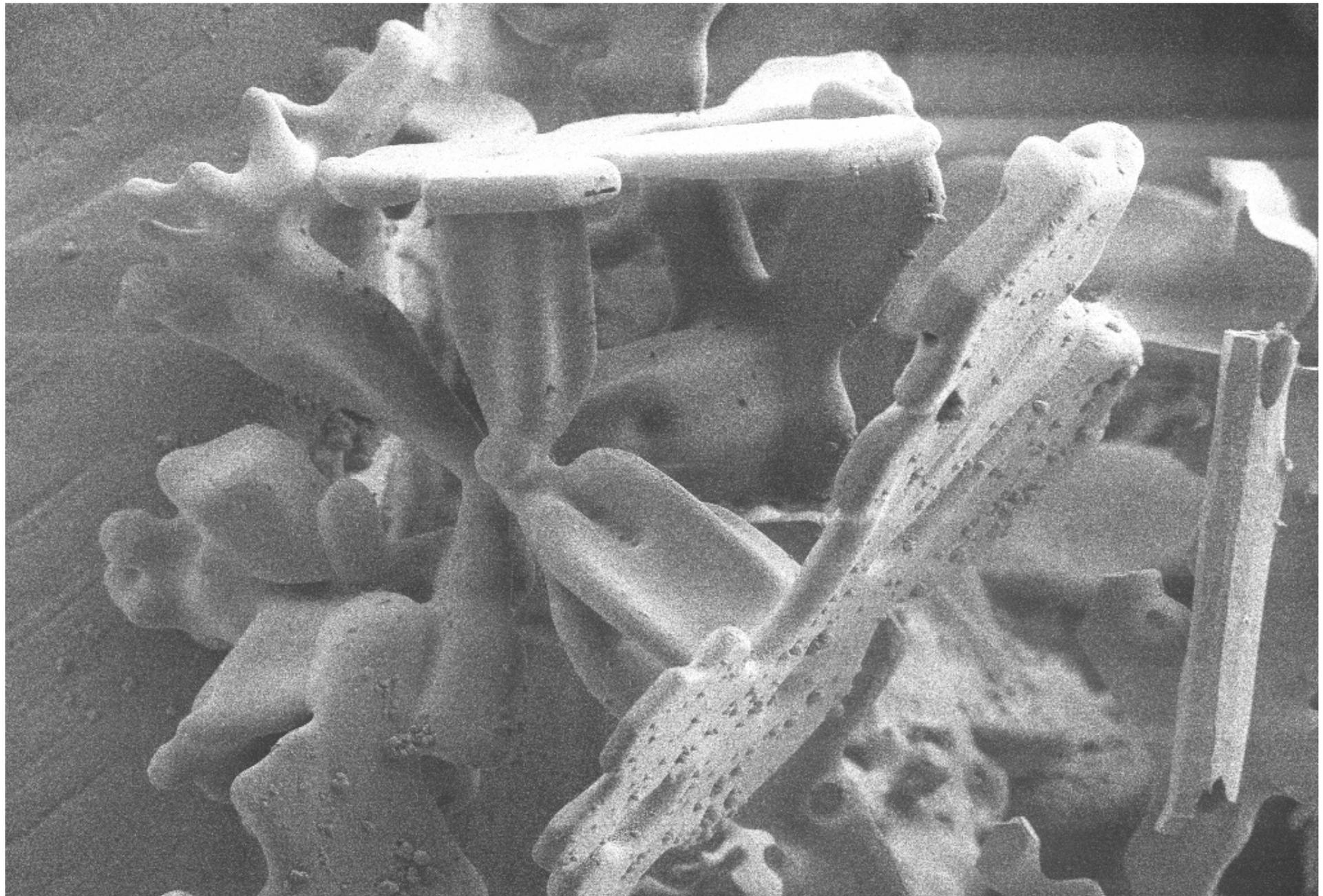


EHT = 1.10 kV  
WD = 7 mm

Signal A = SE2  
Photo No. = 1172

Date :12 Mar 2002  
Time :11:59



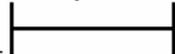


FE-REM Lab GeoZentrum-GÖ

**MAG = 230 X**

File Name = CdP-15-47c-07.tif

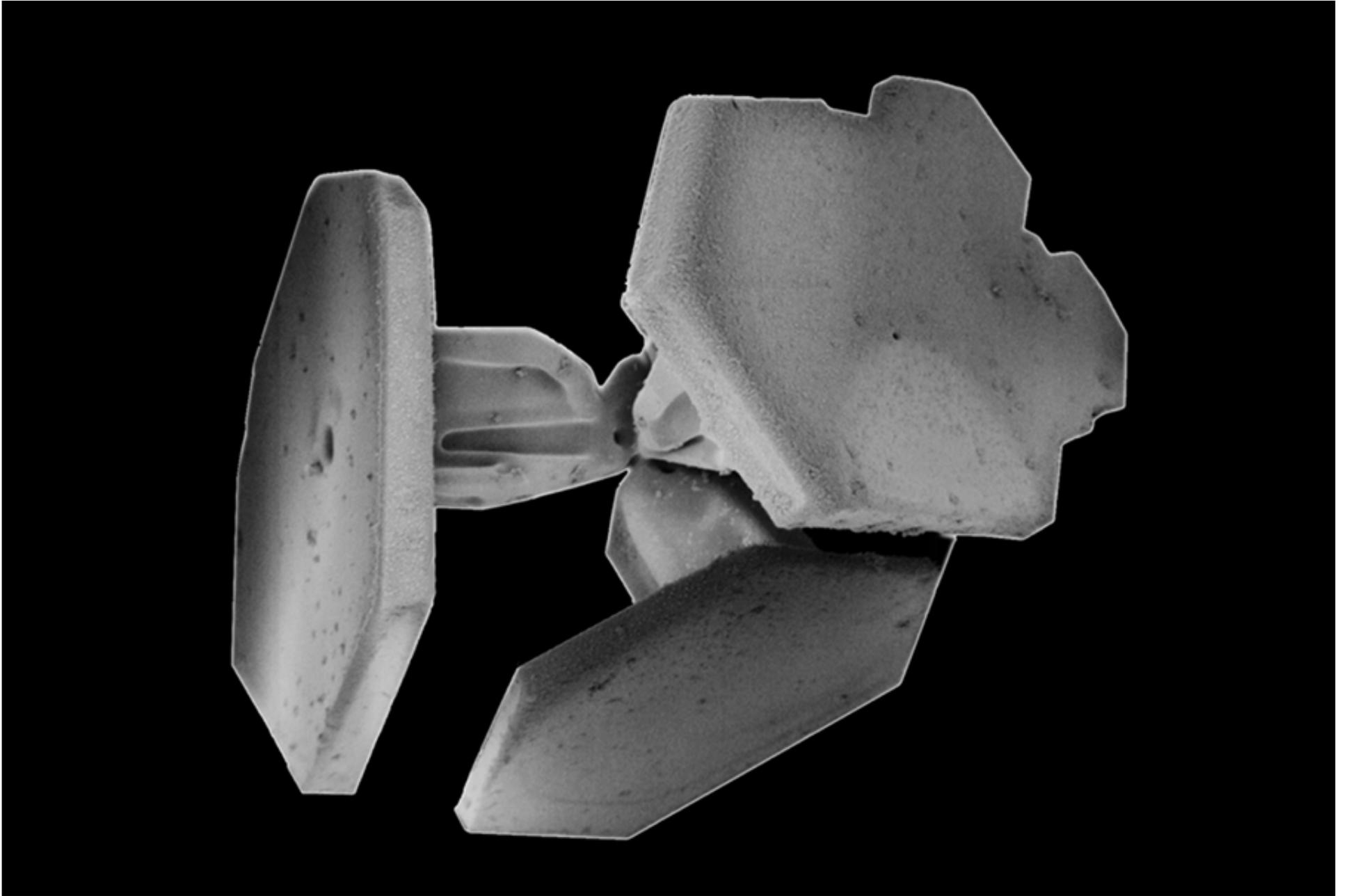
100µm

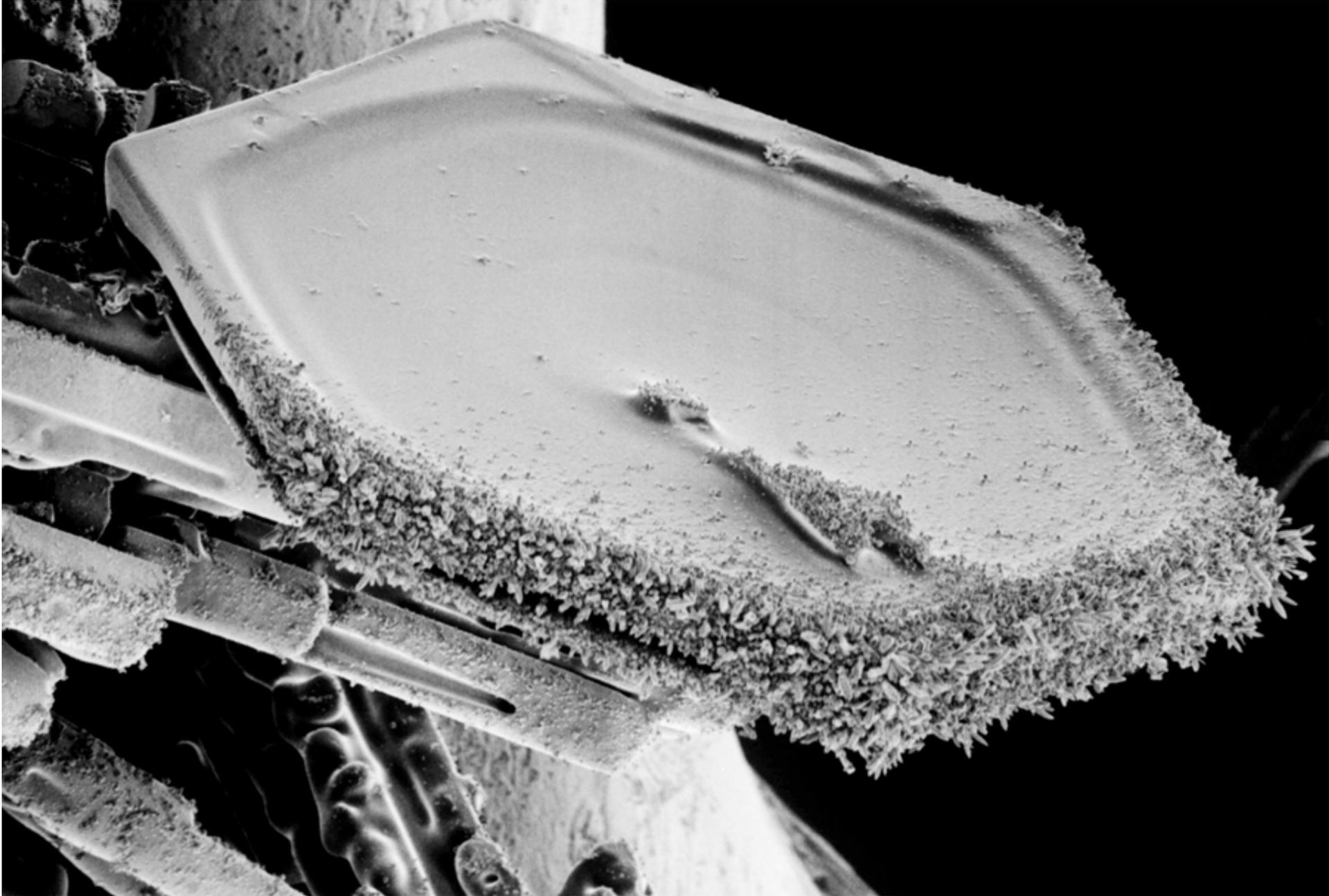


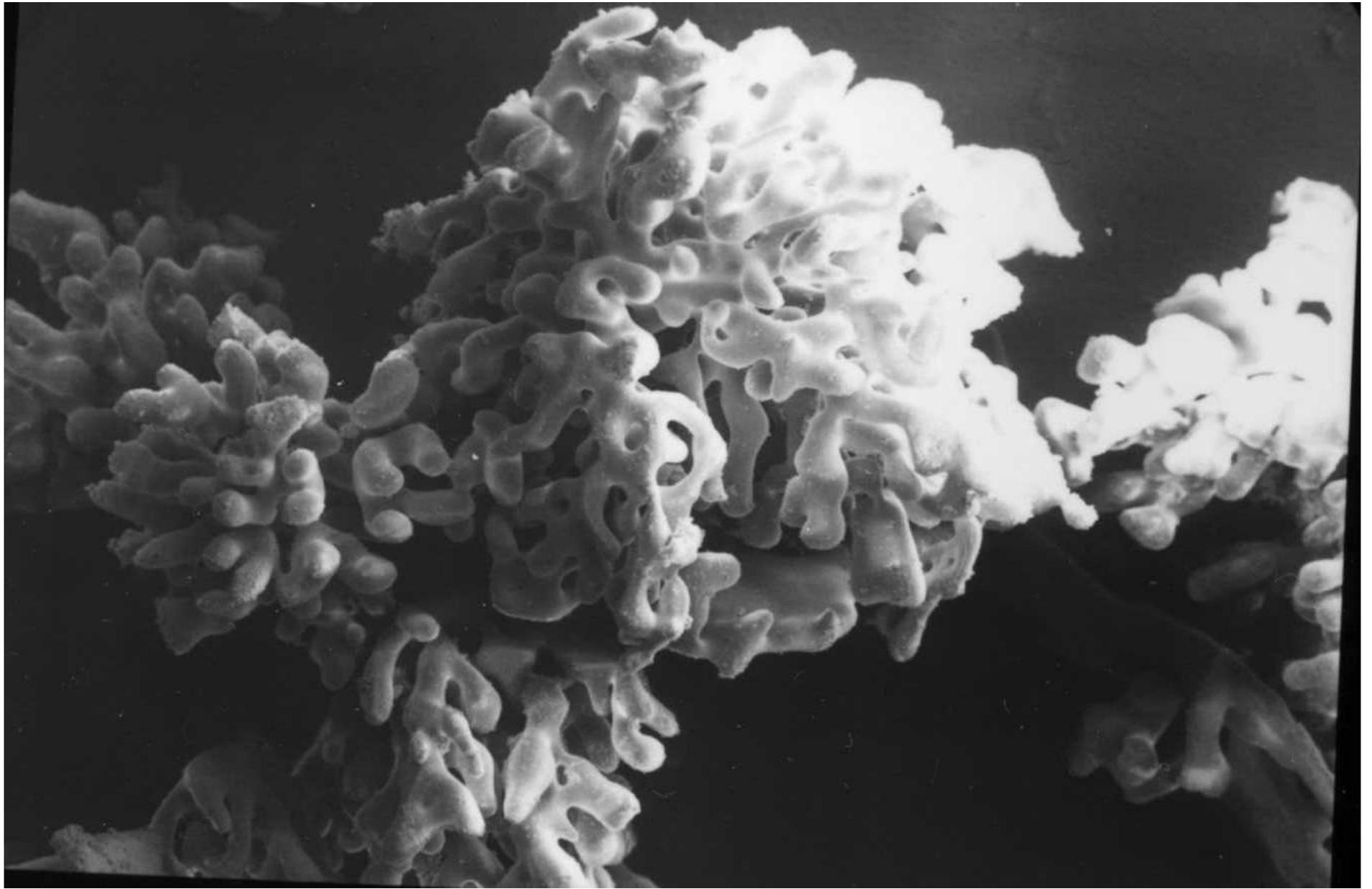
EHT = 2.00 kV  
WD = 7 mm

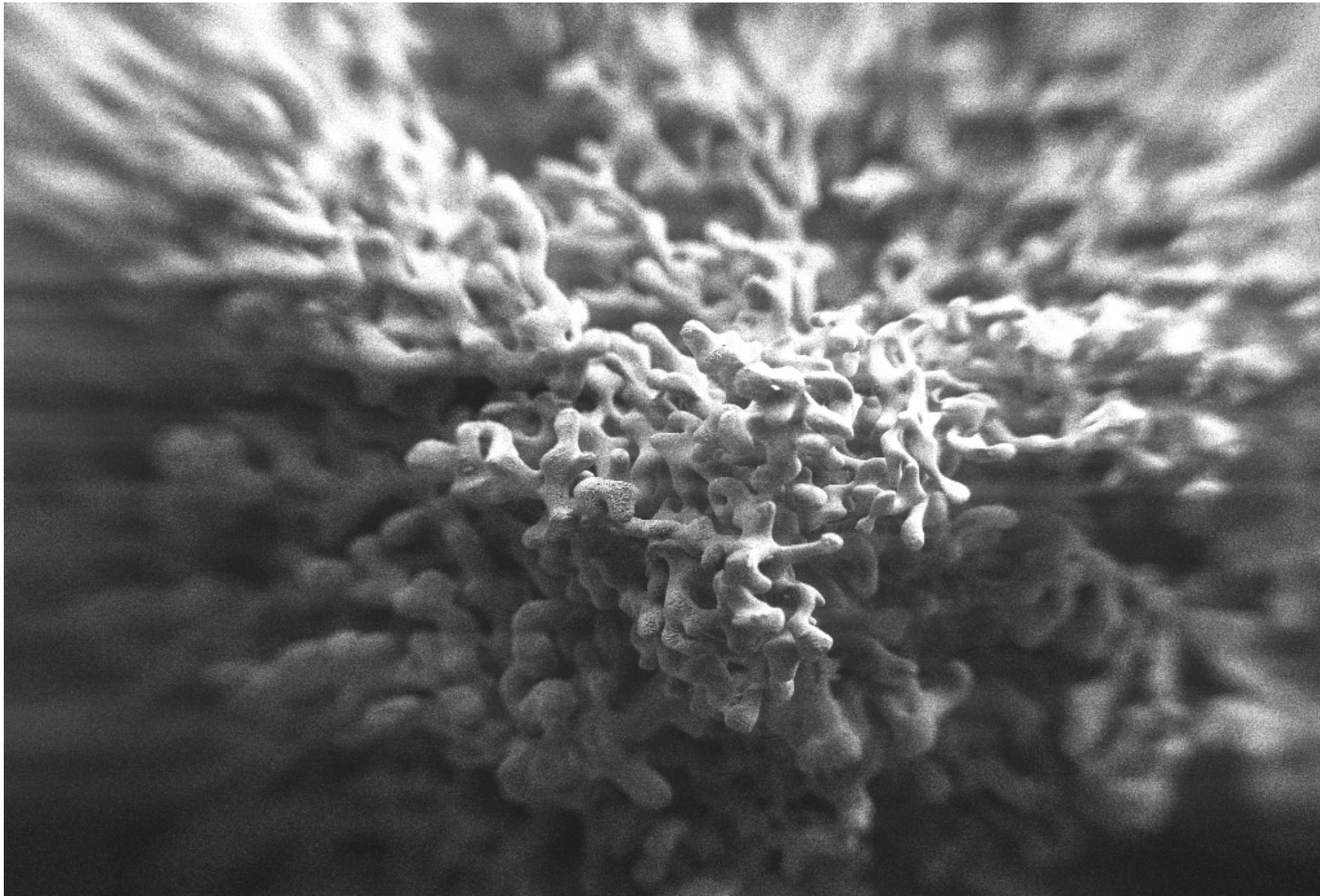
Signal A = SE2  
Photo No. = 1193

Date :13 Mar 2002  
Time :10:19







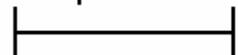


FE-REM Lab GeoZentrum-GÖ

**MAG = 158 X**

*File Name = roule2\_18.tif*

200µm



EHT = 1.00 kV

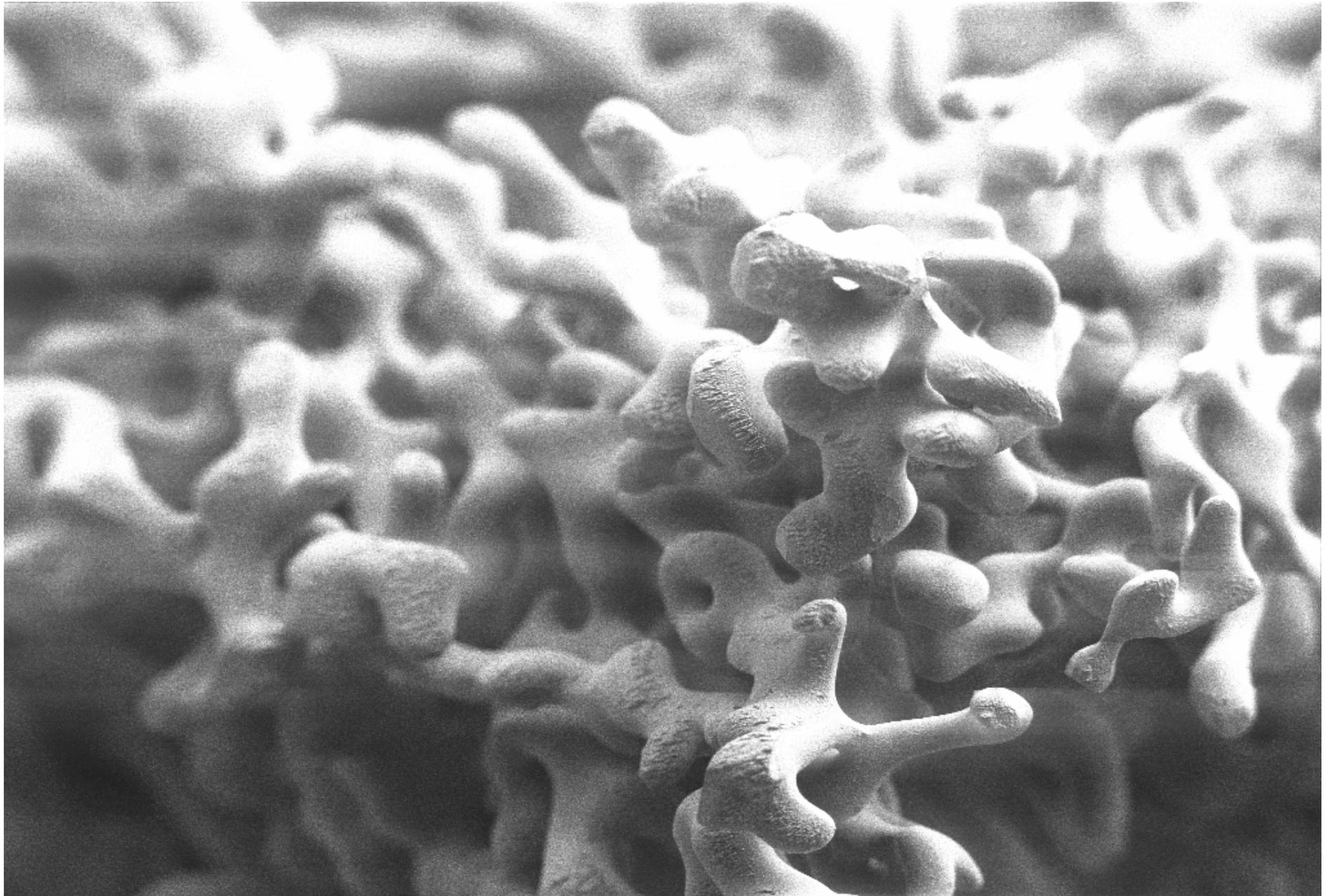
WD = 7 mm

Signal A = SE2

Photo No. = 998

Date :11 Mar 2002

Time :12:18

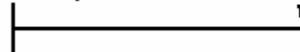


FE-REM Lab GeoZentrum-GÖ

**MAG = 432 X**

File Name = route2\_19.tif

100µm



EHT = 1.00 kV

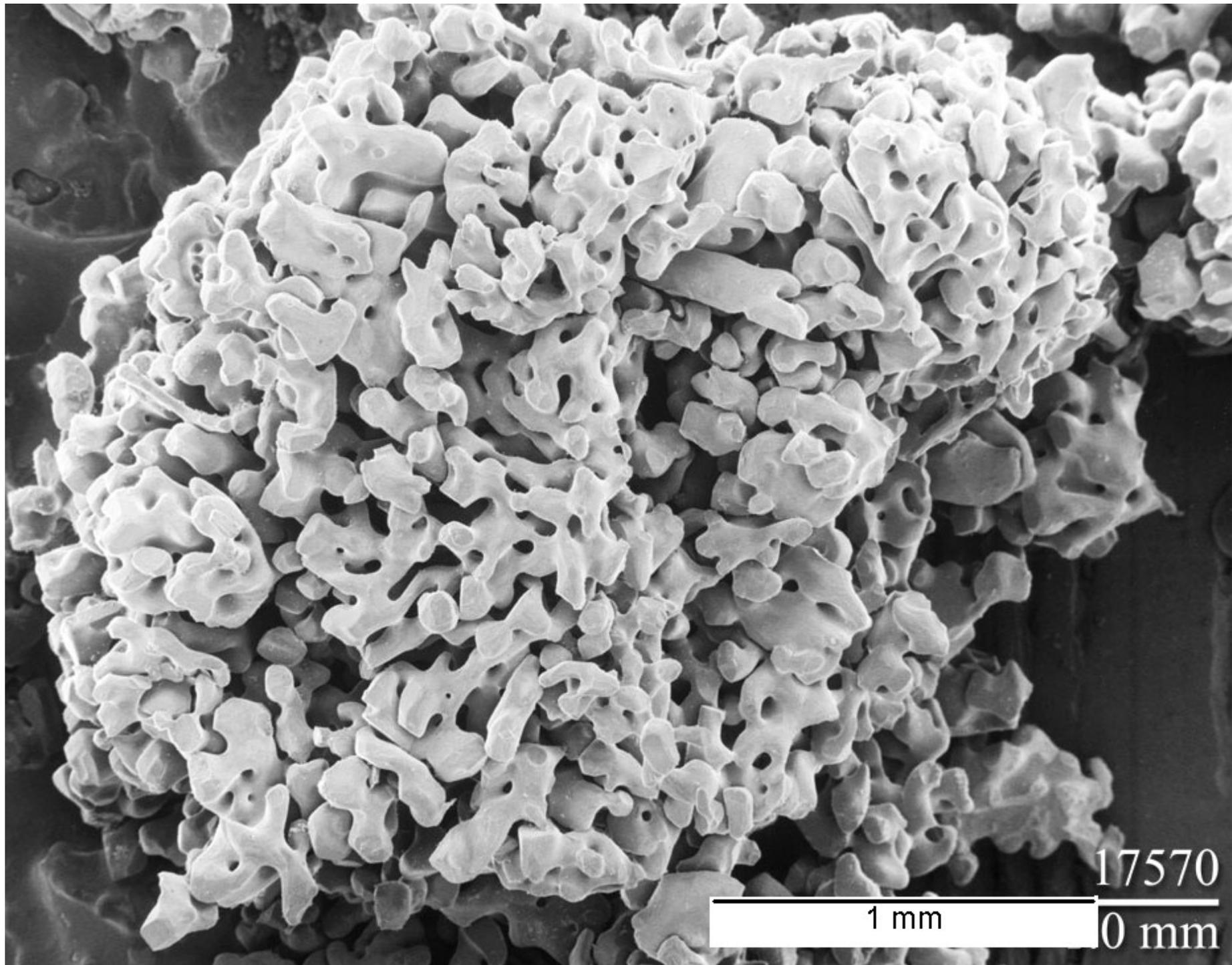
WD = 6 mm

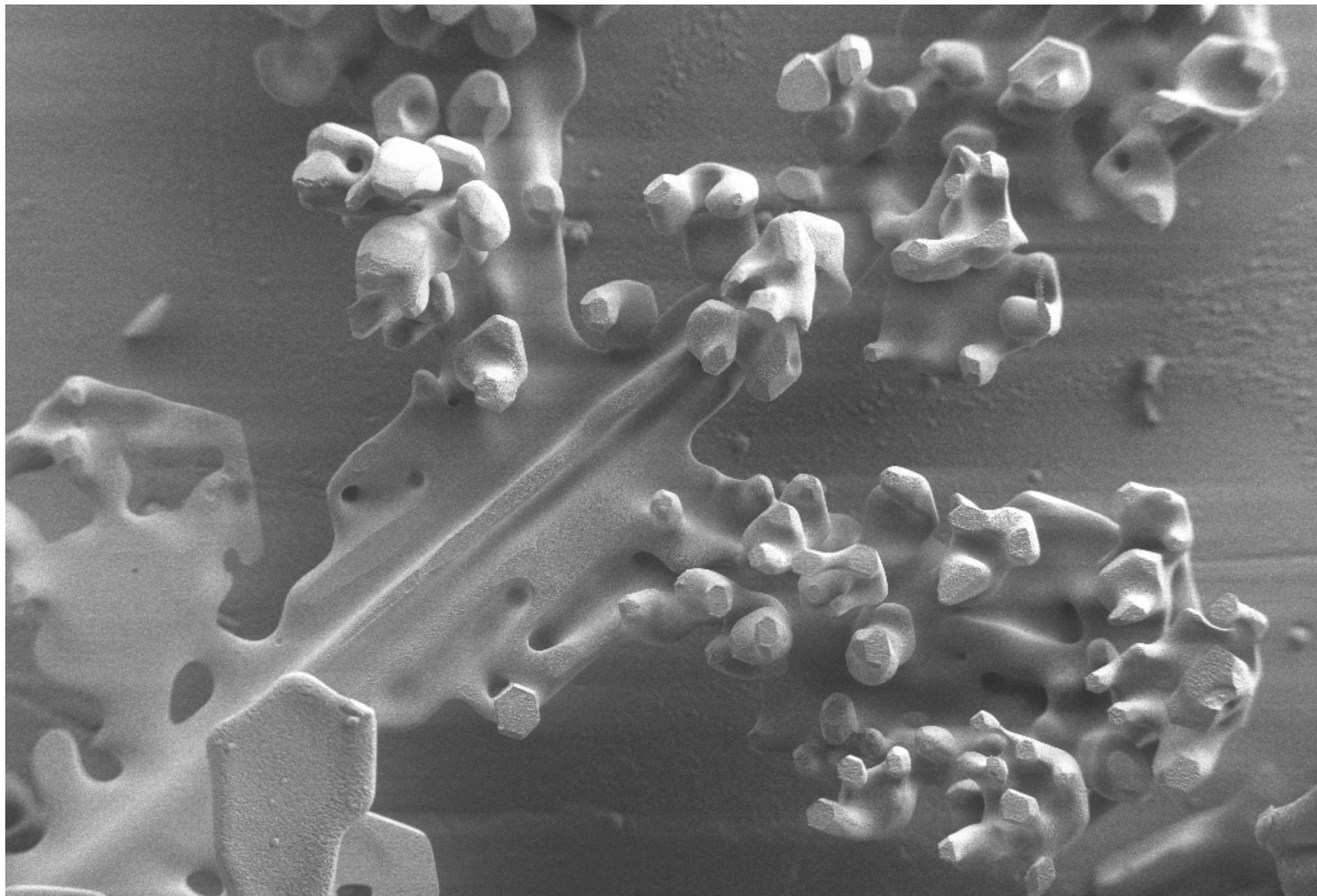
Signal A = SE2

Photo No. = 999

Date :11 Mar 2002

Time :12:20



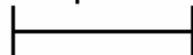


FE-REM Lab GeoZentrum-GÖ

MAG = 260 X

File Name = grp9\_36.tif

100µm



EHT = 1.40 kV

WD = 7 mm

Signal A = SE2

Photo No. = 853

Date :27 Feb 2002

Time :10:47

