UE: LG.2.11 Métamorphisme et Magmatisme: processus pétrologiques, géochimie et géochronologie et géodynamique

Manteau et magmatisme mantellique

- Magmatologie expérimentale

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1 Introduction

Les pionniers

Jacques-Joseph EBELMEN (1814-1852)
administrateur de la manufacture de porcelaine de Sèvres
Synthèse de minéraux (spinelle, corindon, émeraude).

Gabriel Auguste DAUBREE

(1814-1896)

Etudes synthétiques de géologie expérimentale (1879)

Métallogénie et météorites

Ferdinand FOUQUÉ (1828-1904)

synthèses de minéraux volcaniques

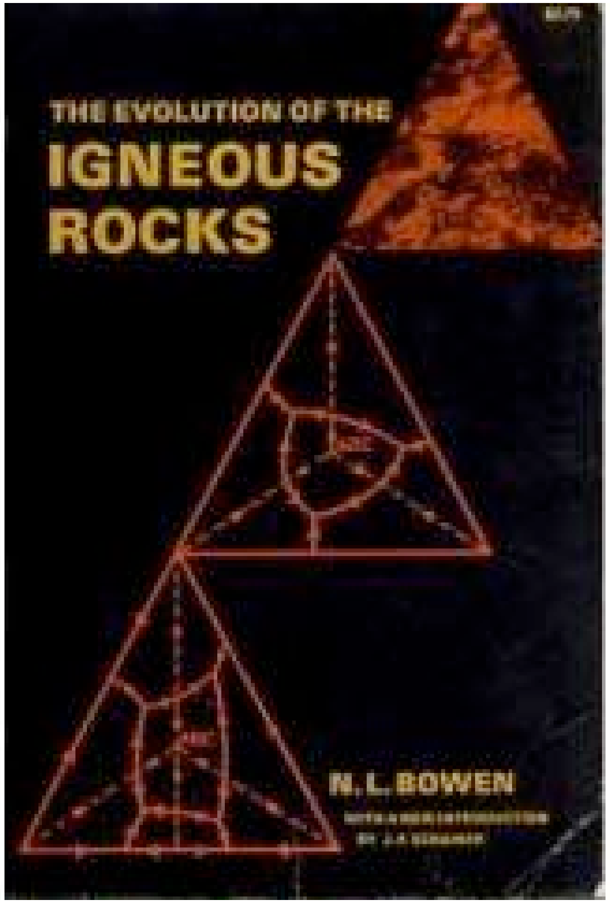
Synthèse des minéraux et des roches (1882)

Auguste MICHEL-LEVY (1844-1911)
fondateur de la minéralogie micrographique

Le père de la magmatologie expérimentale

Norman L. BOWEN

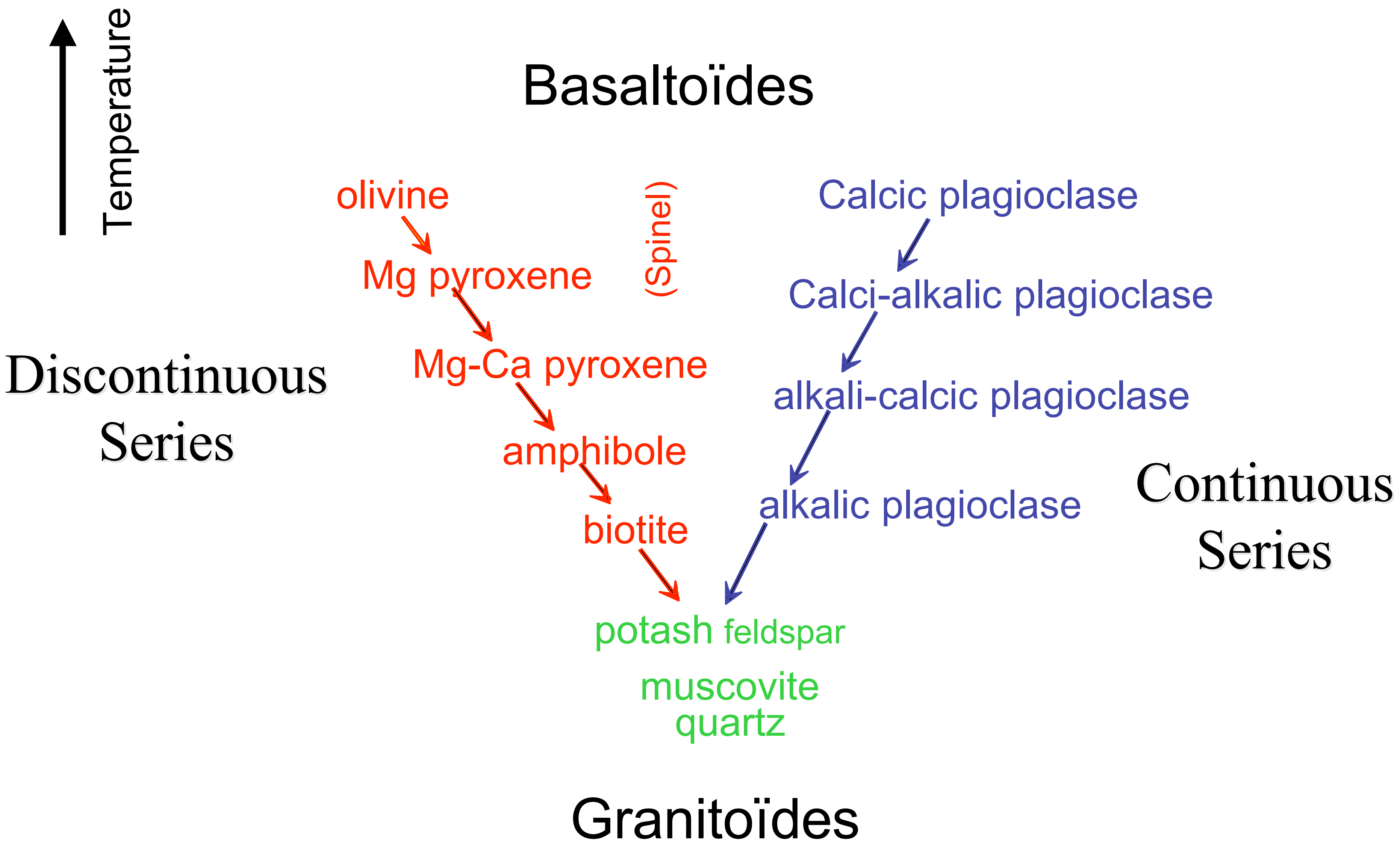
1887-1956



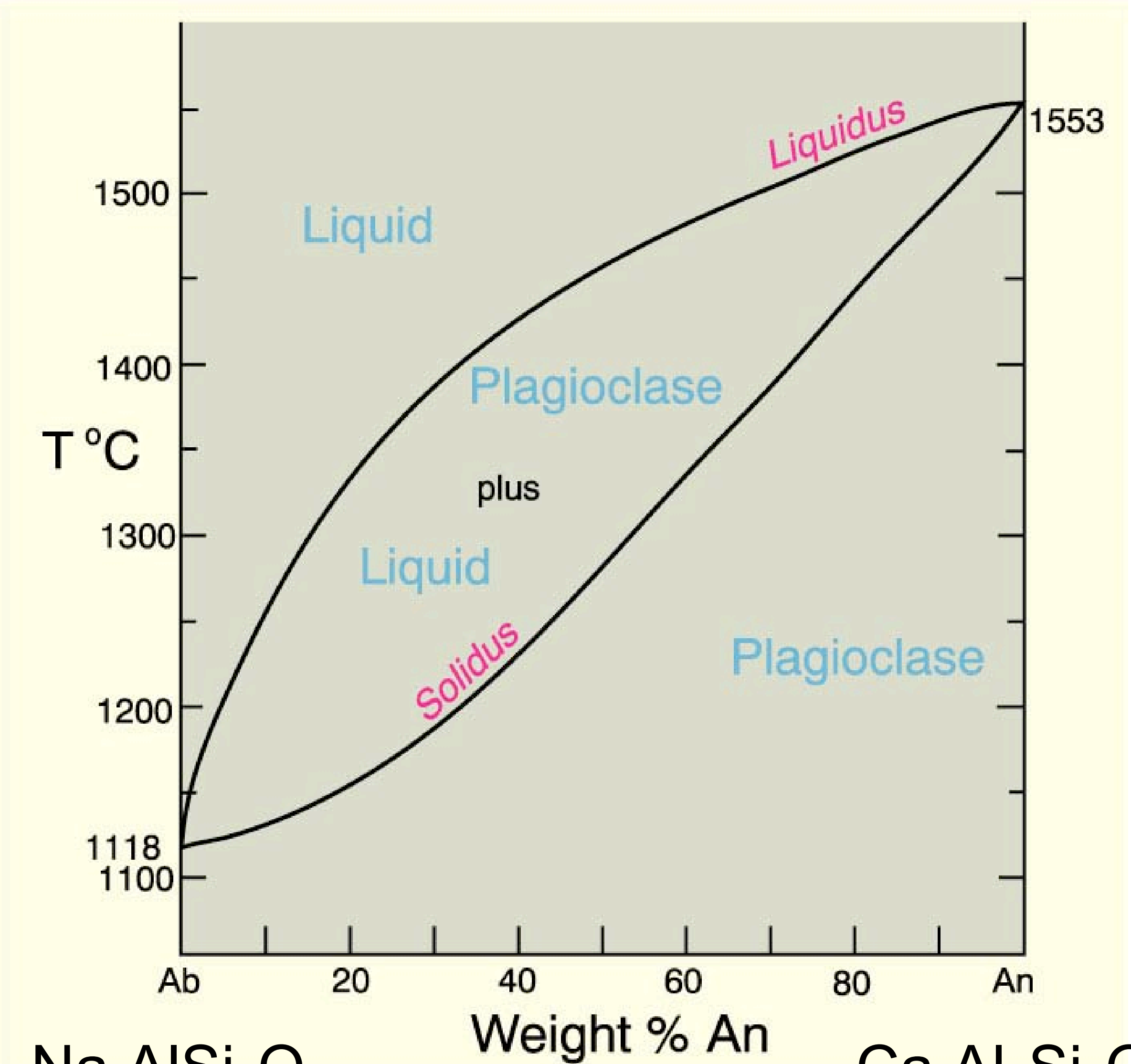
Bowen, N. L., The later stages of the evolution of the igneous rocks, Journal of Geology, 23, 1 – 89, 1915.

Bowen, N. L., Evolution of the Igneous Rocks, Princeton University Press, Princeton, 1928.

Bowen's Reaction Series



Isobaric T-X phase diagram at atmospheric pressure. After Bowen (1913) Amer. J. Sci., 35, 577-599.

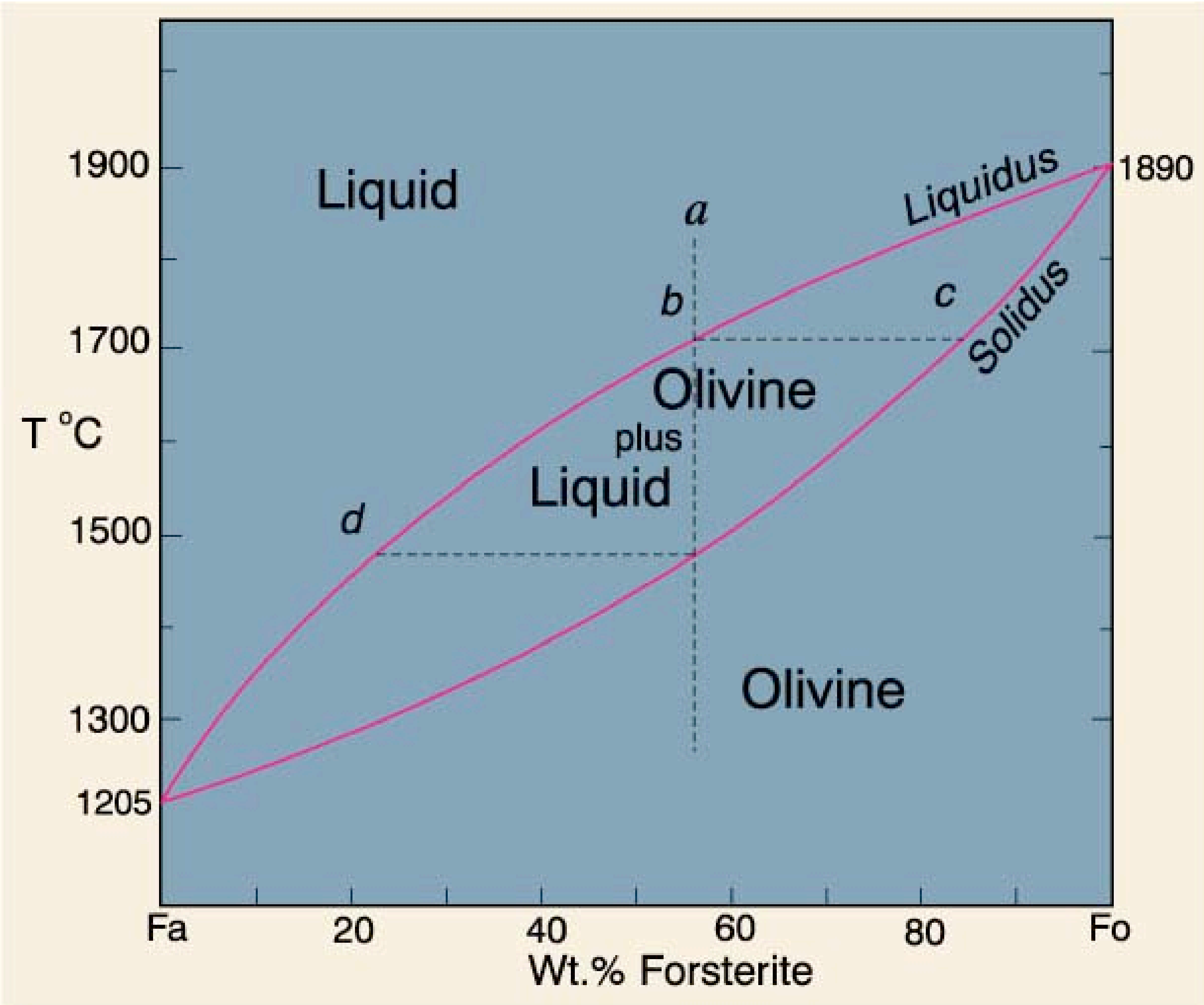


Na $AlSi_3O_8$ Ca $Al_2Si_2O_8$

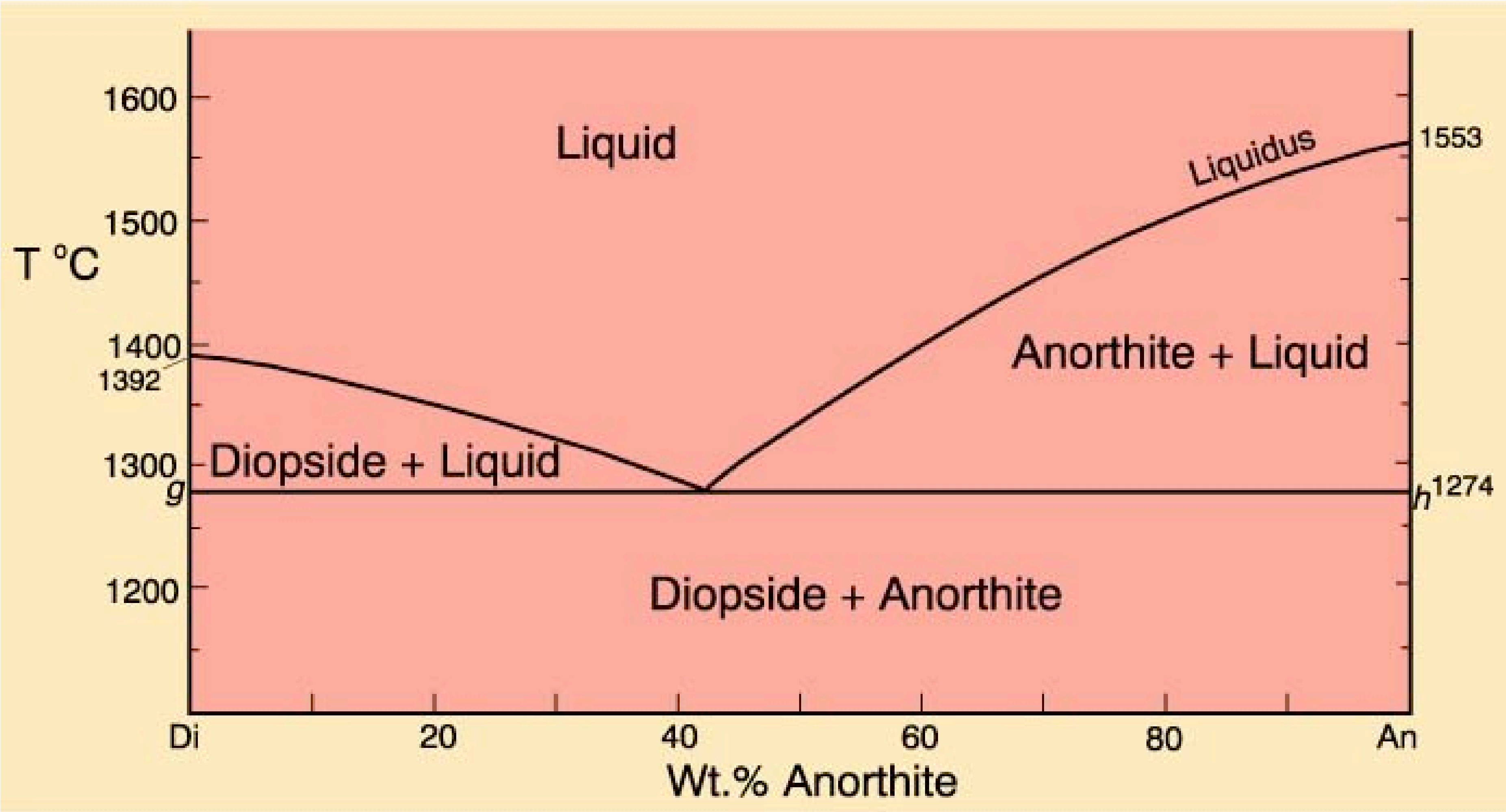
Liquidus: courbe séparant le domaine où la phase liquide existe seule de celui où elle coexiste avec des cristaux

Solidus: courbe séparant le domaine où la phase solide existe seule de celui où elle coexiste avec une phase liquide

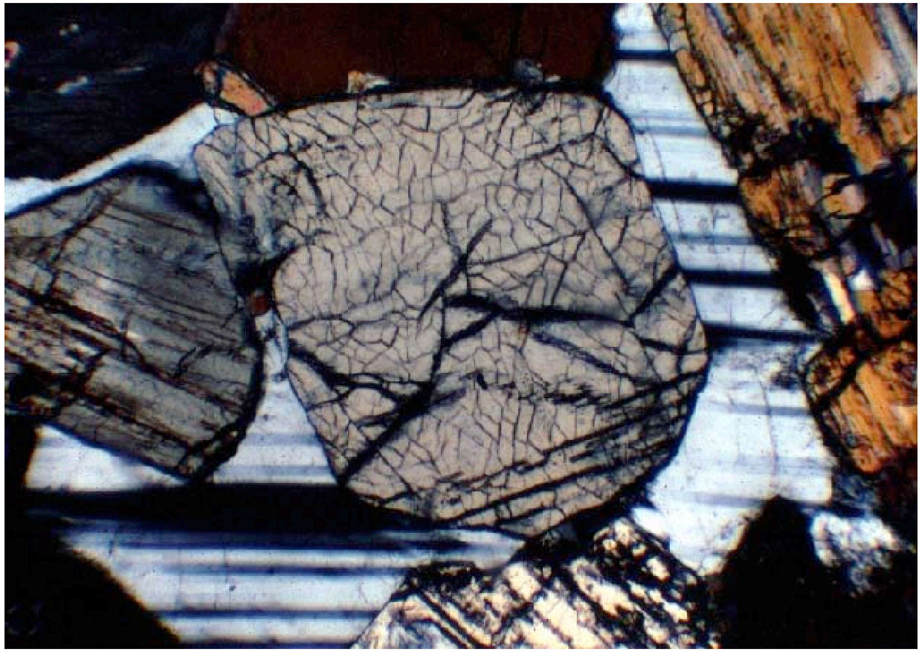
Solution solide: Na Si ⇔ Ca Al



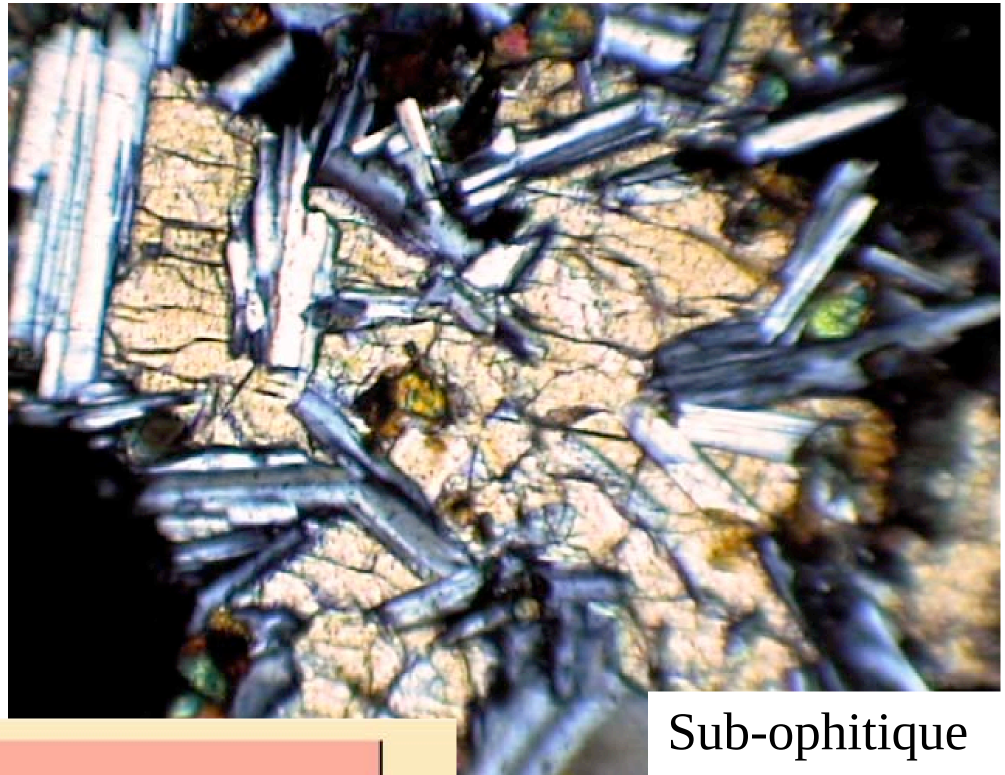
Isobaric T-X phase diagram at atmospheric pressure After Bowen and Shairer (1932), Amer. J. Sci. 5th Ser., 24, 177-213.



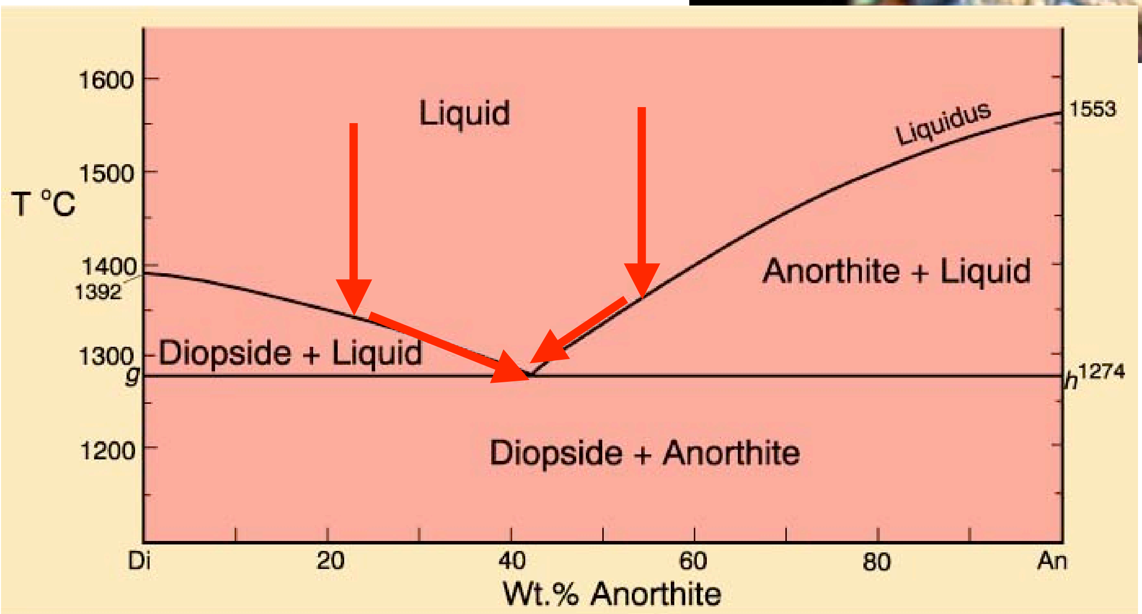
Isobaric T-X phase diagram at atmospheric pressure.
After Bowen (1915), Amer. J. Sci. 40, 161-185.



Le pyroxène se forme avant le plagioclase

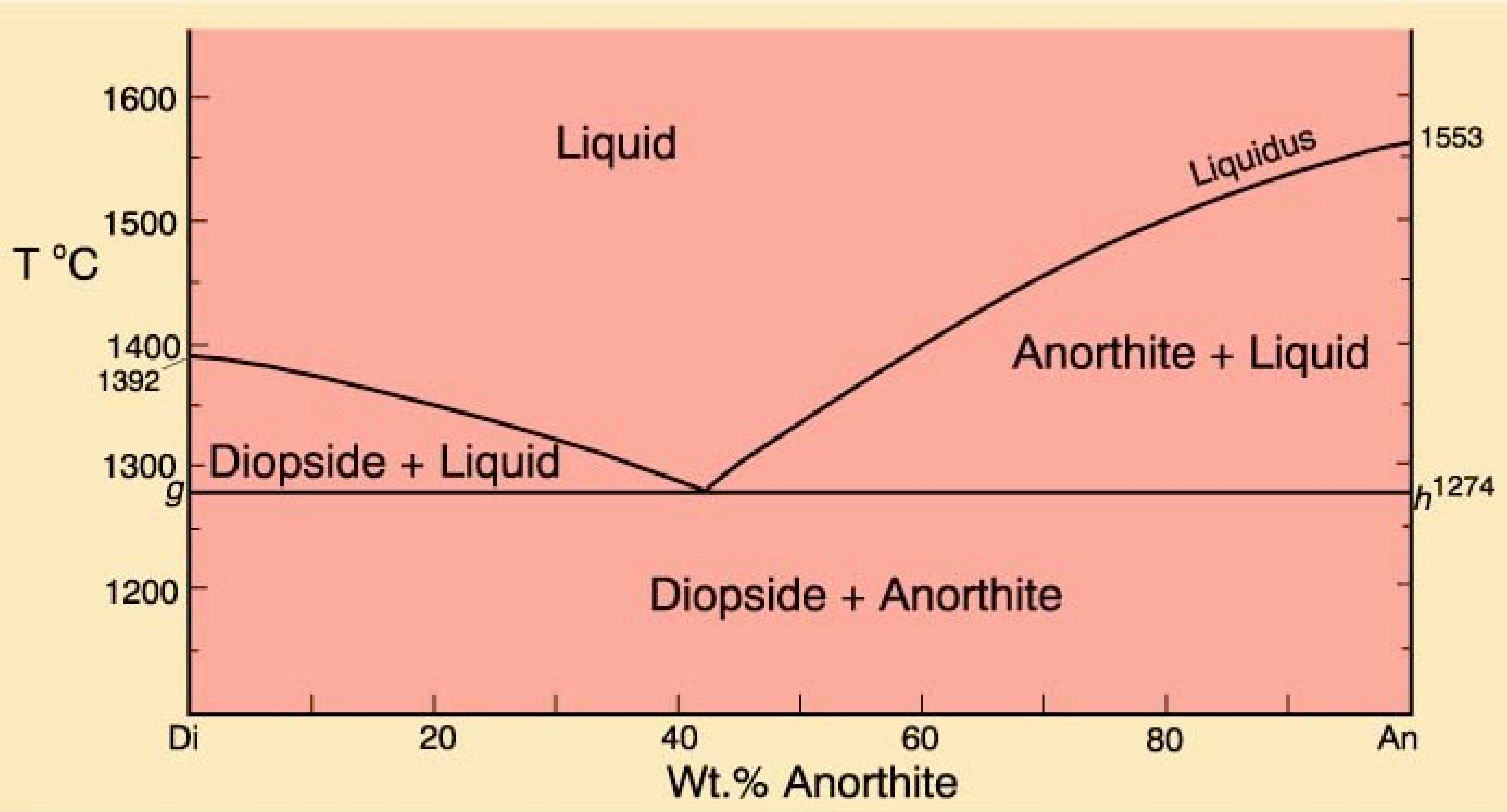


Sub-ophitique



Le plagioclase se forme avant le pyroxène

Comment construit-on ces diagrammes de phases?



Isobaric T-X phase diagram at atmospheric pressure.
After Bowen (1915), Amer. J. Sci. 40, 161-185.

2 Dispositifs expérimentaux

2-1: Hautes températures-Basses pressions (HT-BP)

- Four a moufle
- Four vertical
- Platine chauffante
- Nébulotron

Rappel: Unités de pression

1 atm. = 101 330 Pa

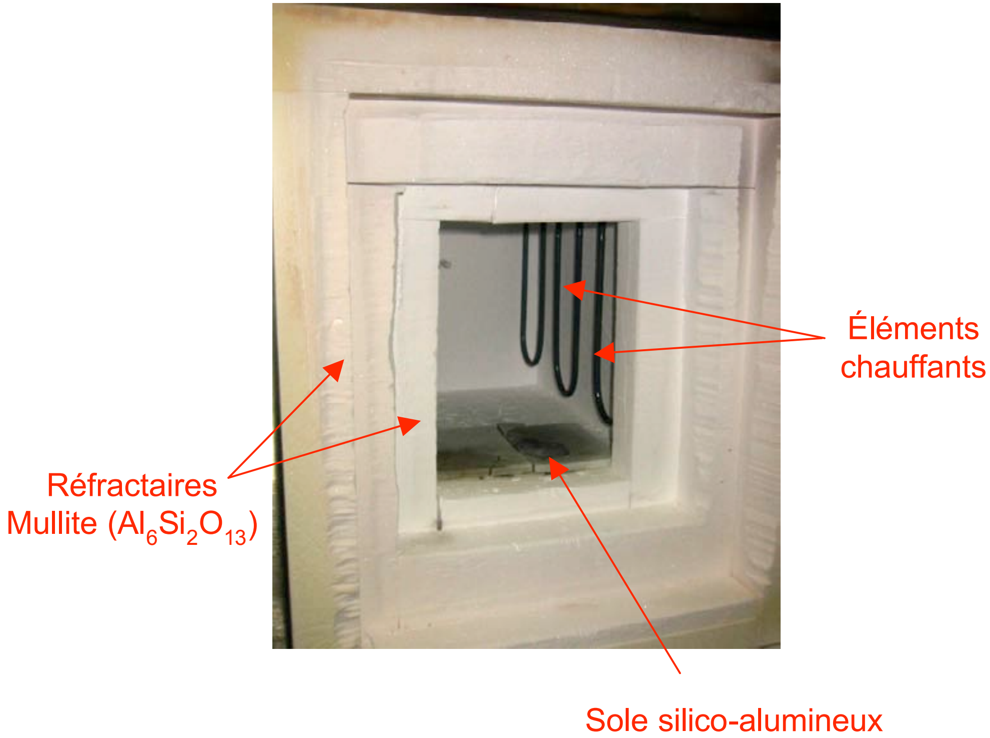
1 Pa = 10^{-5} bar

1 GPa = 10^{9} Pa

1 GPa = 10 Kbar

four à moufle

Photos: L. Tissandier



-Temp max : 1650°C
- programmation
- volume plus important

- pas de flux de gaz

Applications

- **Synthèse de verres**
- **cristallisation**

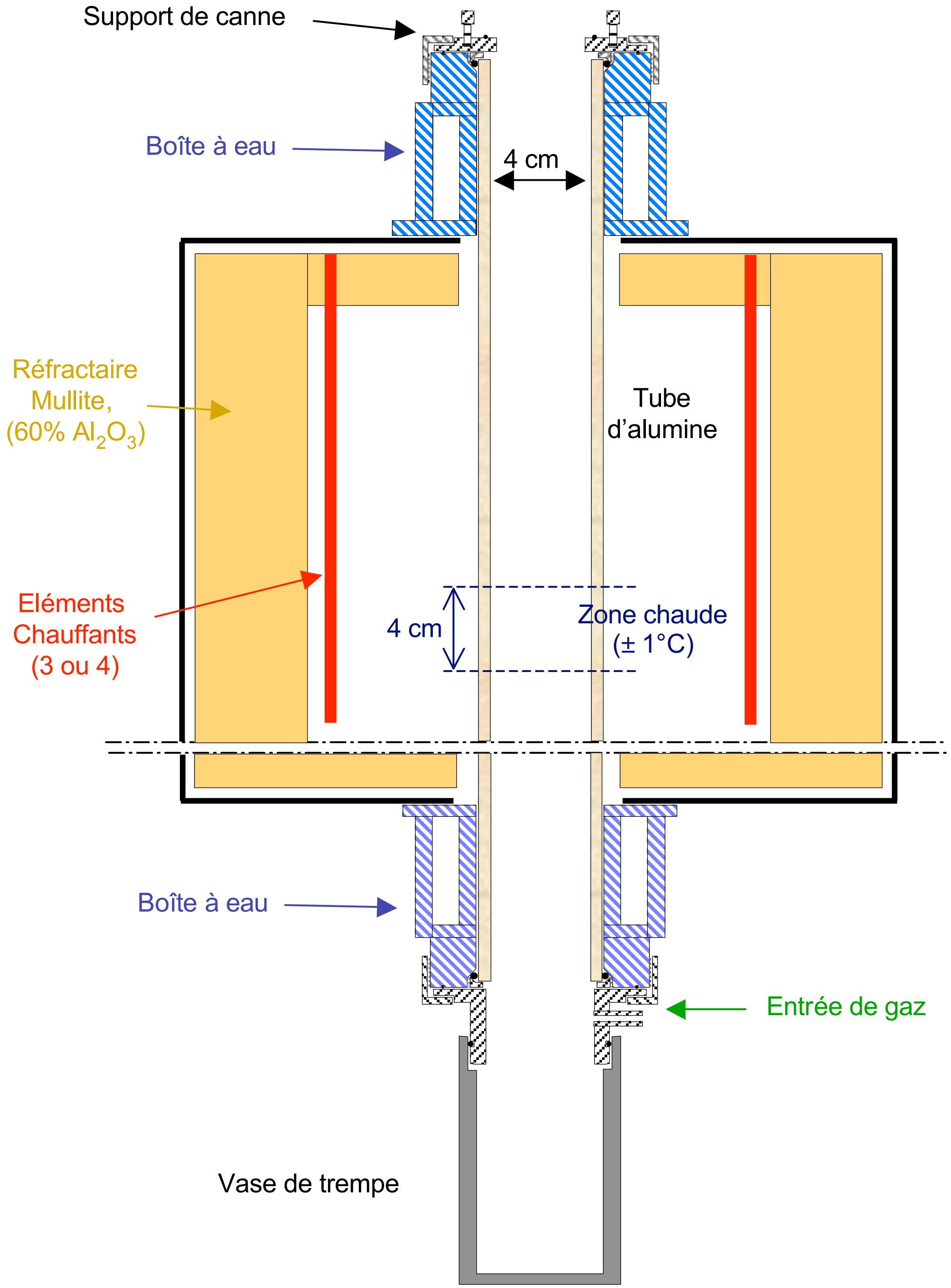
Fours verticaux à atmosphère contrôlées

-Temp max : 1700°C
- programmation
- contrôle de fO_2 *(CO, CO_2, H_2…)*
(atm → 10^{-20} bar)

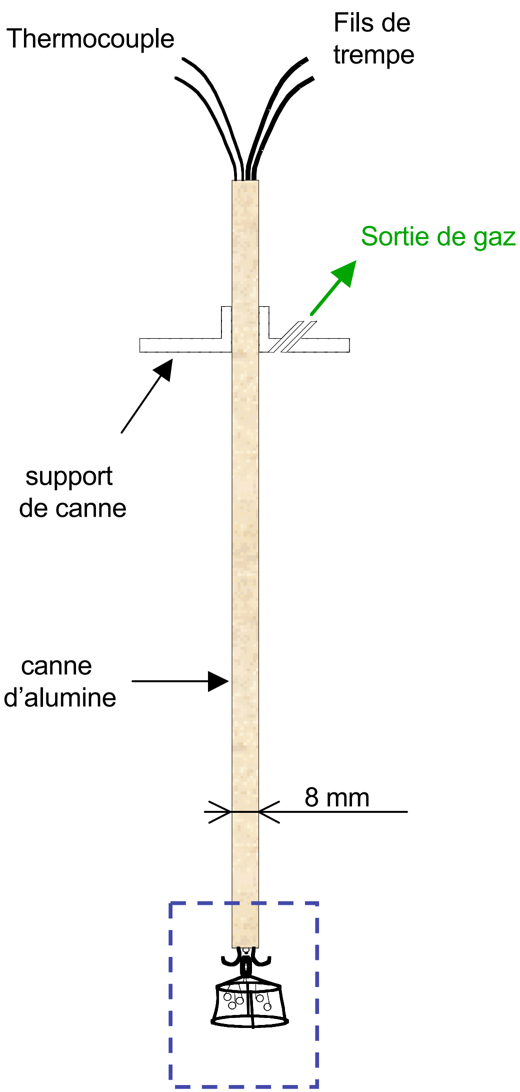
- trempe dans atmosphère du four

Applications

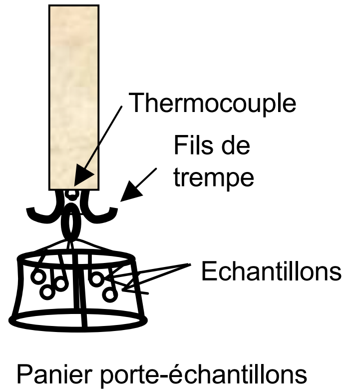
- **relations de phases**
- **cristallisation**
- **coefficients de partage**
- **évaporation**
- **...**



Support de canne
Boîte à eau
4 cm
Réfractaire
Mullite,
(60% Al_2O_3)
Tube
d'alumine
Eléments
Chauffants
(3 ou 4)
4 cm
Zone chaude
(± 1°C)
Boîte à eau
Entrée de gaz
Vase de trempe

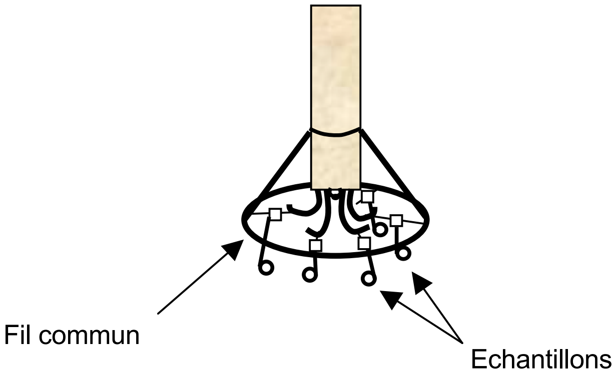


Système monotrempe

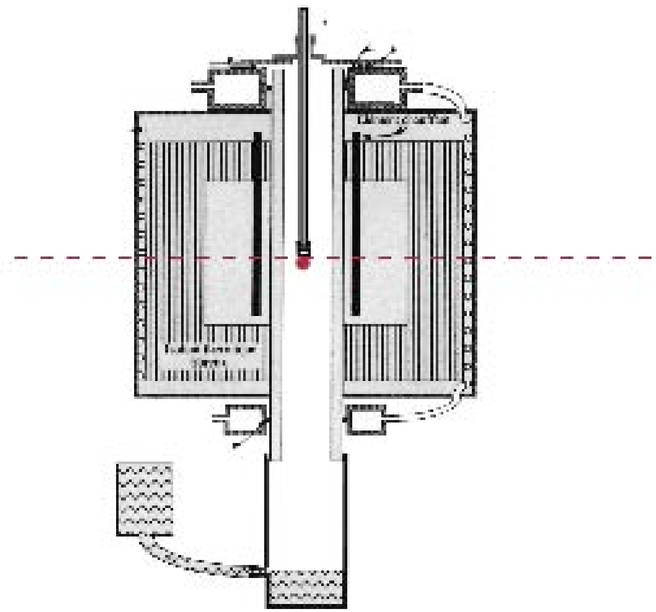


➡ *même expérience pour différents compositions*

Système multitrempe



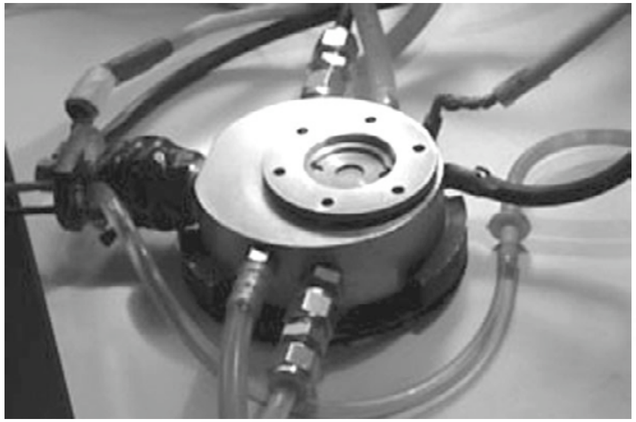
➡ *mêmes conditions pour durées différentes*

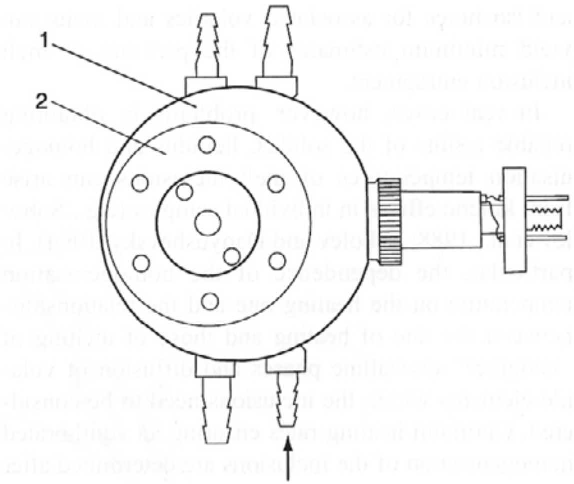


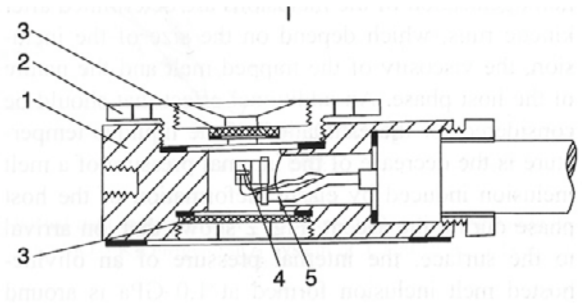
Conventional dynamic
crystallization

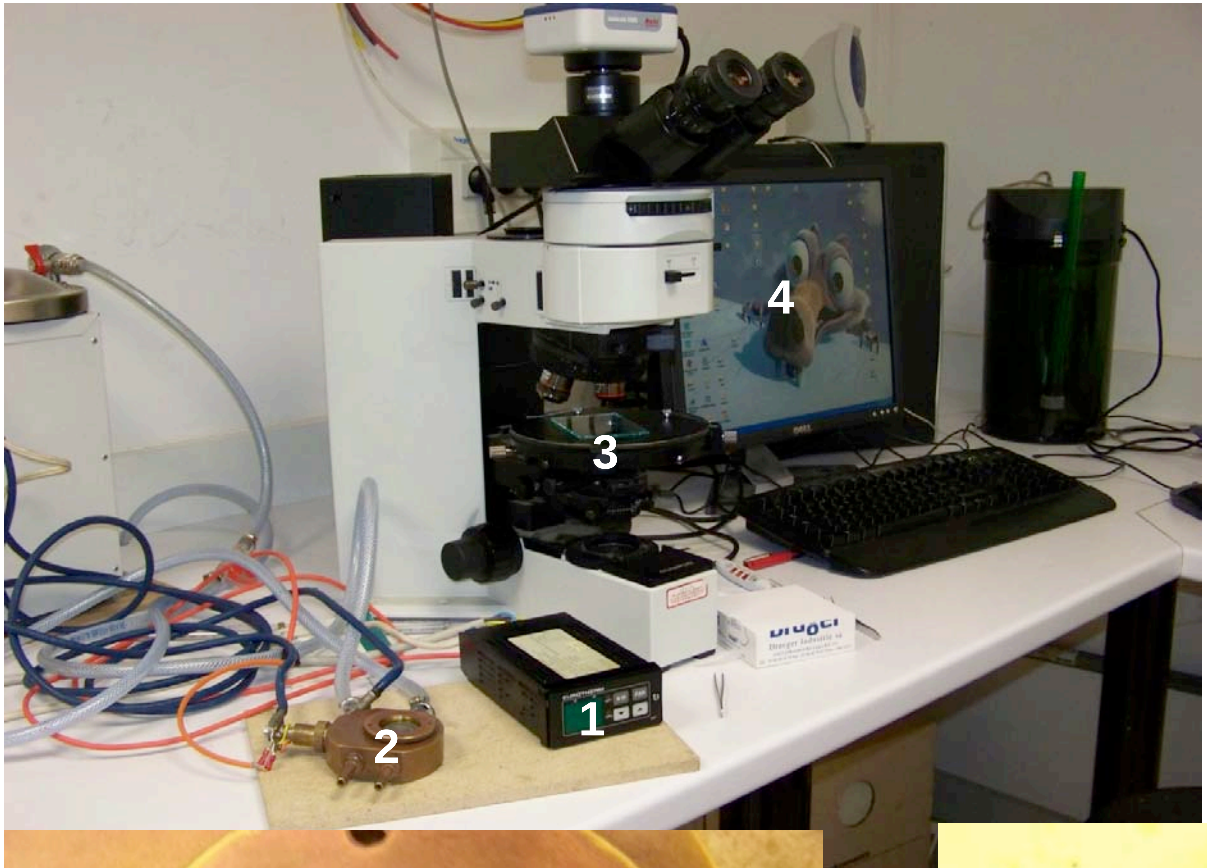
Four vertical = four trempe rapide

Platine chauffante

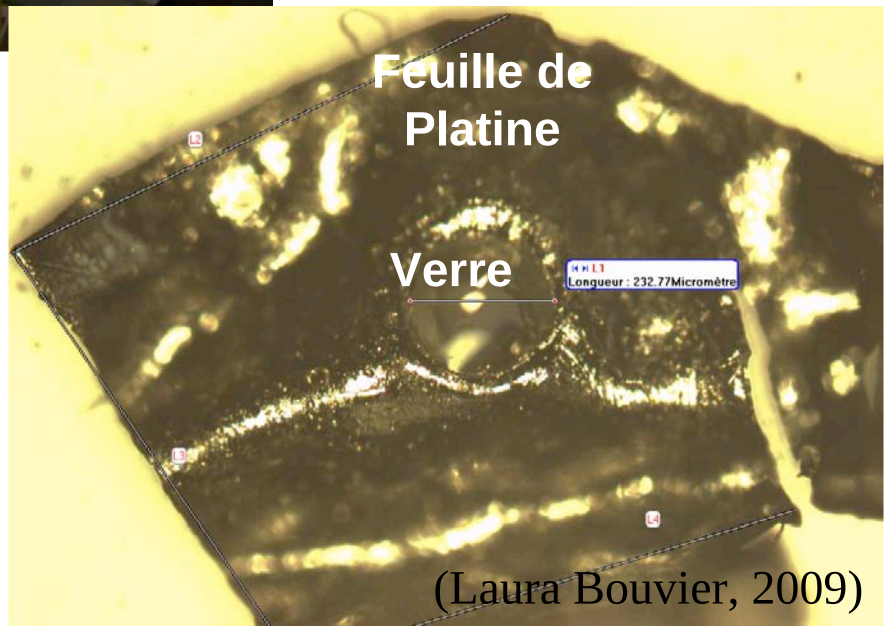




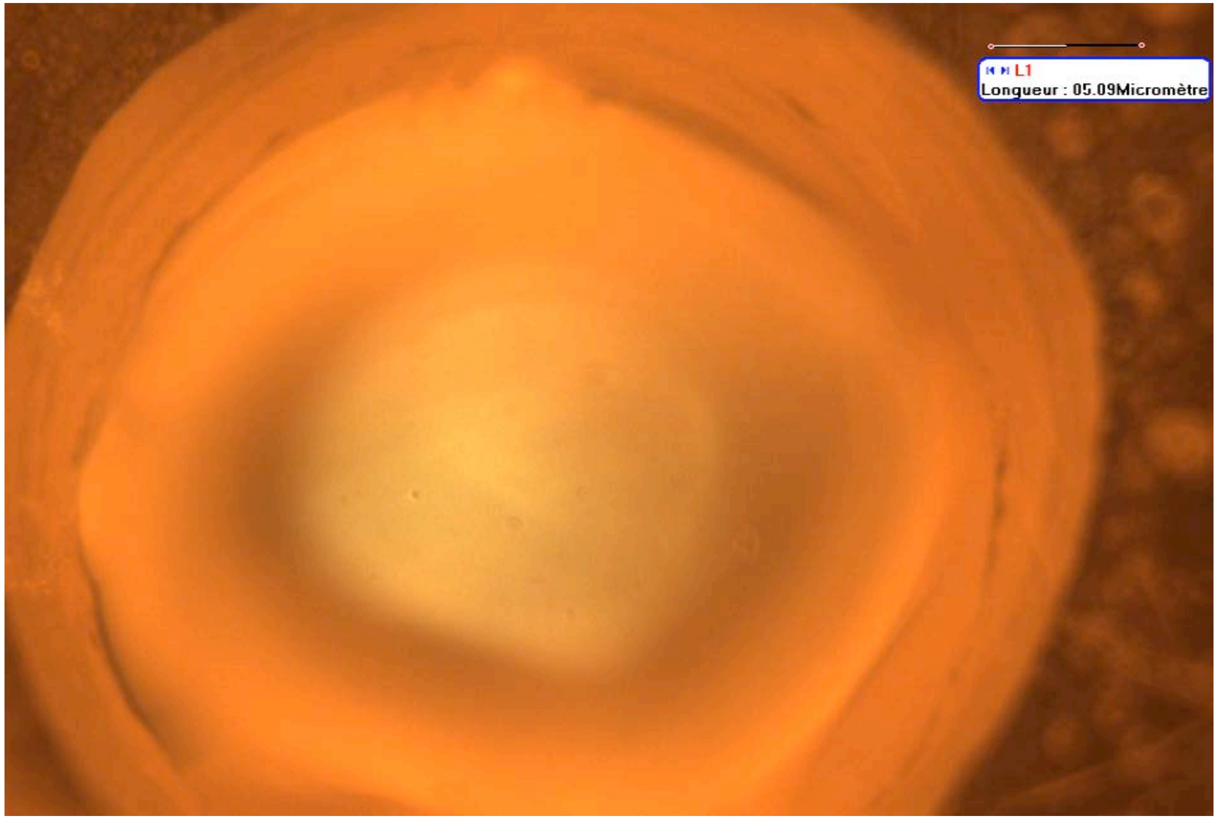




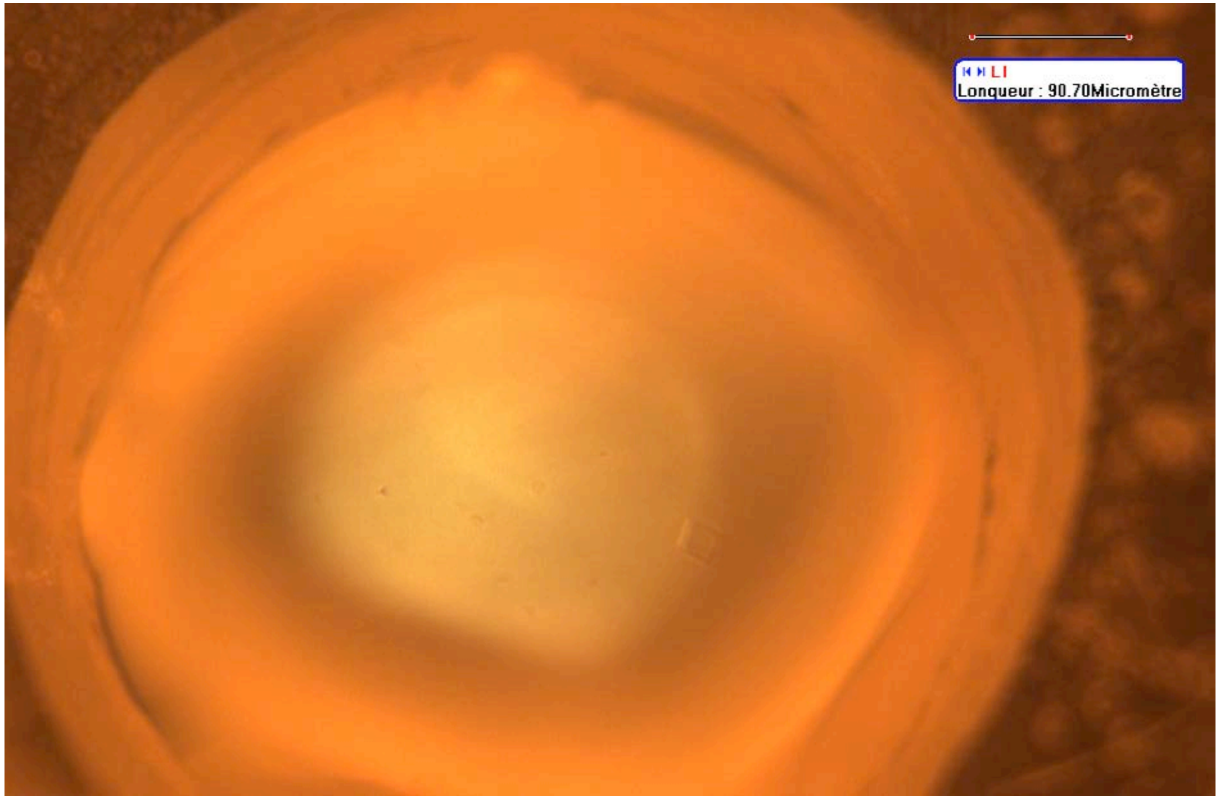
Légende:
1: régulateur de température
2: Platine chauffante russe
3: Microscope avec caméra
4: traitement de données sur logiciel *Motic Images Advanced 3.2*

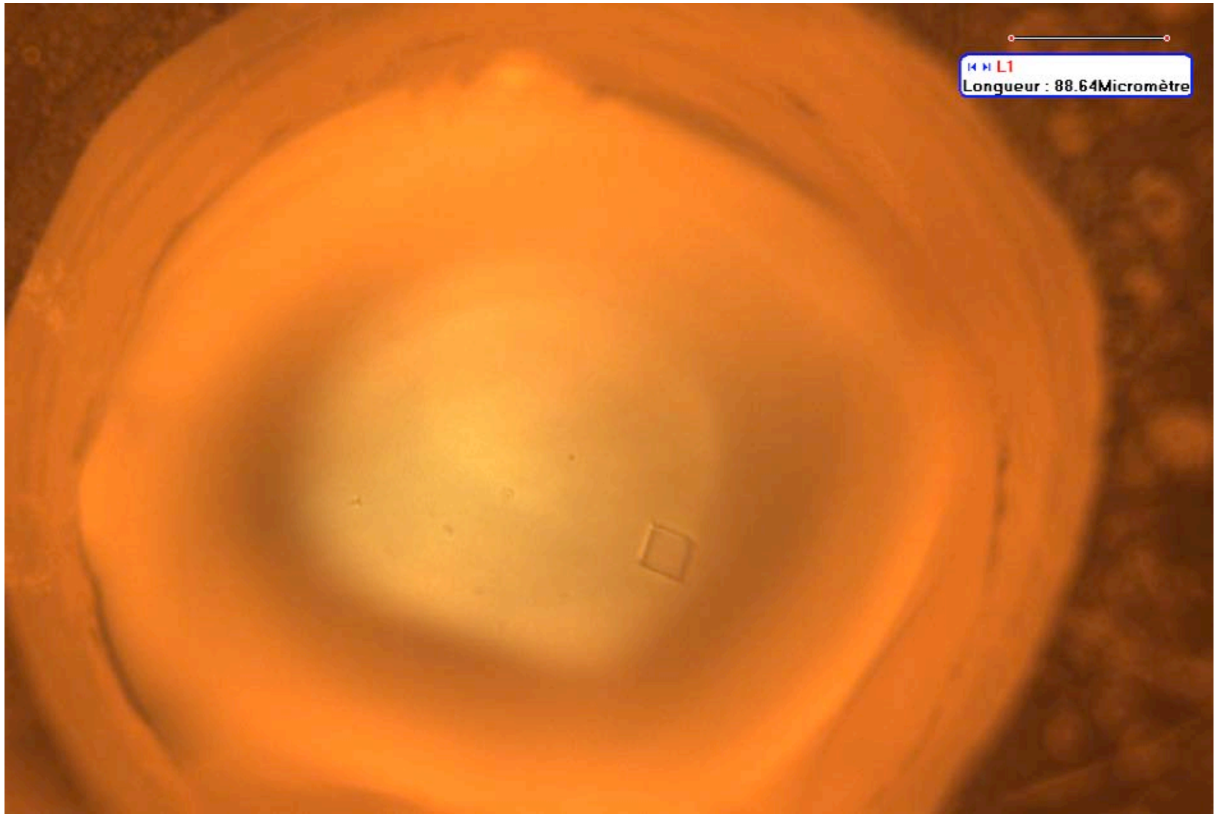


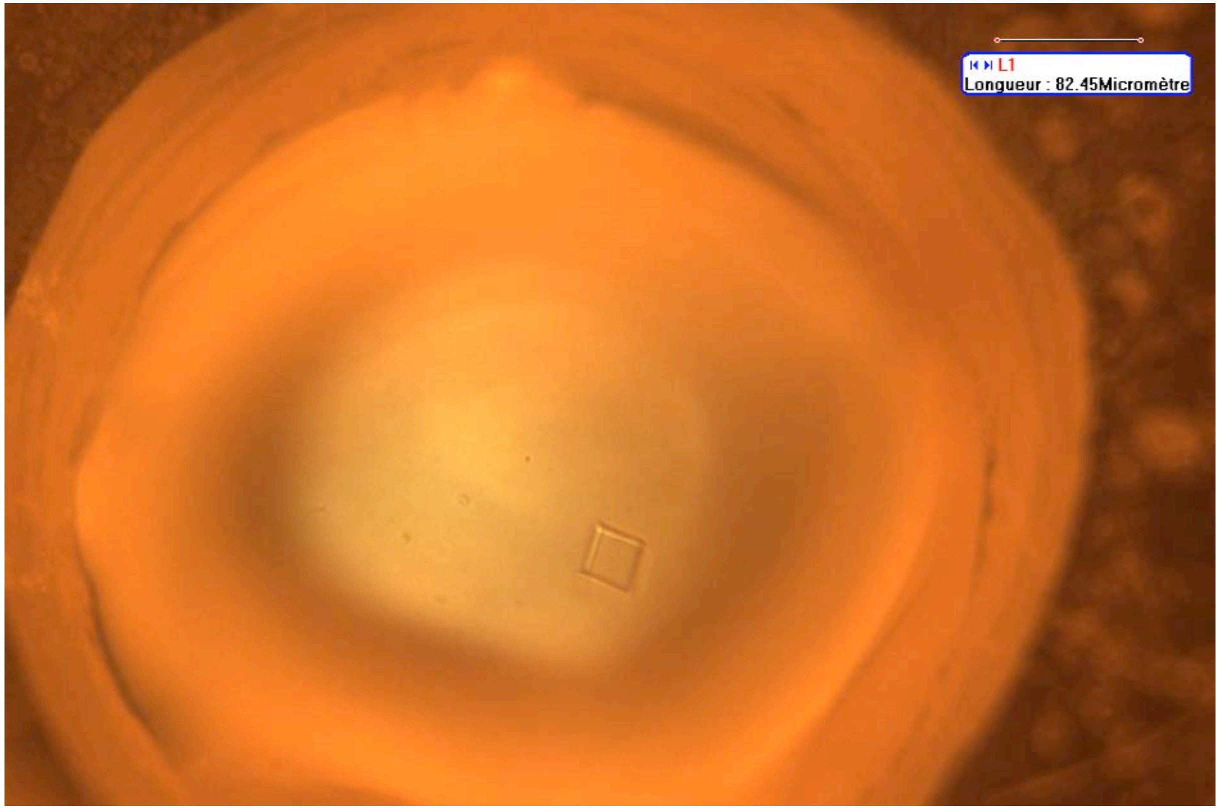
T max: 1600°C

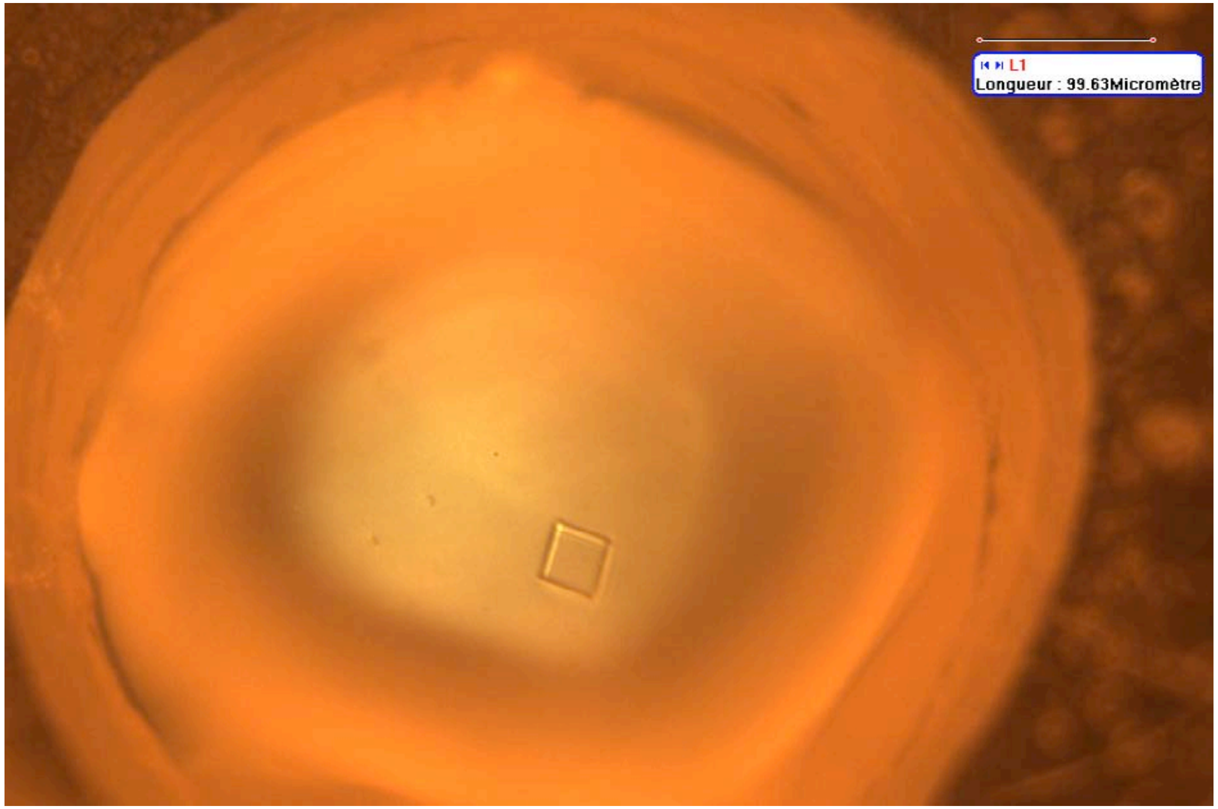


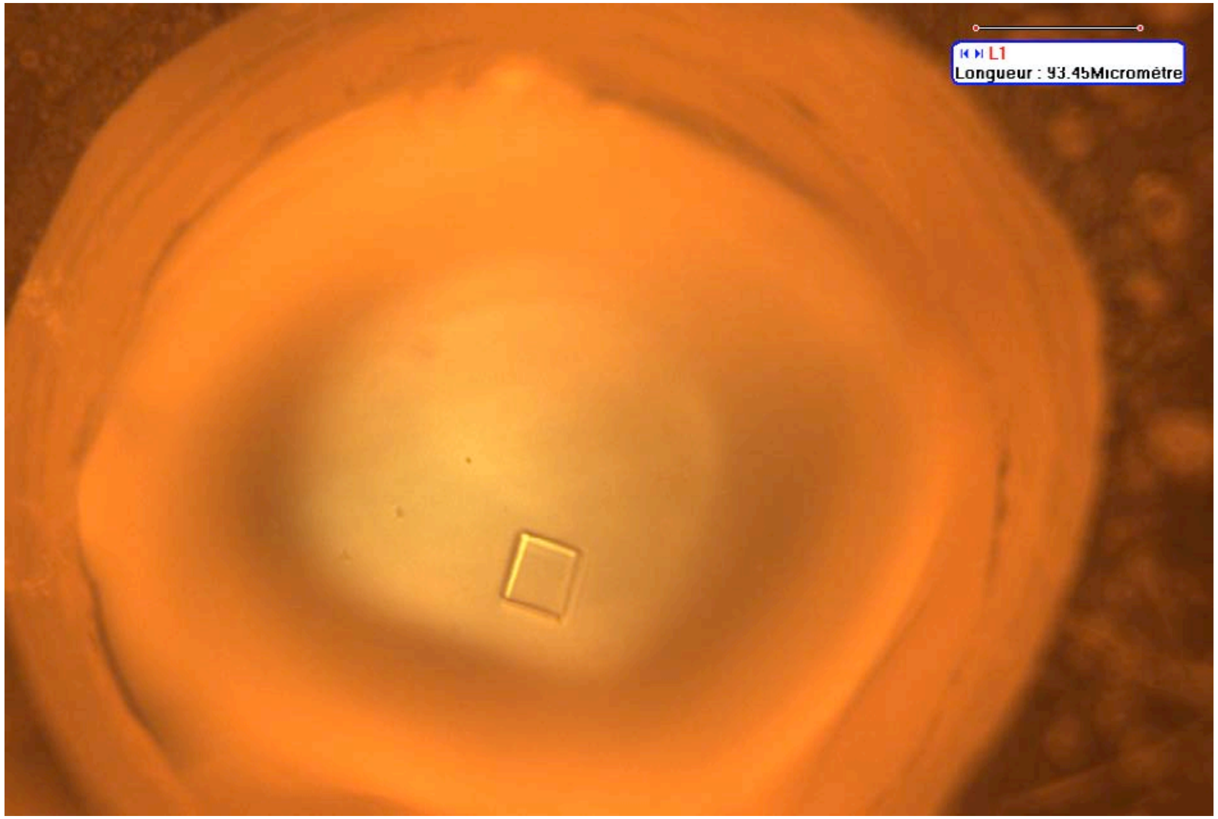
Vitesse de croissance de la mélilite

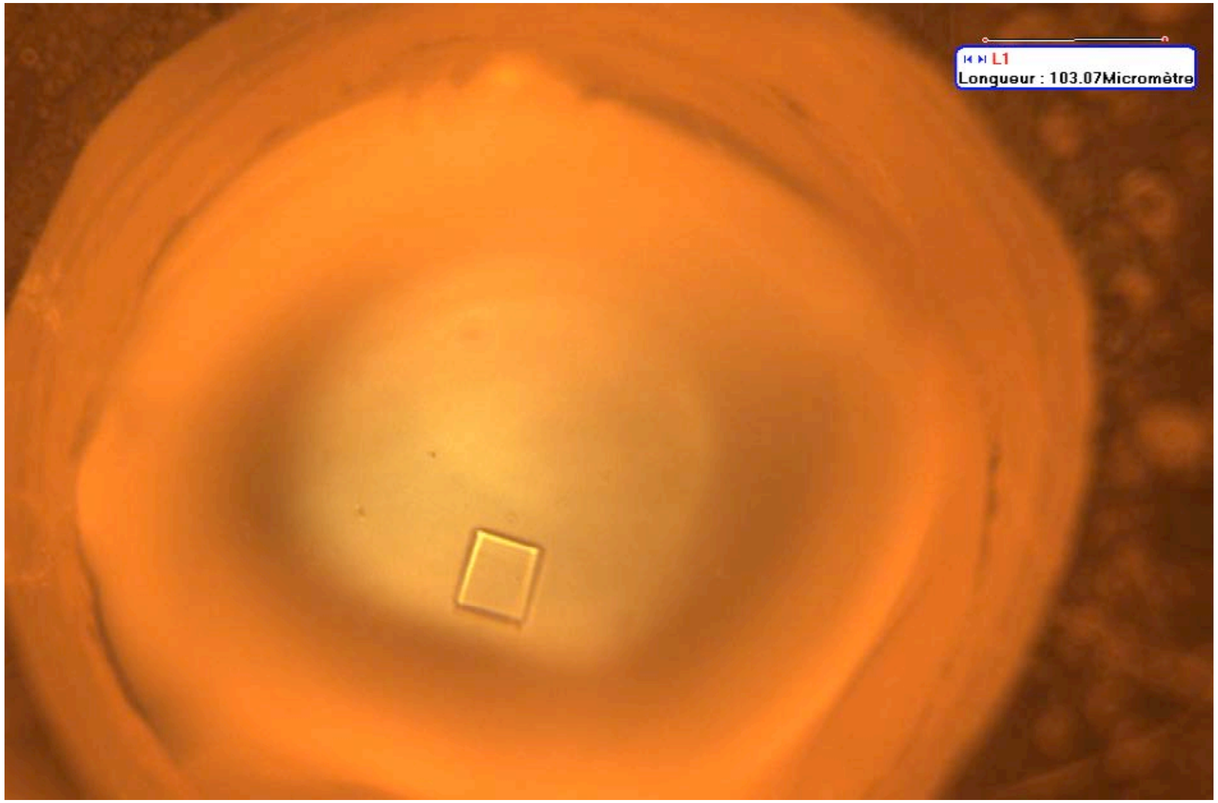

L1
Longueur : 90.70Micromètre

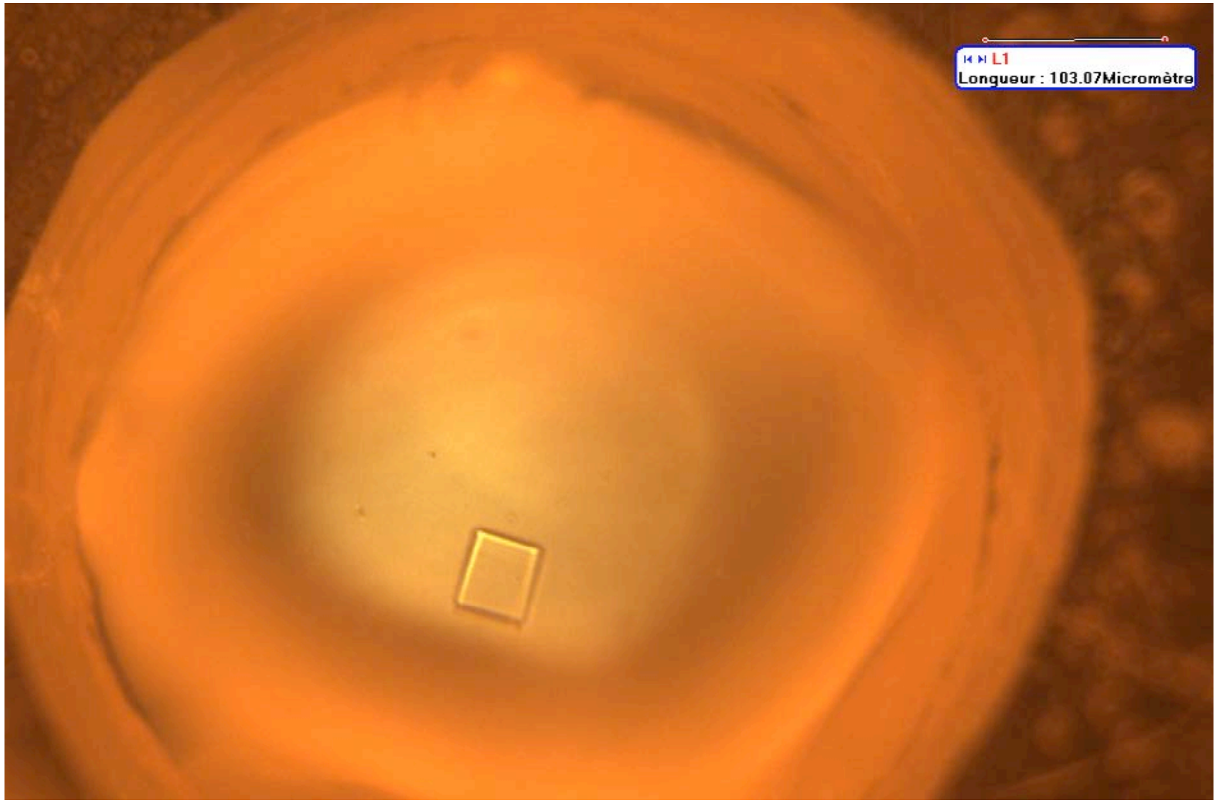

L1
Longueur : 88.64Micromètre

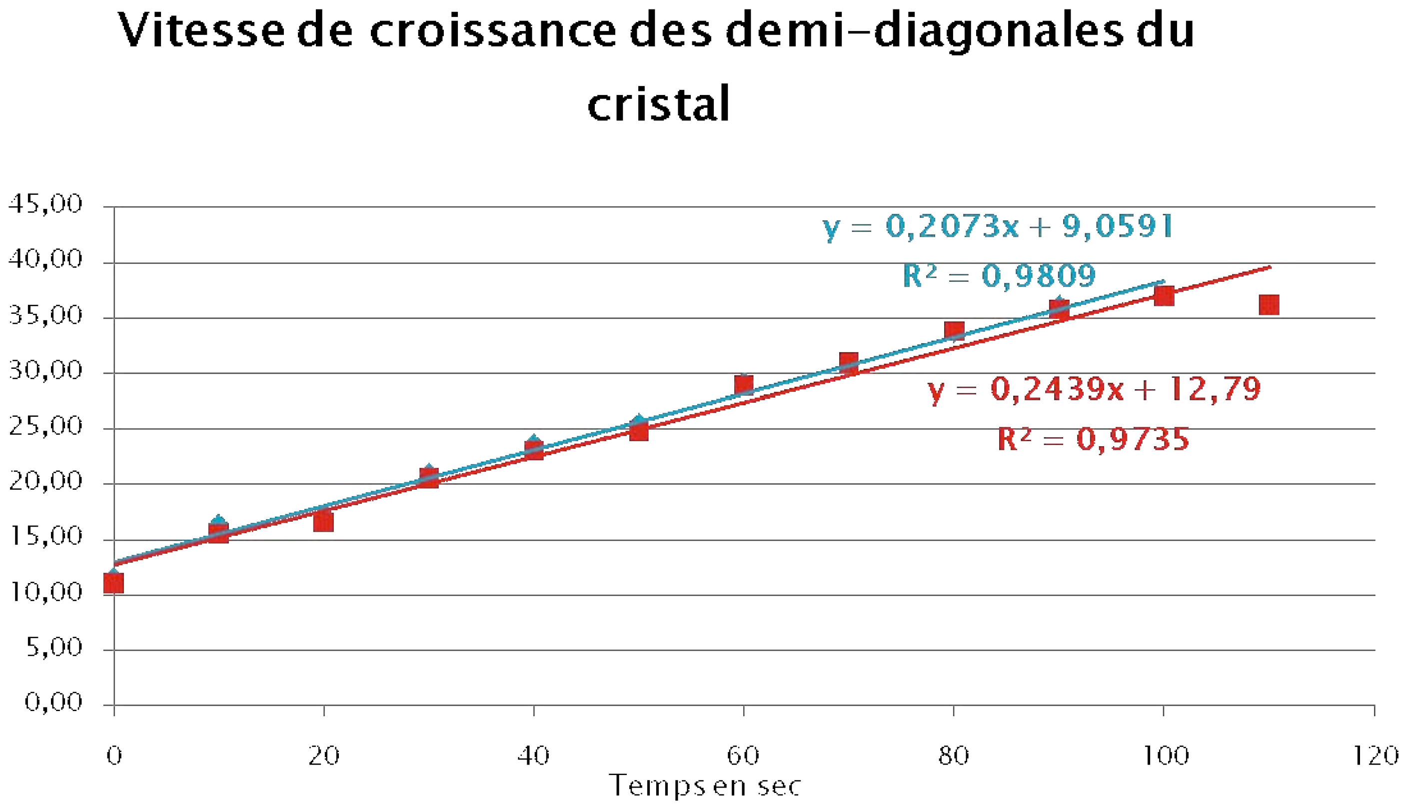

L1
Longueur : 82.45Micromètre


L1
Longueur : 99.63Micromètre


L1
Longueur : 93.45Micromètre


L1
Longueur : 103.07Micromètre


L1
Longueur : 103.07Micromètre



Vitesse de croissance: 0,2073 µm/sec

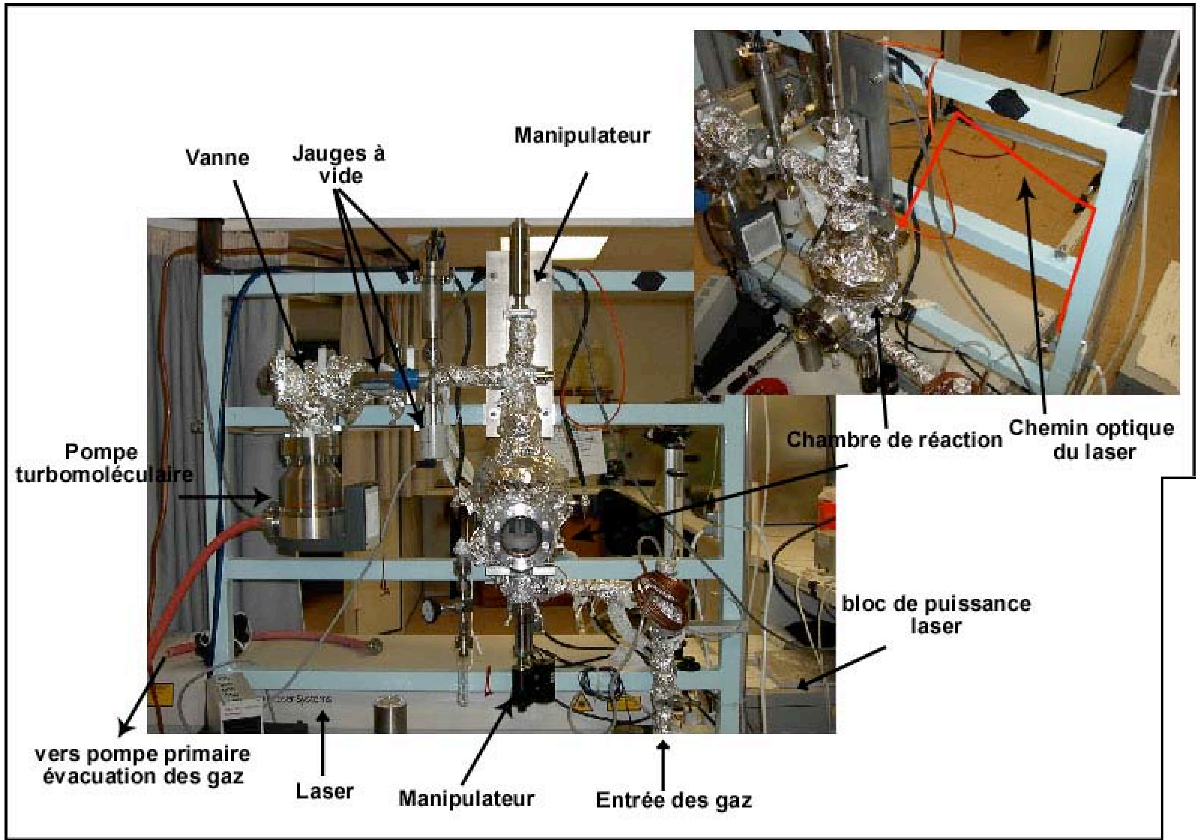
0,2439 µm/sec

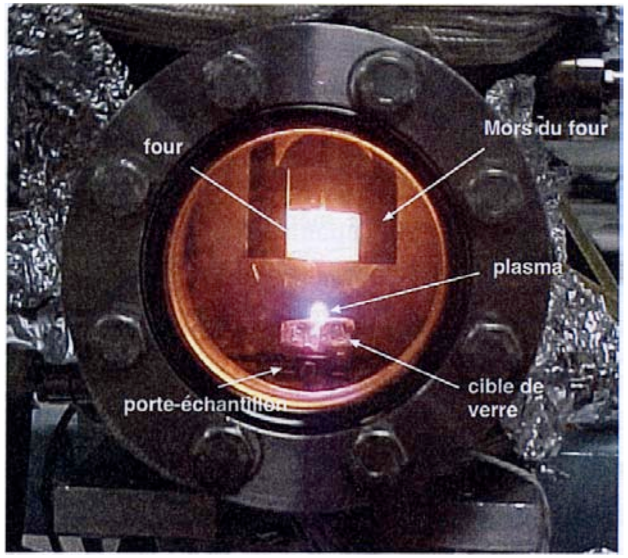
(Laura Bouvier, 2009)

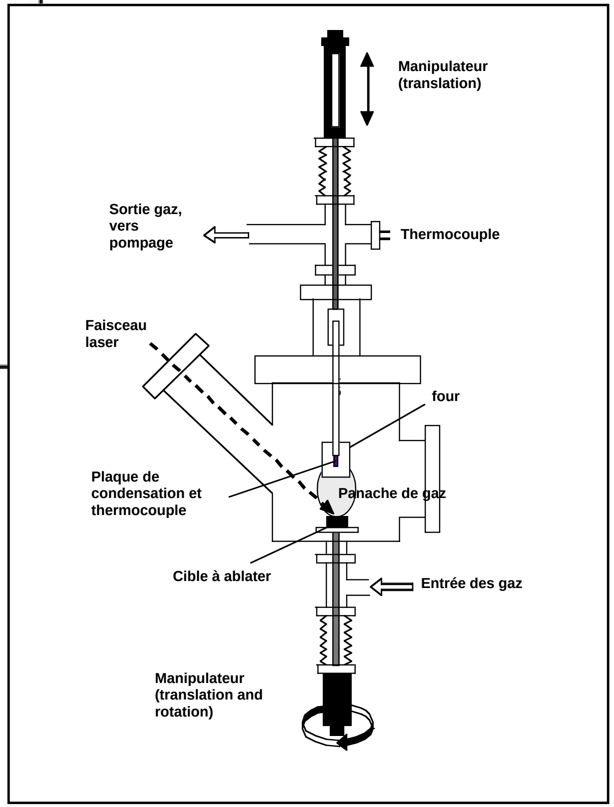

Réseau
CRISTECH
TECHNOLOGIES ET PROCEDES DE CROISSANCE CRISTALLINE

Four à image

Le Nébulotron IV



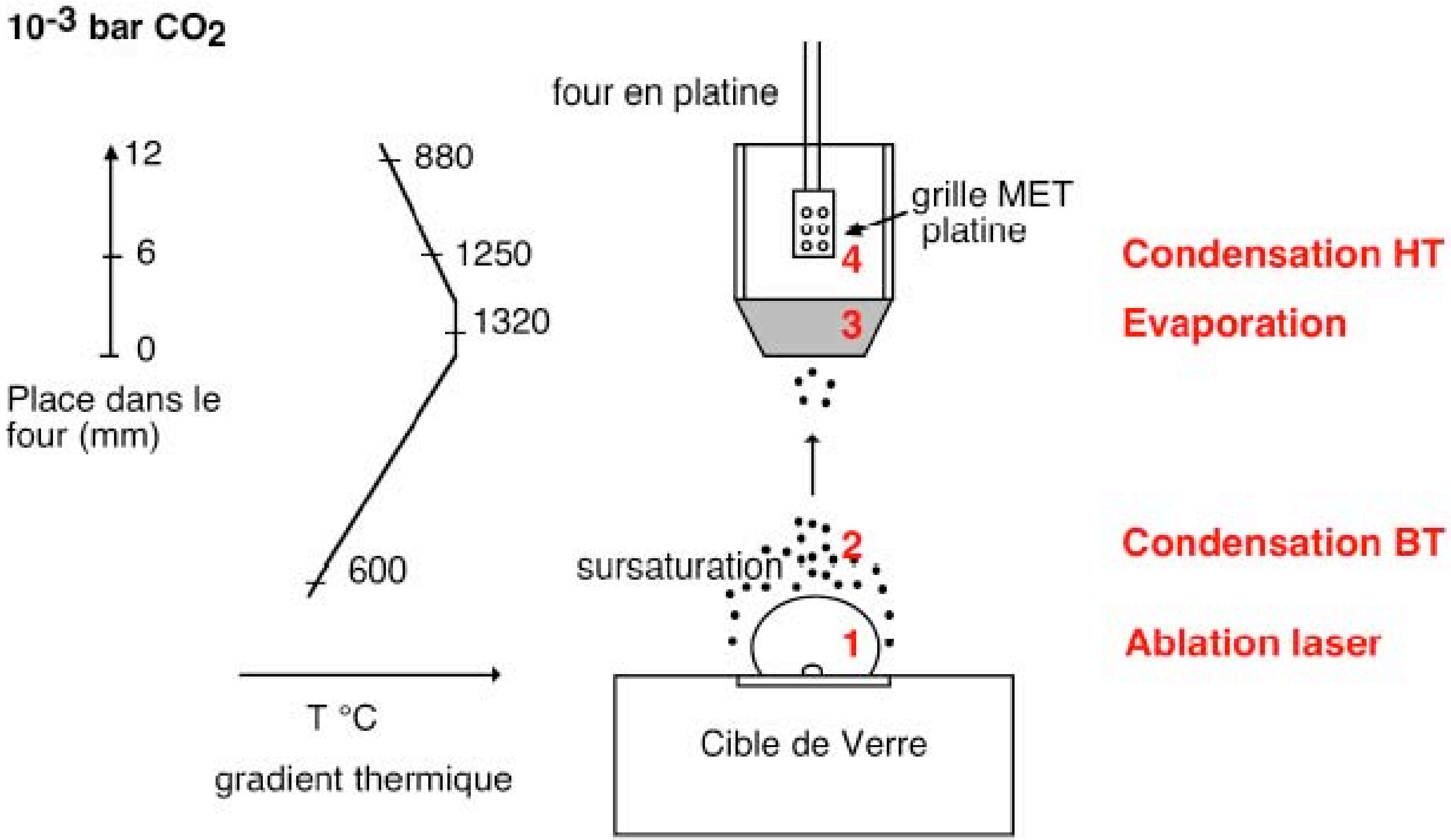




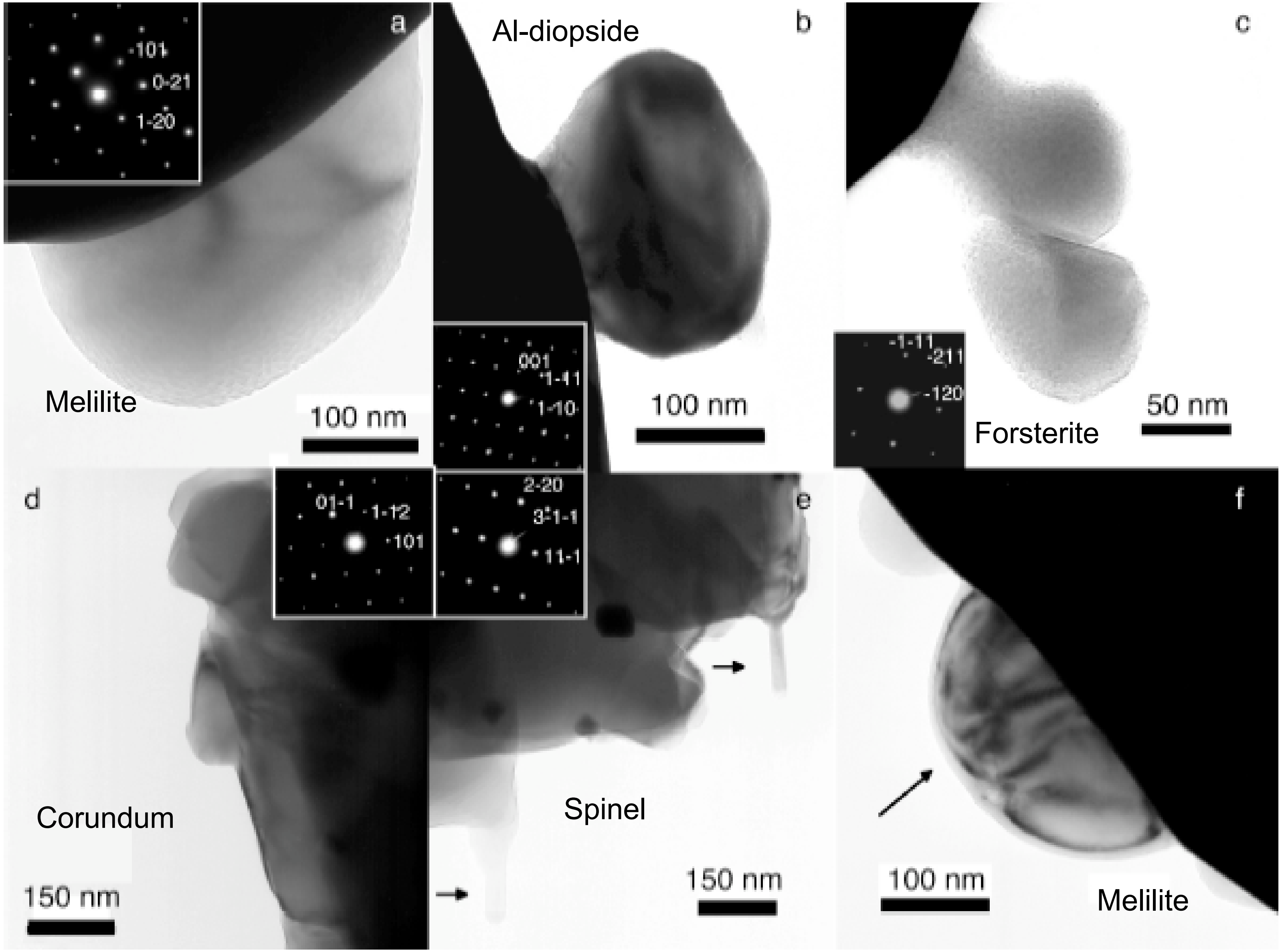
Ablation d'une cible par laser puis évaporation et condensation

Séquence de condensation
Cristallinité des condensats

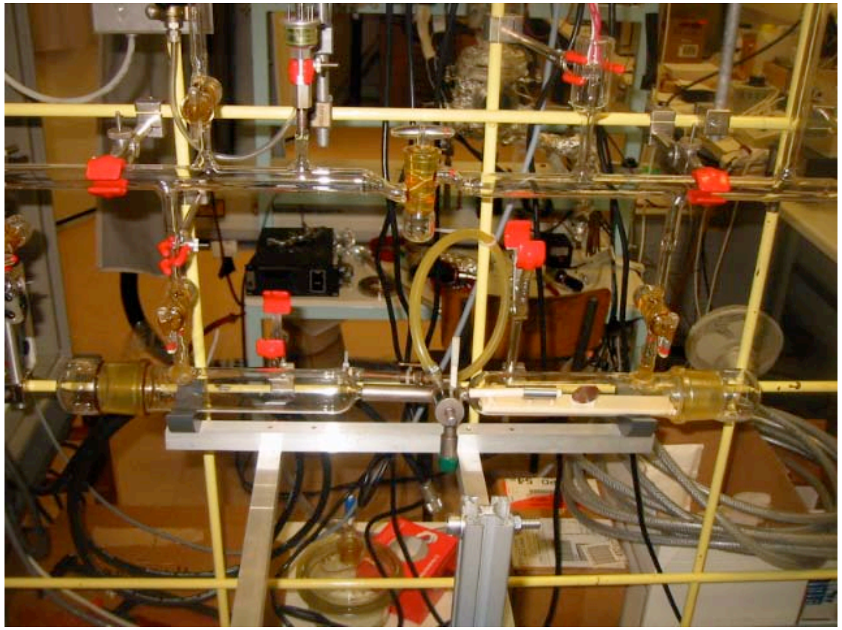
« Condensation d'un gaz de composition solaire »

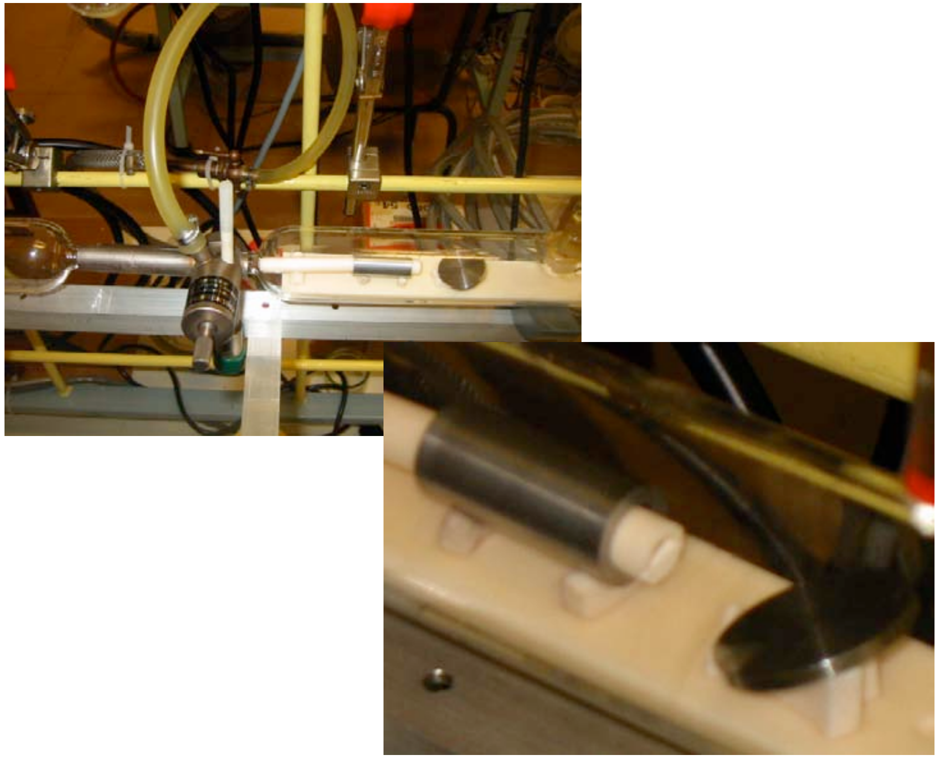


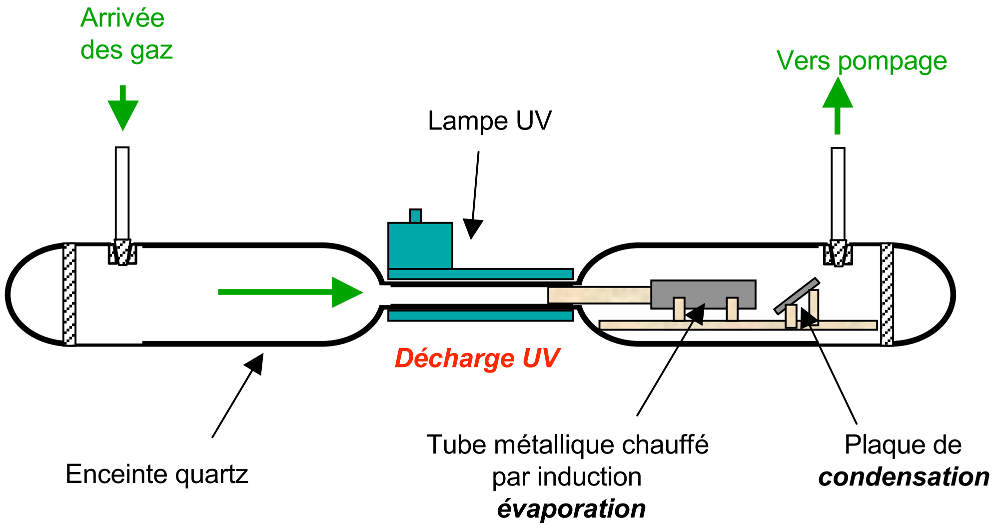
Condensation Haute température d'un gaz de composition solaire



Le Nébulotron V







Gaz porteur dans décharge UV

↓

Ionisation

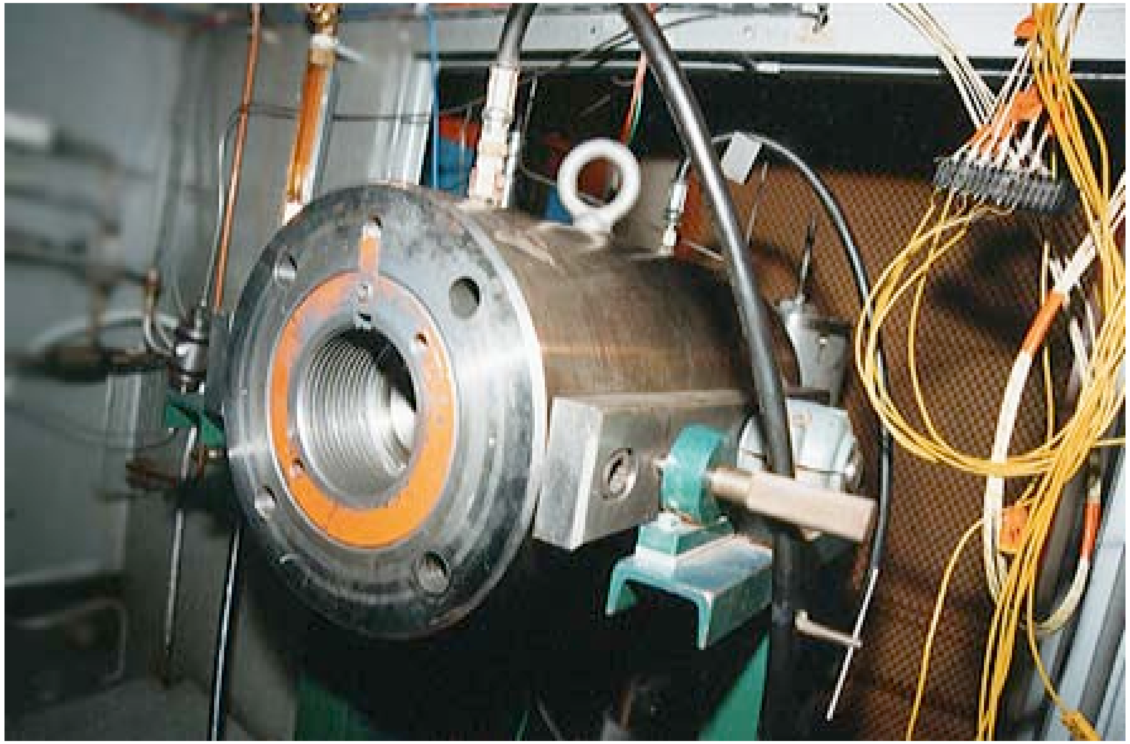
↓

Réactions avec espèces volatilisées

↓

Fractionnements isotopiques ?

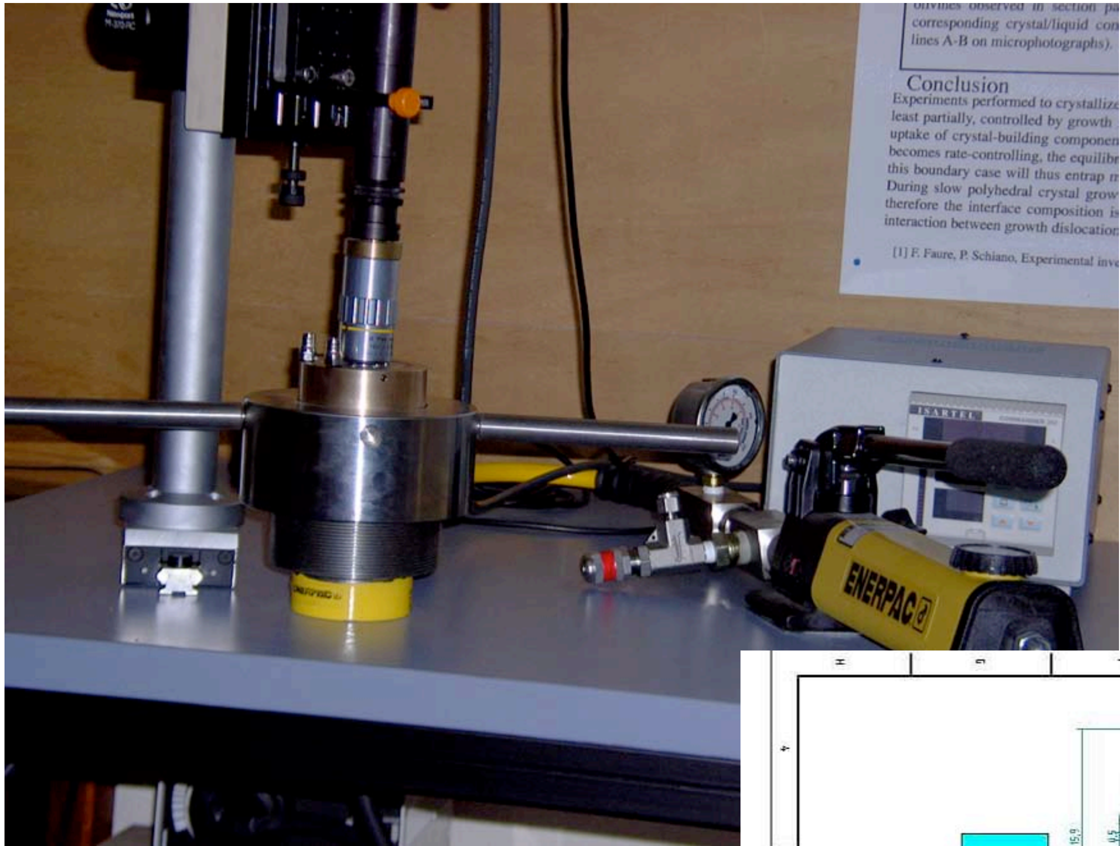
2-2: Hautes pressions (HP)



Autoclave à chauffage externe (0.4 GPa, 900°C)

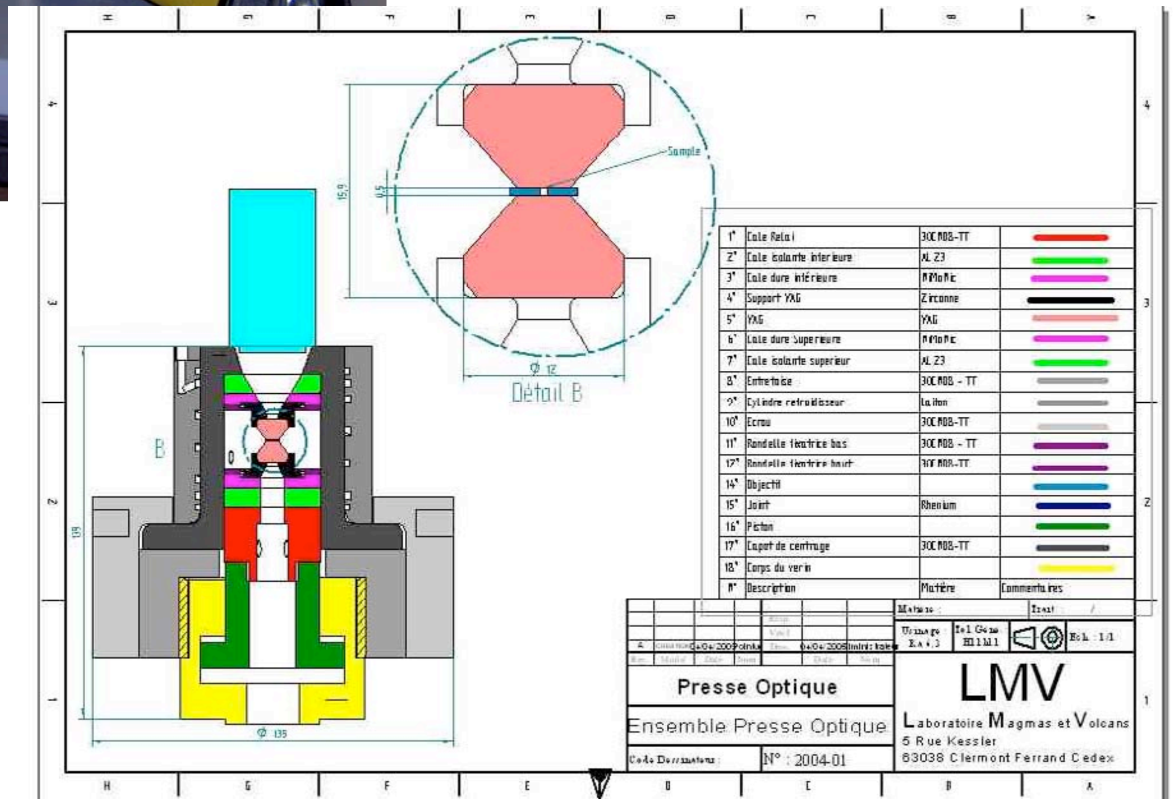
Autoclave à chauffage interne (1.2 GPa, 1400°C)

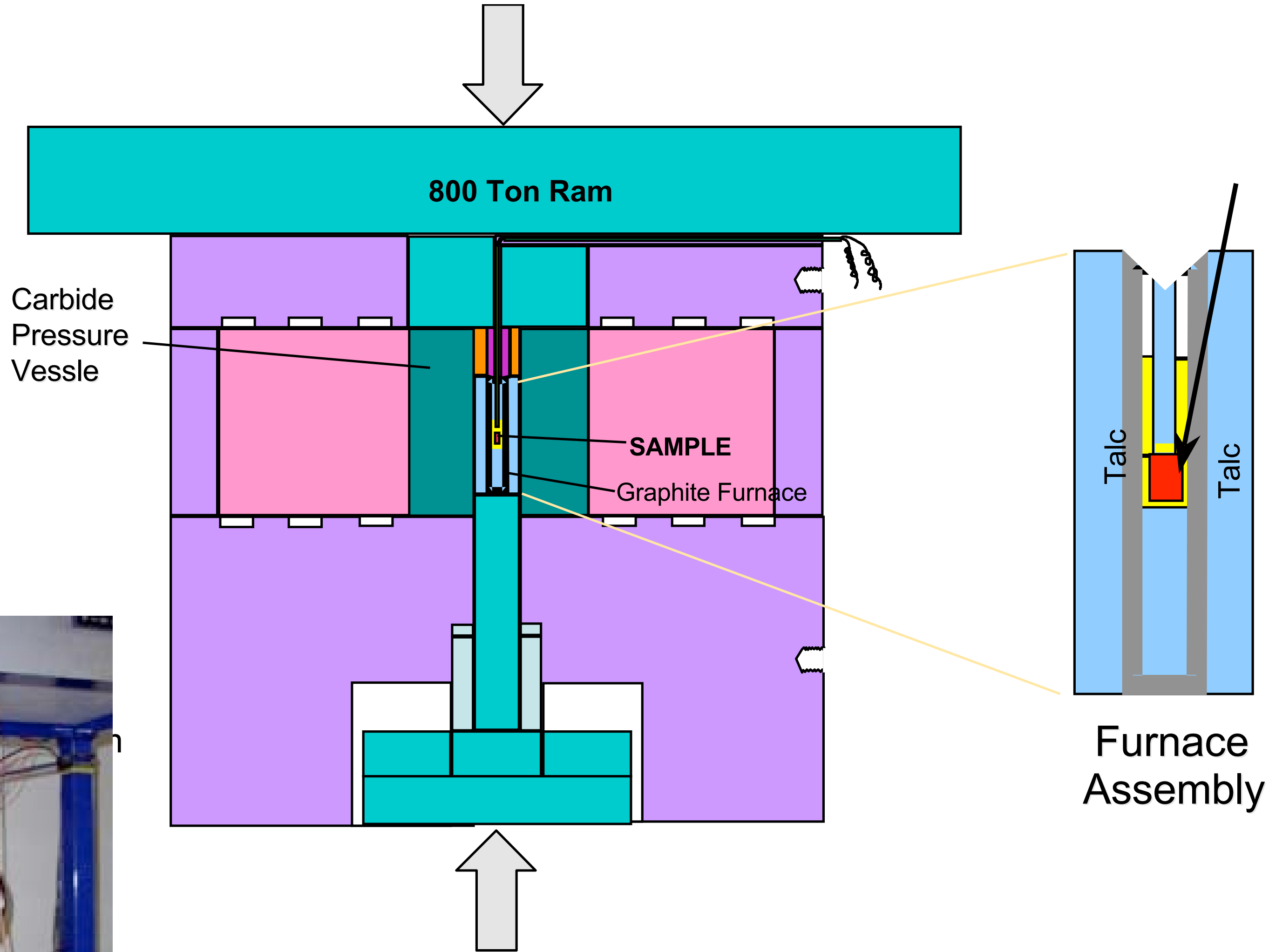
Micropresse HT-HP à contrôle optique



1.5 GPa

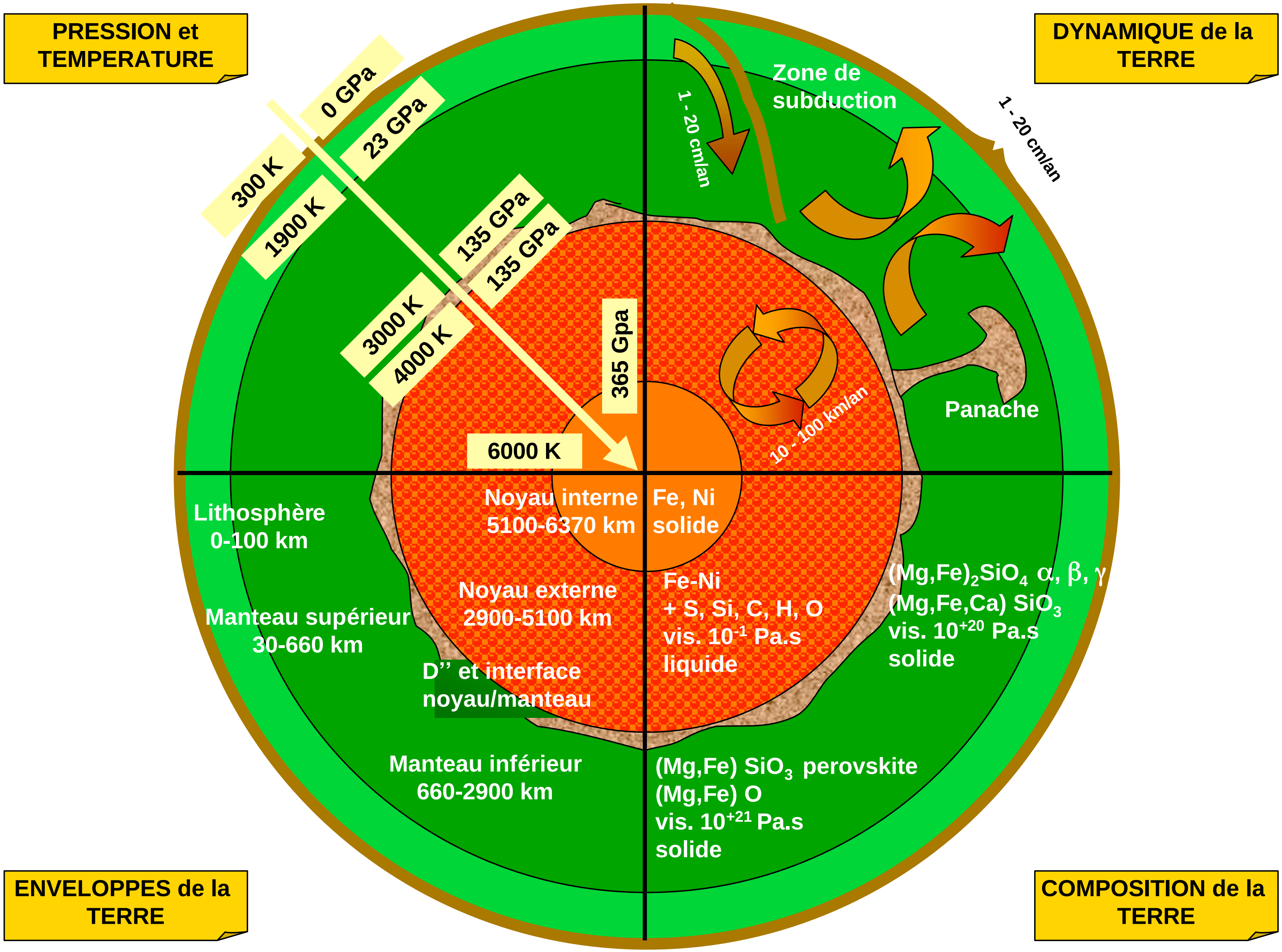
1000°C





After Boyd and England (1960), J. Geophys. Res., **65**, 741-748. AGU

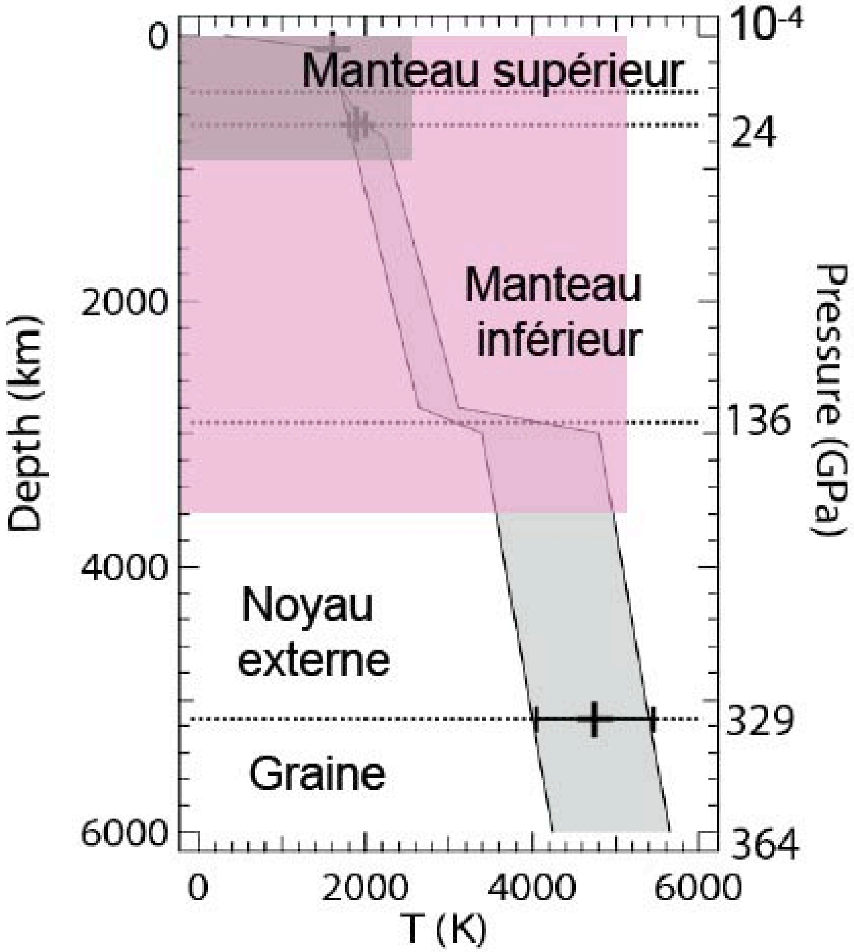
Piston cylindre (4 GPa, 1600°C)

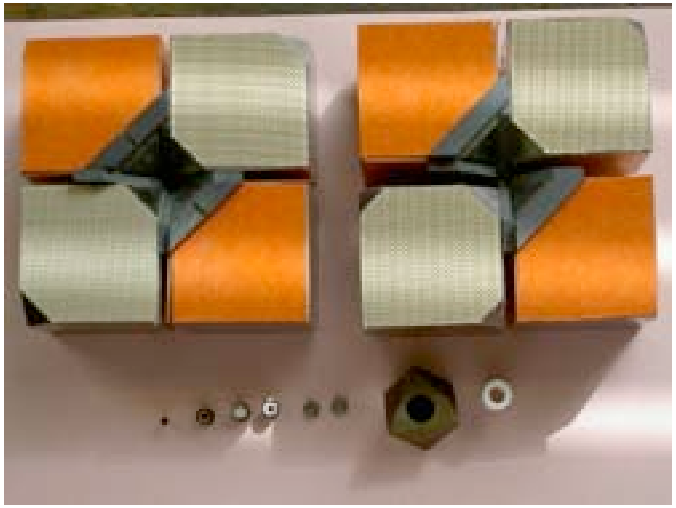


PRESSION et TEMPERATURE
DYNAMIQUE de la TERRE
ENVELOPPES de la TERRE
COMPOSITION de la TERRE
0 GPa
23 GPa
300 K
1900 K
135 GPa
135 GPa
3000 K
4000 K
365 Gpa
6000 K
Zone de subduction
1 - 20 cm/an
1 - 20 cm/an
10 - 100 km/an
Panache
Lithosphère 0-100 km
Manteau supérieur 30-660 km
Manteau inférieur 660-2900 km
Noyau interne 5100-6370 km
Noyau externe 2900-5100 km
D'' et interface noyau/manteau
Fe, Ni solide
Fe-Ni + S, Si, C, H, O vis. 10^{-1} Pa.s liquide
$(Mg,Fe)_2SiO_4$ α, β, γ $(Mg,Fe,Ca)\ SiO_3$ vis. 10^{+20} Pa.s solide
$(Mg,Fe)\ SiO_3$ perovskite $(Mg,Fe)\ O$ vis. 10^{+21} Pa.s solide

2-3: Très hautes pressions (THP)

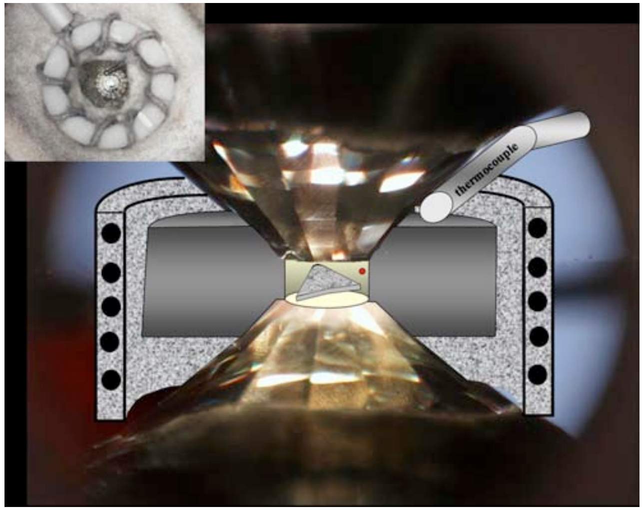
Presse multi-enclume (25 GPa, 2200°C)

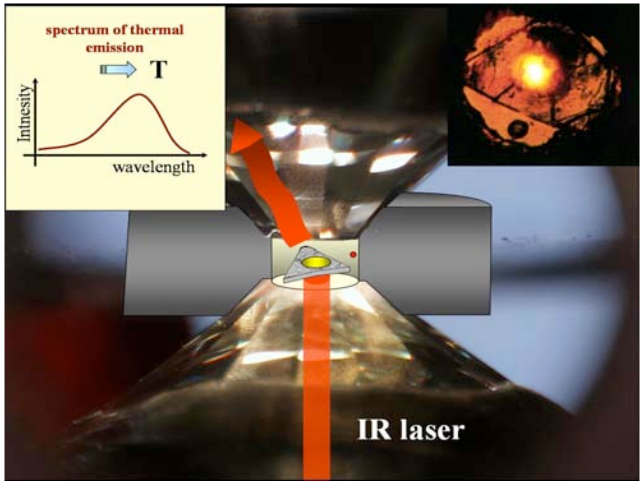




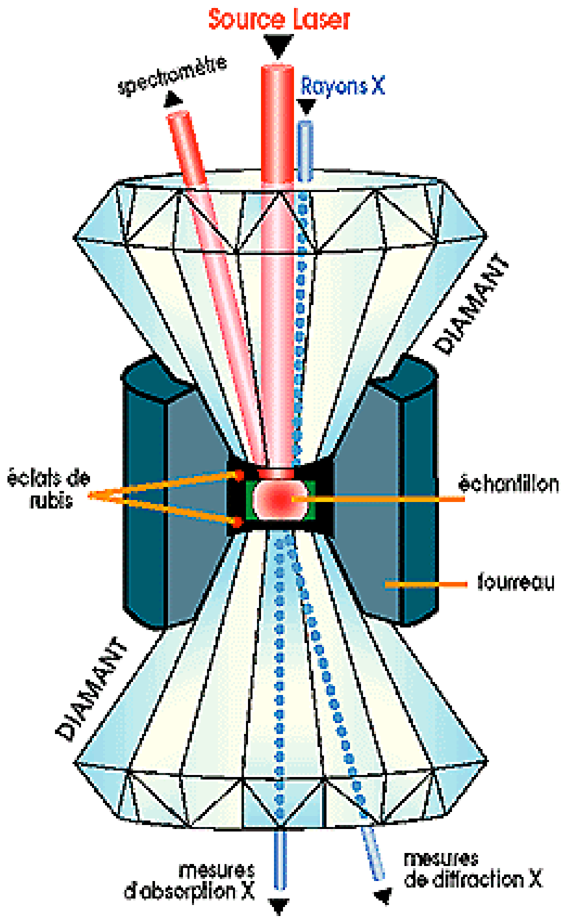
système d'enclumes en carbure (32 mm d'arête). En bas : céramiques constituant la cellule de haute pression.

Chauffer un échantillon dans une cellule diamant
L'échantillon sous pression est chauffé par des fours résistifs entourant les diamants (pour des températures inférieures à 1500 K)) ou par focalisation du faisceau d'un laser IR de puissance (YAG ou CO^2) pour atteindre des températures de l'ordre de 4000 K.

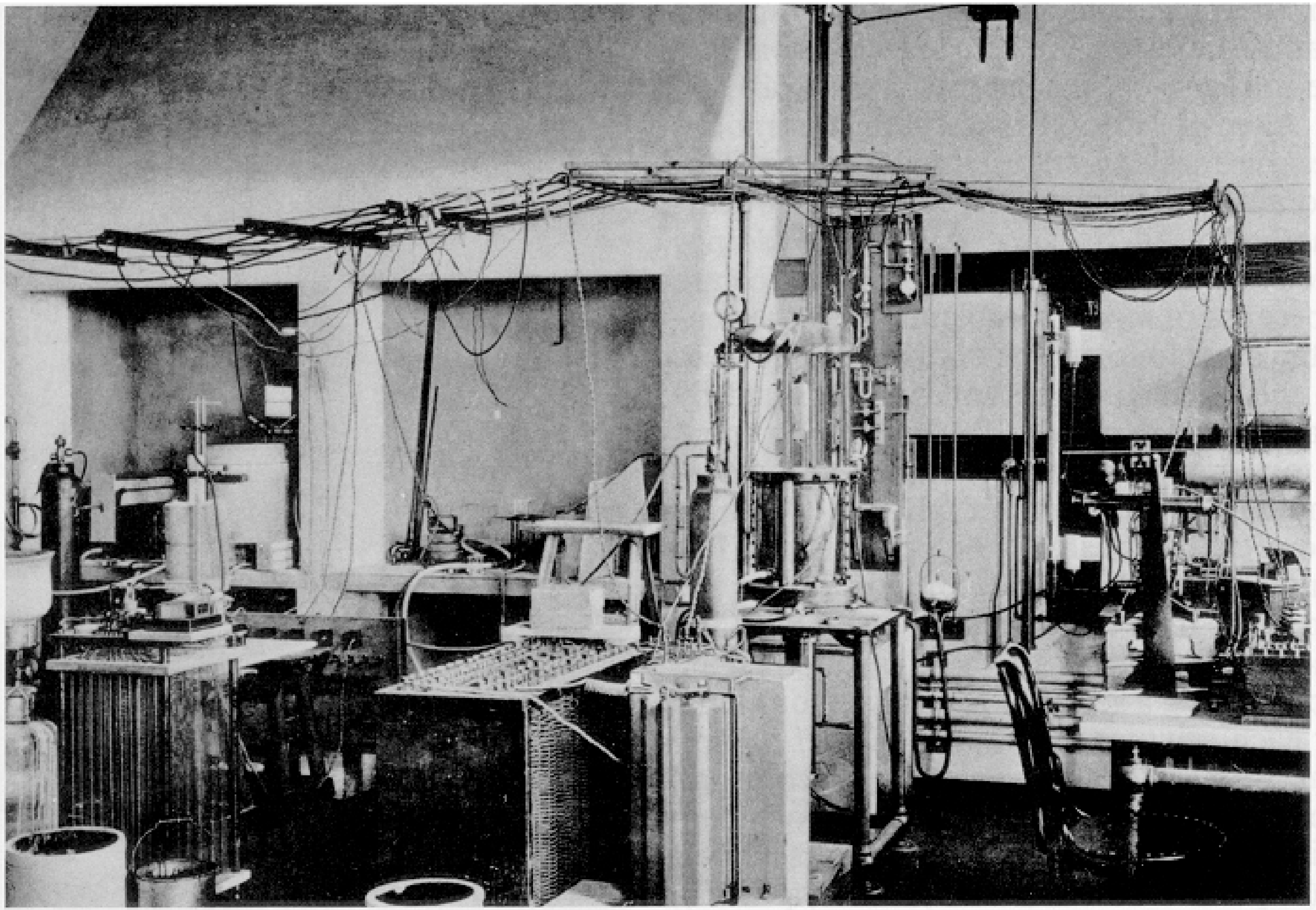




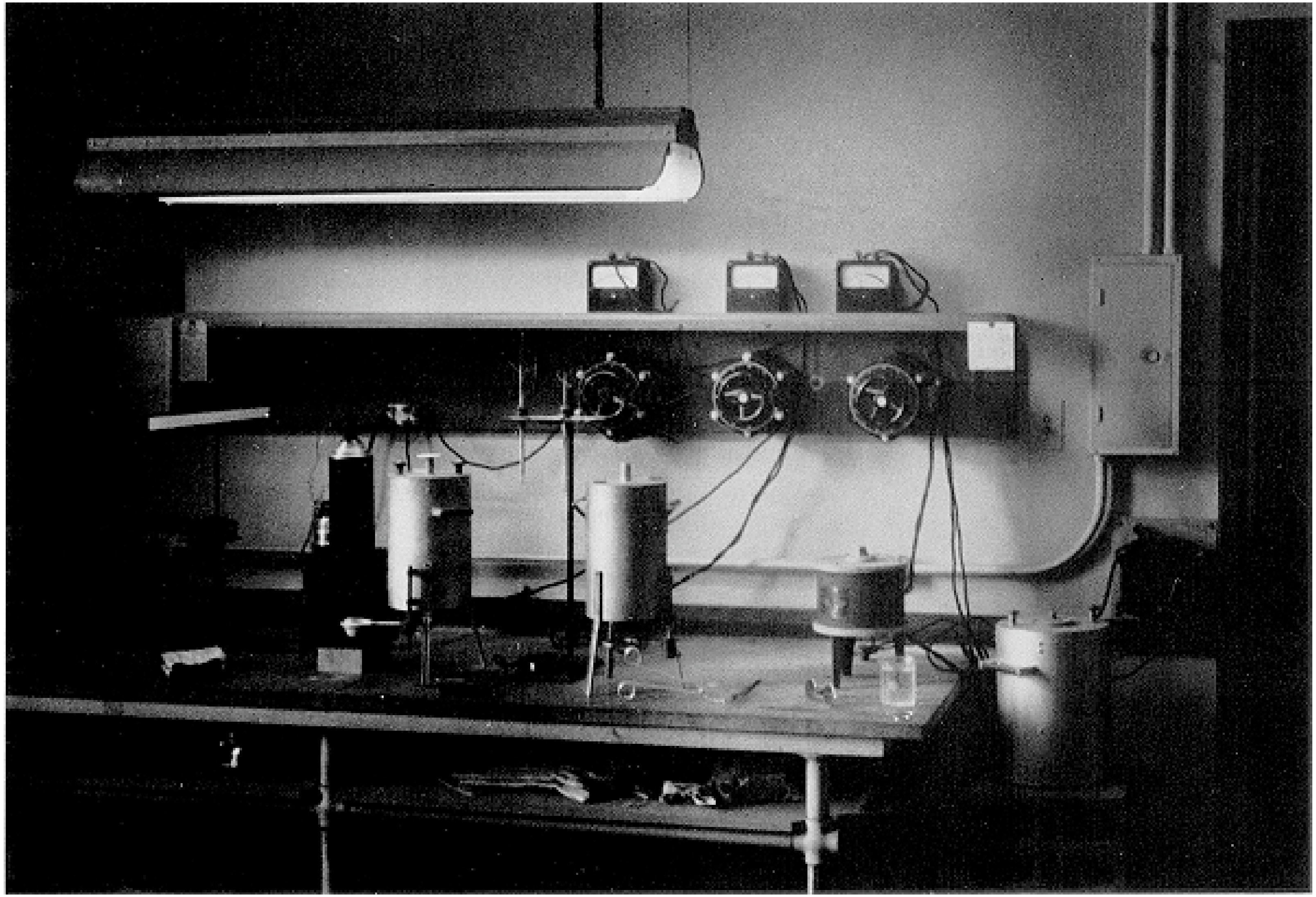
La cellule à enclumes de diamant



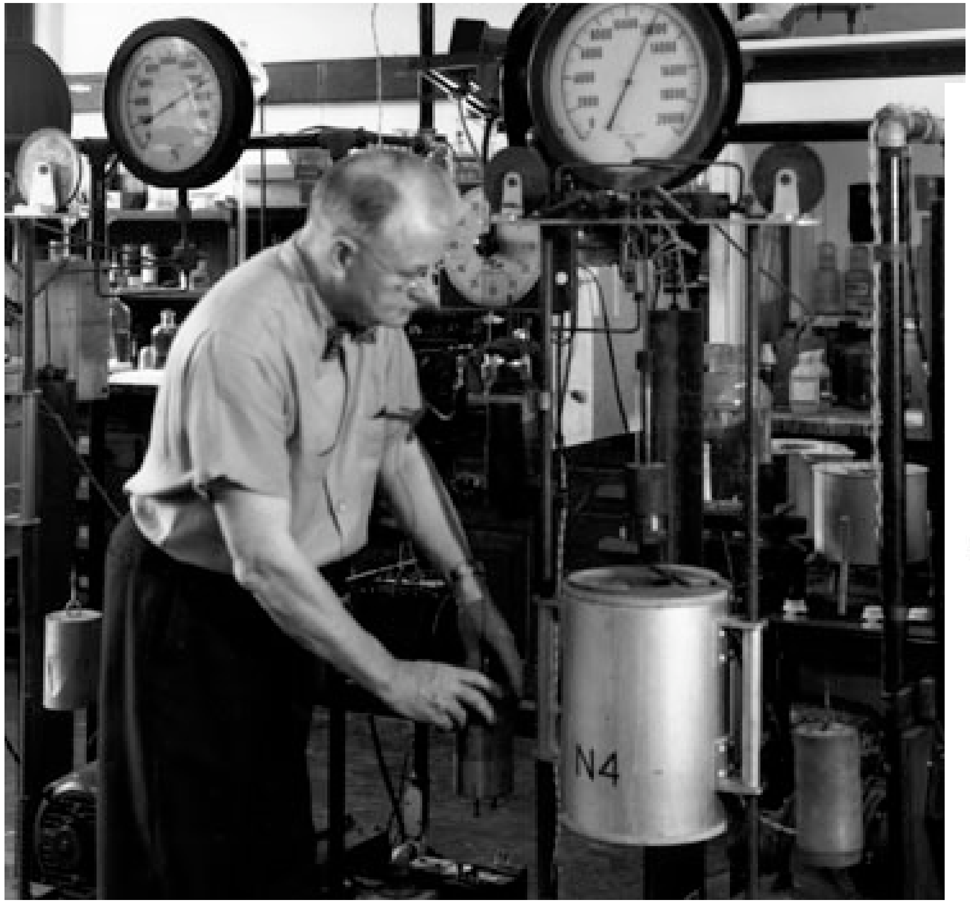
3 historique



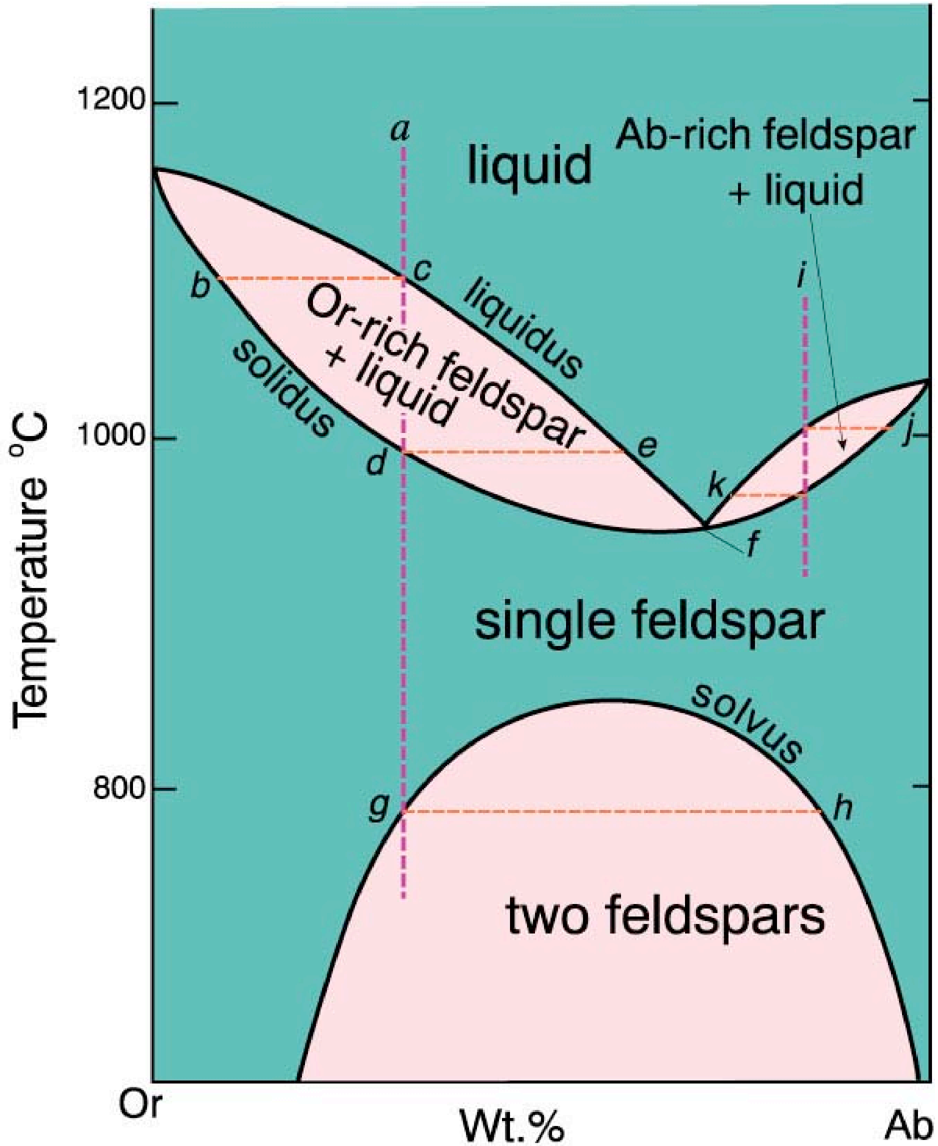
Laboratory of A. L. Day and R. B. Sosman at the Geophysical Laboratory in 1911.



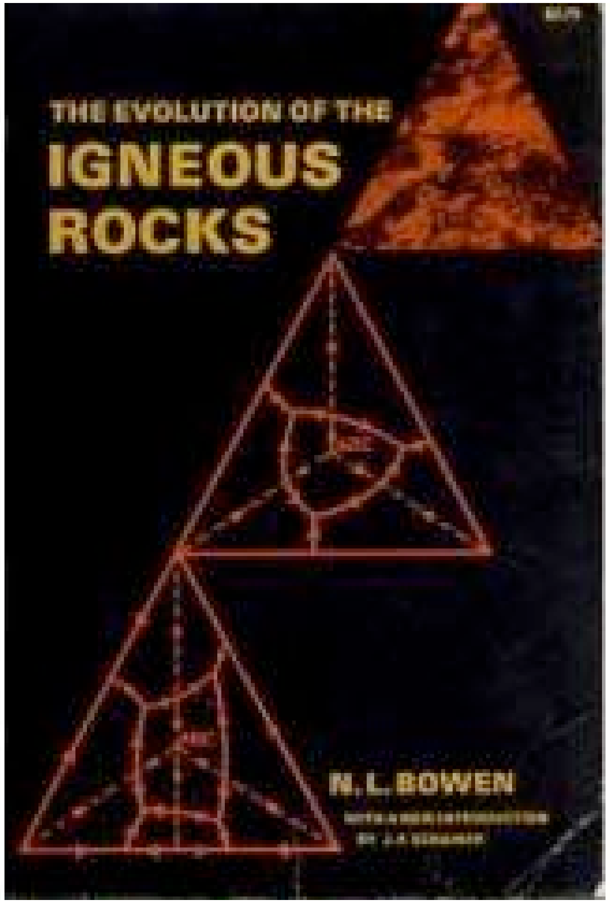
Bowen's laboratory in Rosenwald Hall, University of Chicago, 1946



George W. Morey working in his laboratory at the
Geophysical Laboratory in Washington, D.C., ca. 1950



T-X phase diagram of the system albite-orthoclase at 0.2 GPa H_2O pressure. After Bowen and Tuttle (1950). J. Geology.



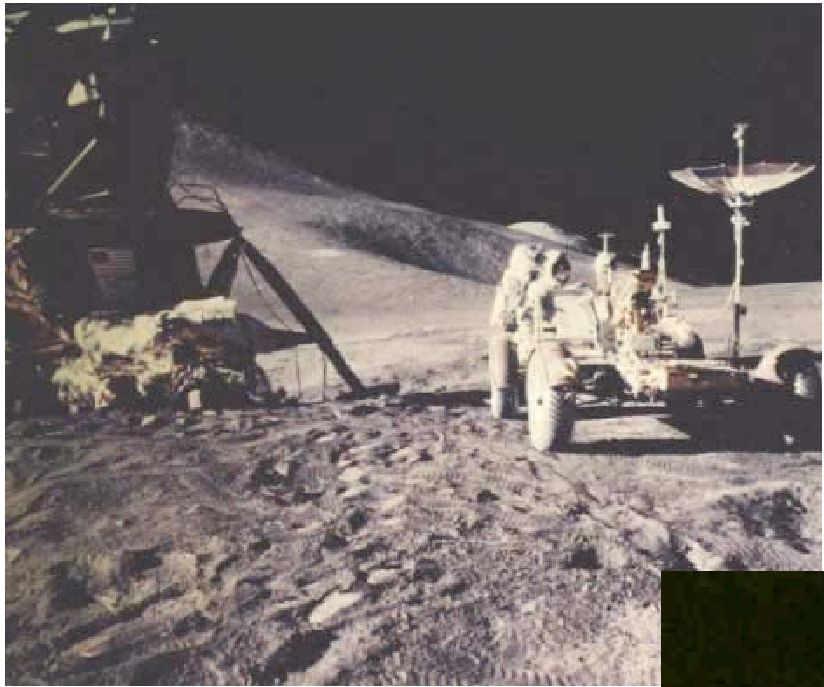
Qu’est ce qui restait à faire

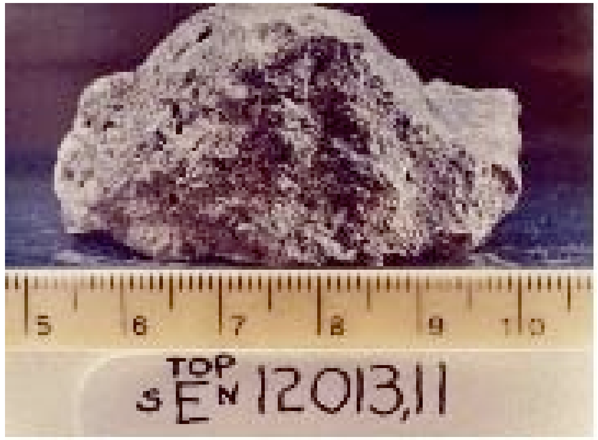
en magmatologie expérimentale?

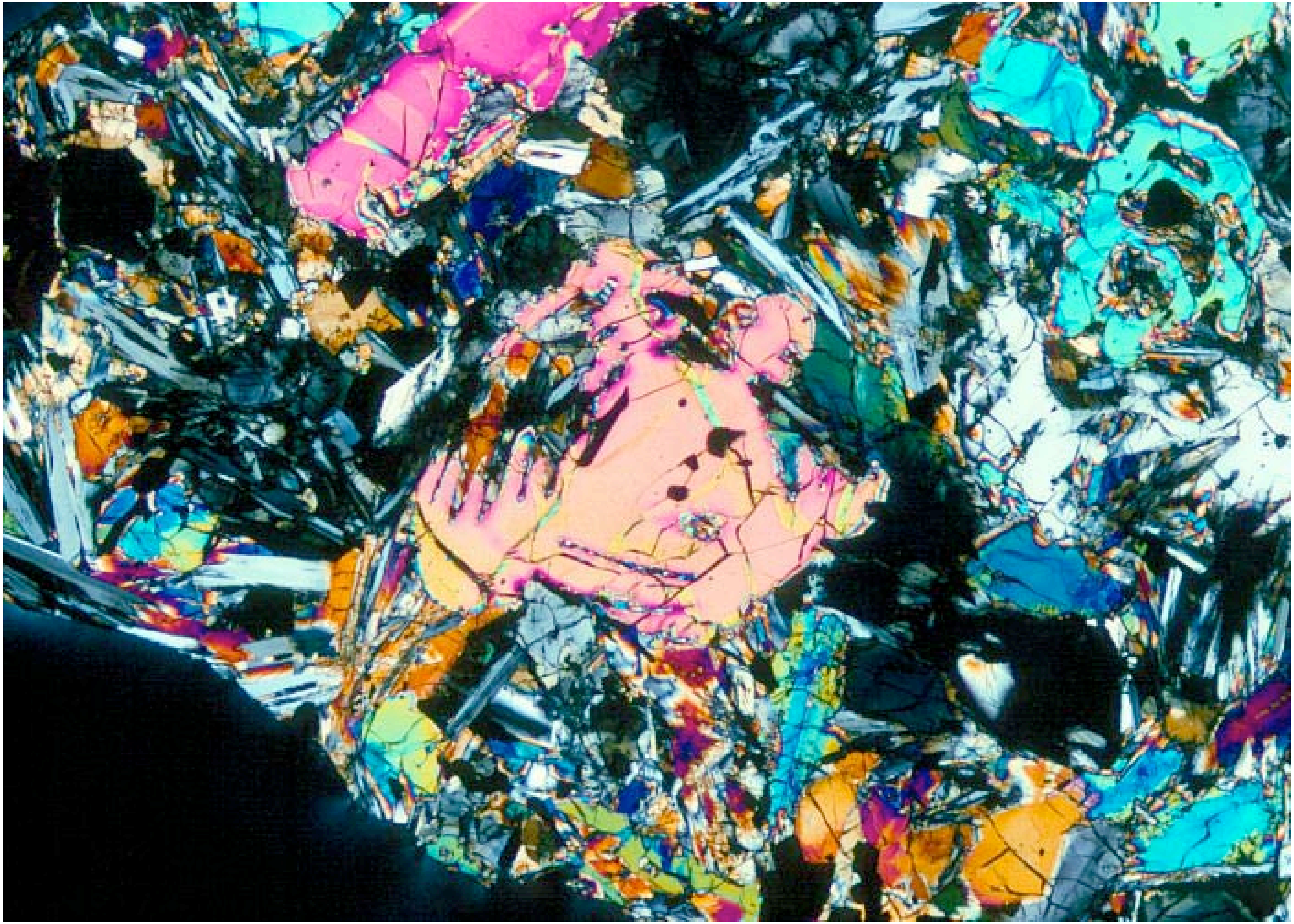
La course aux hautes pressions

Photographie aérienne de missiles nucléaires soviétiques installés à Cuba, le 1er novembre 1962

Construction du mur de Berlin en août 1961.



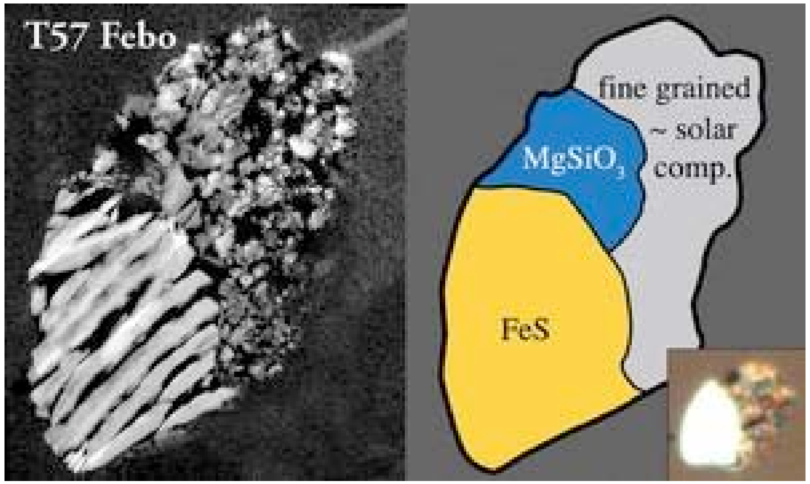

5 6 7 8 9 10
TOP
S E N 12013,11



low-Ti basalt, 40X, cross polarized light

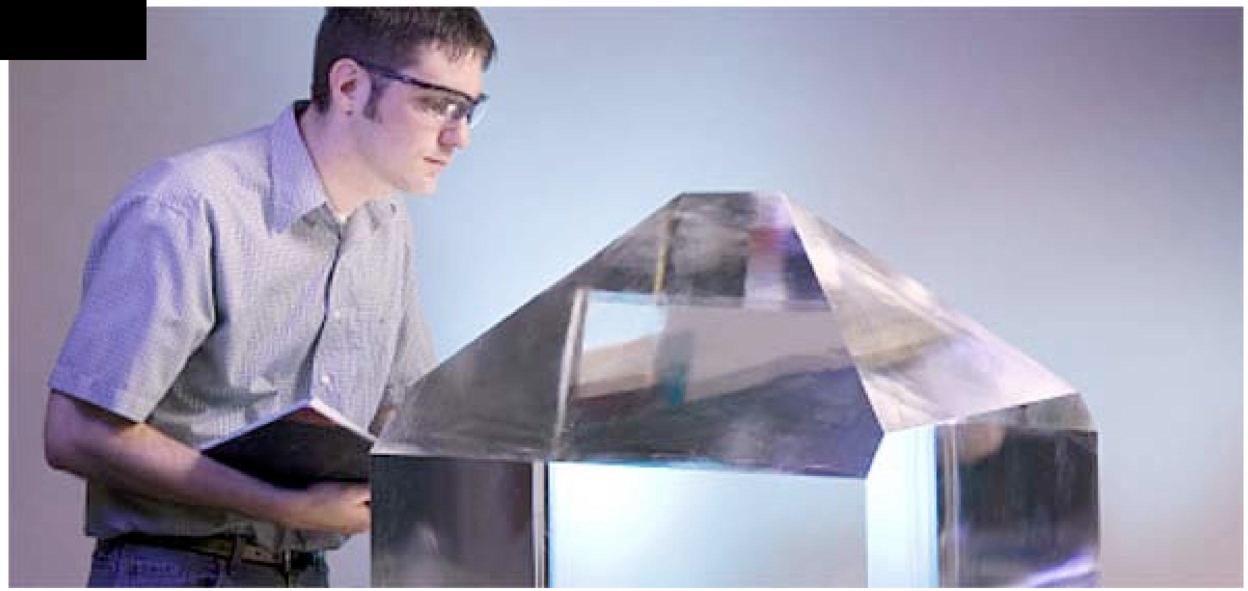
Stardust : la poussière de comète

La vitesse relative de la sonde et des poussières était de 6,1 km/s,



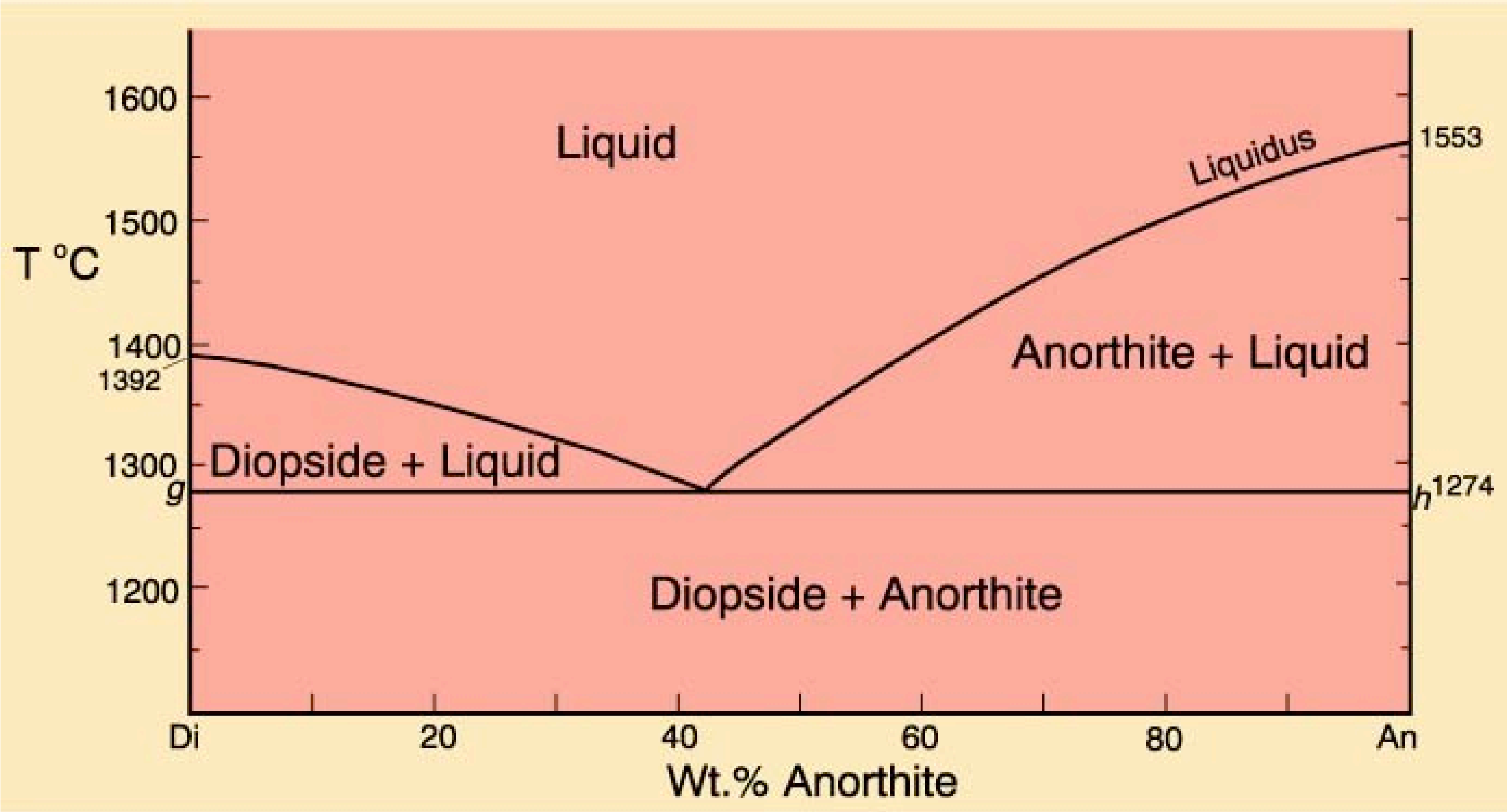
Ce grain est composé de 3 parties : de la pyrrhotite (FeS), de l'enstatite (pyroxène magnésien, MgSiO3) et un agrégat de micrograins dont la composition globale est celle des chondrites (composition solaire).

La guerre des étoiles



4: Diagrammes de phase expérimentaux

4-1) Les paramètres:

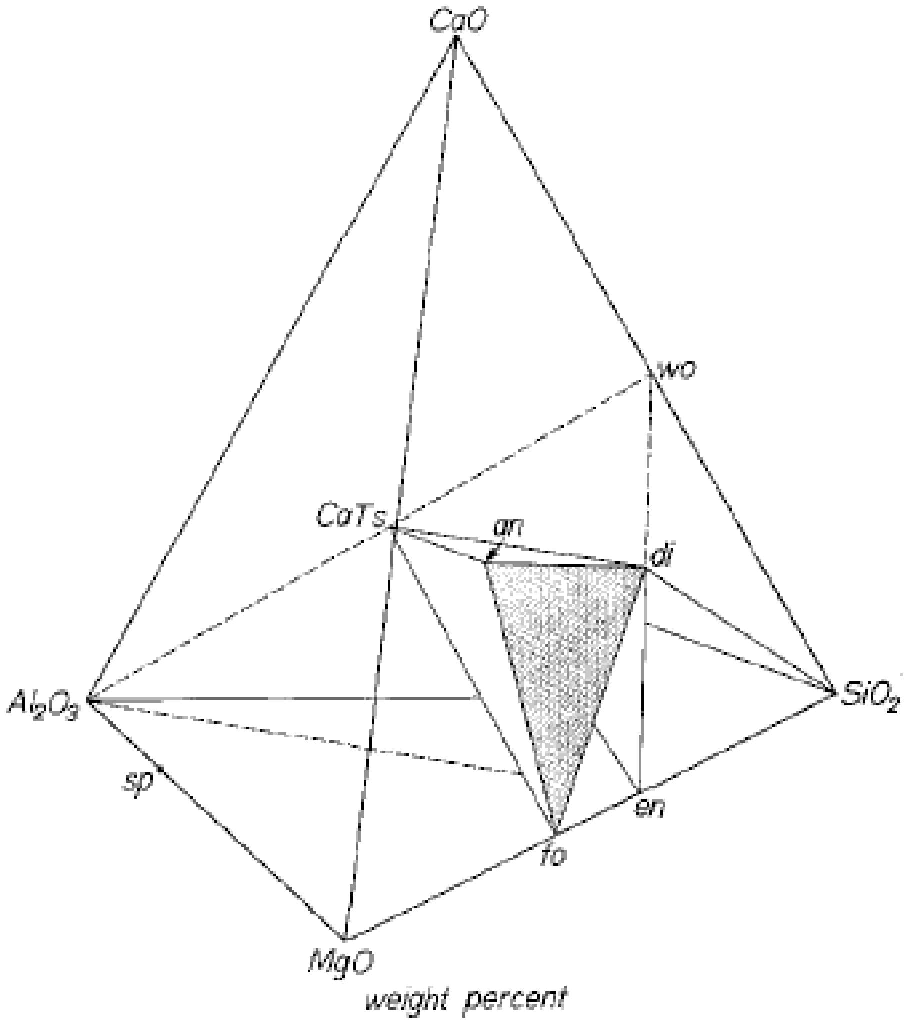


Isobaric T-X phase diagram at atmospheric pressure. After Bowen (1915), Amer. J. Sci. 40, 161-185.

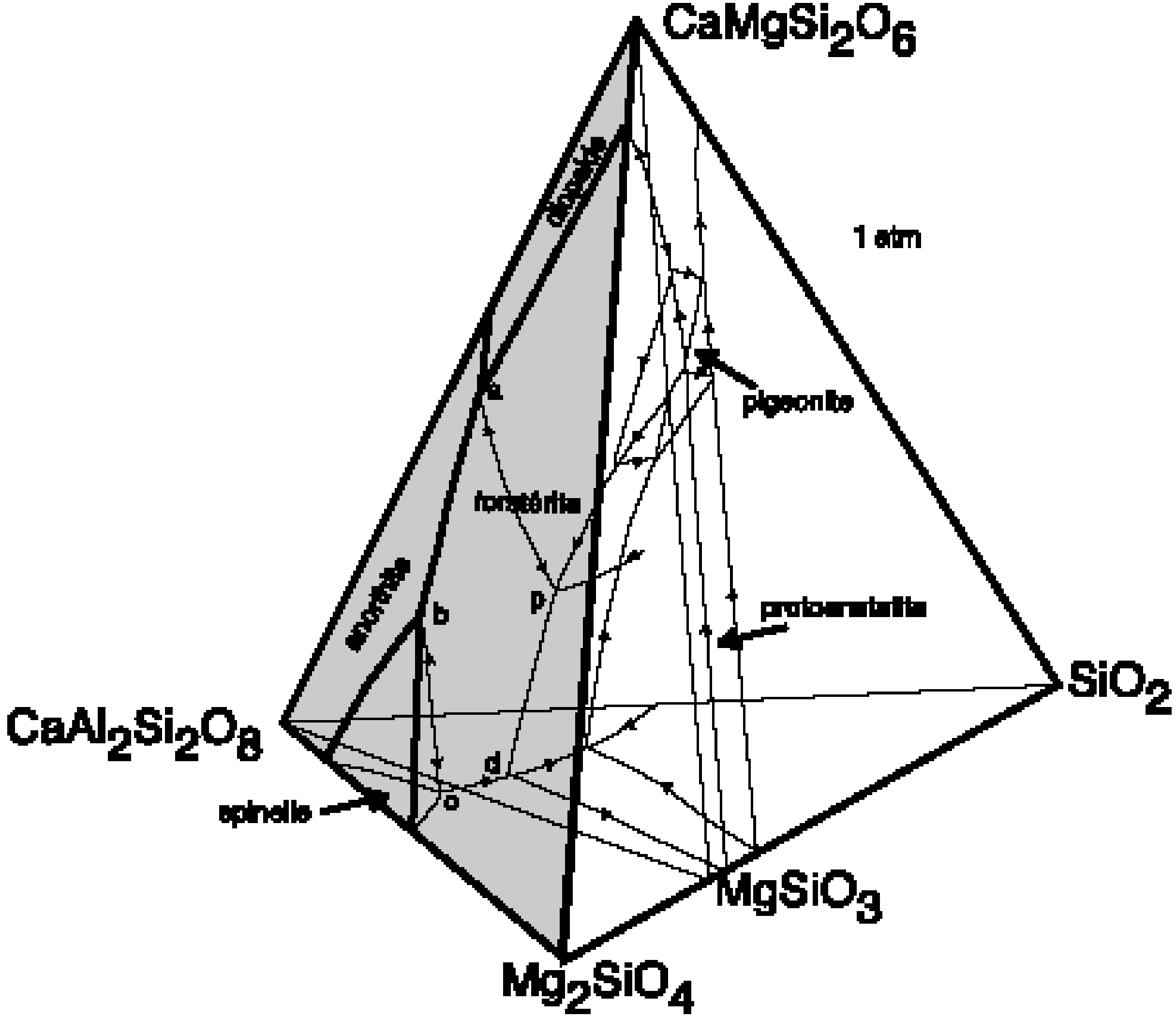
- Compositions
- Températures
- Nature des phases: solides (cristaux), liquide (verre)

4-2) Compositions: système simplifié / système naturel

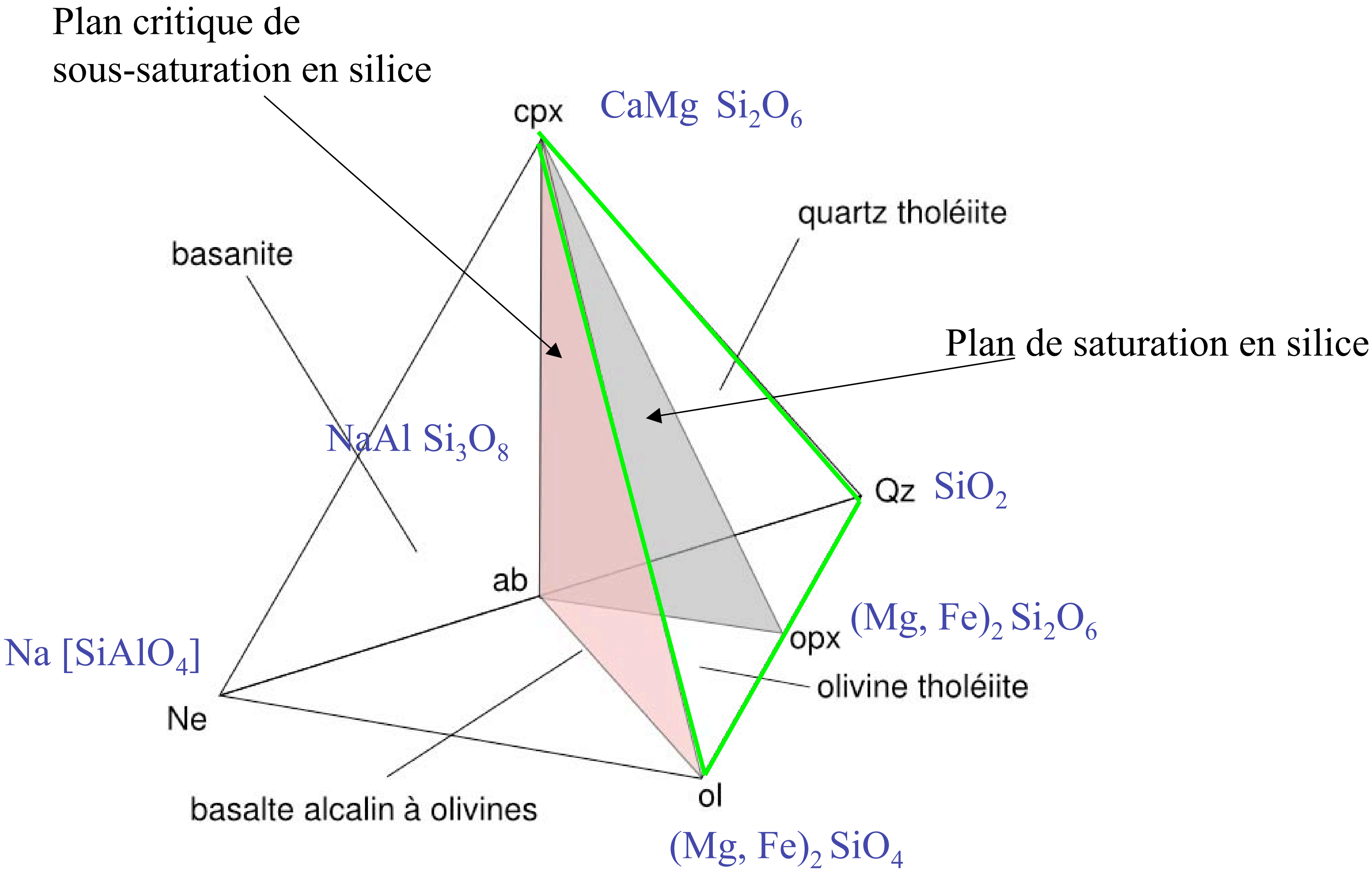
CMAS: $CaO-MgO-Al_2O_3-SiO_2$



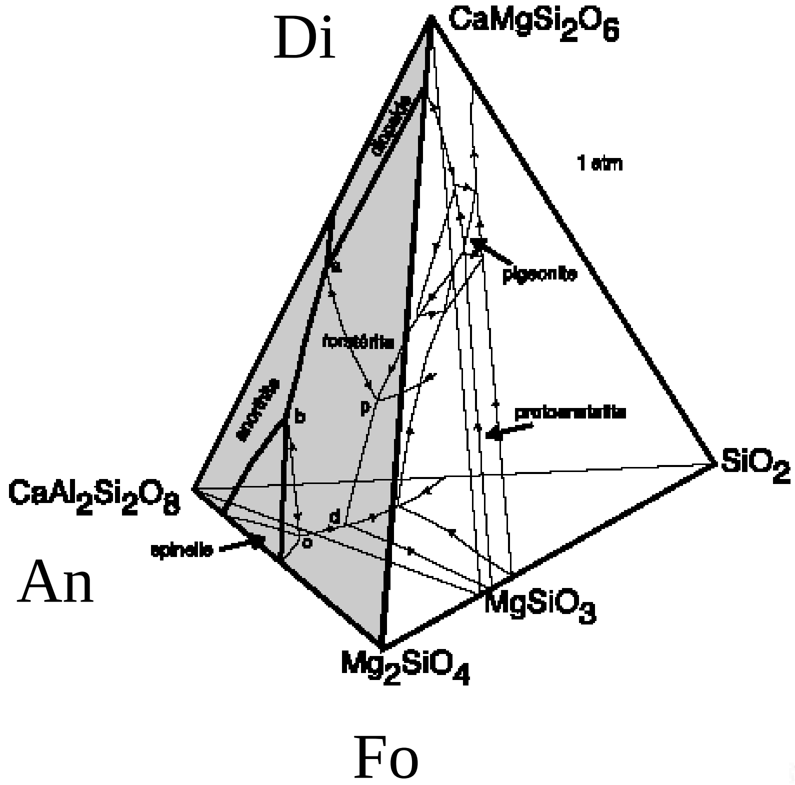
85 à 90% des constituants chimiques des basaltes et des péridotites.

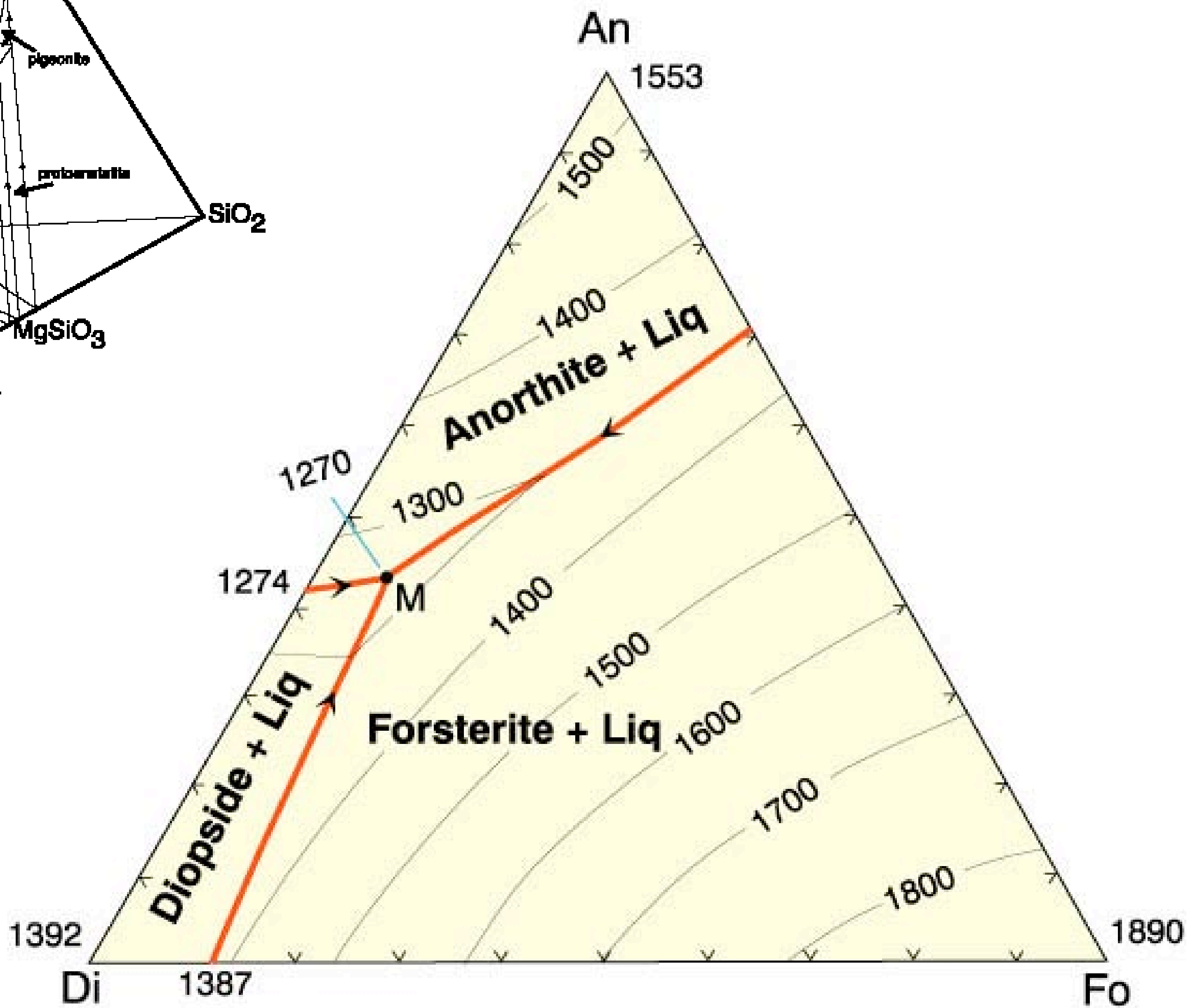


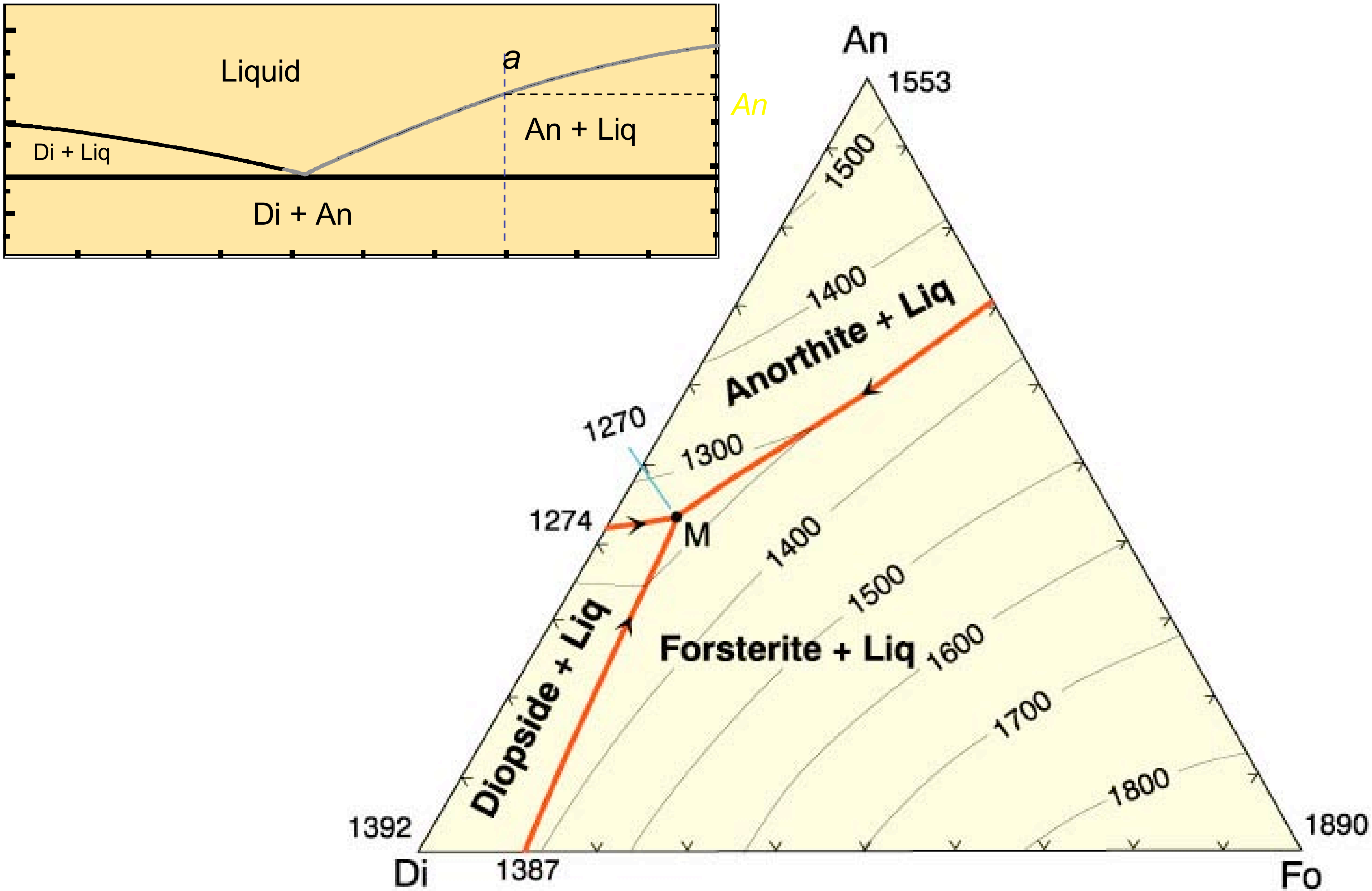
$CaMgSi_2O_6$
1 atm
a
forstérita
pigeonite
p
b
protoenstatite
SiO_2
$CaAl_2Si_2O_8$
d
o
spinelle
$MgSiO_3$
Mg_2SiO_4



Classification de Yoder et Tilley (1962) = classification normative


Di
CaMgSi2O6
diopside
1 atm
pigeonite
forstérite
protoenstatite
anorthite
SiO2
CaAl2Si2O8
spinelle
MgSiO3
Mg2SiO4
An
Fo


An
1553
1500
1400
Anorthite + Liq
1270
1300
1274
M
1400
1500
Forsterite + Liq
1600
Diopside + Liq
1700
1800
1392
1890
Di
1387
Fo



Isobaric diagram illustrating the liquidus temperatures in the Di-An-Fo system at atmospheric pressure (0.1 MPa). After Bowen (1915), A. J. Sci., and Morse (1994), Basalts and Phase Diagrams. Krieger Publishers.

système naturel

- Roches broyées

-Mélange de minéraux

Avantage:

Compositions plus proches de la réalité

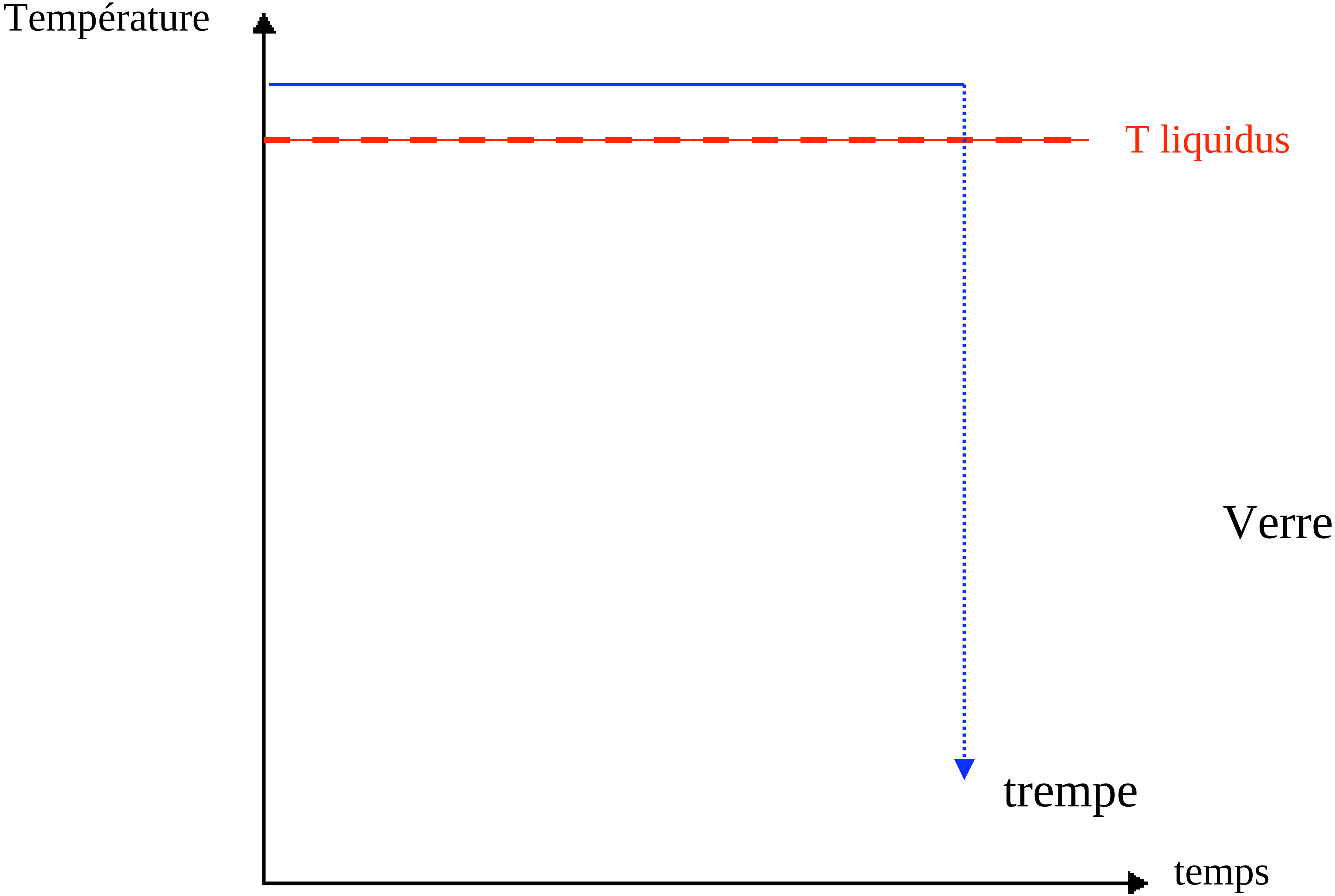
Inconvénients:

problèmes d’homogénéités des produits de départs

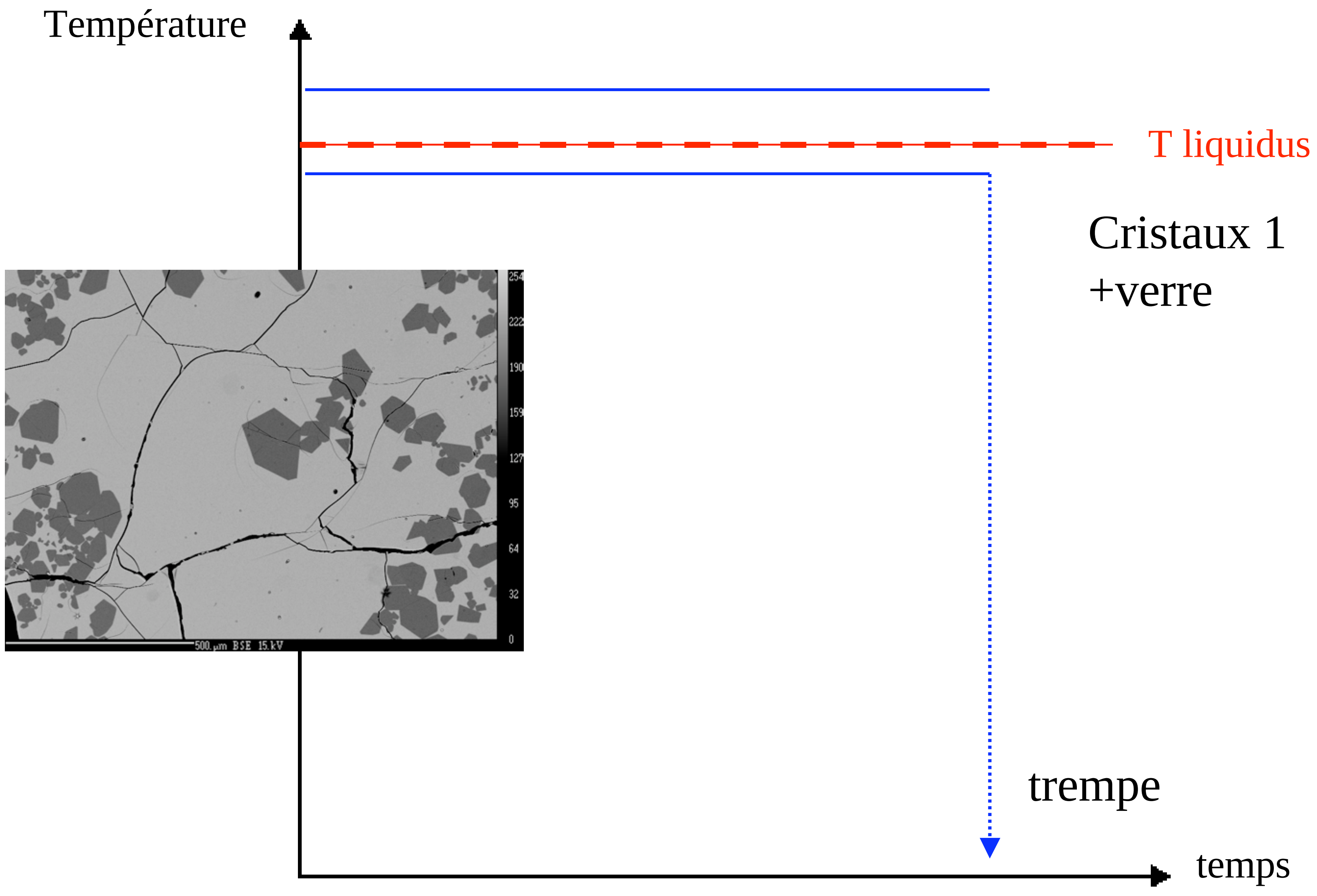
Compositions trop complexes pour l’interprétation

Eléments réactionnels (fer, chrome, sodium…)

4-3 Protocole thermique



Cristallisation isotherme (pour une composition donnée)

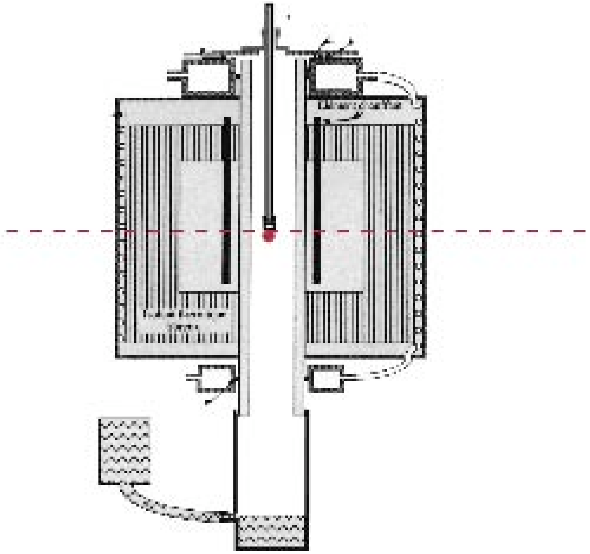


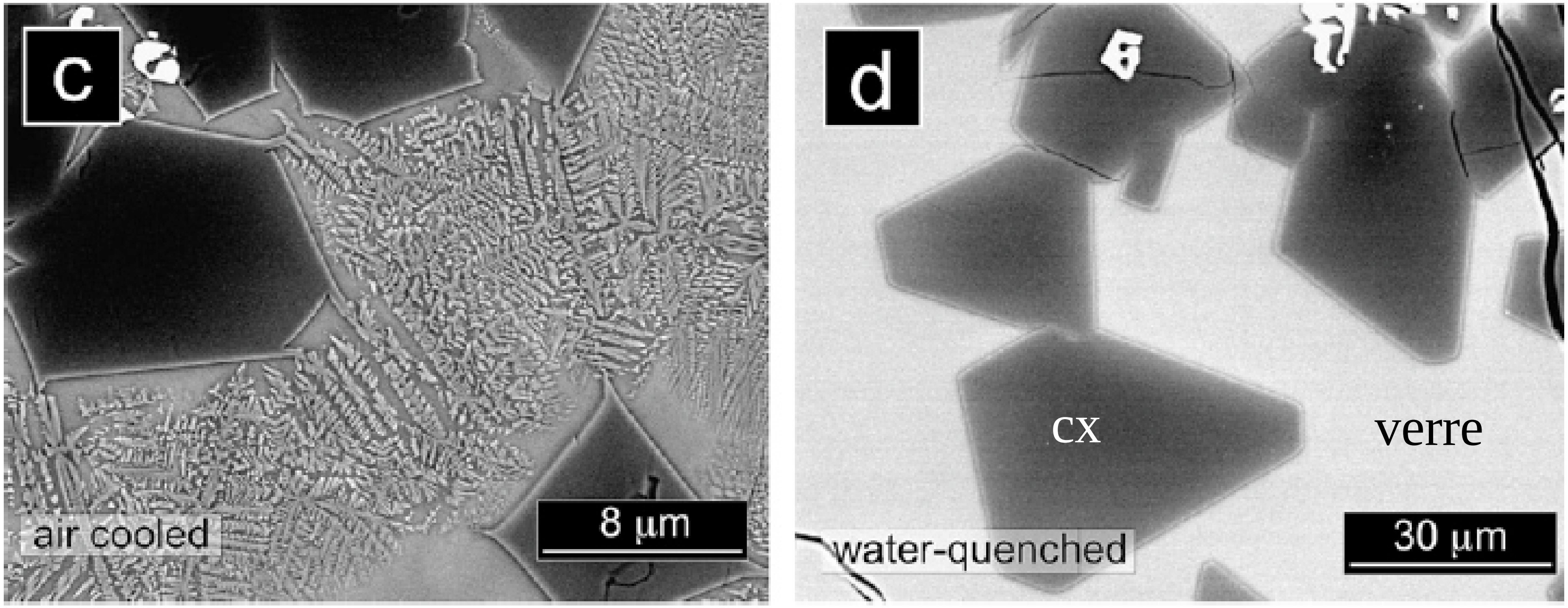
Détermination de la T liquidus

Effet de la trempe:

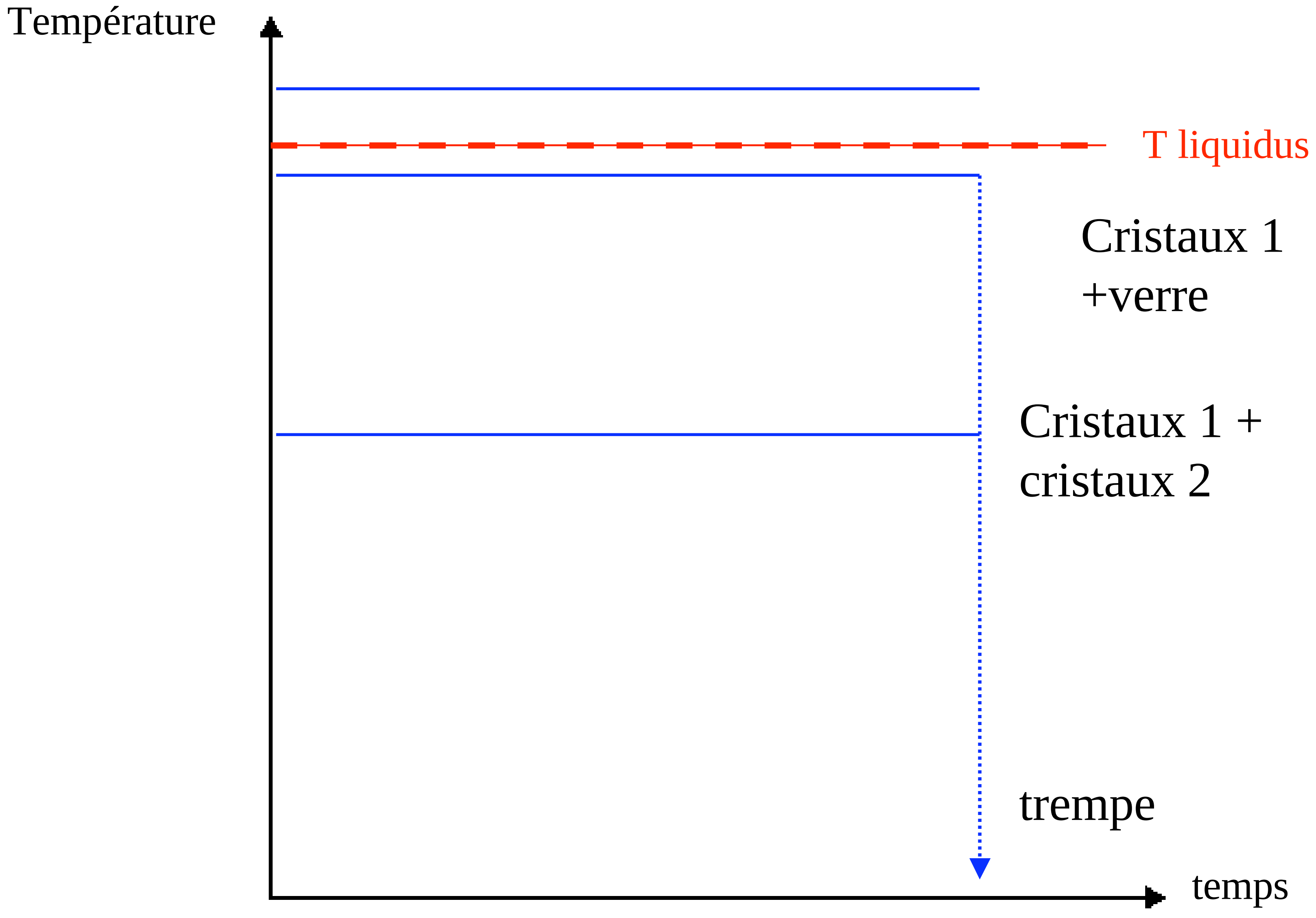
-Dans l'air

-Dans l'eau



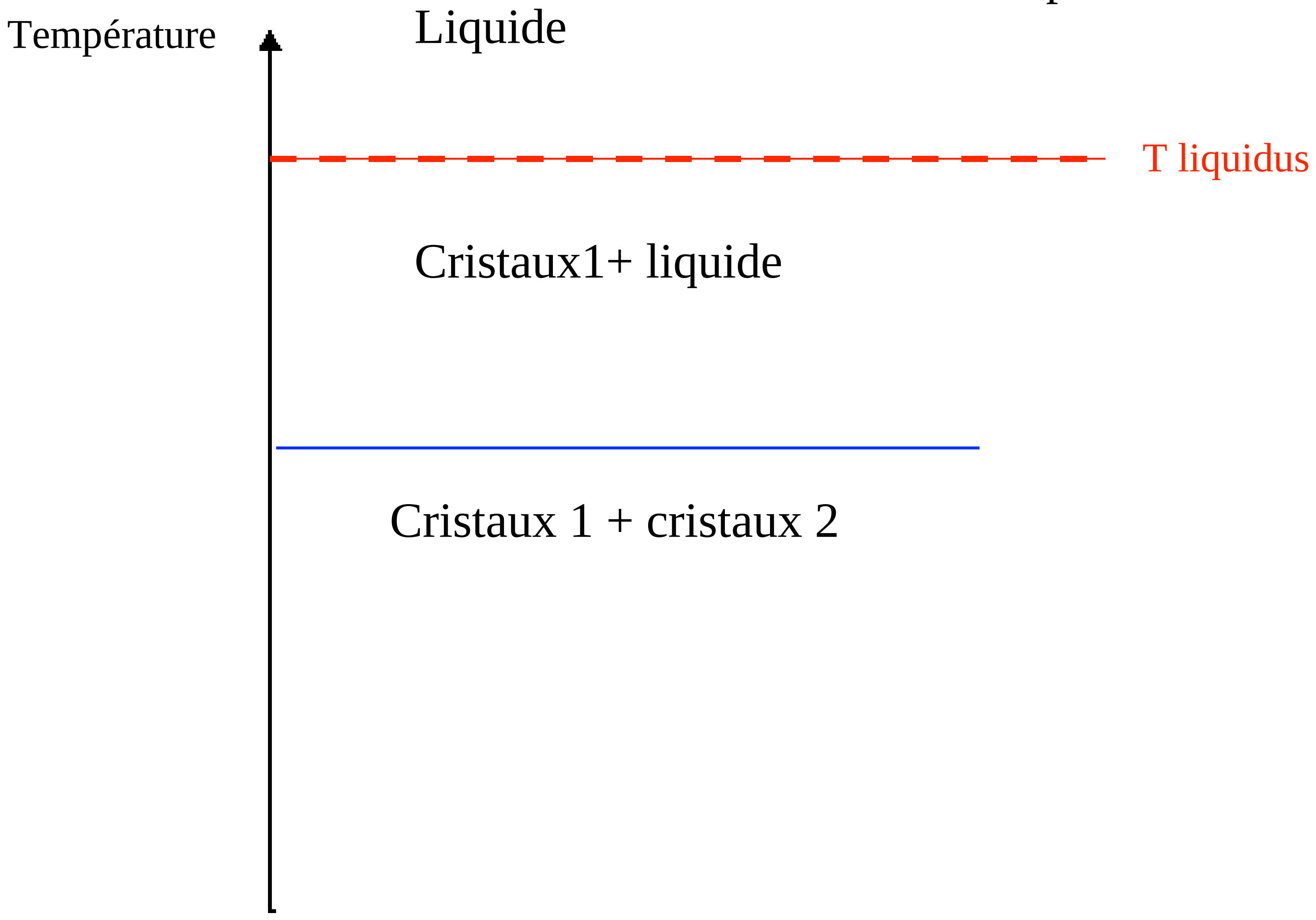


Walton & Herd (GCA, 2007)



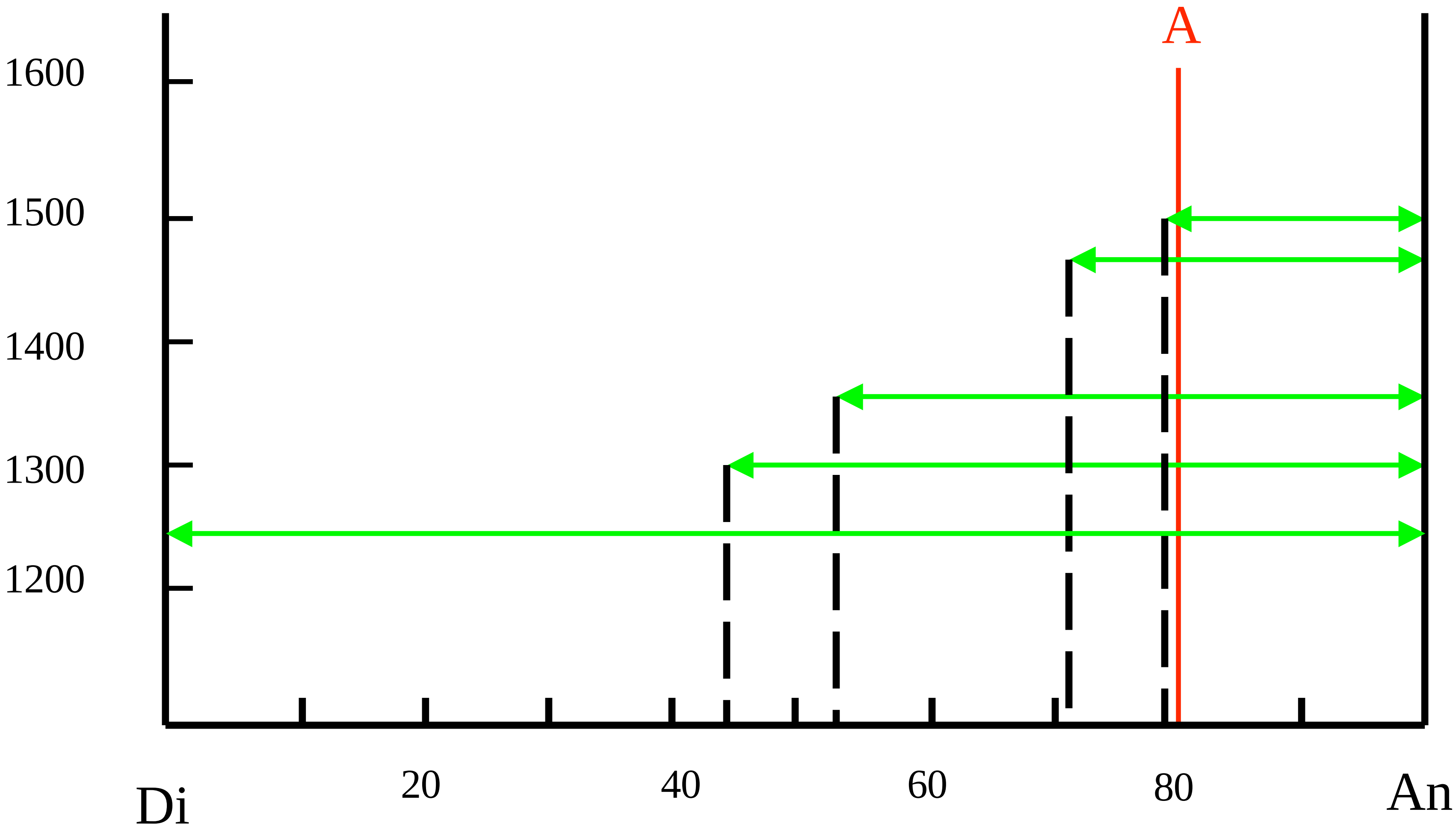
Détermination des champs de stabilités des différentes phases

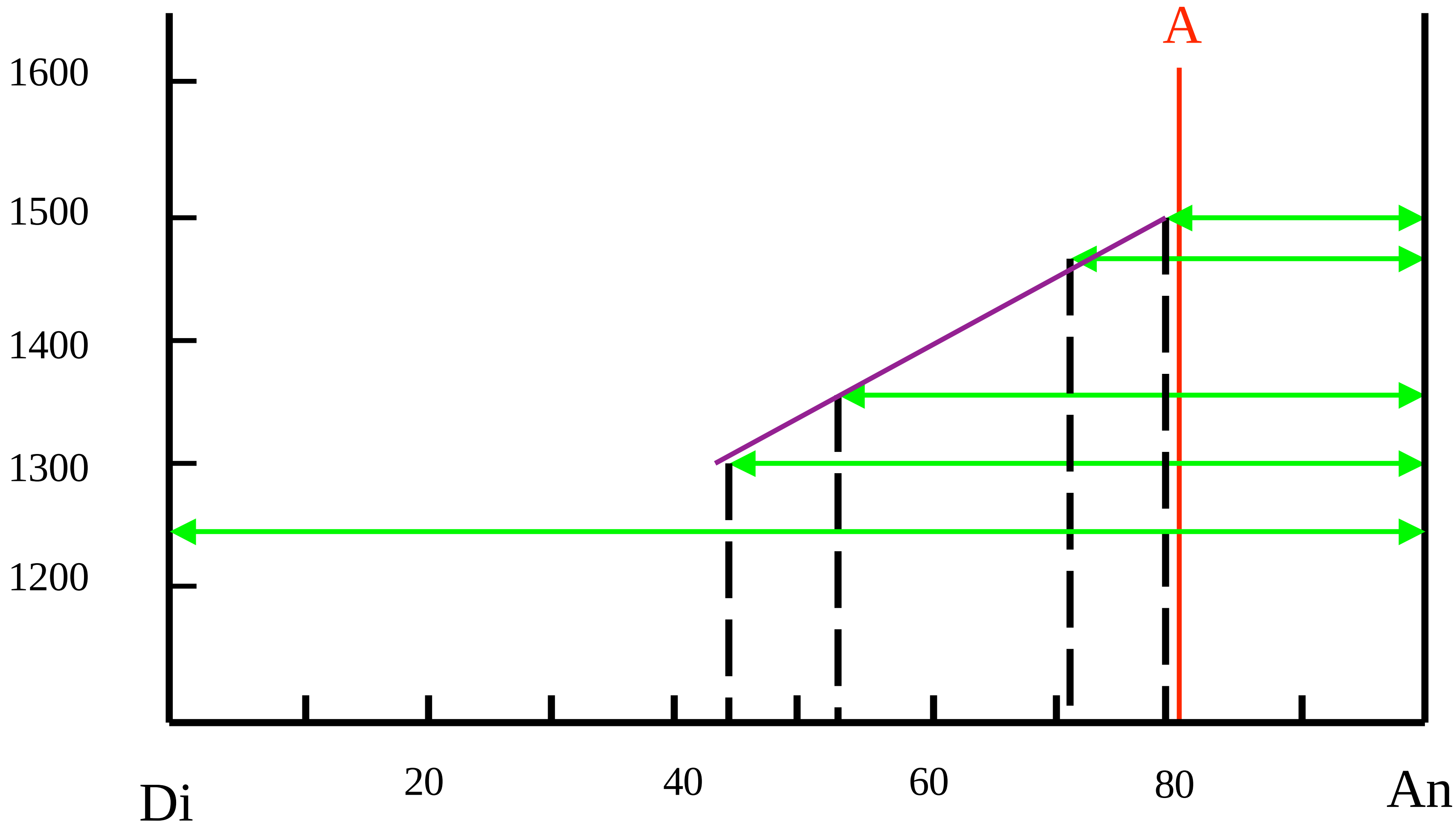
Pour une composition donnée

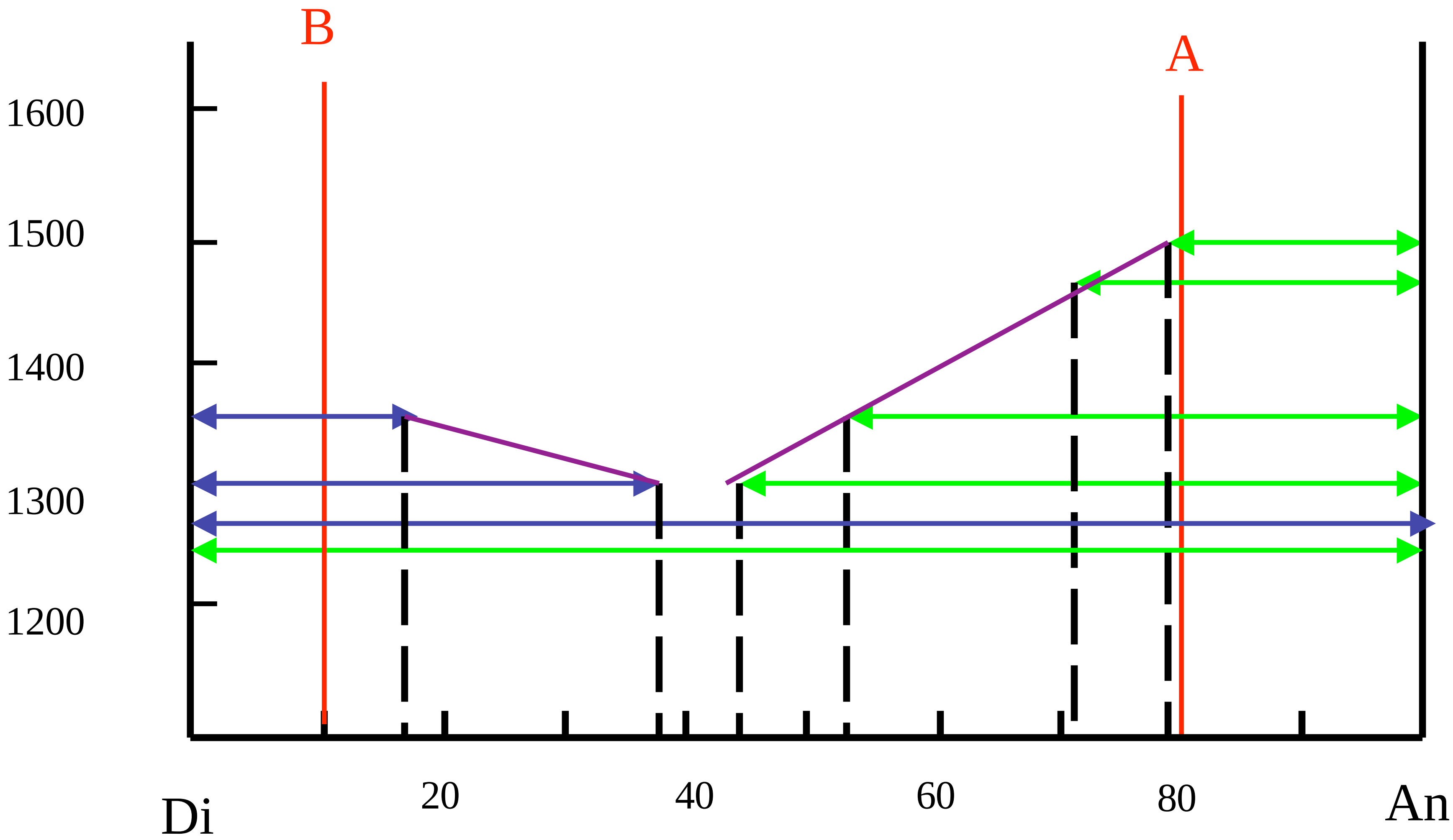


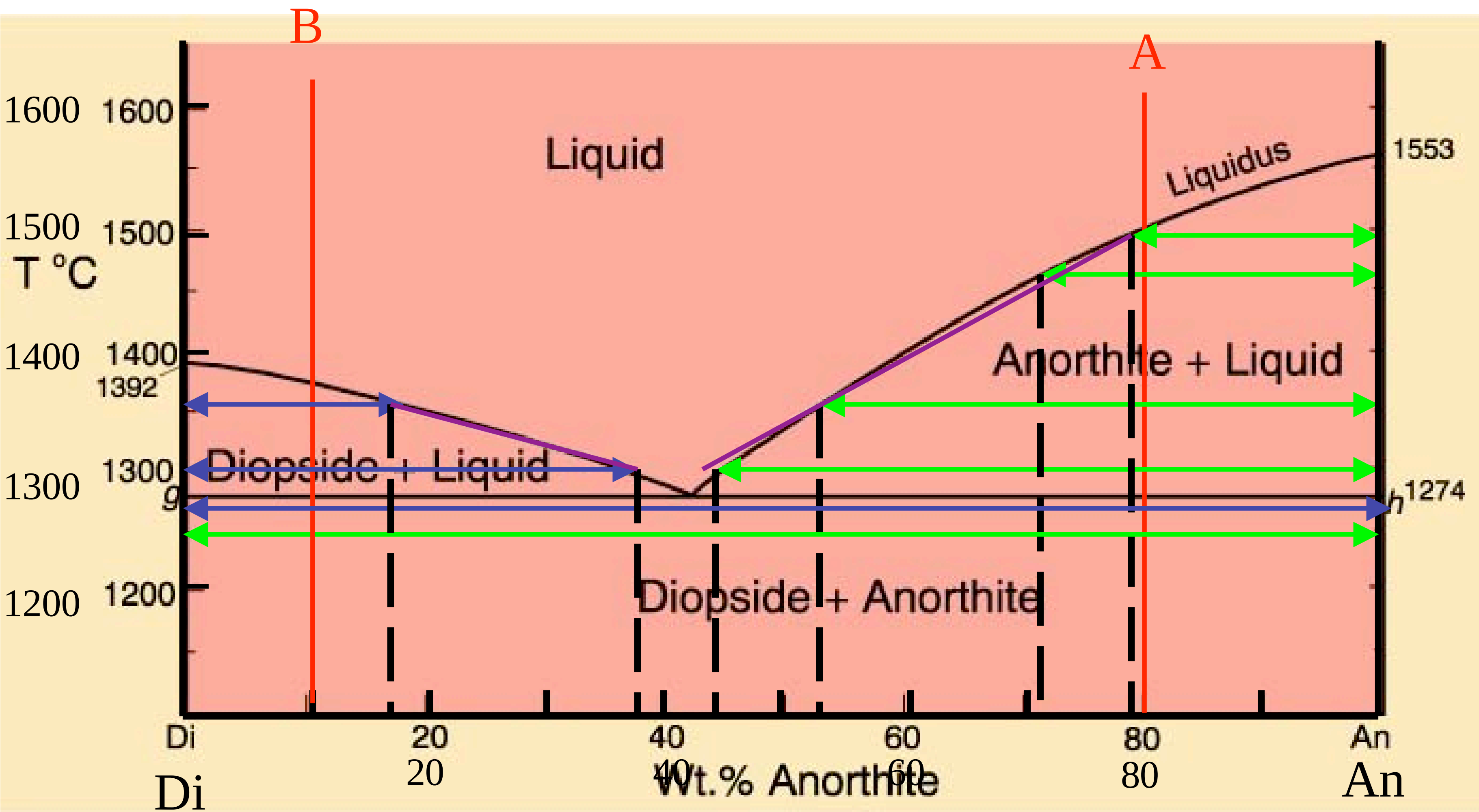
Détermination des champs de stabilités des différentes phases

4-4 Construction du diagramme de phase

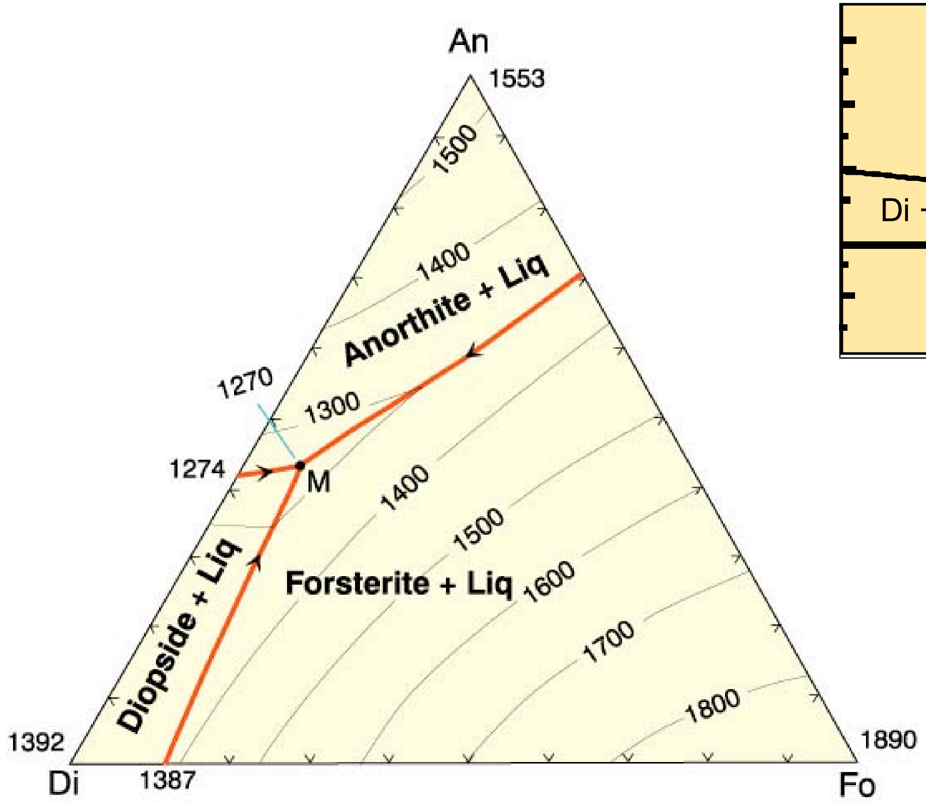


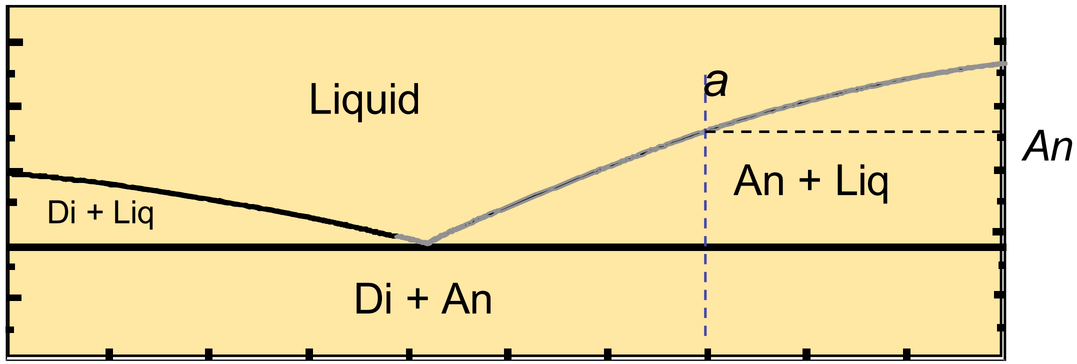

A
1600
1500
1400
1300
1200
20
40
60
80
Di
An

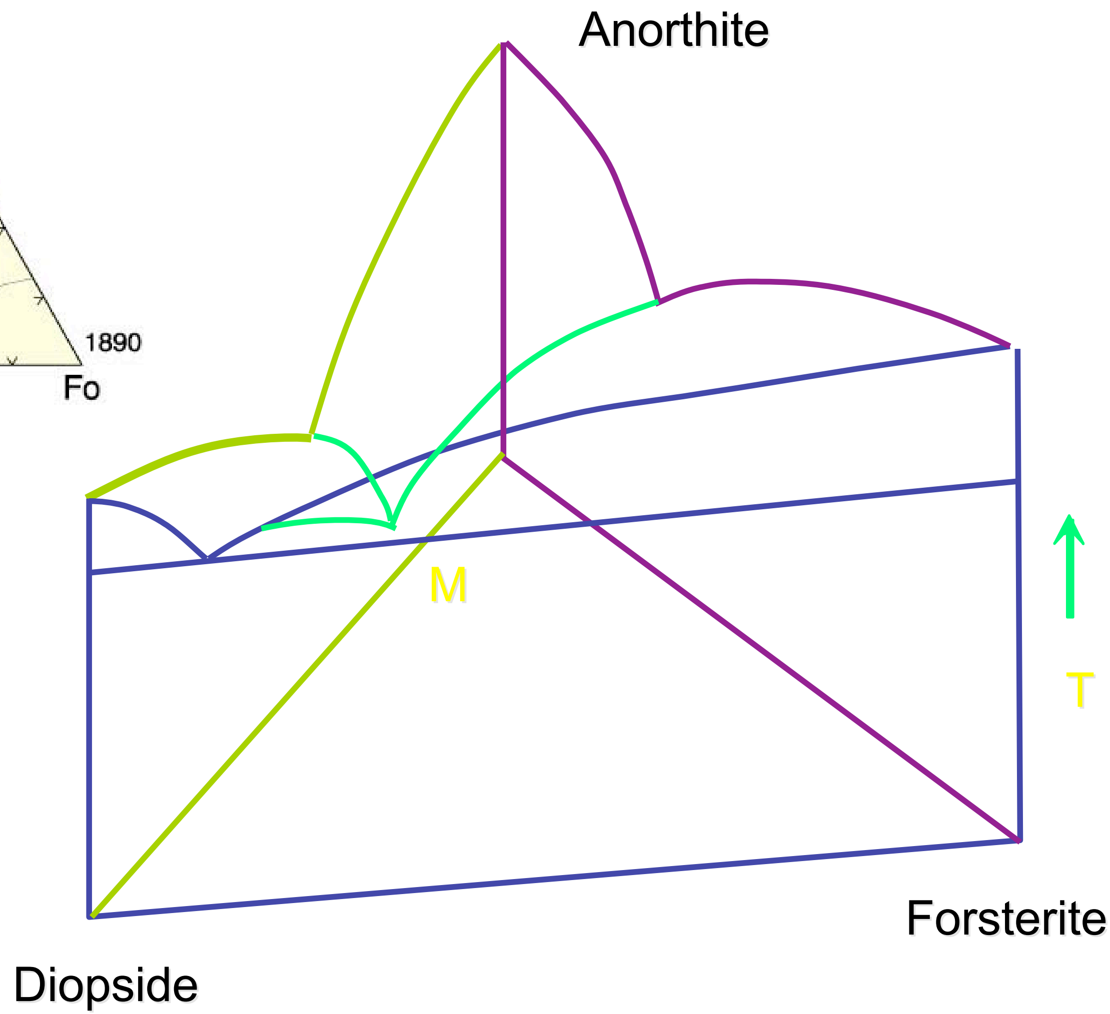

B
A
1600
1500
1400
1300
1200
Di
20
40
60
80
An



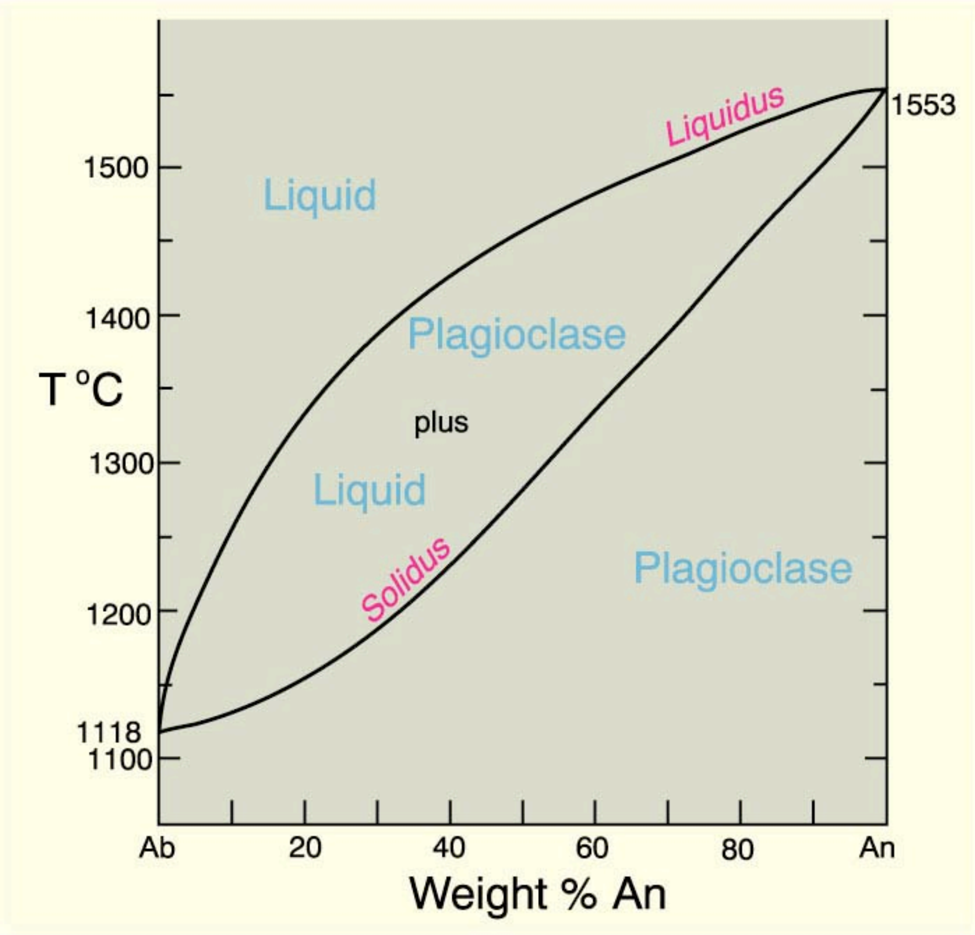
B
A
1600
1500
1400
1300
1200
T °C
Liquid
Liquidus
1553
1392
Anorthite + Liquid
Diopside + Liquid
g
h
1274
Diopside + Anorthite
Di
20
40
60
80
An
Wt.% Anorthite

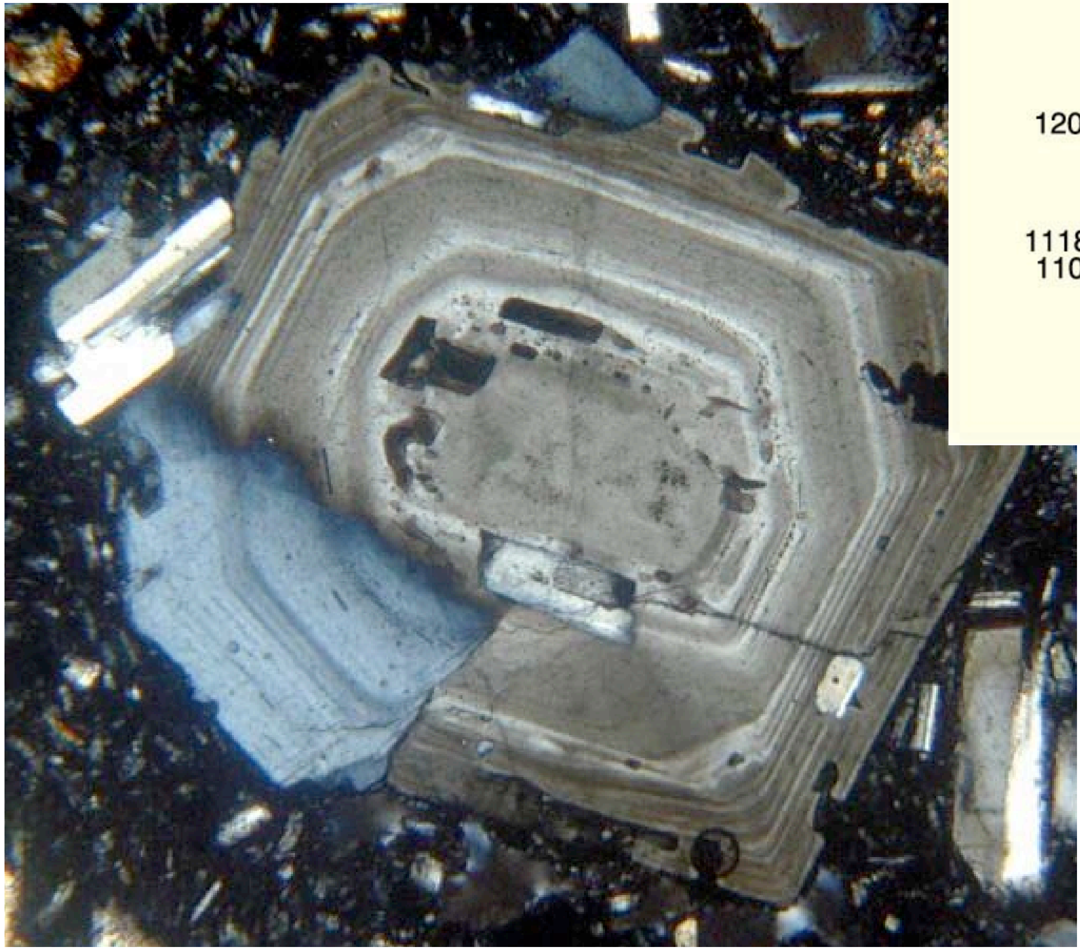

An
1553
1500
1400
Anorthite + Liq
1270
1300
1274
M
1400
1500
Forsterite + Liq
1600
Diopside + Liq
1700
1800
1392
Di
1387
1890
Fo

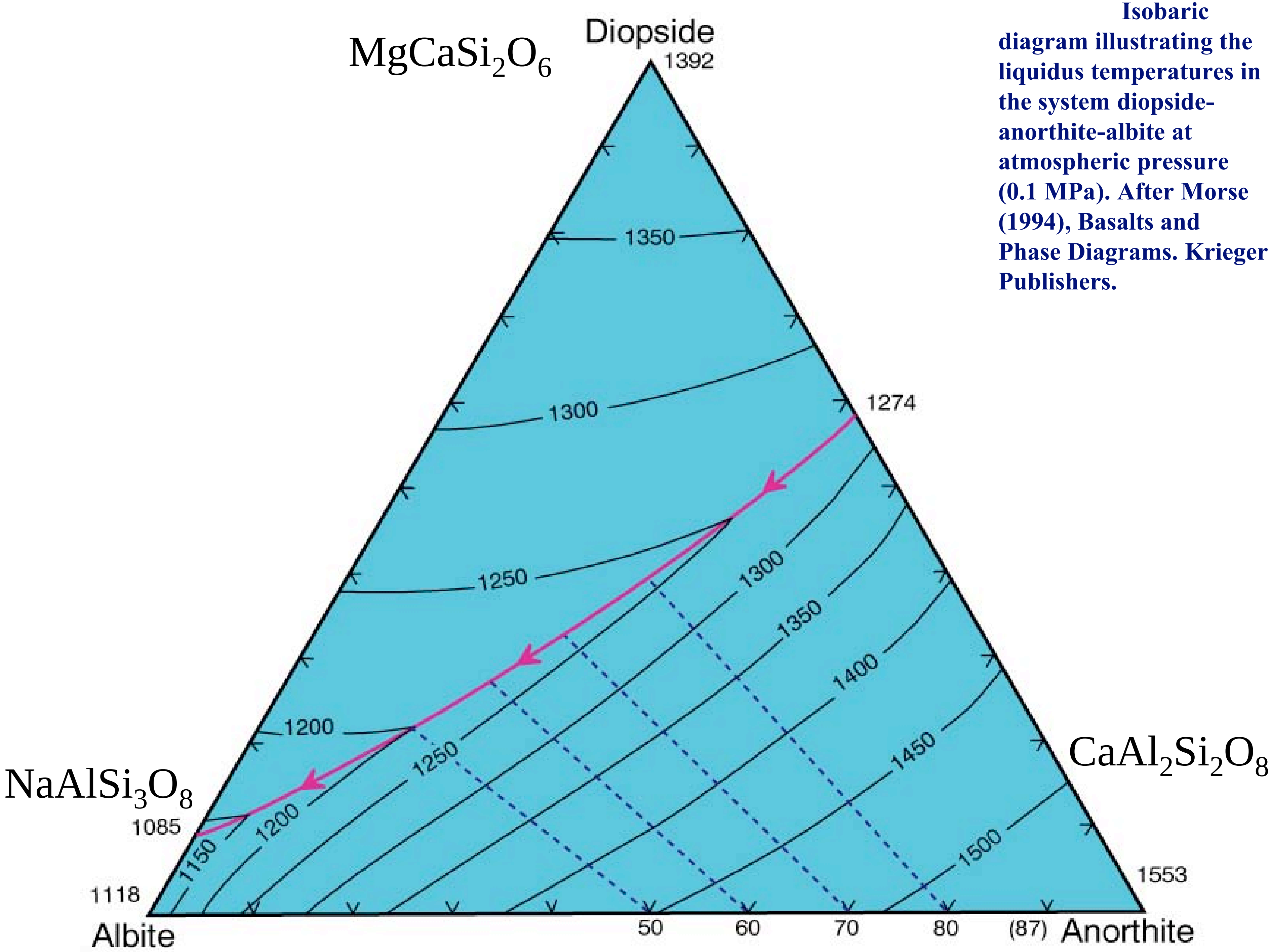

Liquid
a
An
An + Liq
Di + Liq
Di + An


Anorthite
M
T
Forsterite
Diopside

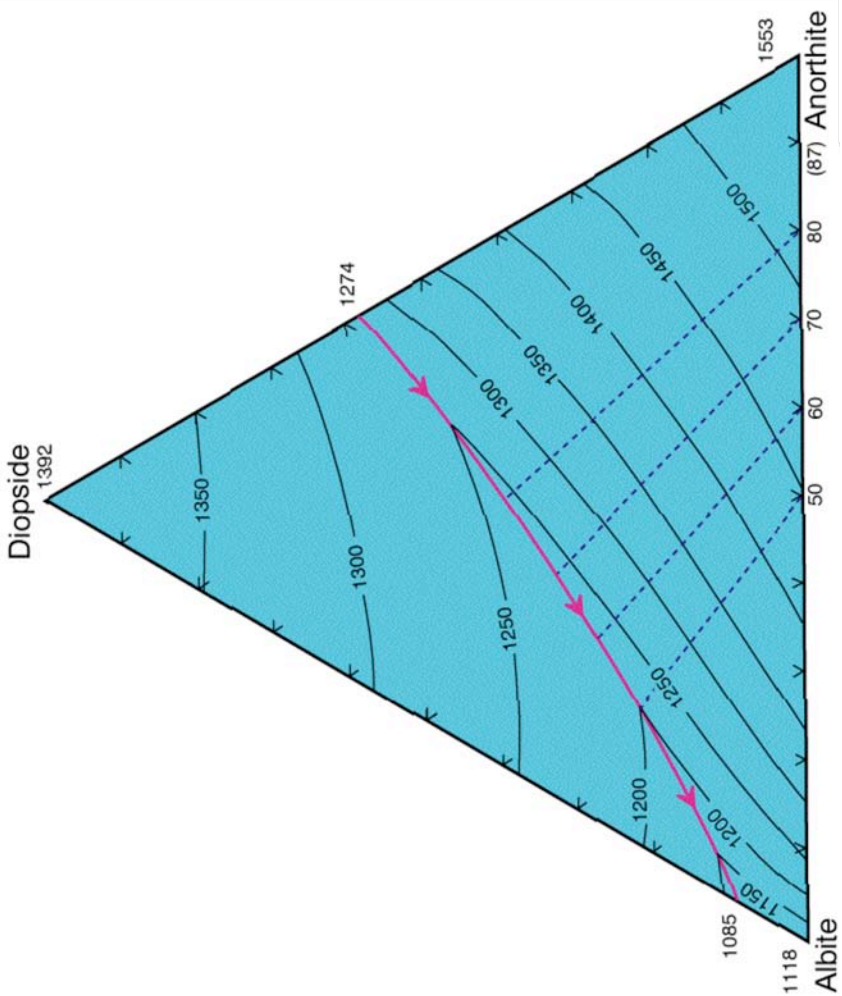
Problème des solutions solides



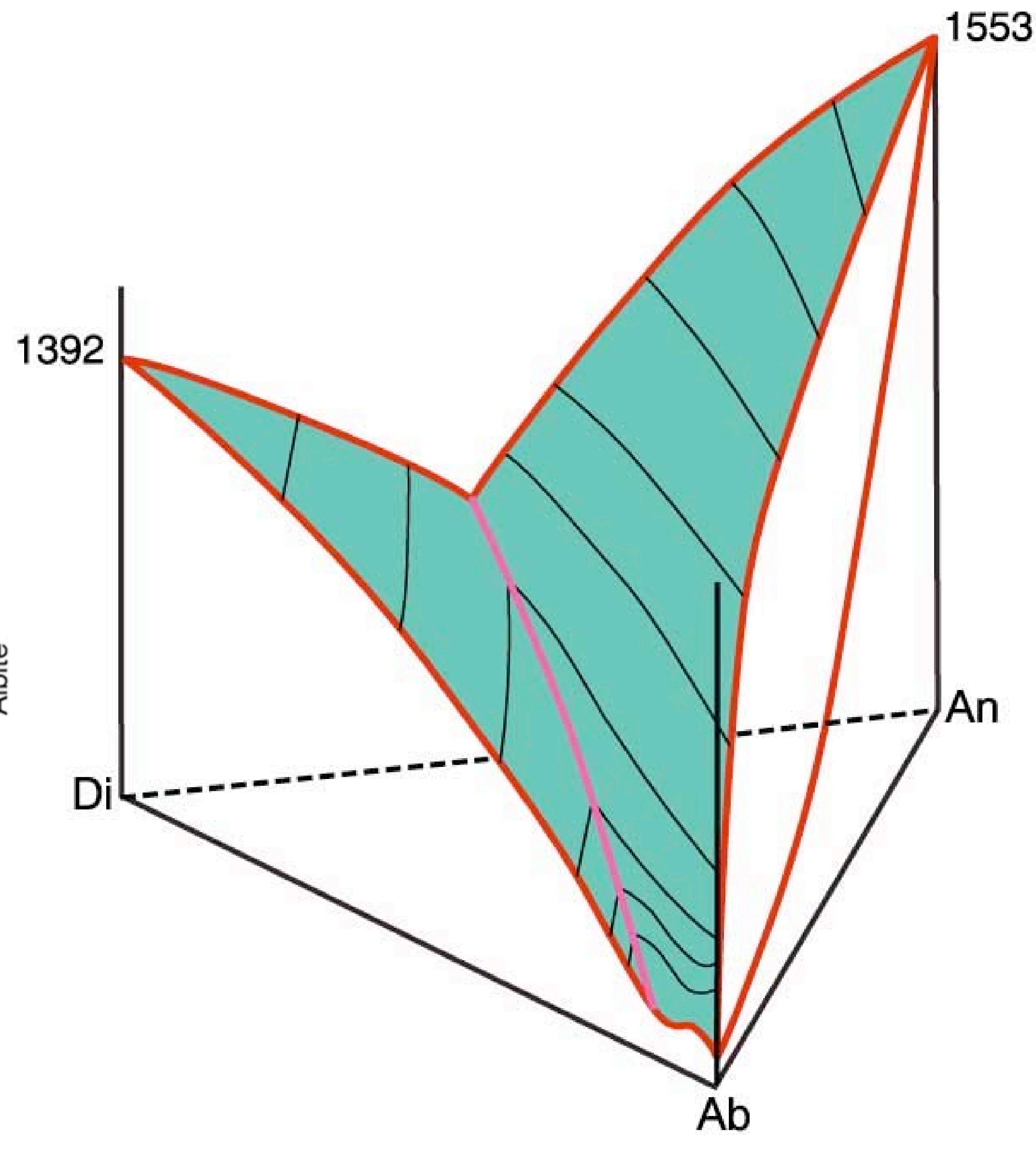




Isobaric diagram illustrating the liquidus temperatures in the system diopside-anorthite-albite at atmospheric pressure (0.1 MPa). After Morse (1994), Basalts and Phase Diagrams. Krieger Publishers.

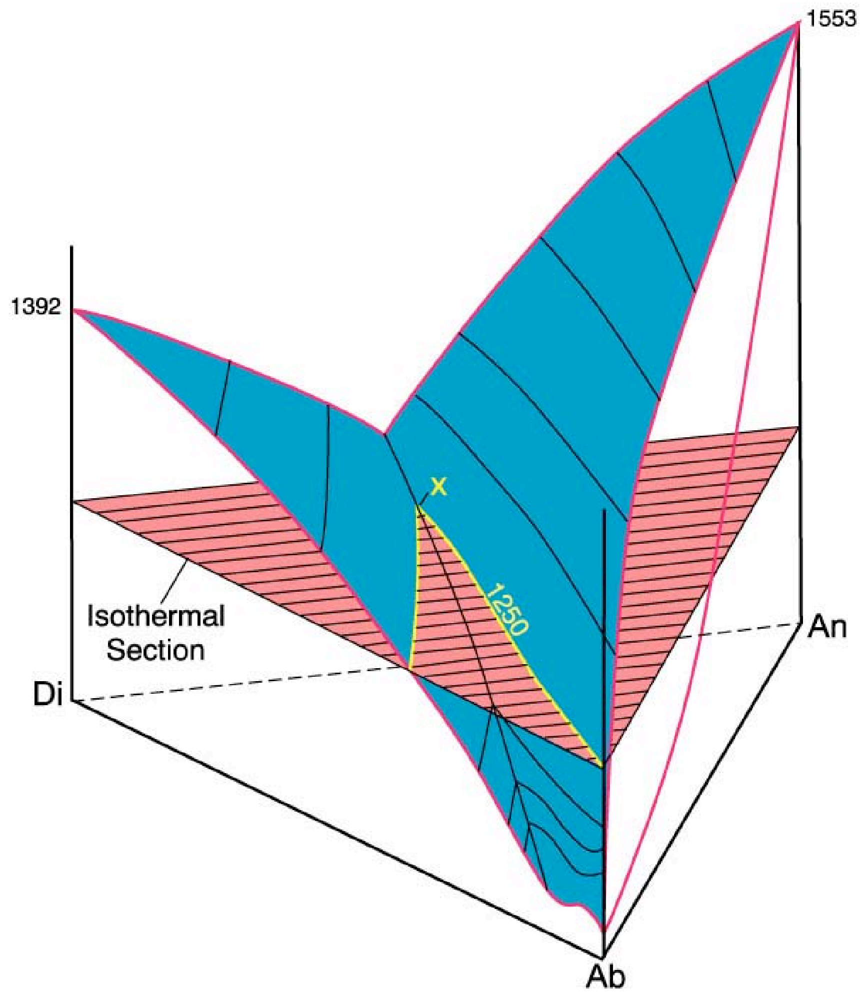


1553
Anorthite
(87)
80
70
60
50
1274
Diopside
1392
1350
1300
1250
1200
1150
1500
1450
1400
1350
1300
1250
1200
1085
1118
Albite



1553
1392
An
Di
Ab

Oblique View



Isothermal Section

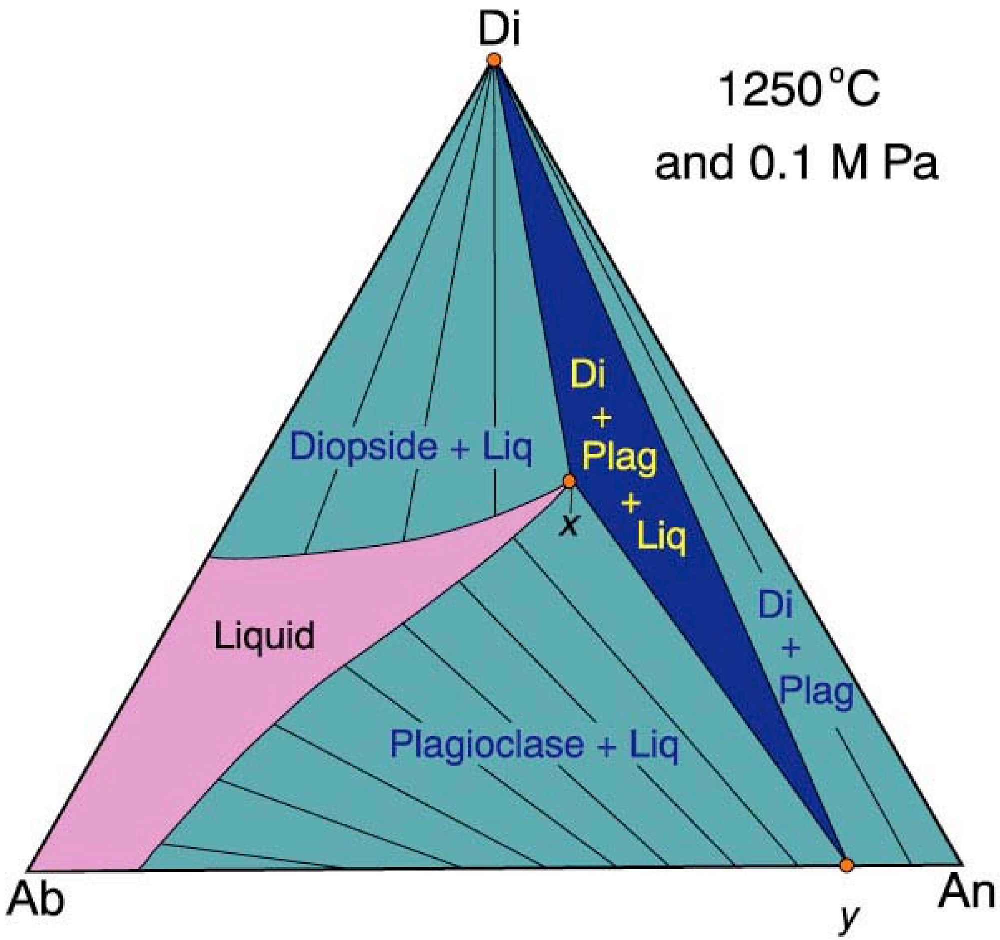
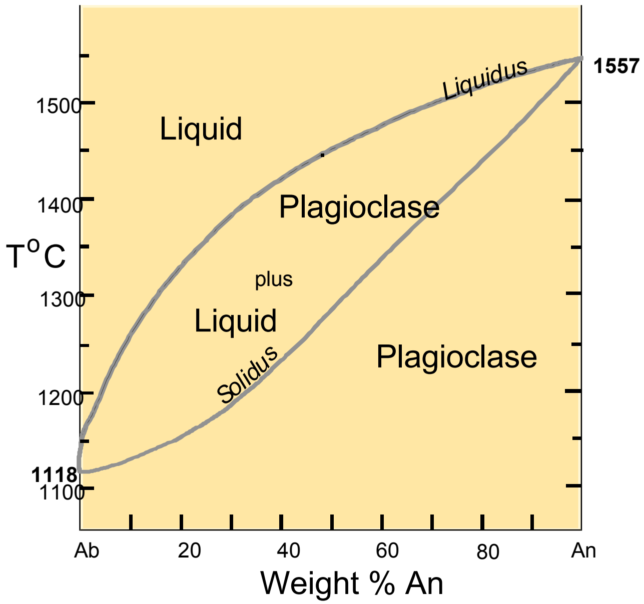
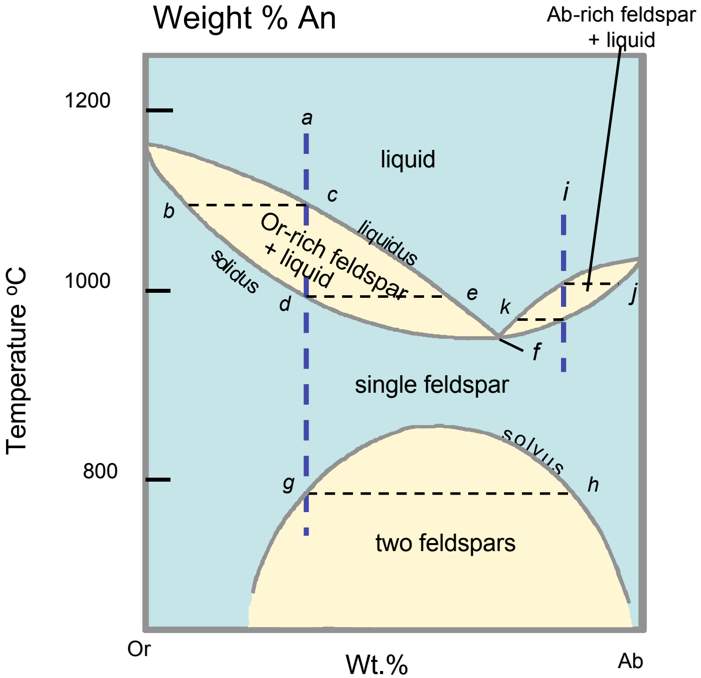


Figure 7-8. Oblique view illustrating an isothermal section through the diopside-albite-anorthite system. Figure 7-9. Isothermal section at 1250°C (and 0.1 MPa) in the system Di-An-Ab. Both from Morse (1994), Basalts and Phase Diagrams. Krieger Publishers.

Le ternaire des feldspaths





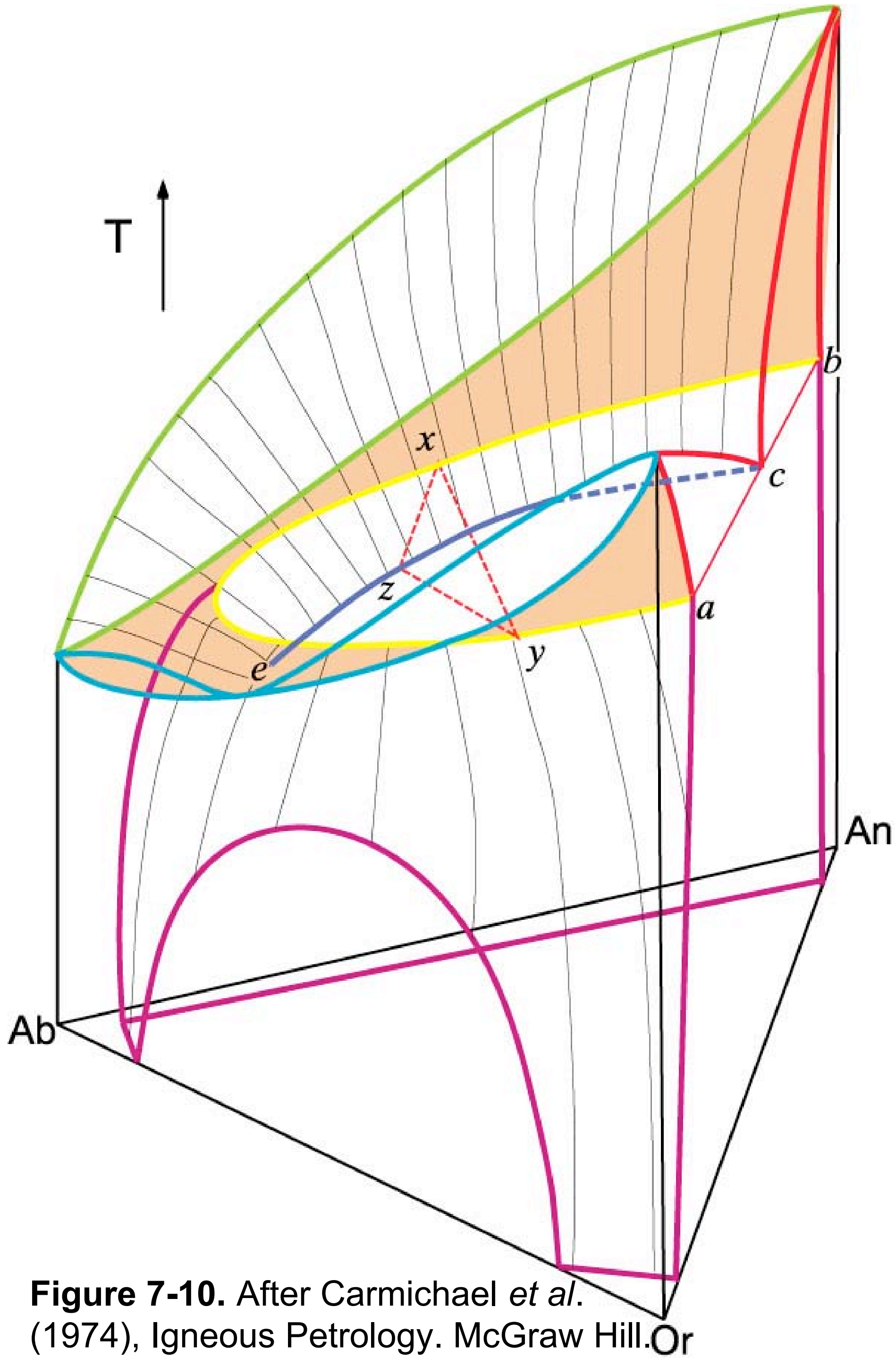
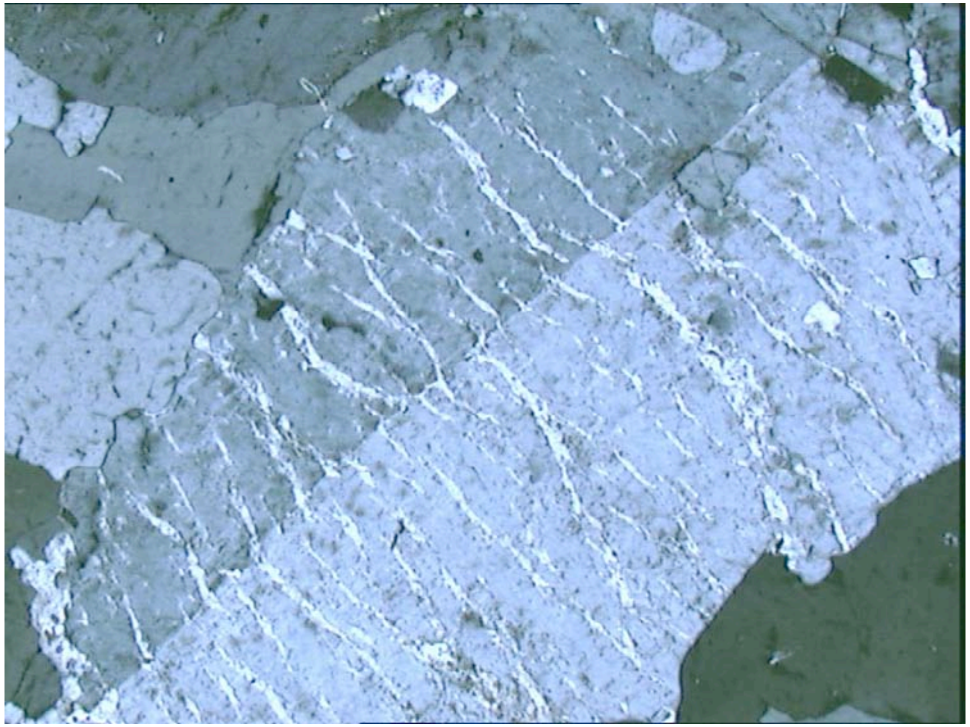
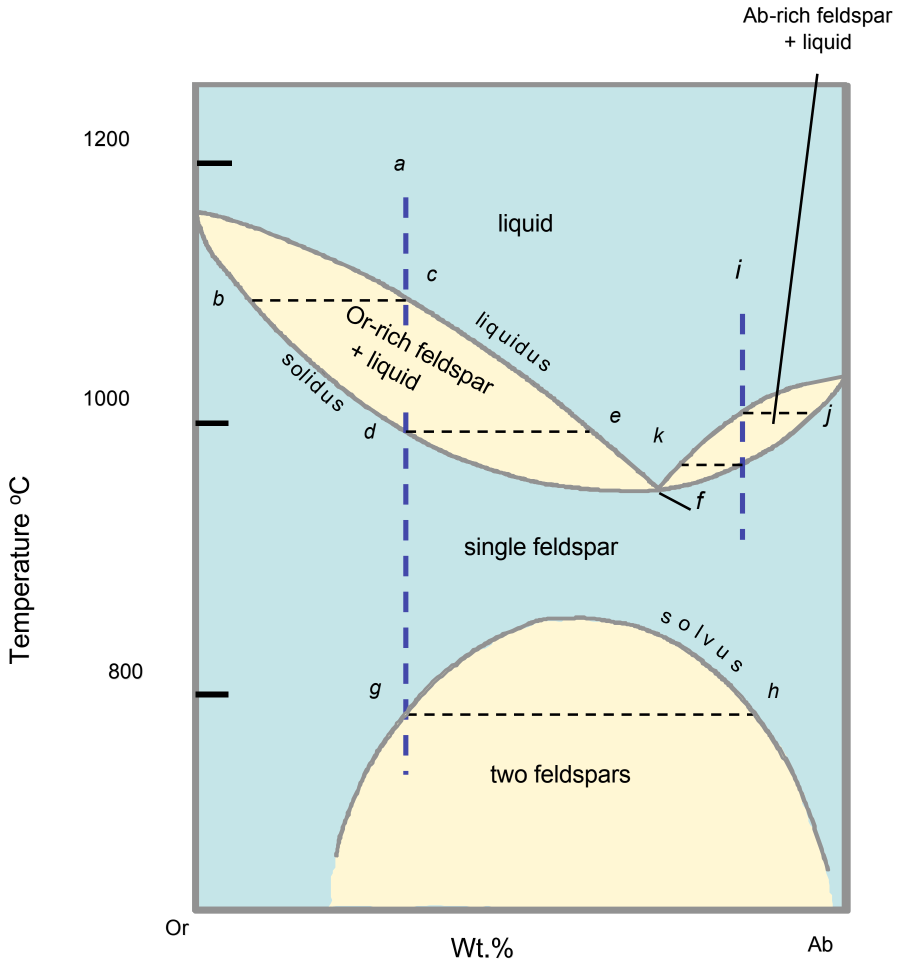
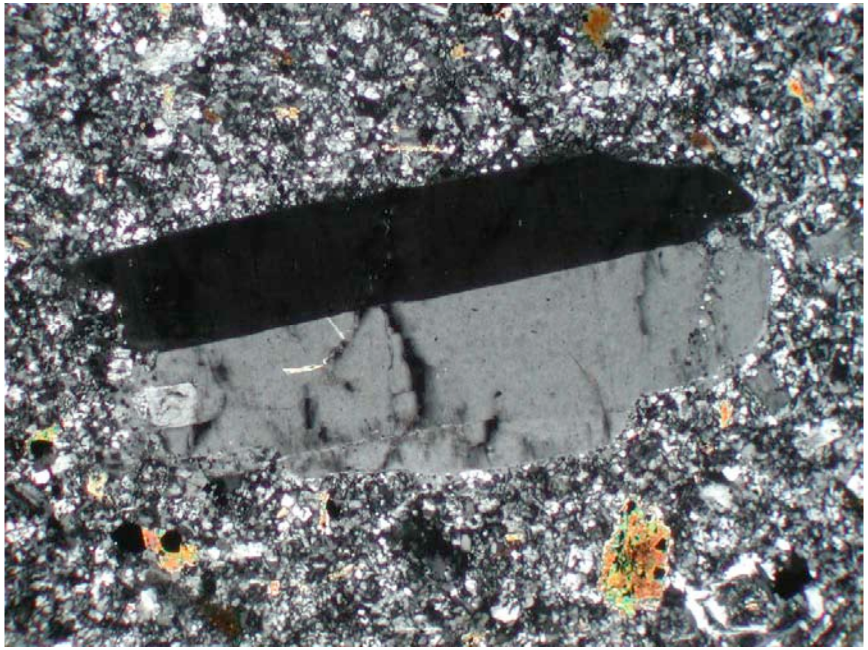


Figure 7-10. After Carmichael *et al.* (1974), Igneous Petrology. McGraw Hill.



Perthite





Sanidine

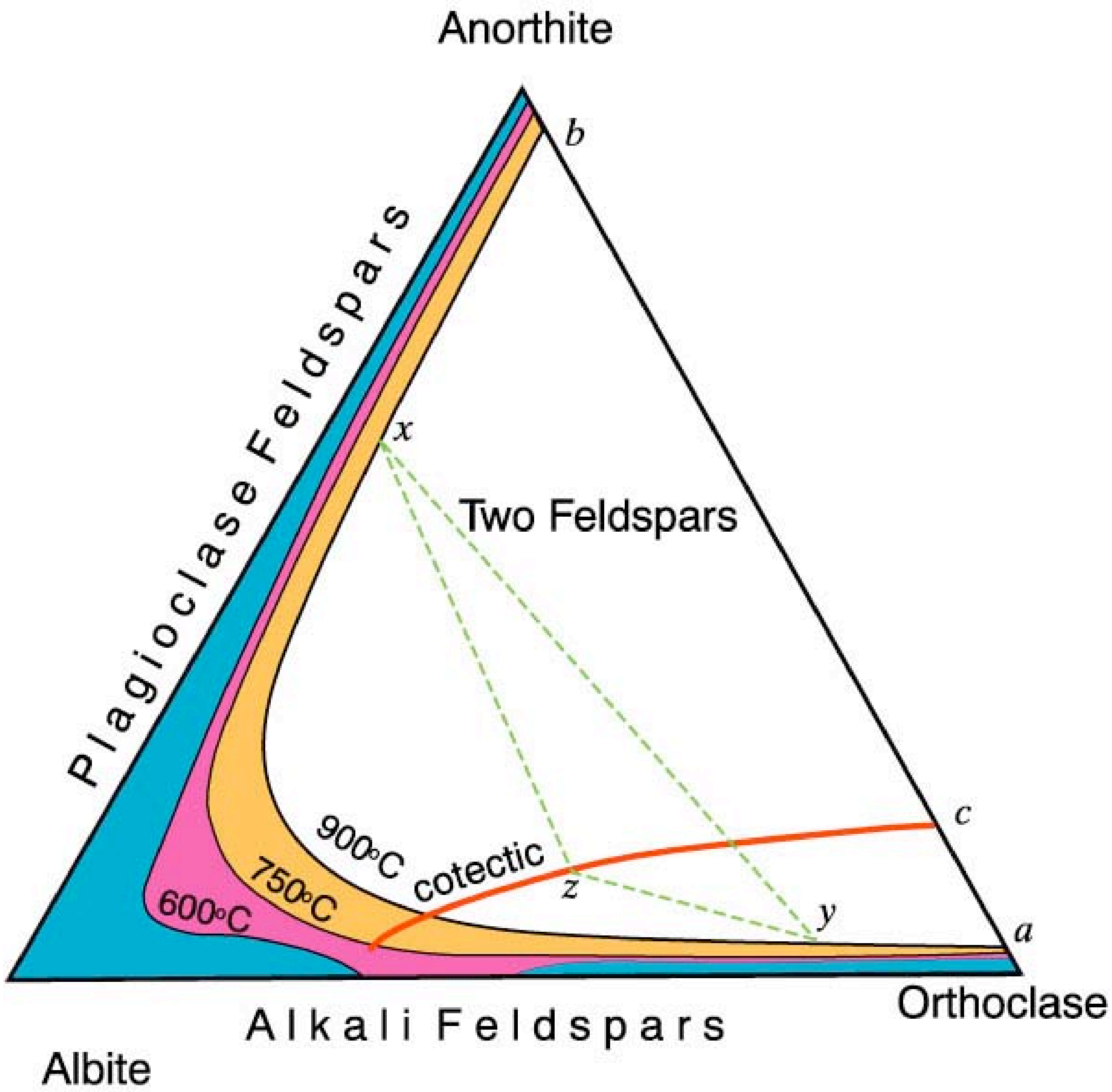
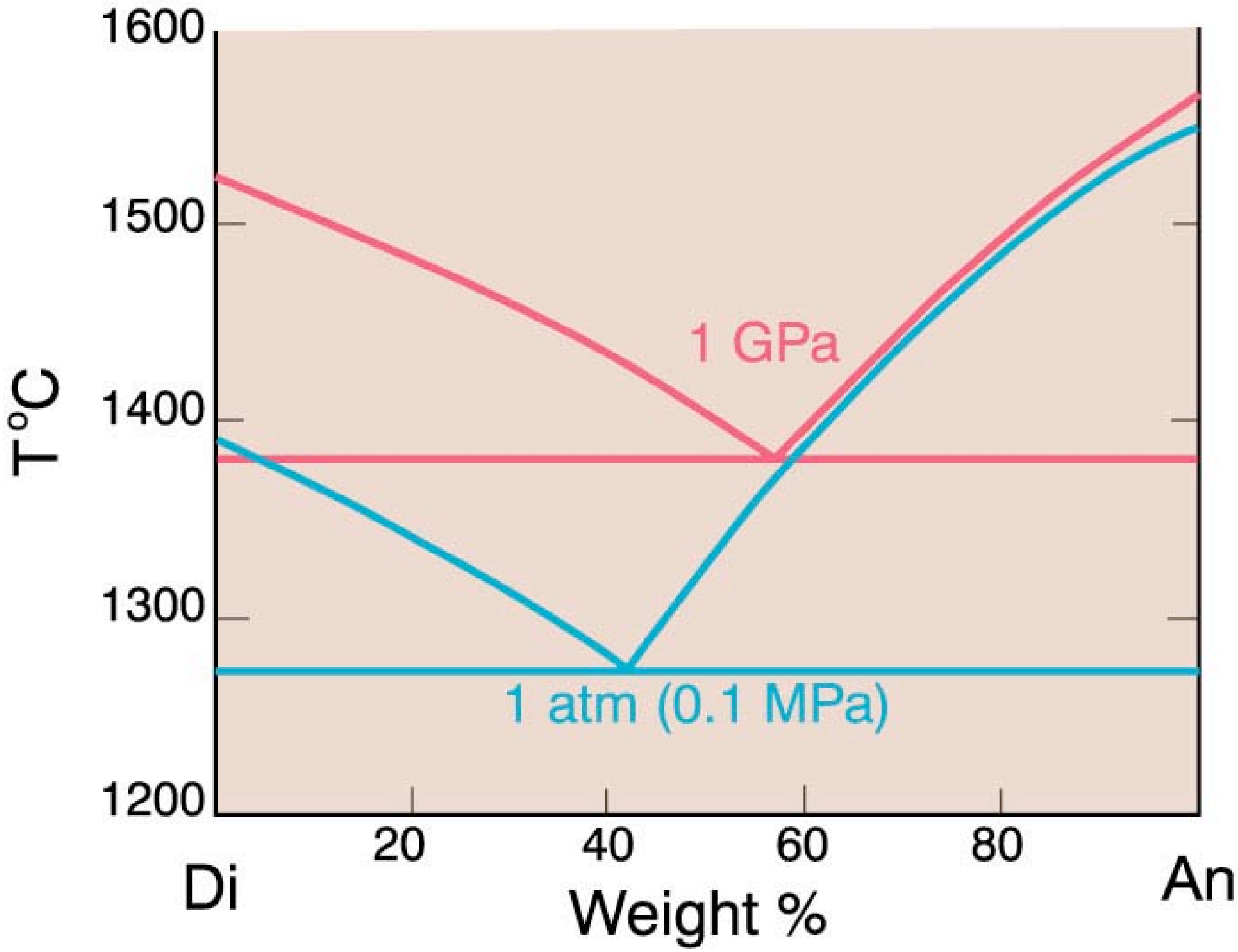


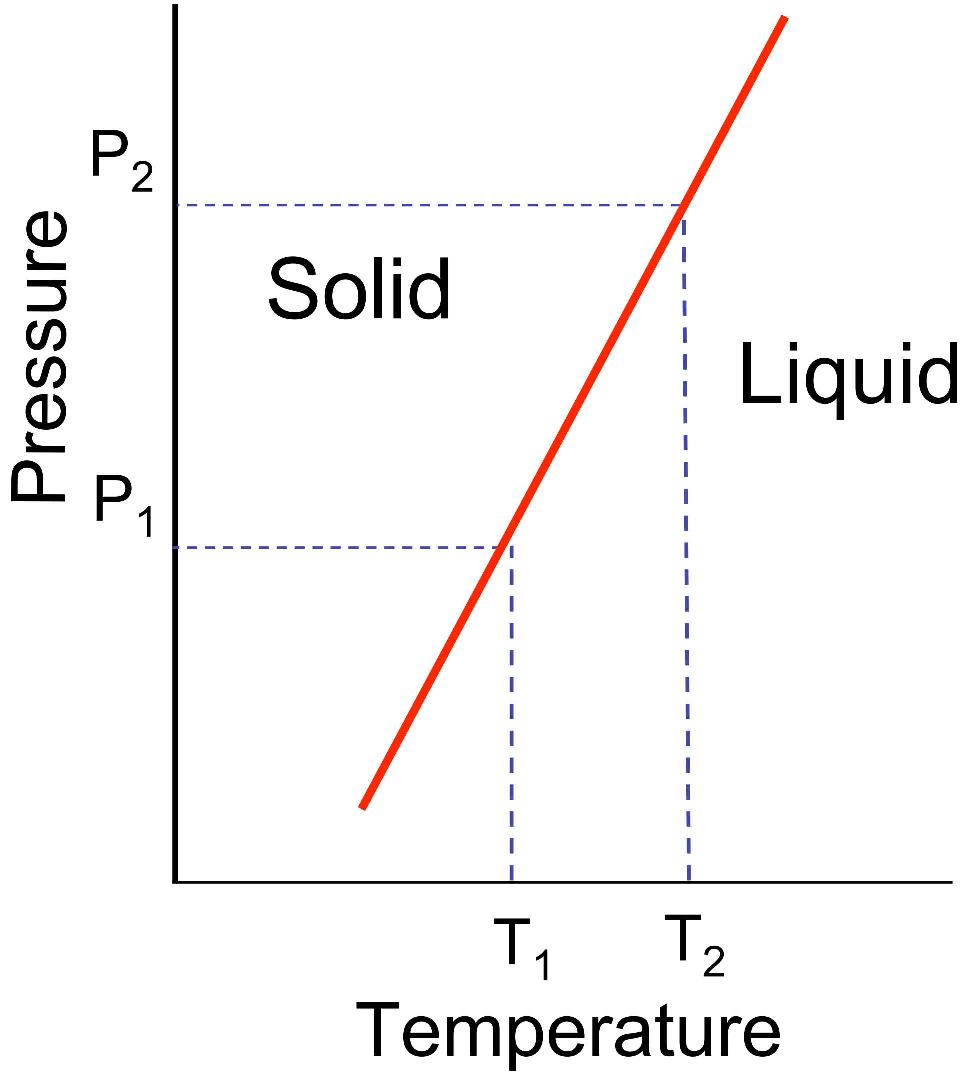
Figure 7-11. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

4-5 Effet de la pression



La pression s'oppose à la fusion

Figure 7-16. Effect of lithostatic pressure on the liquidus and eutectic composition in the diopside-anorthite system. 1 GPa data from Presnall *et al.* (1978). Contr. Min. Pet., 66, 203-220.



P2
P1
Pressure
Solid
Liquid
T1
T2
Temperature

4-6 Effet de l'eau

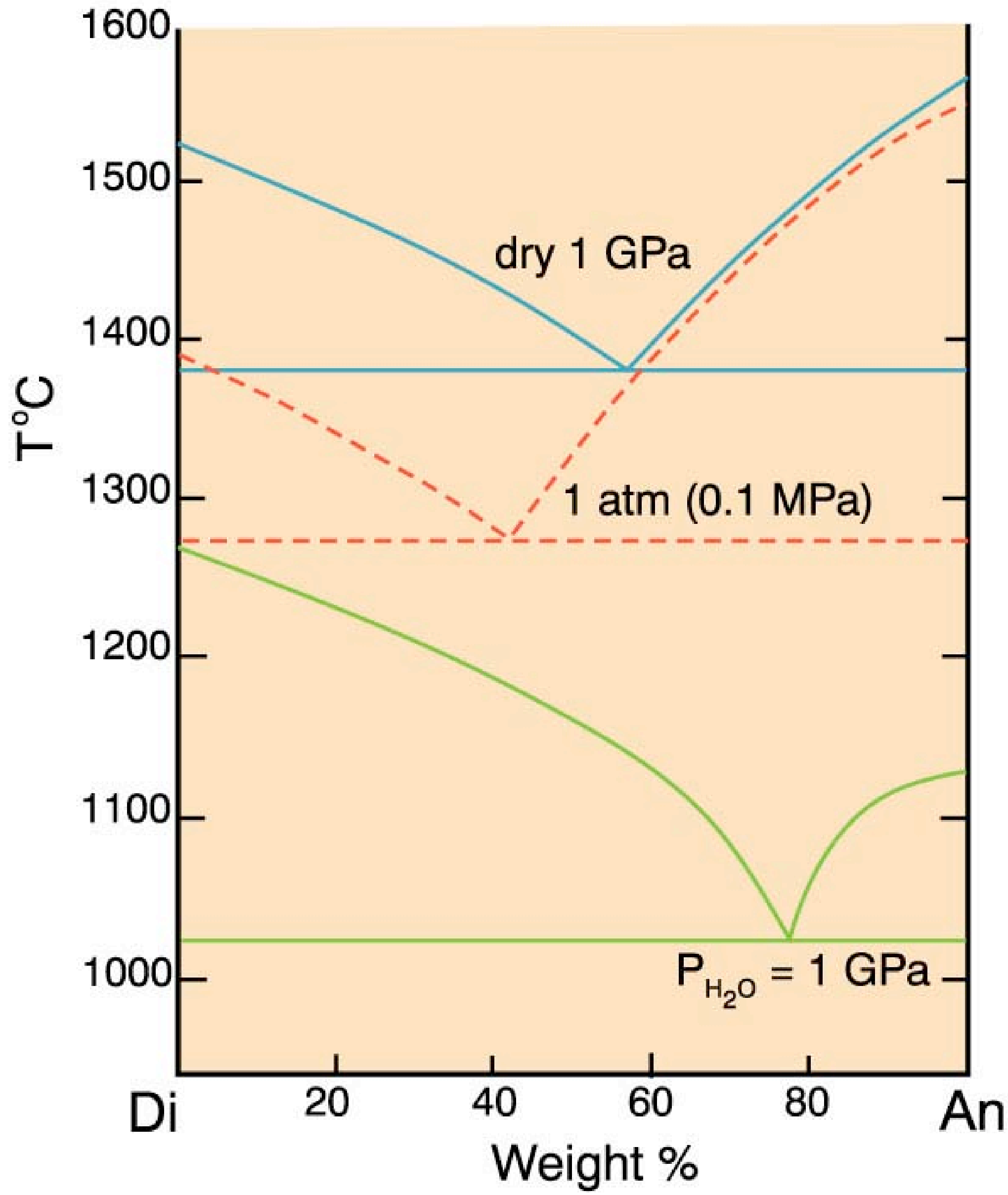


Figure 7-25. The effect of H_2O on the diopside-anorthite liquidus. Dry and 1 atm from Figure 7-16, $P_{H2O} = P_{total}$ curve for 1 GPa from Yoder (1965). CIW Yb 64.