Utiliser la capacité de mémoire en température et en pression du verre pour comprendre les événements géologiques : possibilités et limites

Dominique de Ligny

Universität Erlangen-Nürnberg, Lehrstuhl für Glas und Keramik, Erlangen, Germany

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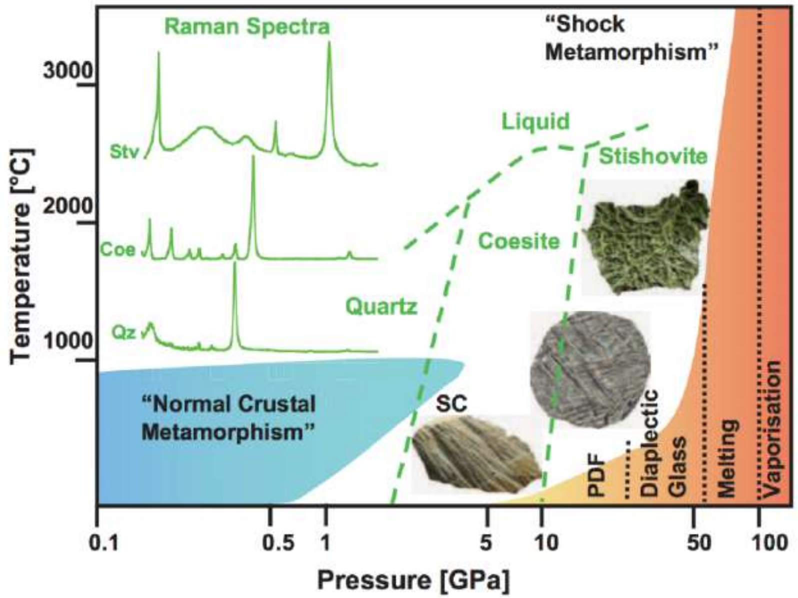
Géologie

- Science historique
- Recherche d'indices pour comprendre les conditions Pression, Température, durée, temps
- Méthodes à l'équilibre
  - Champs de stabilité thermodynamique
  - Equilibre redox
- Méthodes cinétiques
  - Gradient de diffusion
  - Vitesse de croissance
- **Verres ont une mémoire spécifique**



Cicconi & Neuville 2019: Natural glasses. Springer Handbook of Glasses

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Sommaire

- D‘où vient la mémoire du verre
- Comment peut on la lire
- Exemple venant de l‘industrie
  - Vitesse de refroidissement des fibres
  - Aérosol déposition
  - Larmes bataviques
- Tentatives dans la nature
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  - Fulgurites
  - Obsidiennes

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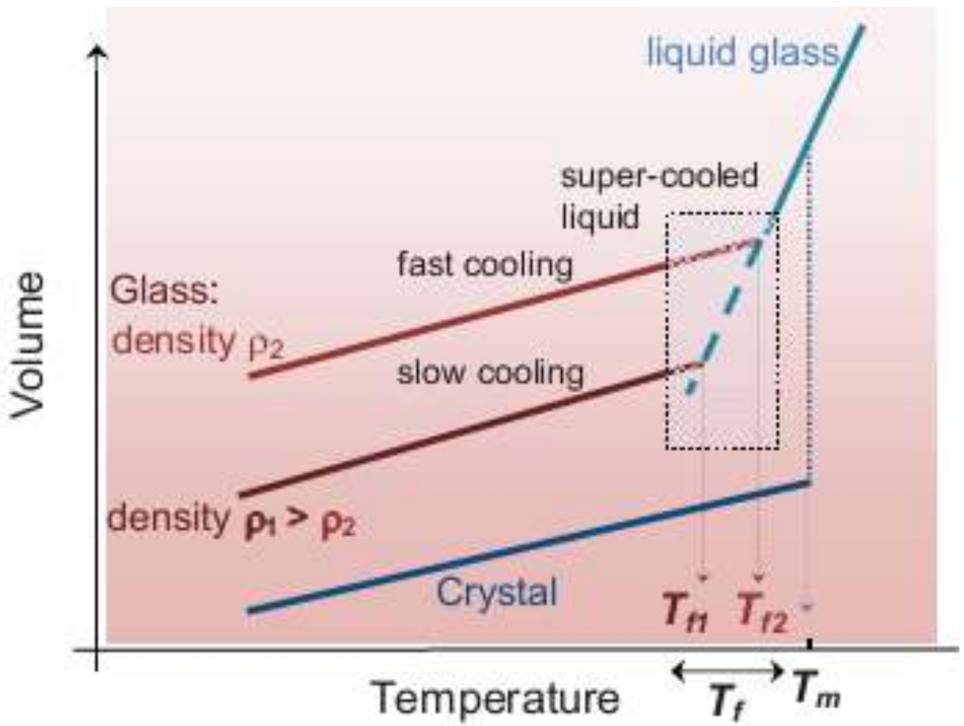
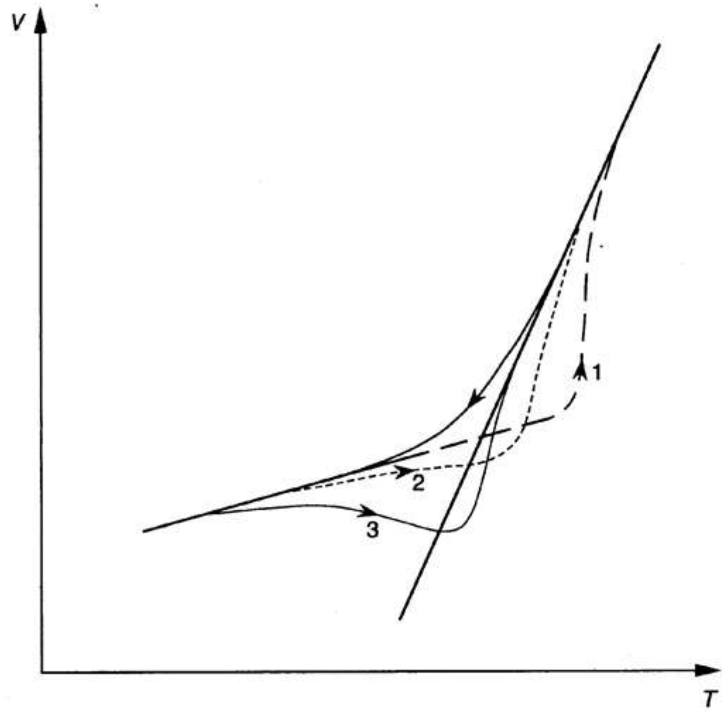
Effet de la température



Refroidissement à différentes vitesses



Chauffage à différentes vitesses

La vitesse de refroidissement dans la zone de transition vitreuse est enregistrée.
La température fictive représente la température de transition vitreuse pour une vitesse de refroidissement donnée.

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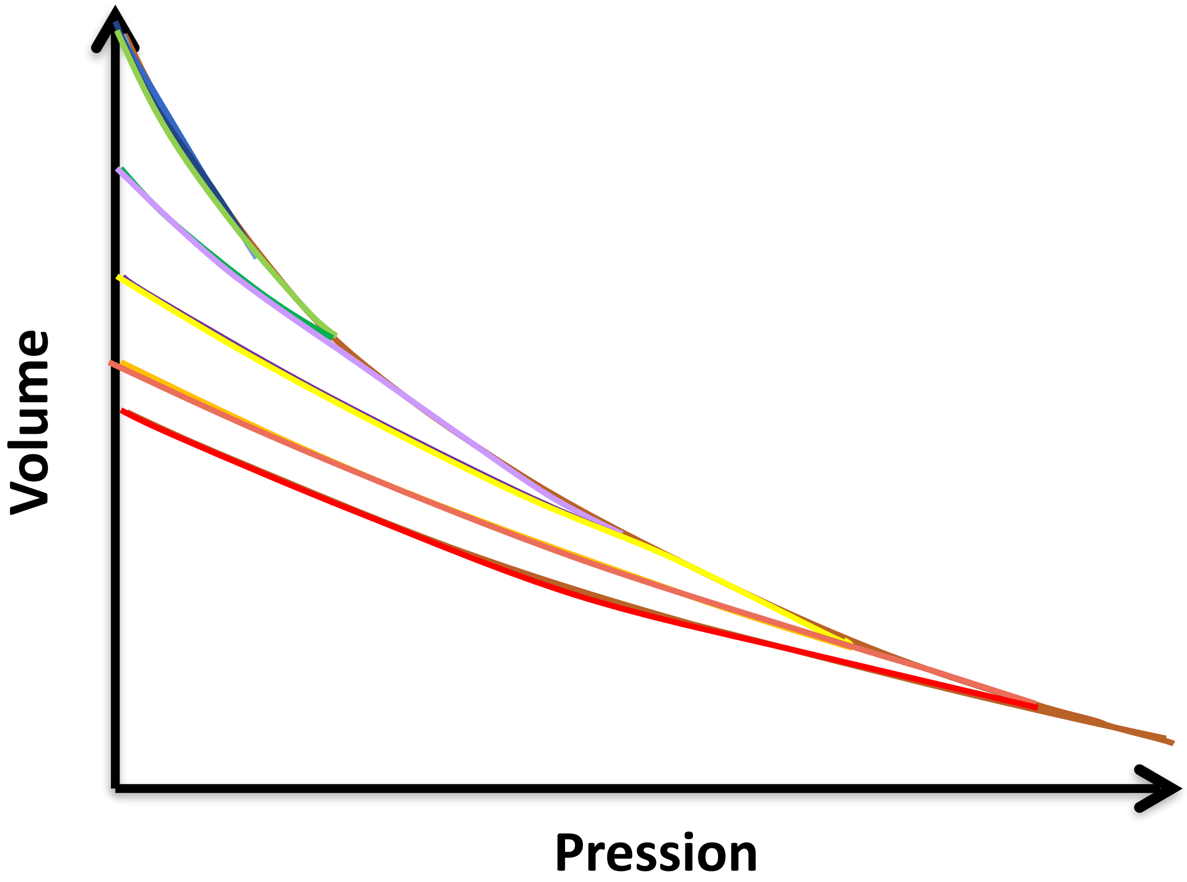
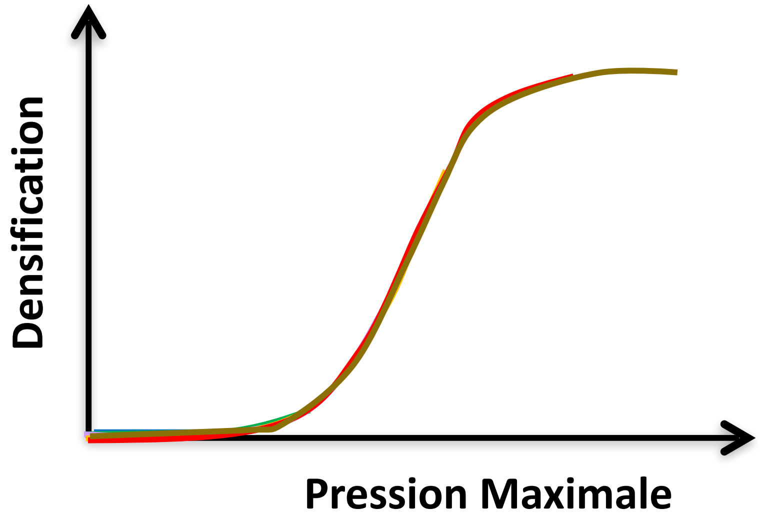
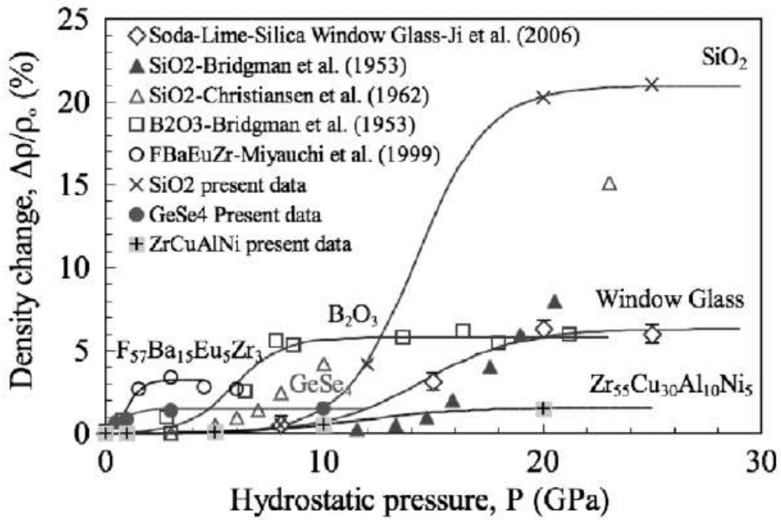
Effet de la pression







La pression maximale est enregistrée

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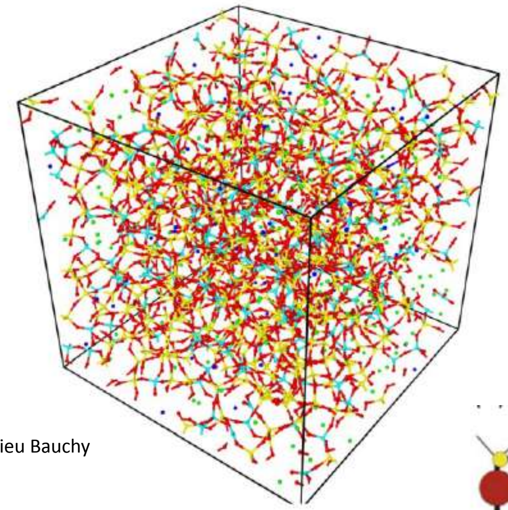
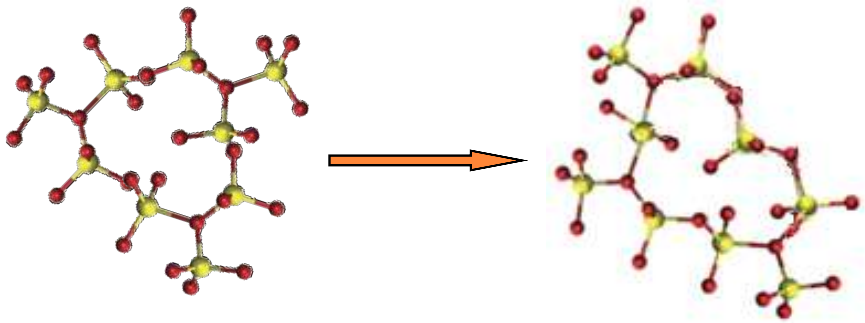
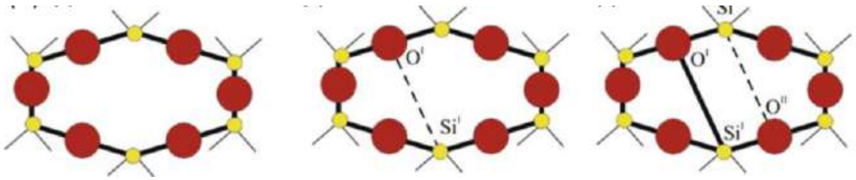
Modifications atomiques liées aux changements de volume



Mathieu Bauchy

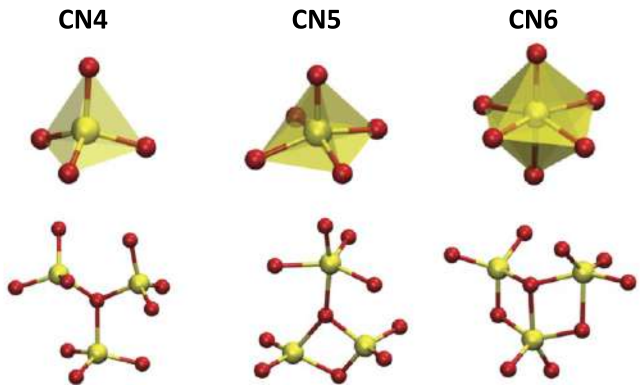


Changement d'angle entre tétraèdres



Zeidler et al. 2014 PRL 113, 135501

Changement des tailles d’anneaux



Misawa et al. Science Advances 2017

Modification de la coordination de l'oxygène des éléments formant le réseau Si, B, Al

provoque également une modification de l'angle et de la taille des anneaux.

T_f	P_{max}
Si-O-Si	
+	-
petit/gros	
+/+	+/-
CN	
-	+

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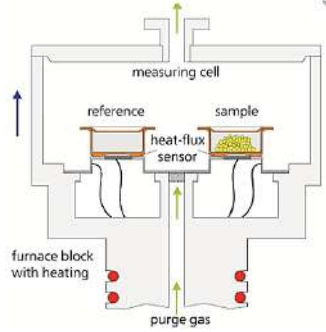
Lire la mémoire du verre

Différents instruments

Methode	Taille observée	Forme	Calibration
DSC Calorimétrie	mm	Poudre	pas
Volume	mm	Régulière	pas
Indice de réfraction	100 µm	Régulière	Coef. photoélastique
Densité	cm	Complexe	pas
Raman	1 µm	Complexe	Spécifique
Brillouin	1 µm	Complexe	Spécifique
Luminescence	1 µm	Complexe	Spécifique



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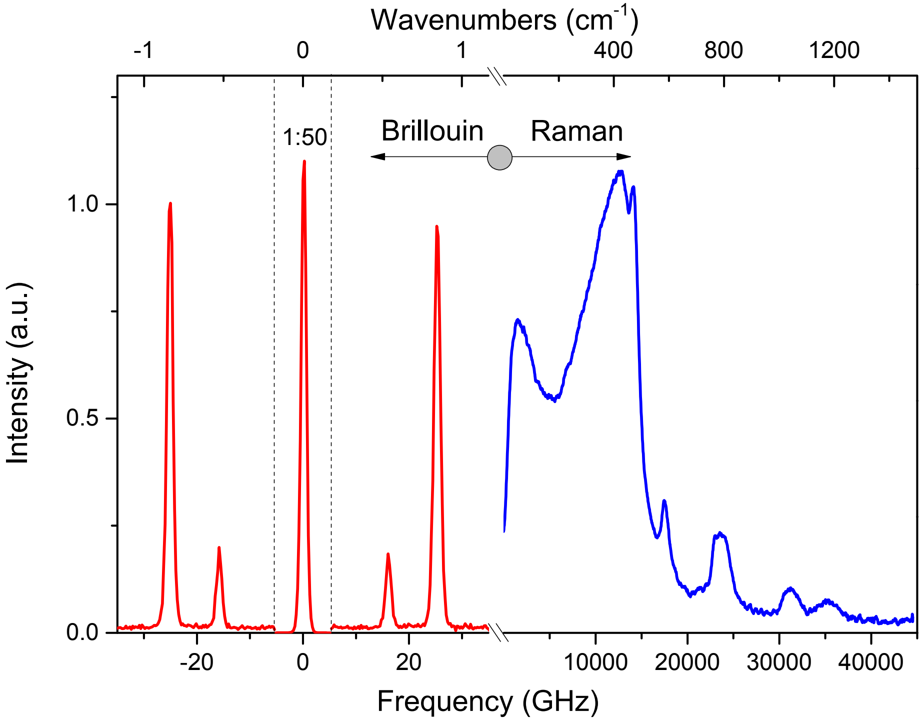
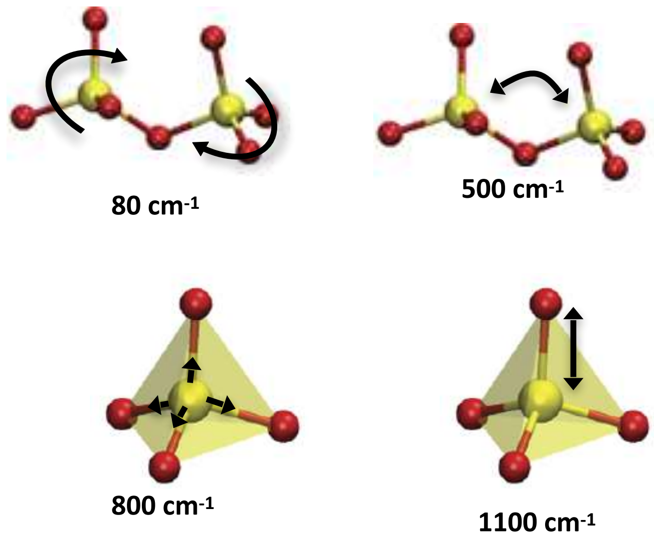
Spectroscopie vibrationelle



Raman analysis



interpretation du Brillouin

Vitesse du son

$$c = \frac{\lambda}{\sqrt{2}n} f^{90}$$

λ – longueur d'onde du laser
n – indice de réfraction
f^{90} – fréquence

module de cisaillement

$$G = \rho c_t^2$$

module d'imcompressibilité

$$K = \rho c_l^2 - \frac{4}{3}\mu$$

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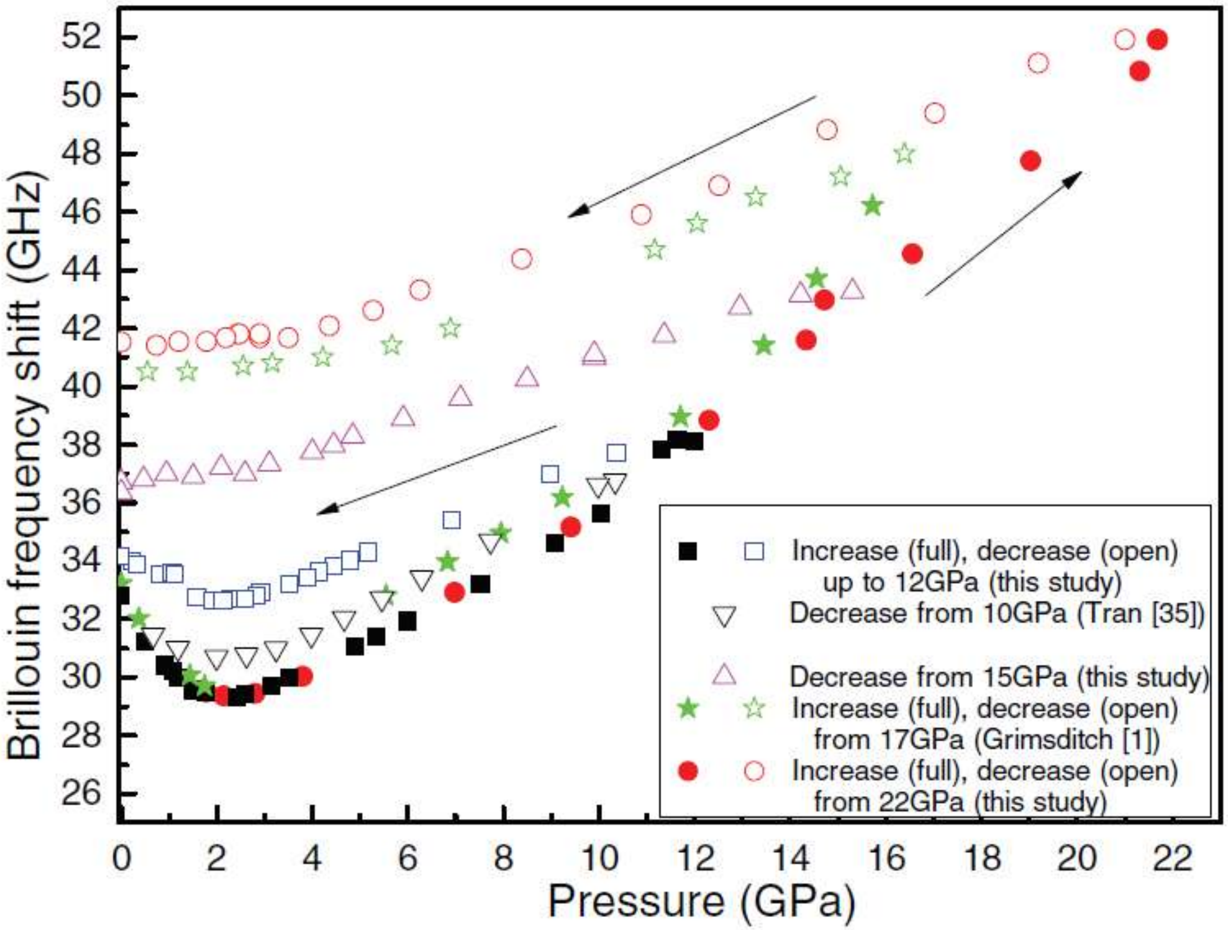
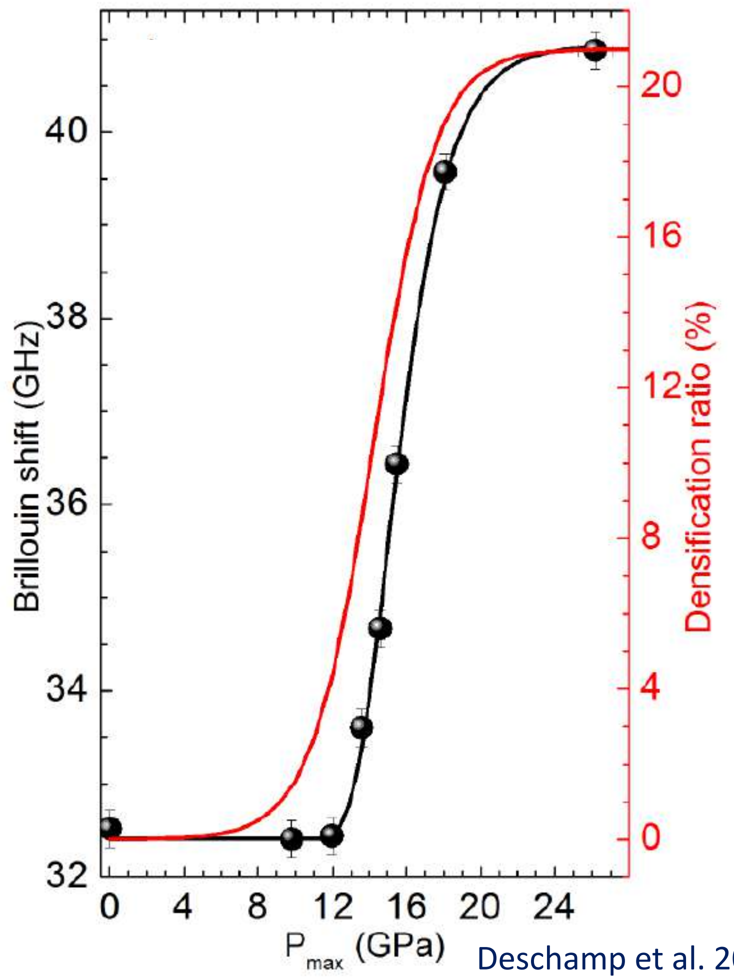
Spectroscopie Brillouin





Deschamp et al. 2014

Le signal Brillouin montre une évolution progressive avec une pression maximale. Pas tout à fait proportionnel à la compression.

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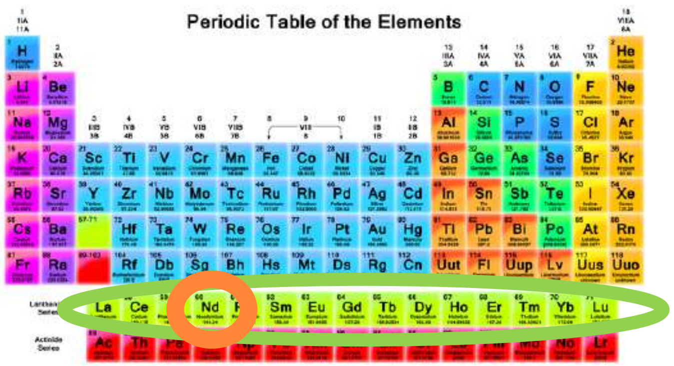
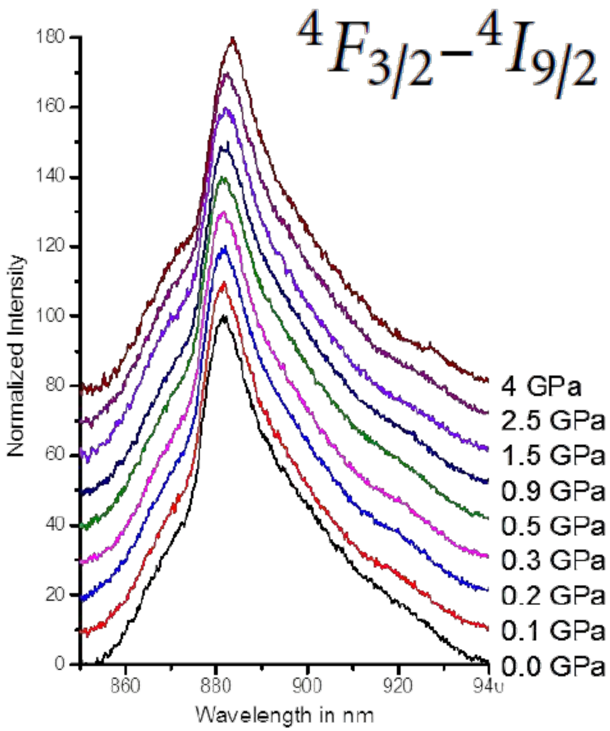
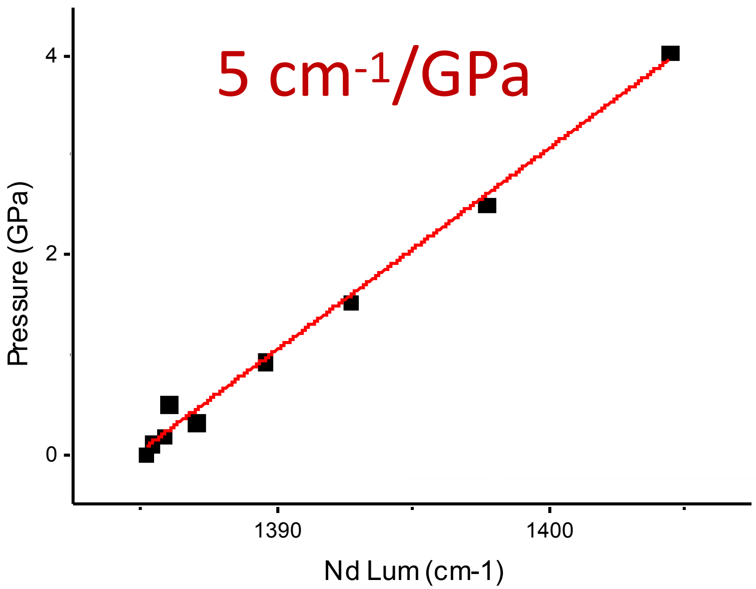
Luminescence des Terres Rares







La luminescence est proportionnelle à la densité, soit par compression, soit par contrainte résiduelle.

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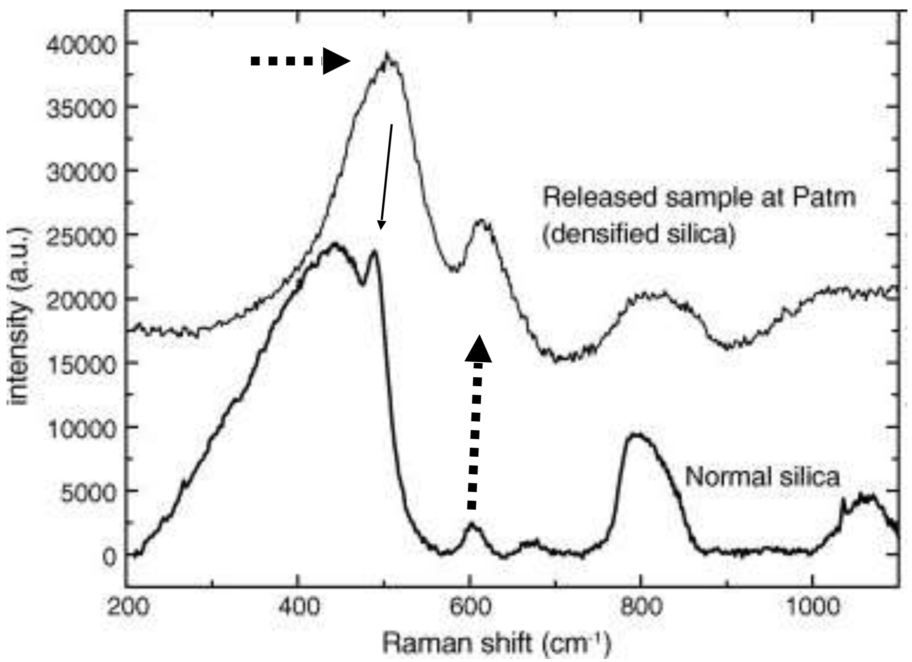
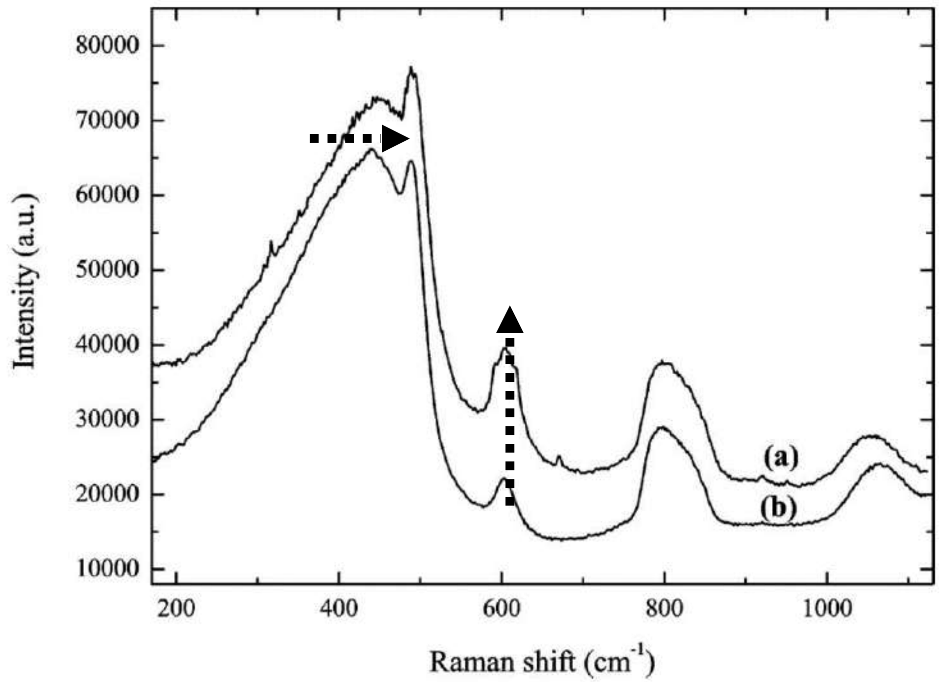
Verre SiO_2 , que peut on espérer voir?

Haute Pression



Haute Température



Pression et Trempes rapides induisent une densification
D1 très distincte si Trempe rapide

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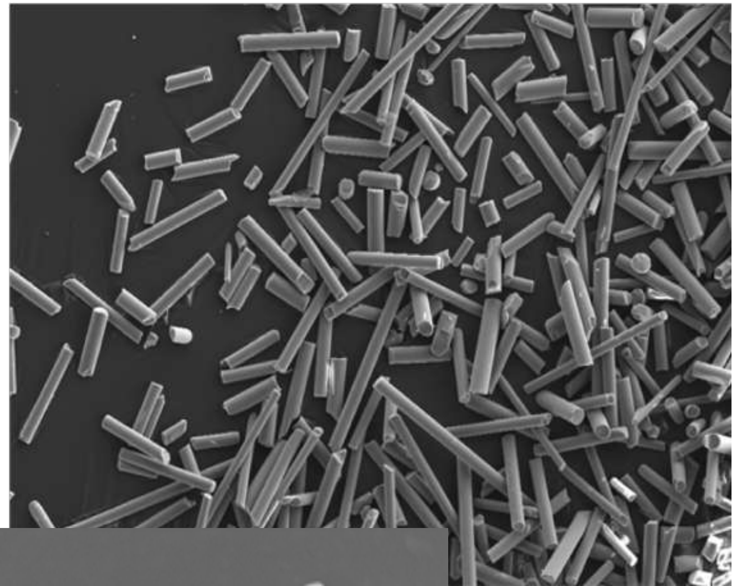
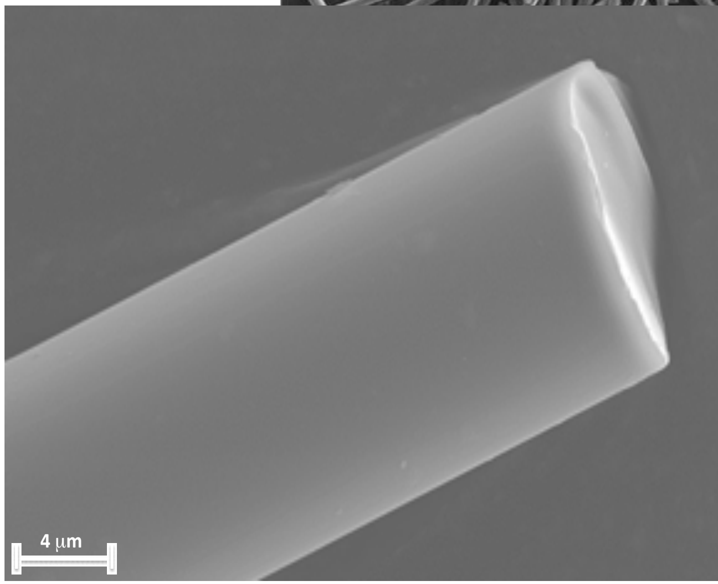
Vitesse de refroidissement des fibres

ISG International Standard Glass
60.2 SiO_2 -16.0 B_2O_3 -12.6 Na_2O -3.8 Al_2O_3 - 5.7 CaO -1.7 ZrO_2





Analogie entre l'auto-irradiation et la température fictive élevée

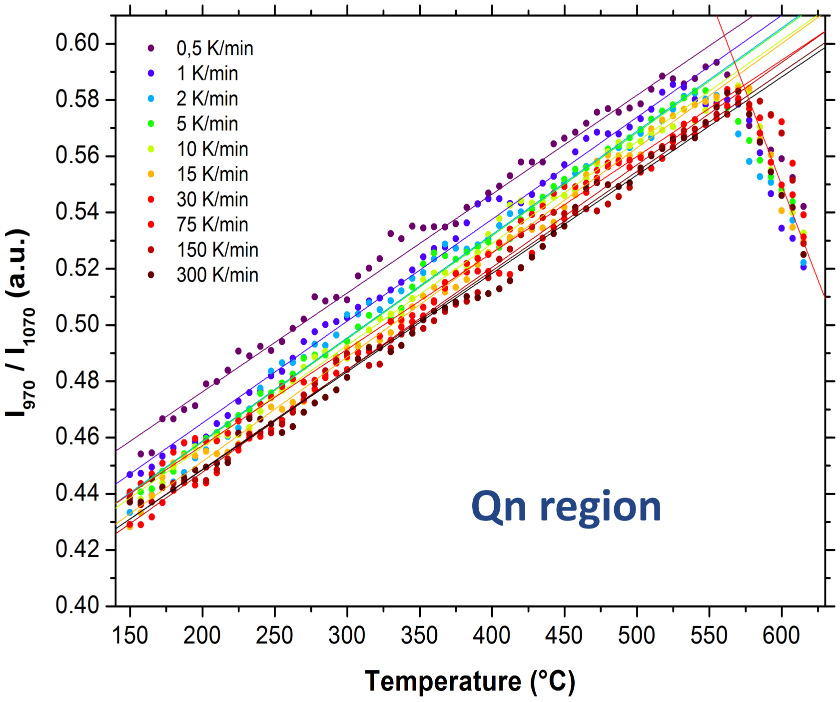
Grands échantillons irradiés difficiles à produire

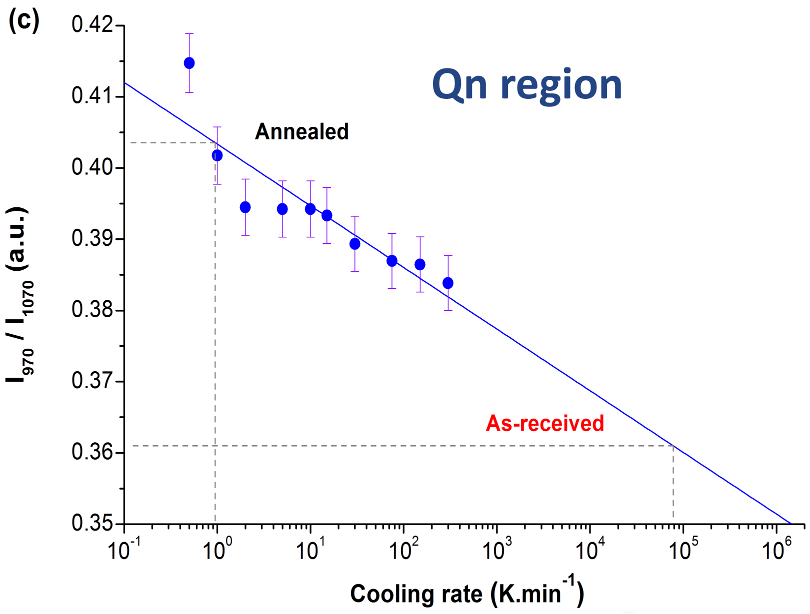
Les fibres sont un bon moyen d'obtenir des échantillons hypertrempés.

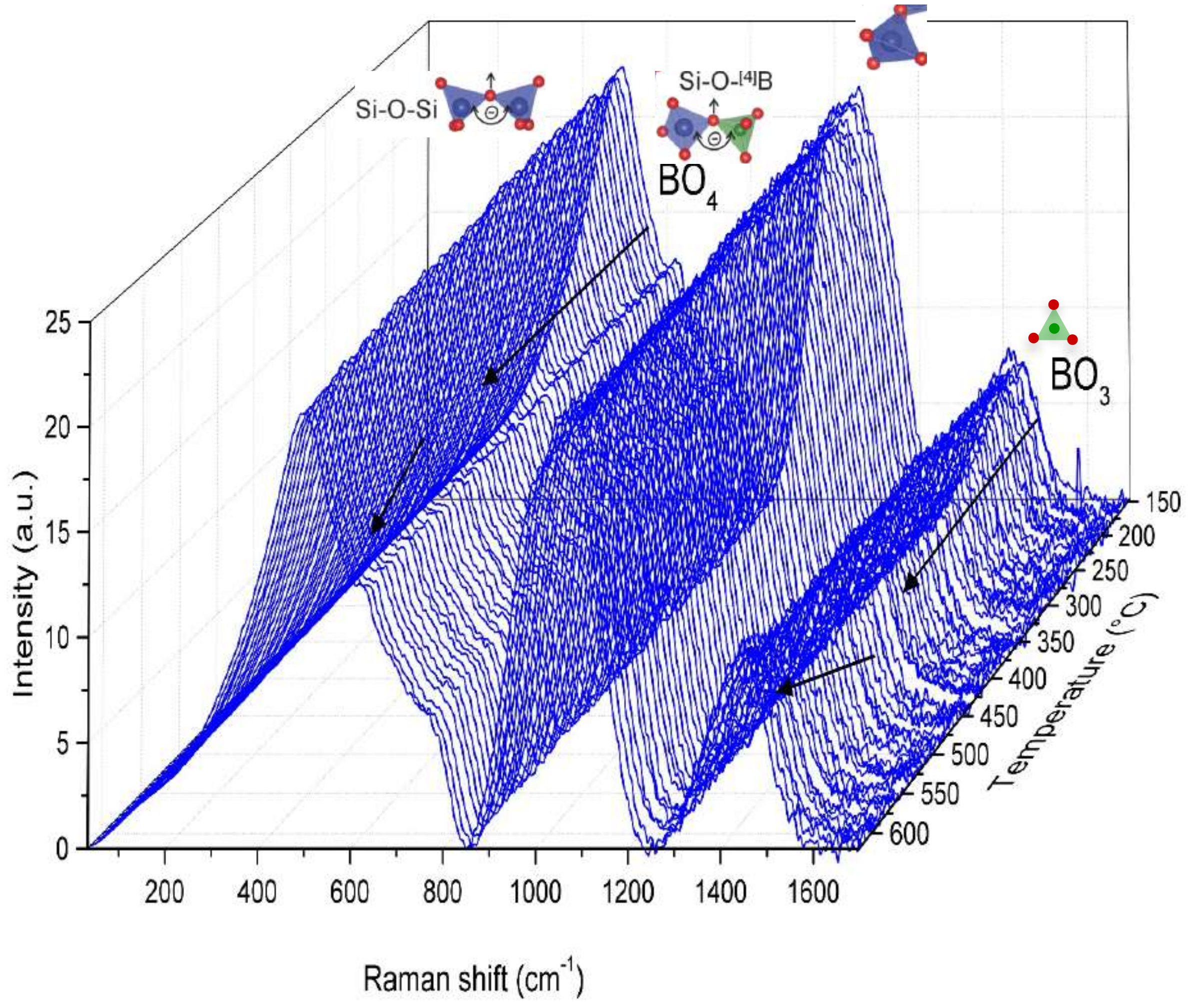
Quel est le taux de refroidissement ou la température fictive de la fibre ?

Ici, il est difficile d'effectuer une mesure DSC directe

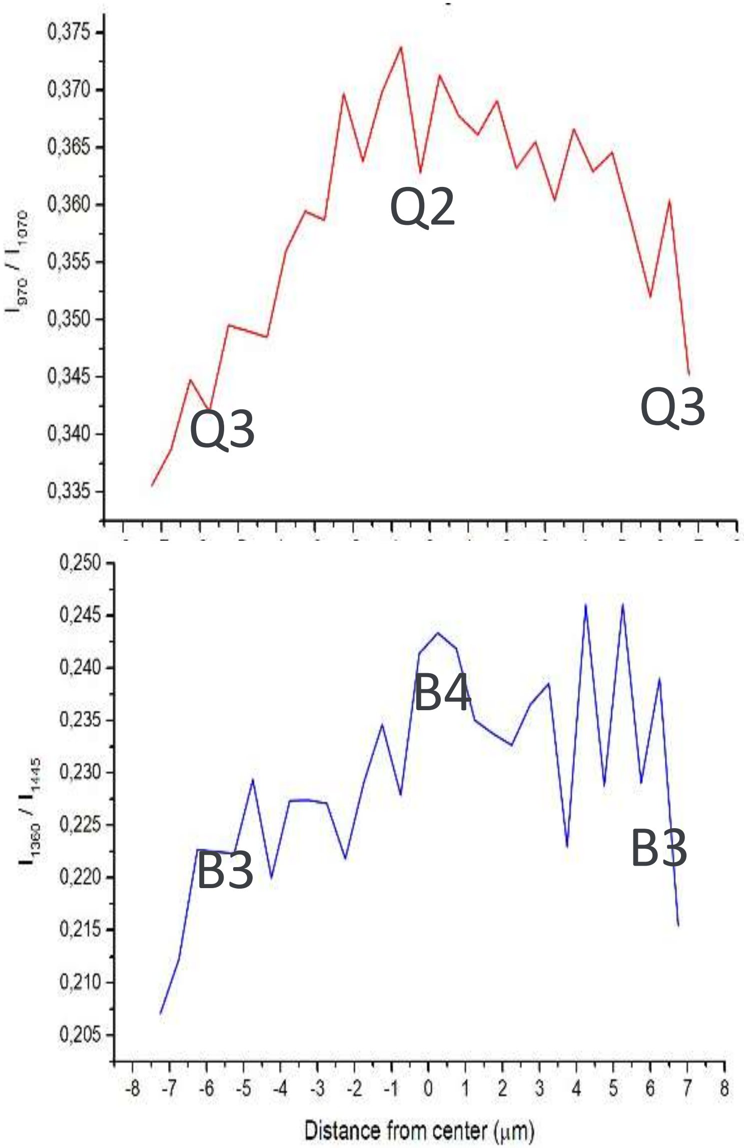
Vitesse de refroidissement des fibres

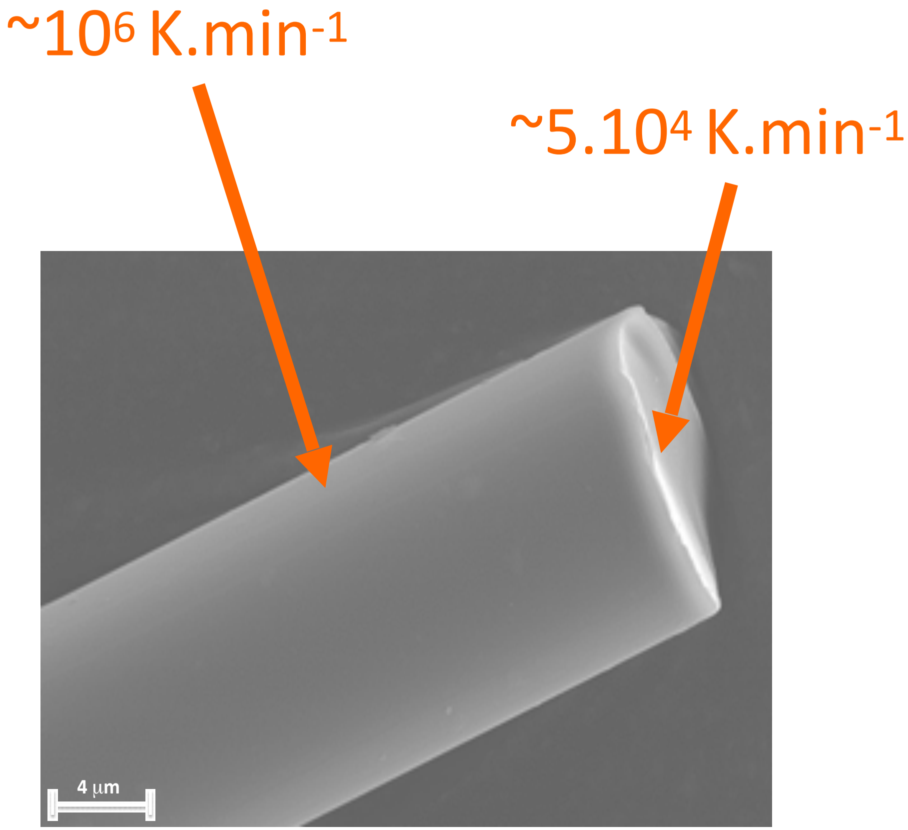






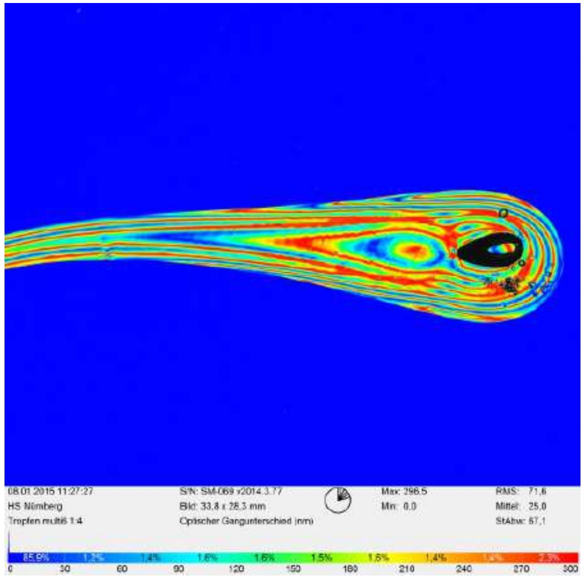
Vitesse de refroidissement des fibres

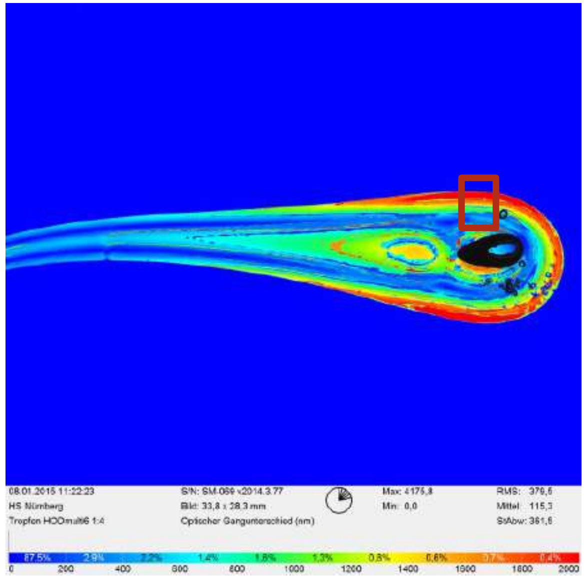




Larmes bataviques

Mystery of Prince Rupert's Drop at 130,000 fps - Smarter Every Day 86
YouTube





Forme complexe
Approximation à un cylindre avec un coefficient photoélastique de 2.7 TPa^{-1}
500 Mpa pour les 2-3mm

Accroissement de densité de 3,7% pendant la relaxation

$$K = \rho \frac{\mathrm{d}P}{\mathrm{d}\rho}$$

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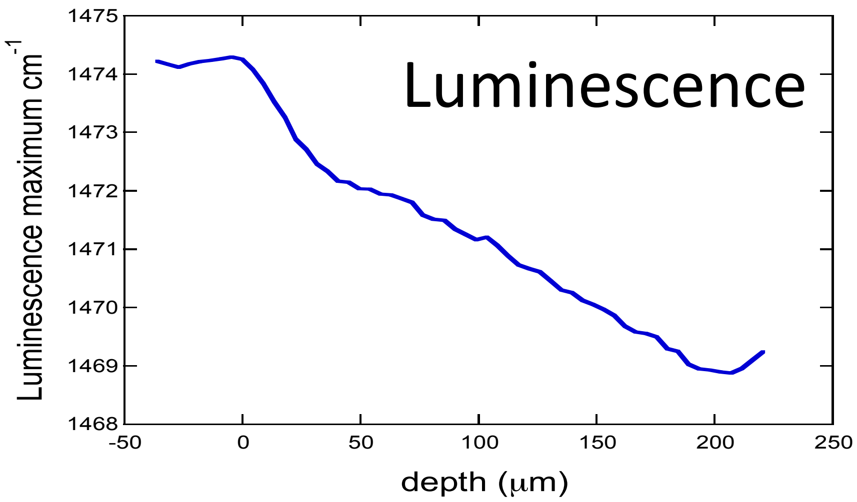
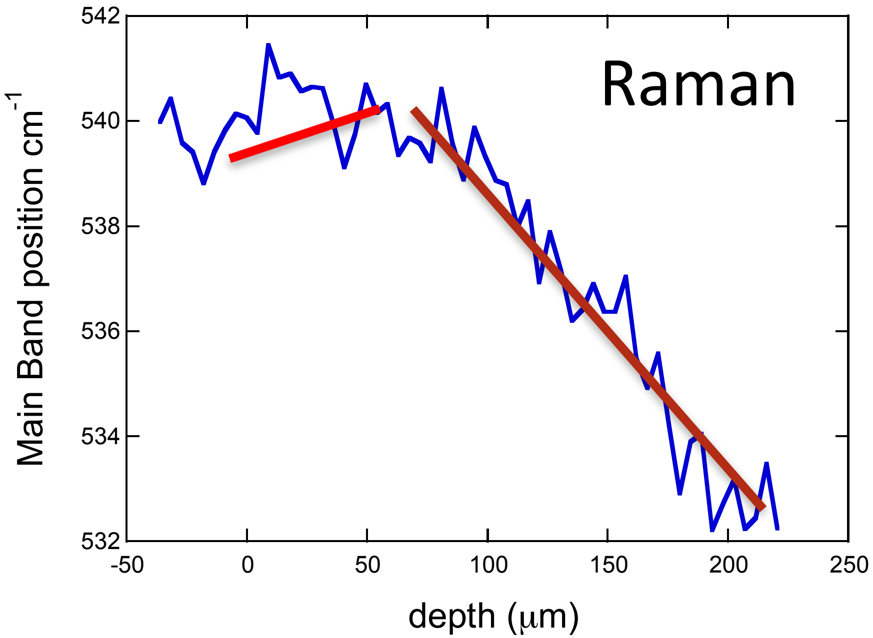
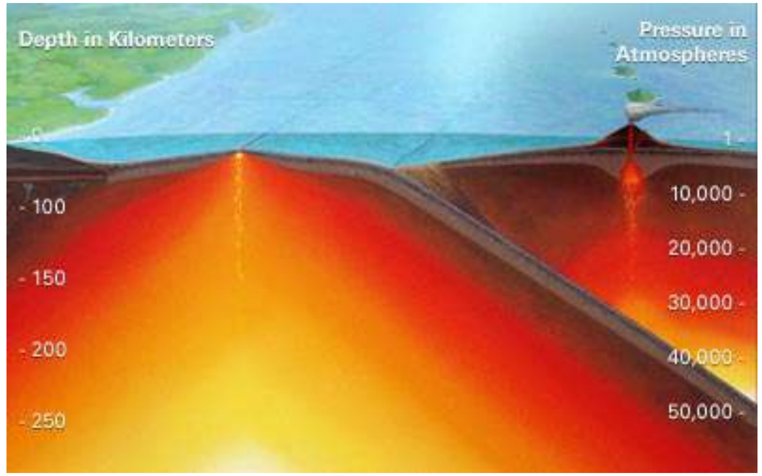
Avec K=40 Gpa alors ΔP= 1,5 GPa

Larmes bataviques







Variation de 1GPa entre la surface et 200 μm en profondeur

En surface un effet aussi lié à la vitesse de refroidissement

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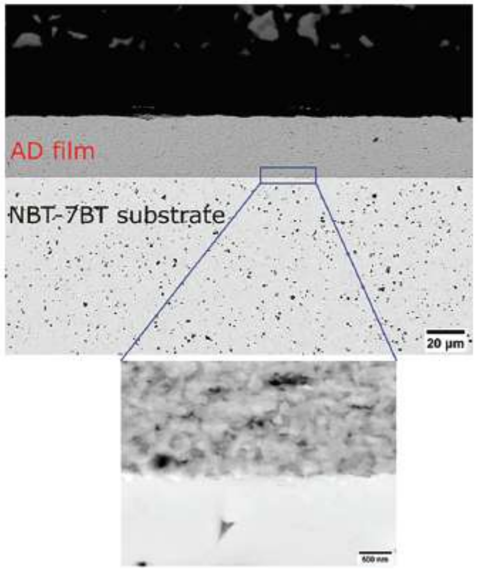
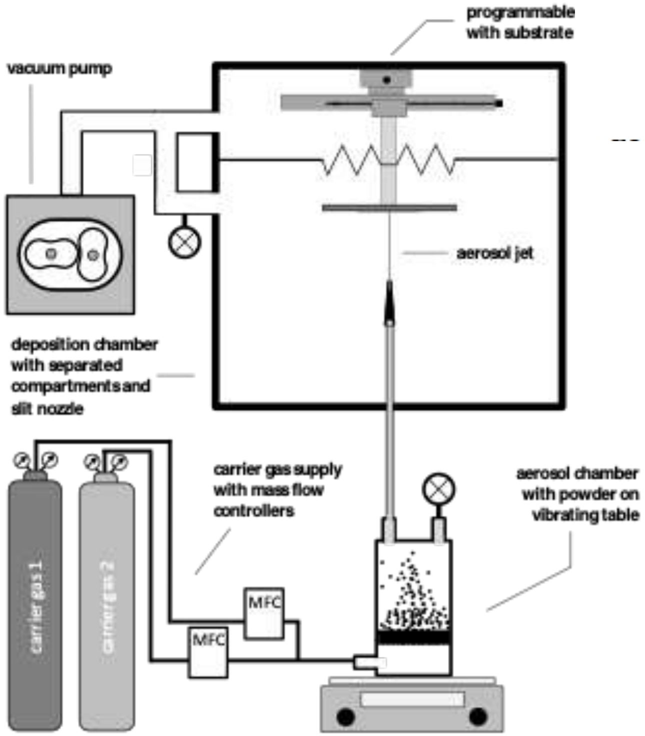
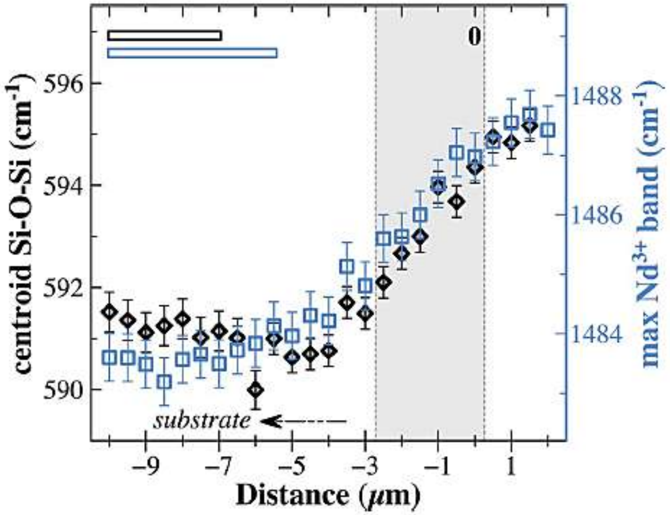
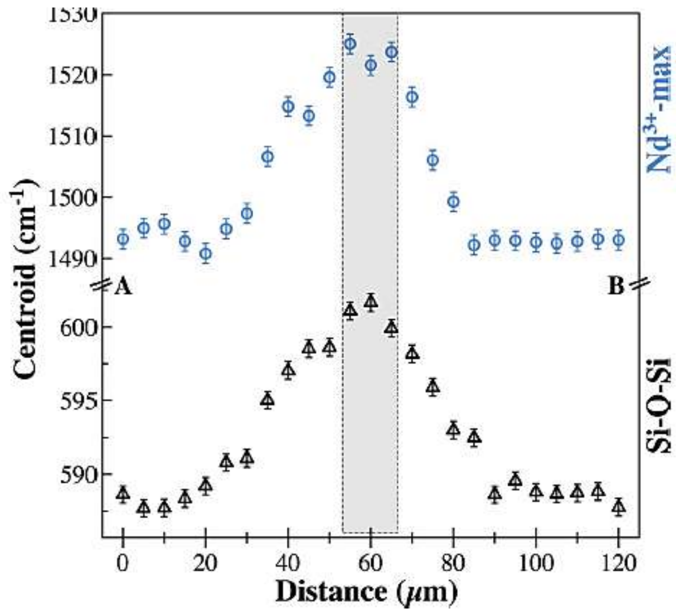
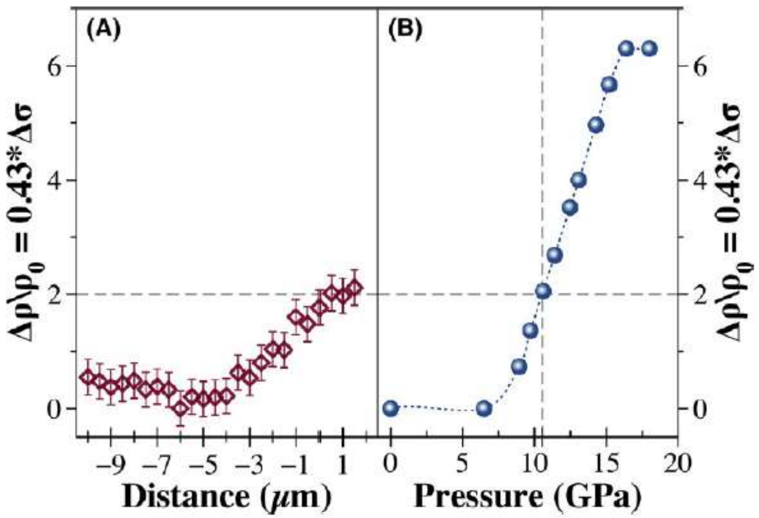
Aérosol déposition











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Pendant la déposition la pression augmente jusqu'à 10GPa

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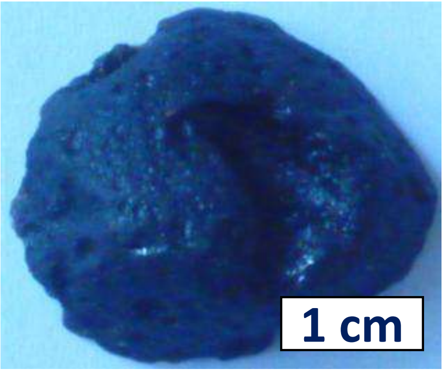
Tectites

- Glass transition temperature:
  - Moldavite: $T_g \approx 740°C$
  - Chinoises et Thailandaises: $T_g \approx 680°C$
- Est il possible de détecter un effet par spéctroscopie?

Tectite Chinoise



Moldavite

Tectite Thai

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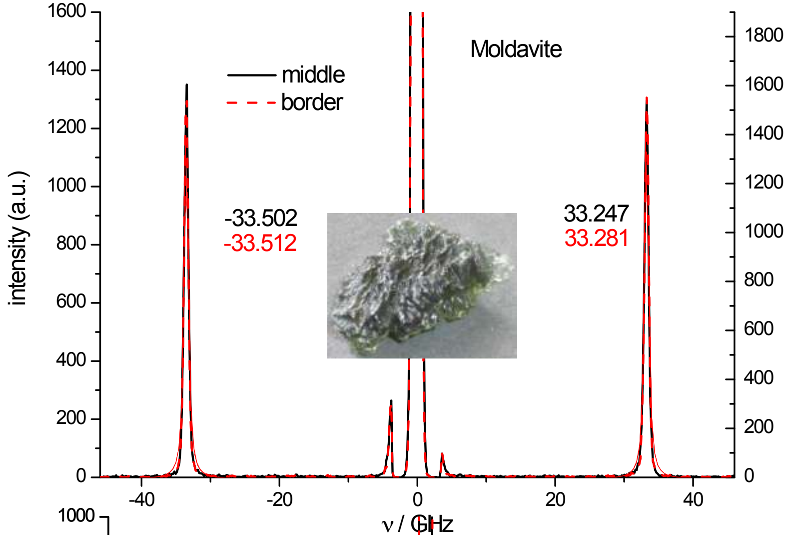
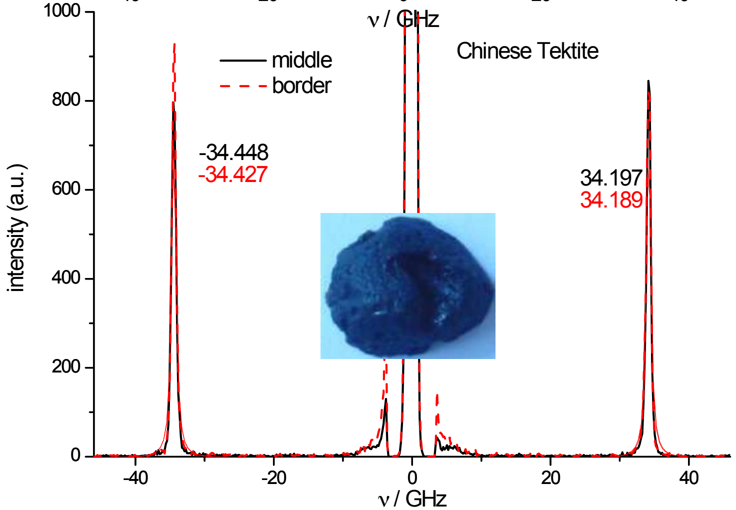
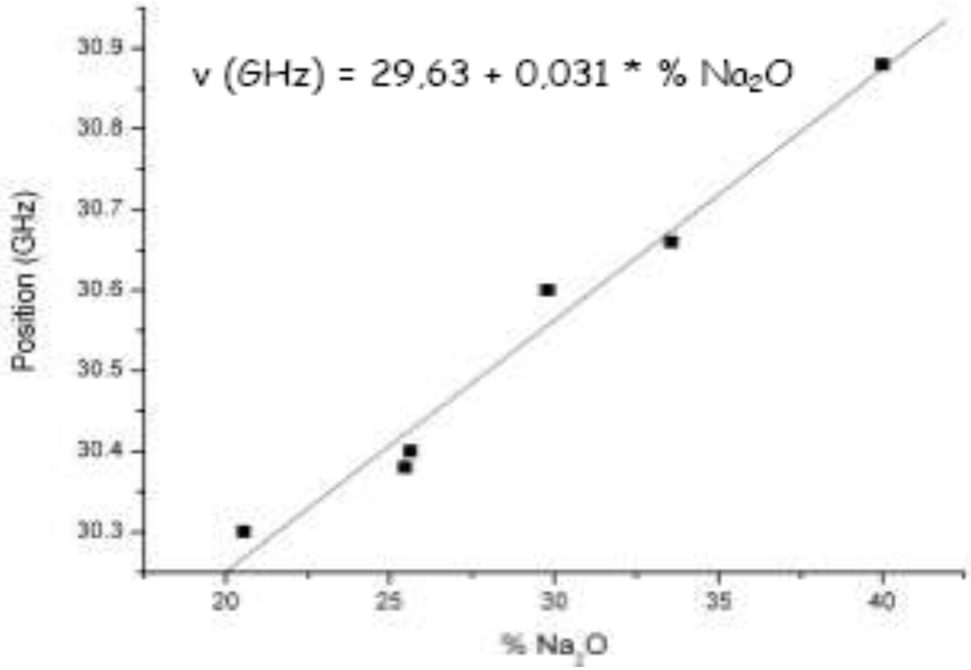
Tectites Brillouin





Alkali content ↓

Tektite	ν_{max} / GHz (middle)	ν_{max} / GHz (border)
Moldavite	-33.502 33.247	-33.512 33.281
Thai T.	-34.365 34.138	-34.301 34.146
Chinese T.	-34.448 34.197	-34.427 34.189



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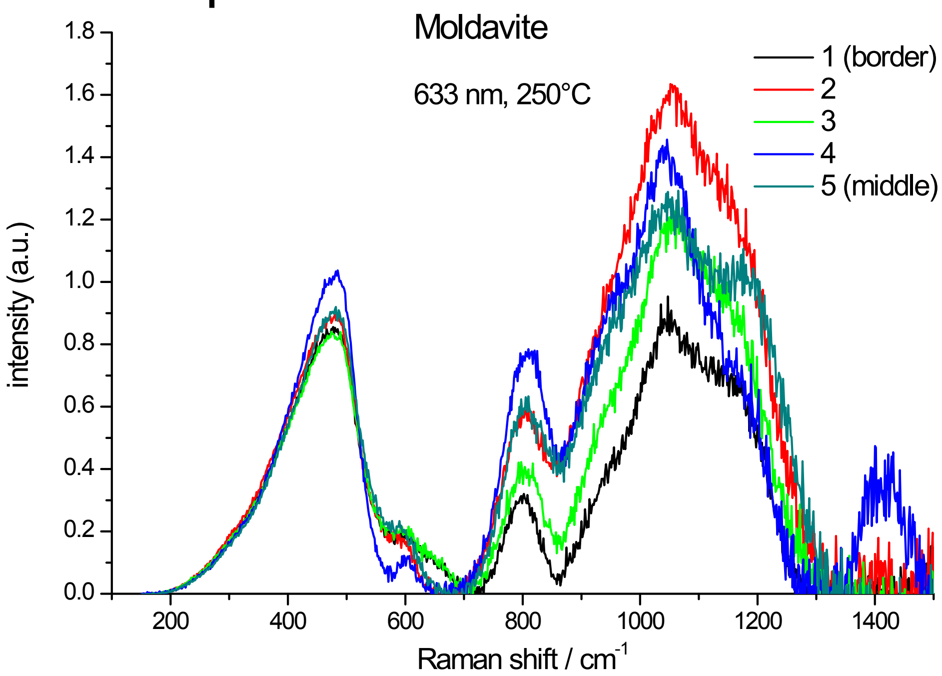
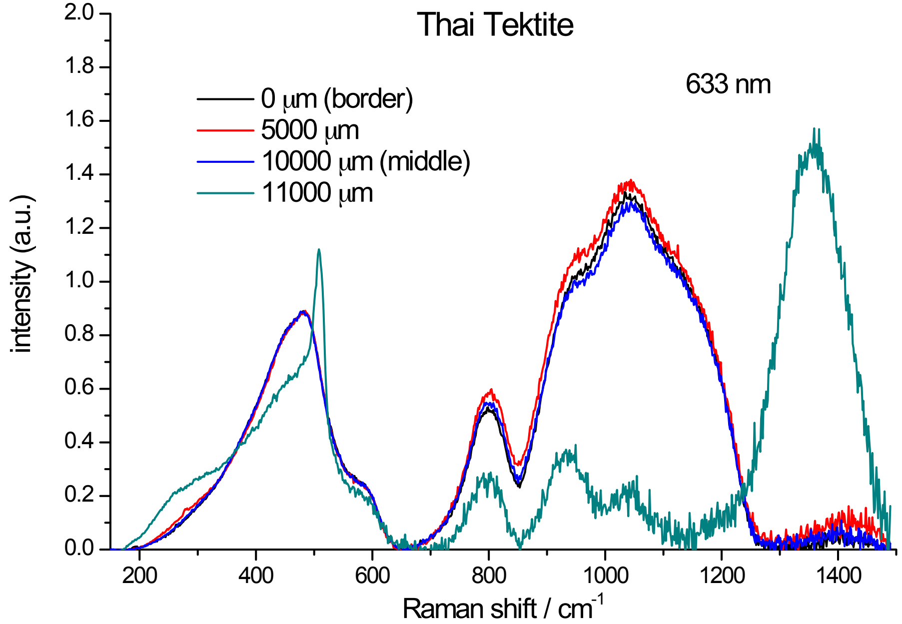
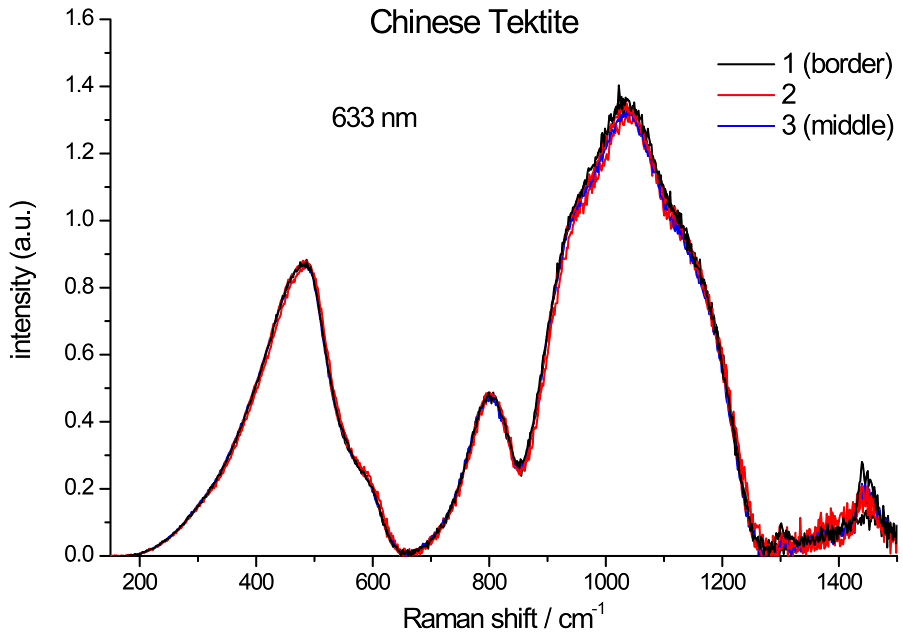
Tectites Raman

- Pas de changements significatifs du bord vers le centre
- Inhomogénéités dominant le spectre
- Cristallisation
- Graphite ?







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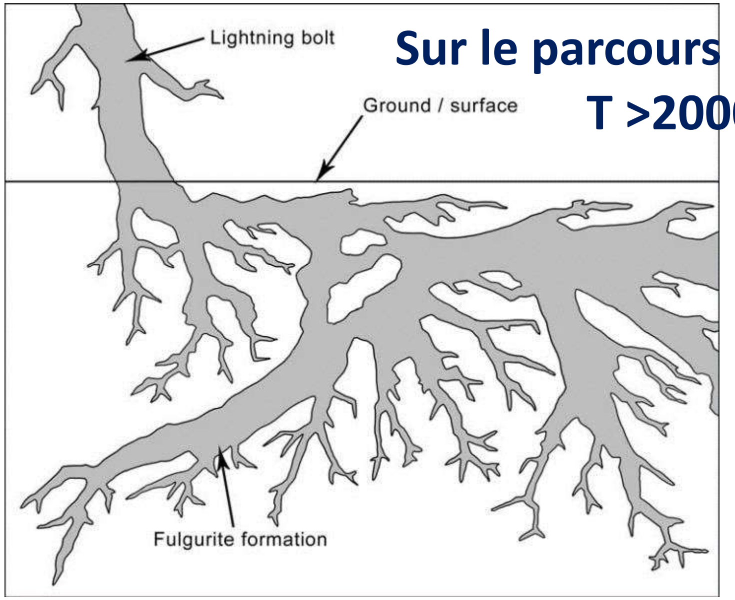
Fulgurites

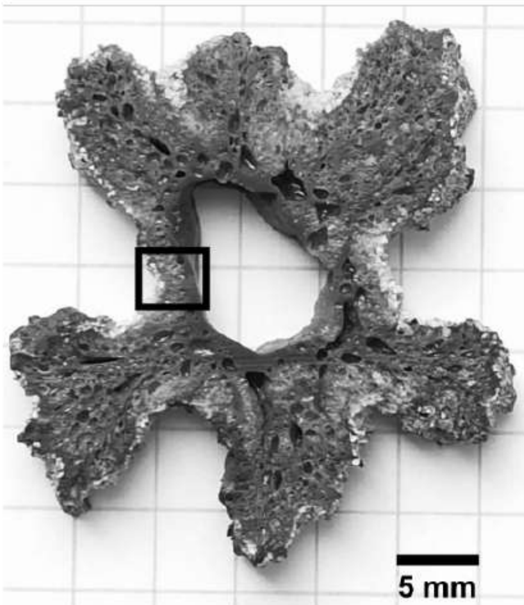


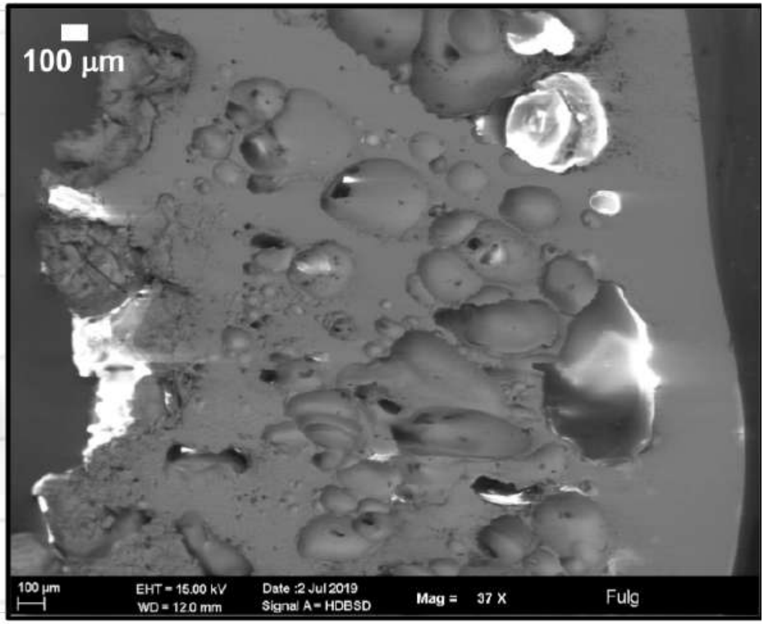
Sur le parcours du courant
T >2000 K

tubes creux avec beaucoup de vésicules crées par vaporisation

Surface externe irregulière

Surface interne lisse





Cicconi & Neuville 2019: Natural glasses. Springer Handbook of Glasses

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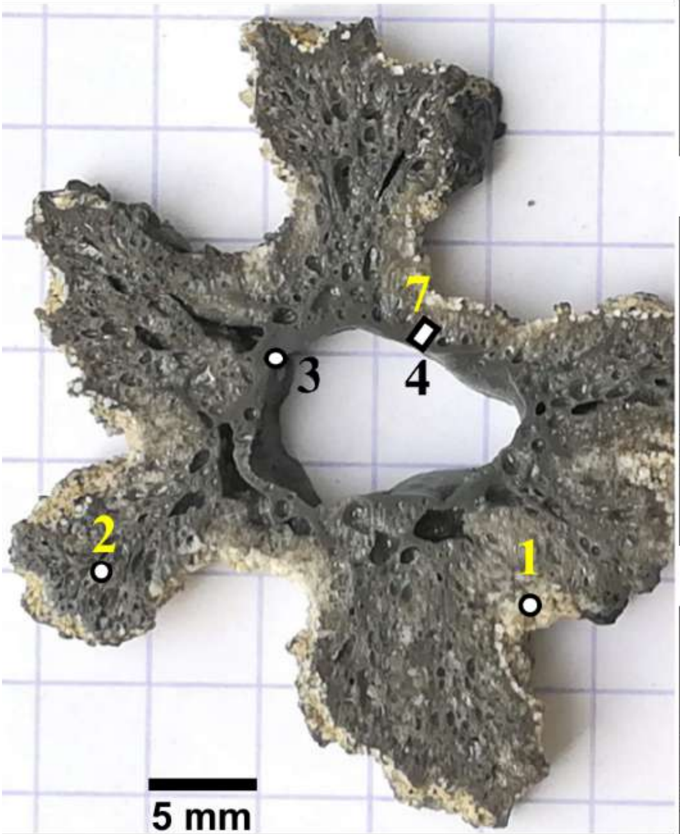
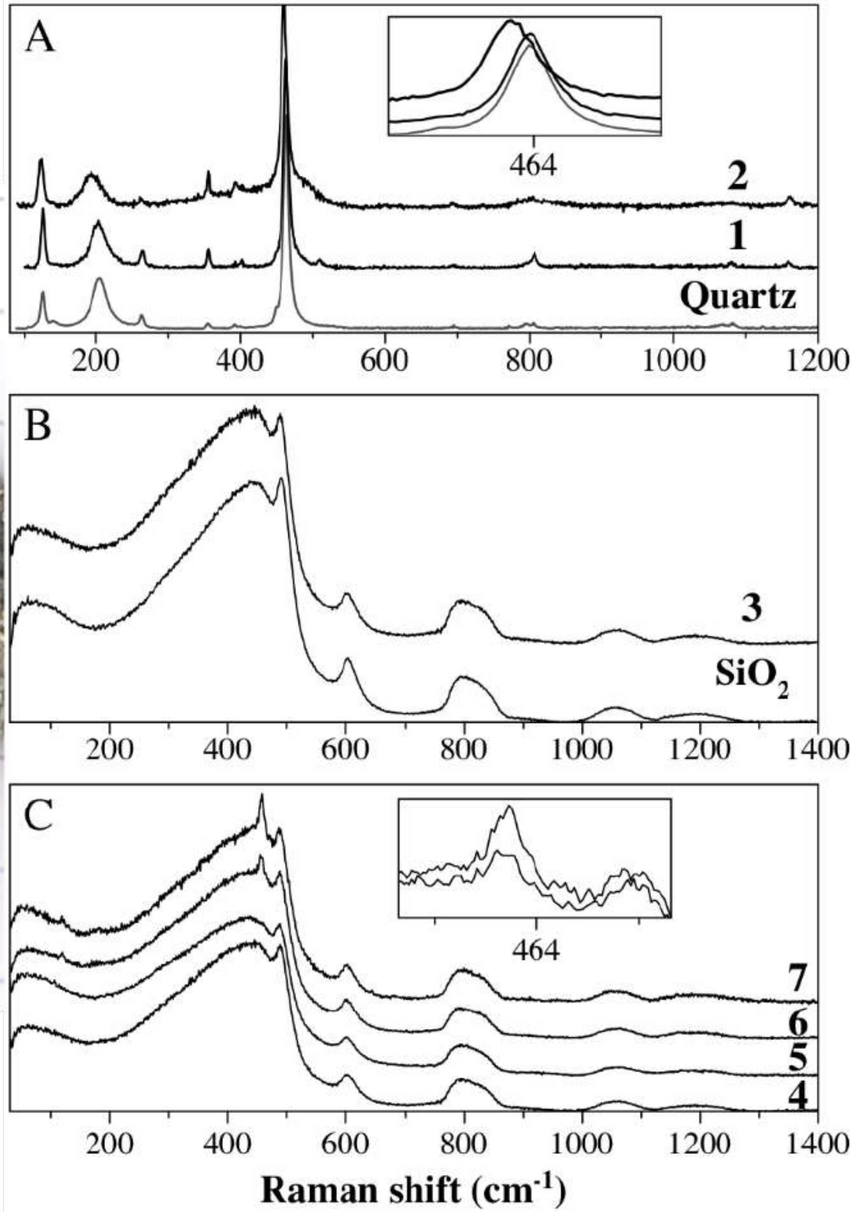


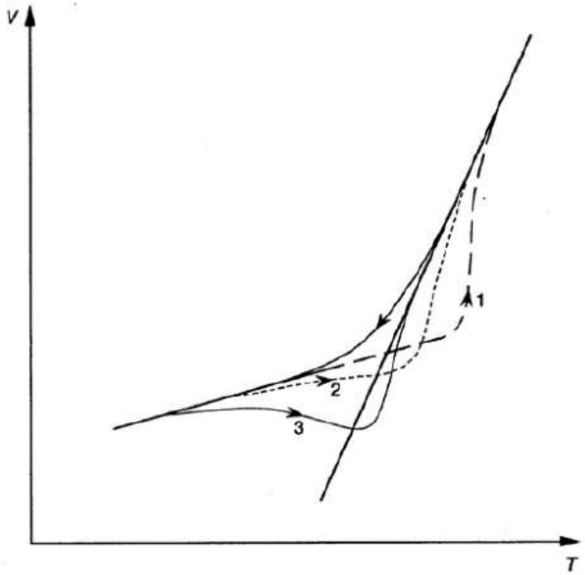


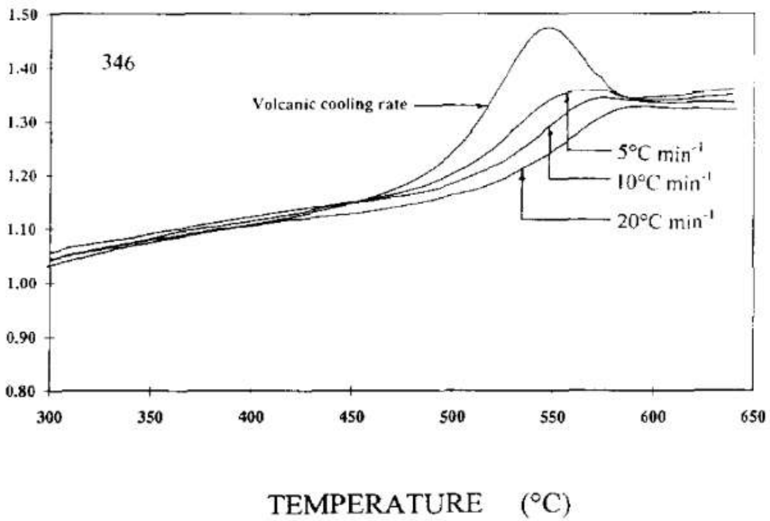
α-Quartz: décalage suggérant une augmentation de la pression de 25 GPa

Quasiement verre de silice pure
Pas de D1 particulièrement marquée

Cicconi et al. 2021: Non-Magmatic Glasses . Review in Mineralogy and Geochemistry

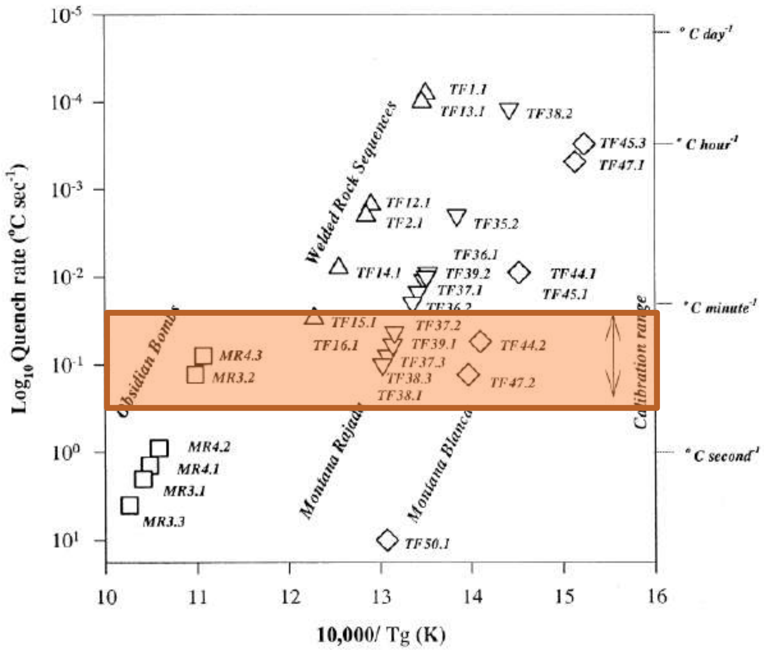
Obsidiennes



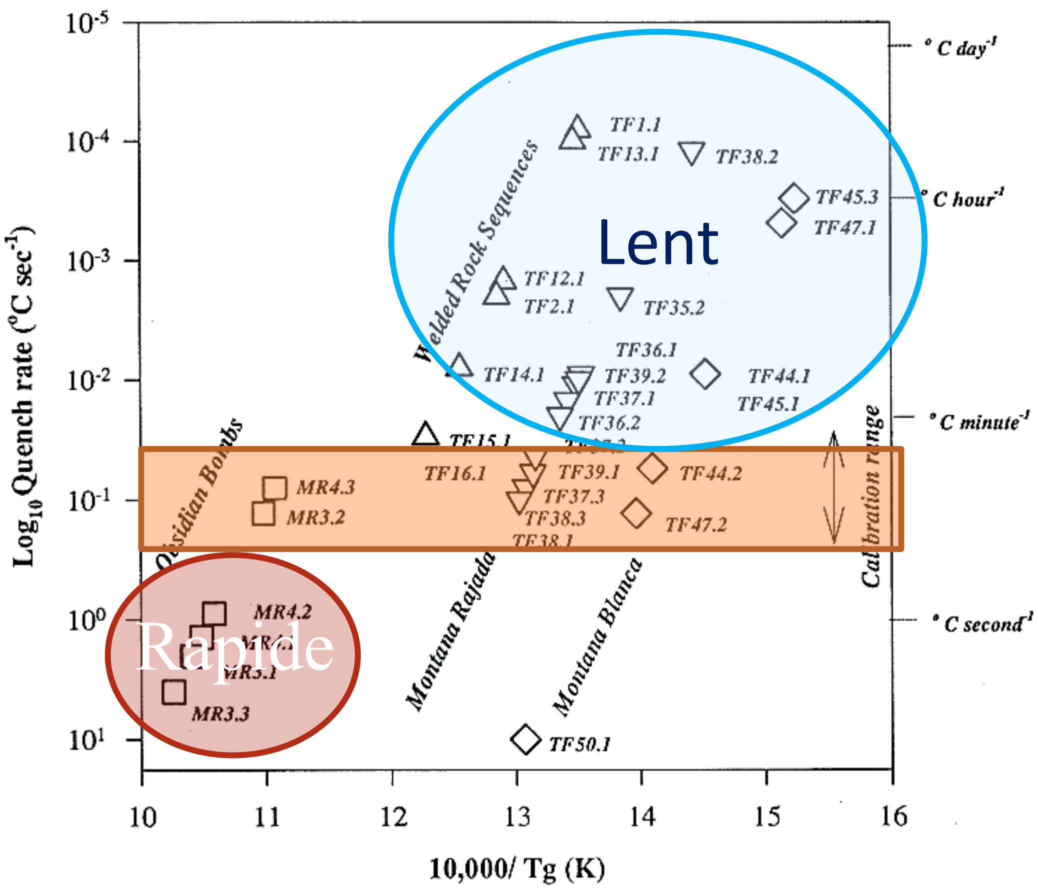


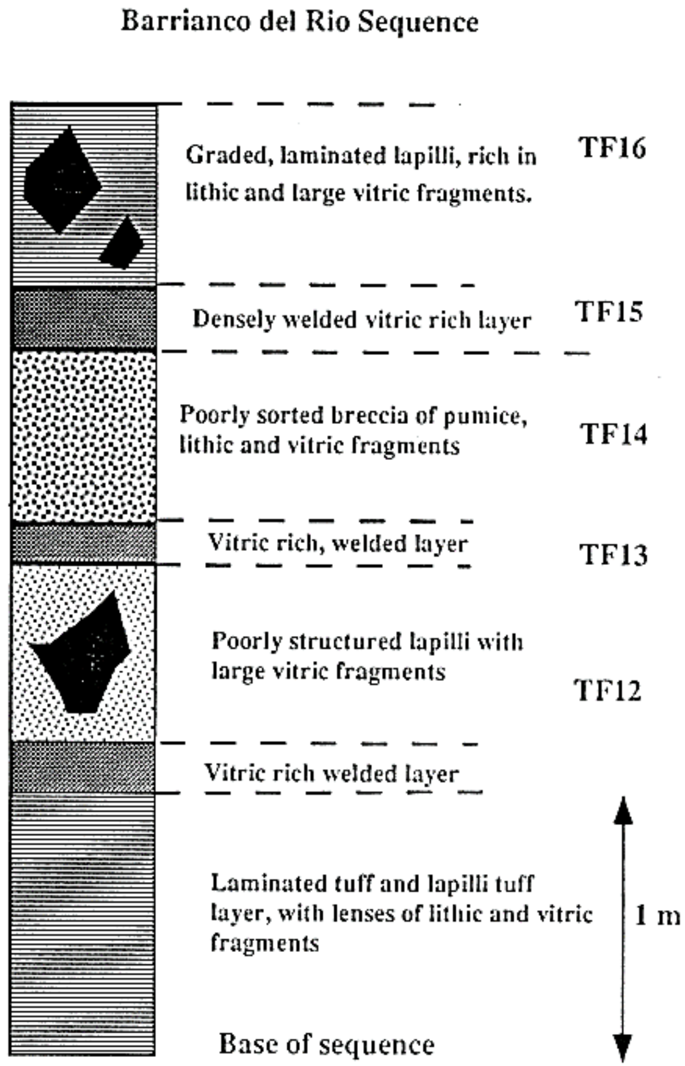
$$-\log_{10}|q| = -\log_{10}|q0| + \frac{H}{RT_g}$$

Wilding et al. Contrib.Min.Petrol 1996



Obsidiennes





Wilding et al. Contrib.Min.Pet 1996

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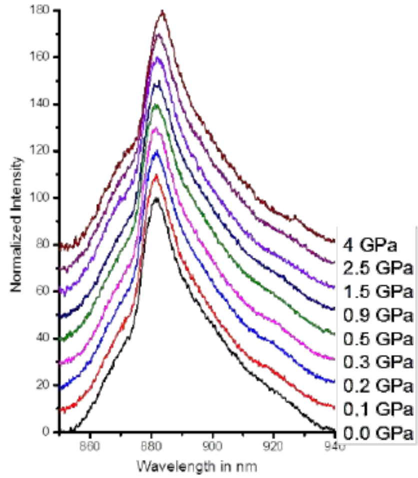
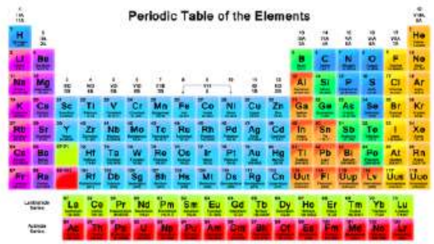
– Moldavite: 2-10°C/s (CTE, Arndt et al. 1976)
– Tektite: 1-10°C/s (DSC, Wilding et al. 1996)

Conclusion

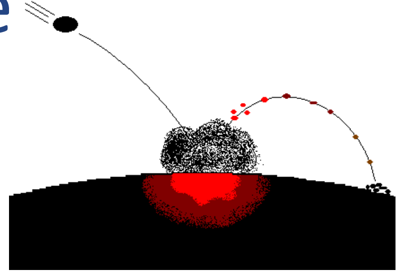
- Le verre a une mémoire
- Cette mémoire peut être lue en utilisant les spectroscopies de vibrations et de luminescence



- Grande variabilité chimique de la nature couvre bien des effets



- Les éruptions volcaniques, les chutes de météorites et la foudre ne sont pas des effets si extrême que cela



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FAU GLAS WW3


VAYAGIF.COM

Lena Bressel, Gérard Pankzer et Bernard Champagnon -ILM Lyon 1
Rita Cicconi, Daniel Neuville – IPG Paris

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Tectites

- Glass transition temperature:
  - Moldavite: $T_g \approx 740°C$
  - Chinoises et Thailandaises: $T_g \approx 680°C$
- cooling rates:
  - Moldavite: 2-10°C/s (from thermal expansion measurements, Arndt et al. 1976)
  - Tektite: 1-10°C/s (from DSC measurements, Wilding et al. 1996)
- possible to detect with spectroscopy?

Chinese Tektite

Moldavite

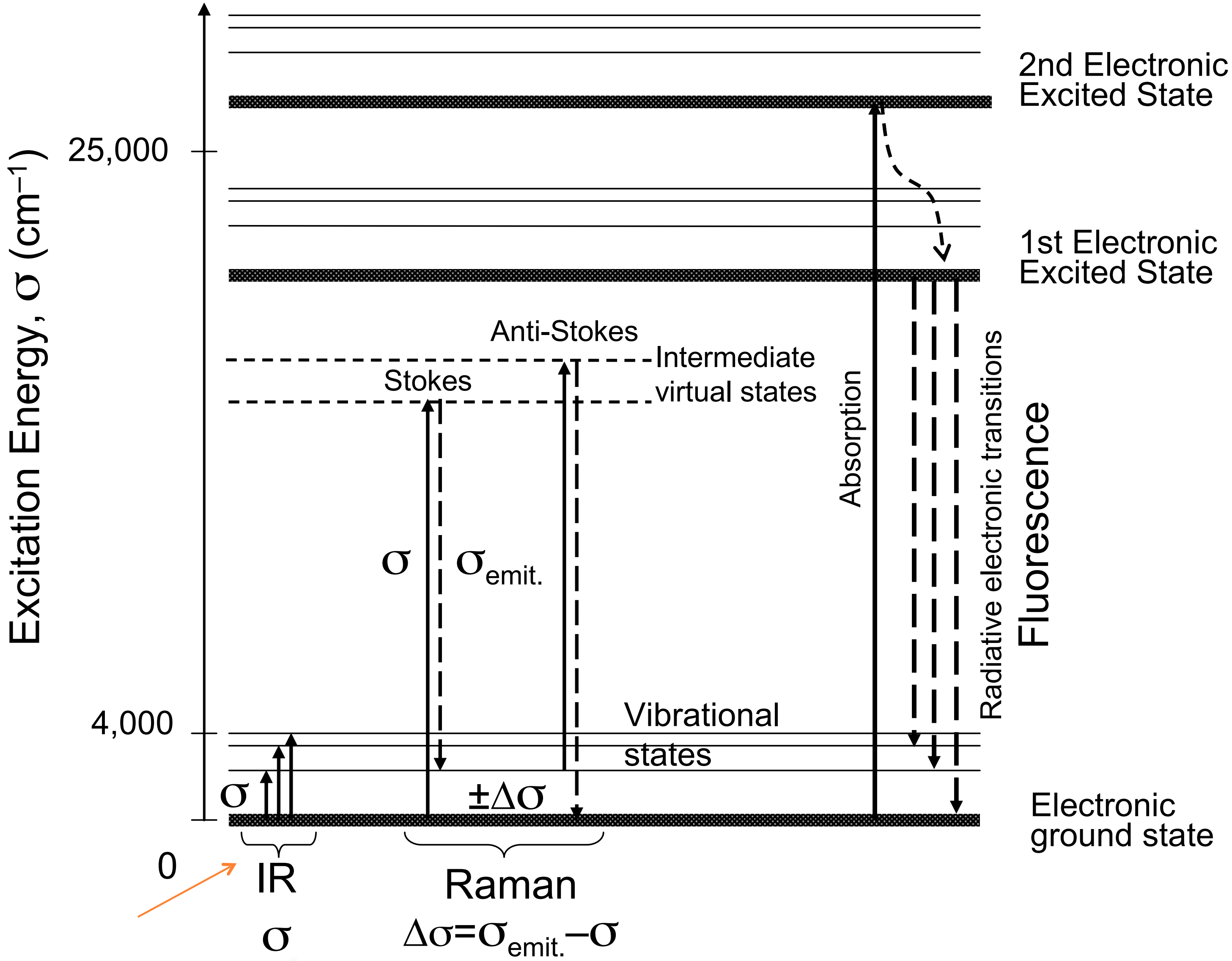
Thai Tektite

1.1 Who is Prince Rupert

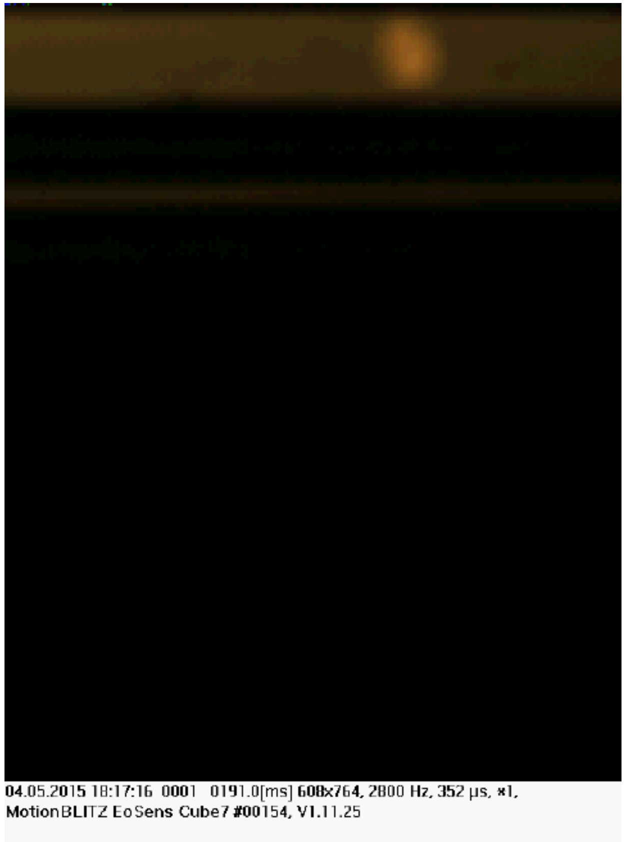
Mystery of Prince Rupert's Drop at 130,000 fps - Smarter Every Day 86 YouTube

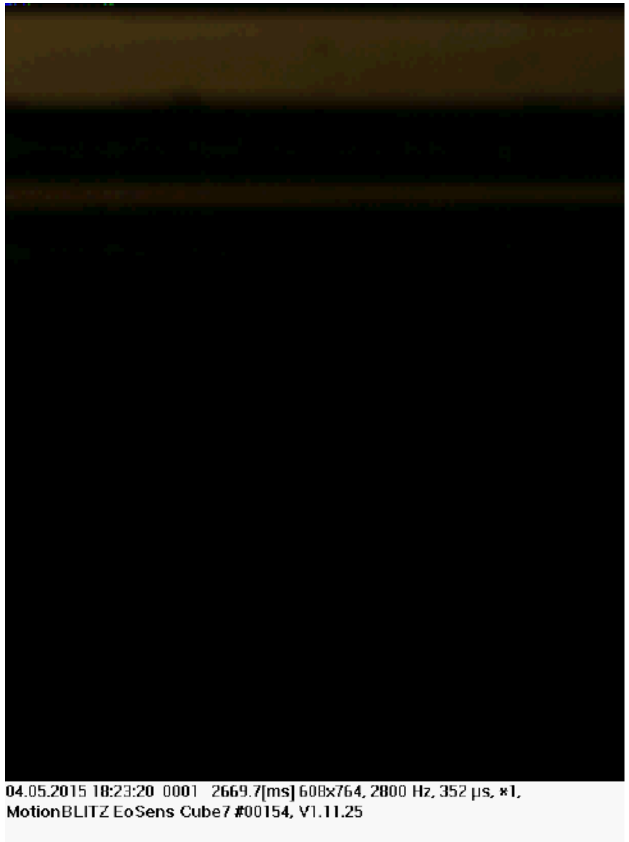
Rupert, Count Palatine of the Rhine, Duke of Bavaria, Duke of Cumberland 1619-1682

1. Fluorescence / Raman / absorption IR



Bologneser Tränen





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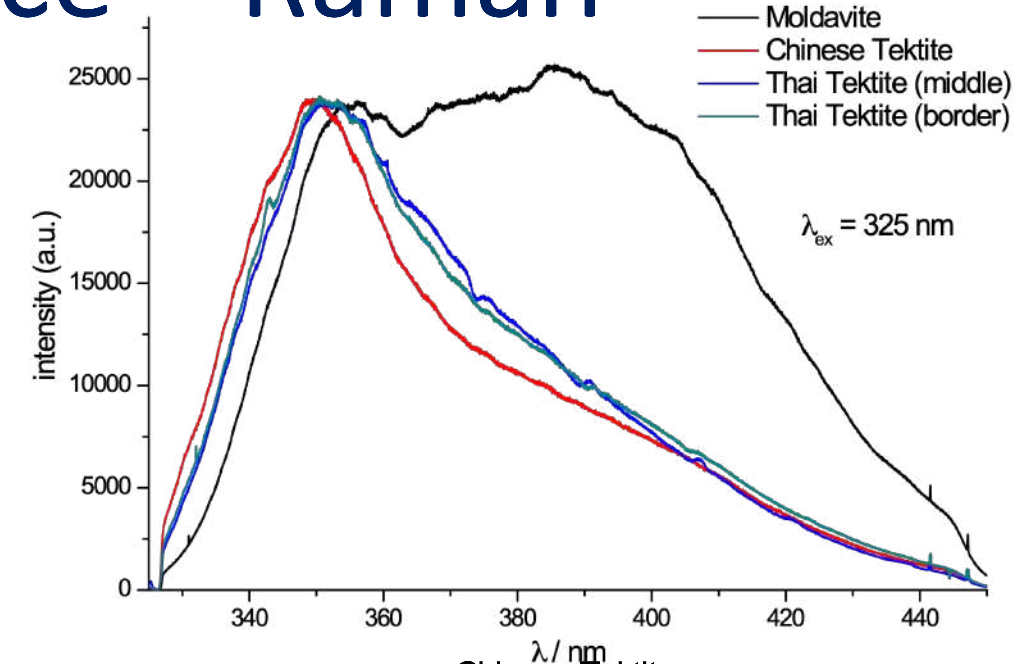
TECHNISCHE HOCHSCHULE NÜRNBERG
GEORG SIMON OHM

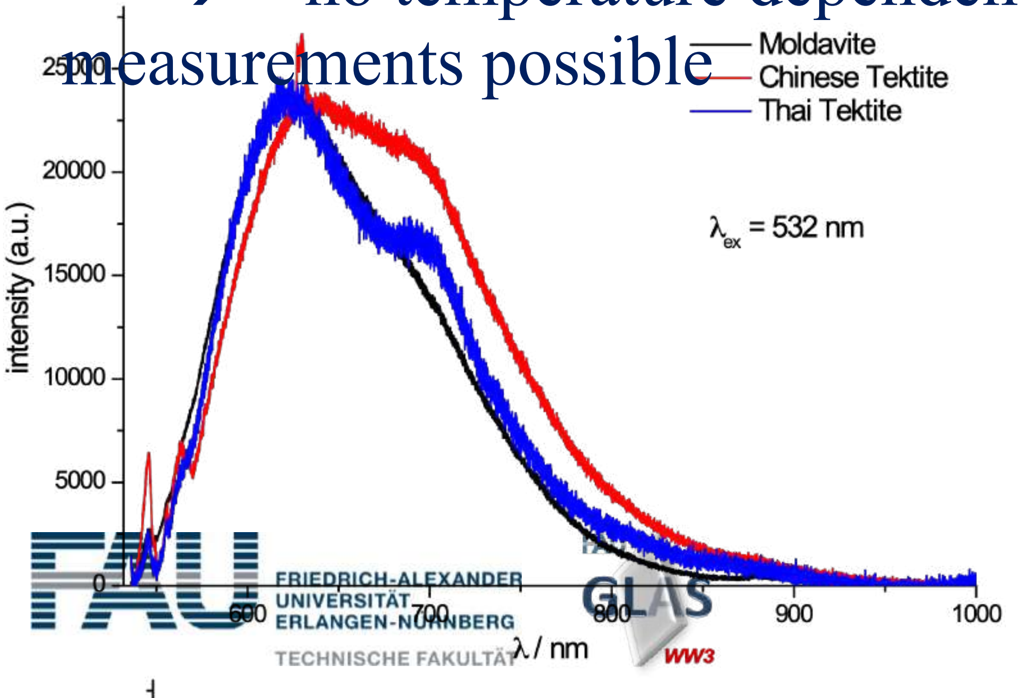
Luminescence – Raman

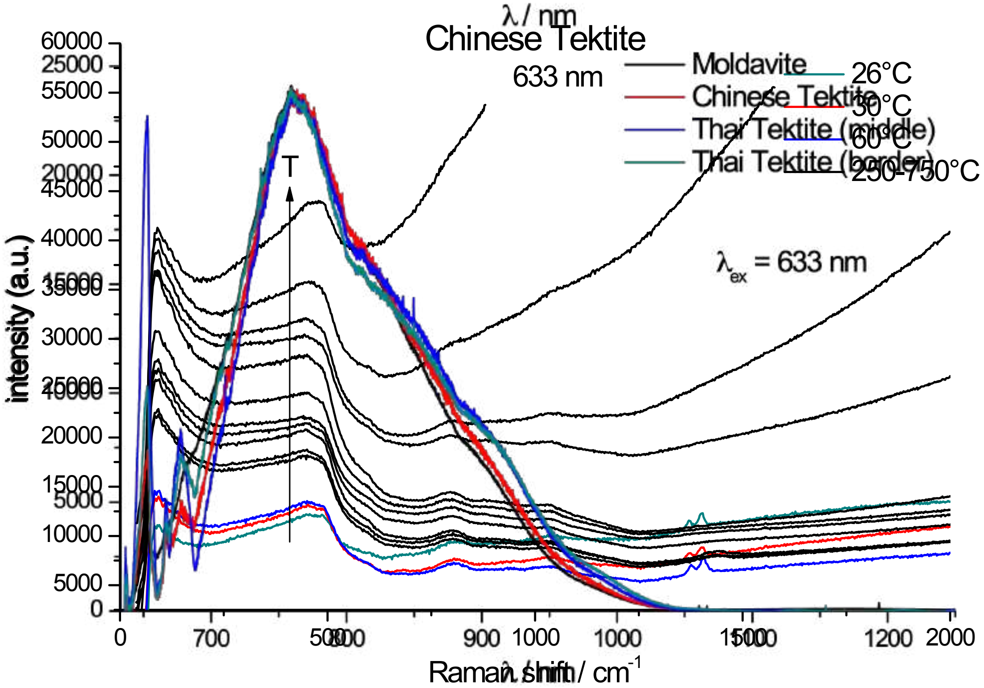
- strong luminescence
  (especially at low wavelength)



heating: diminution of luminescence but increasing black body radiation

→ no temperature dependent measurements possible



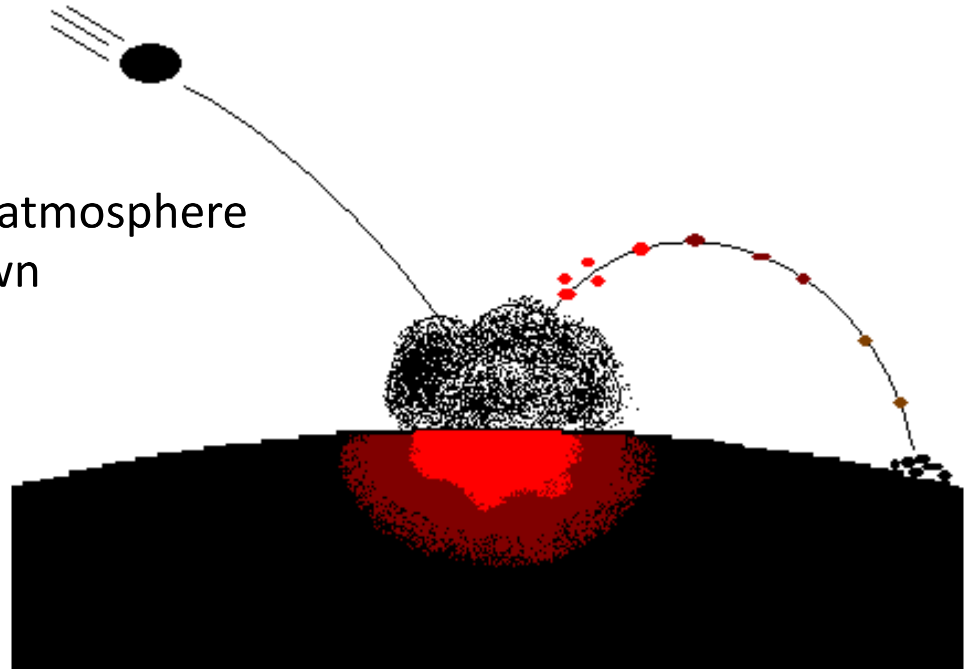


Tektites – Overview
what is this?

- natural glasses
- four known strewn fields (North American, Czechoslovakian, Ivory Coast, Australasian)
- main composition: SiO_2 (70-80%), Al_2O_3 (9-20%), FeO (1-6%), CaO (1-4%), MgO (0.1-3.5%), Na_2O (0.5-2.3%) and K_2O (1-3.5%), MnO/TiO_2 ($< 1\%$)

- origin is still controversial
- believed to result from meteorite impacts
- meteorite hits the surface
- earth liquefies
- drops of the liquefied earth are thrown in the atmosphere
- while flying through the air the drops cool down and solidify into the tektite glasses

- here studied three types of tektites: Moldavites, Chinese tektites, Thai tektites



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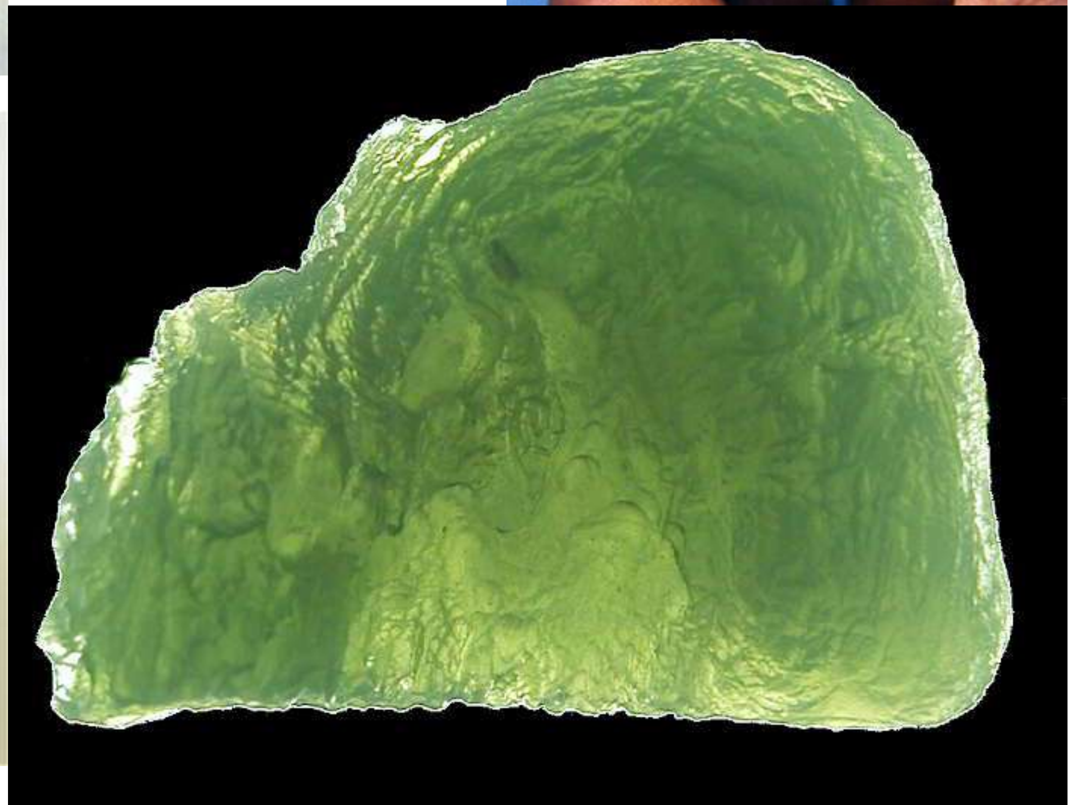
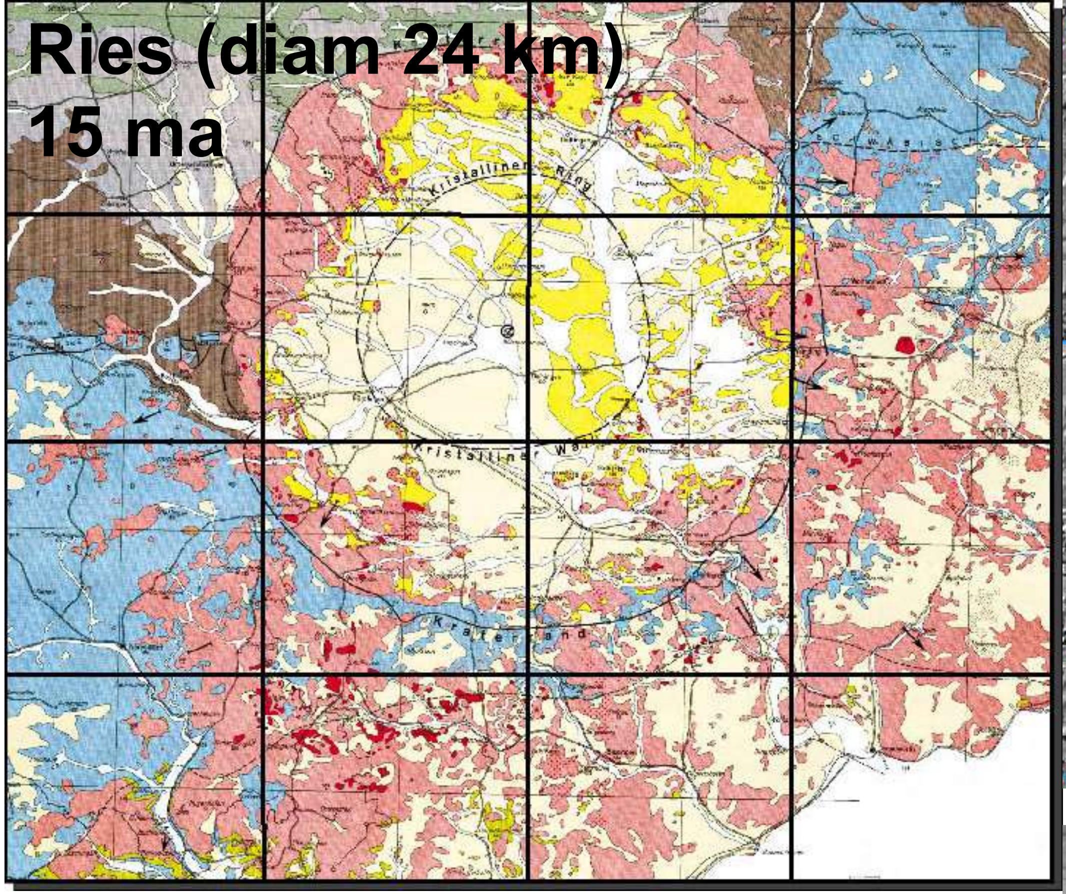
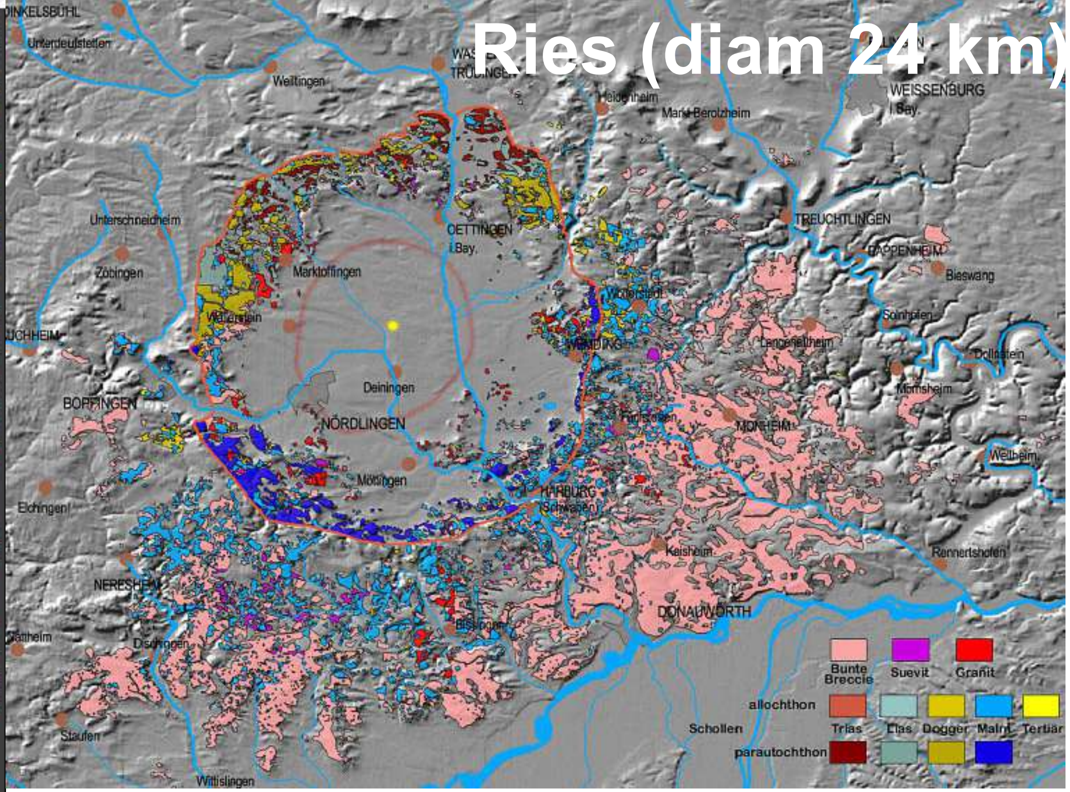
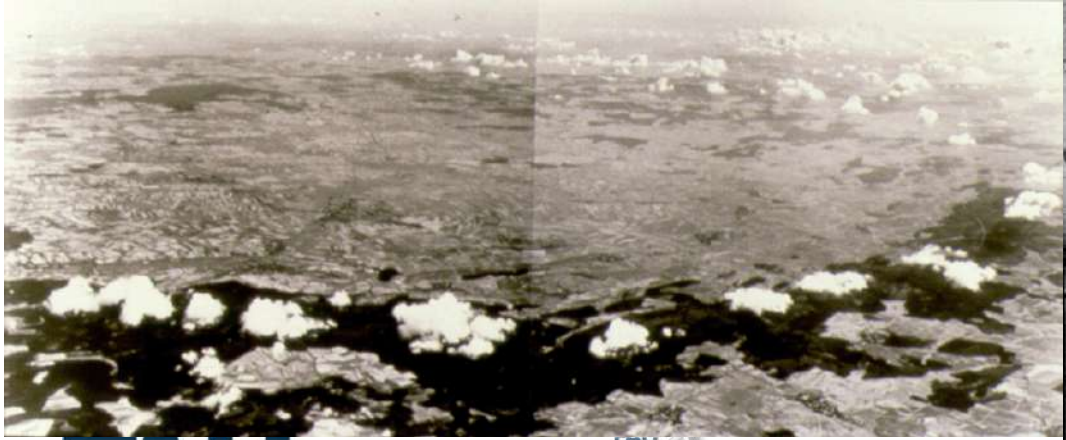
indice









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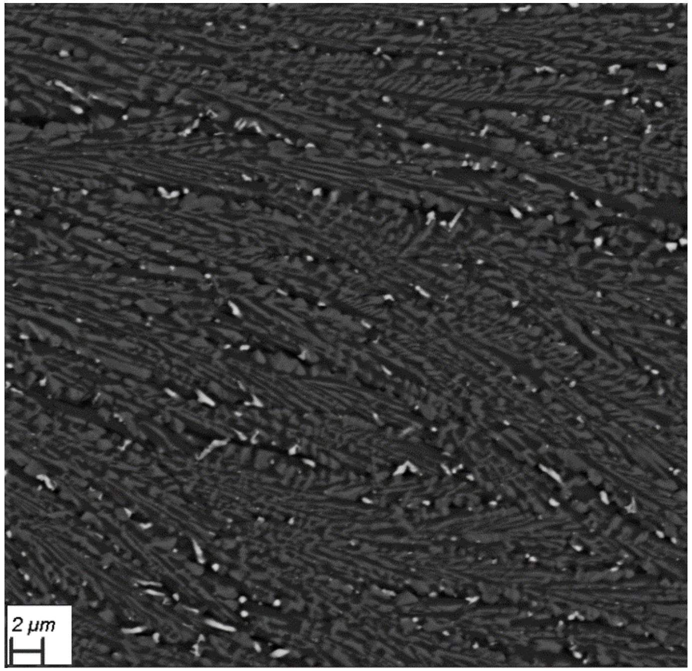
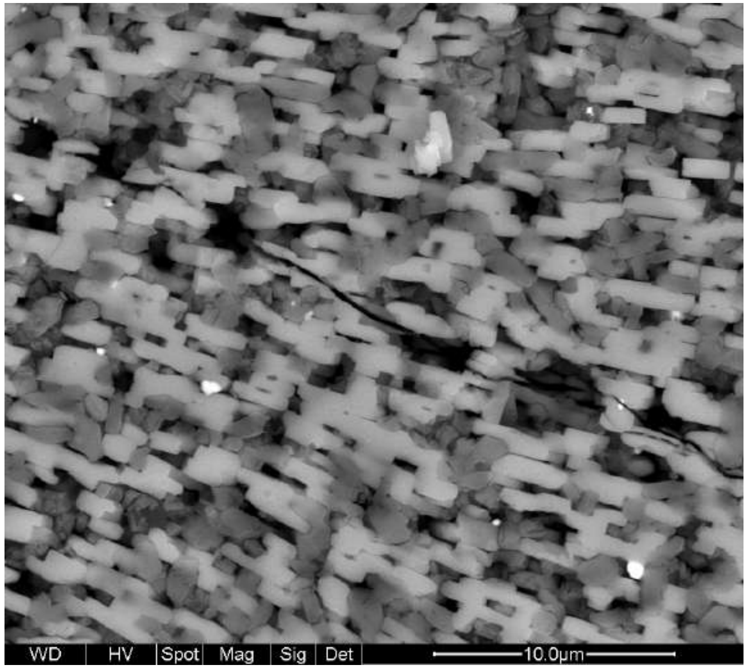
Rocks



→ History of the volcanic area

Glass-ceramics

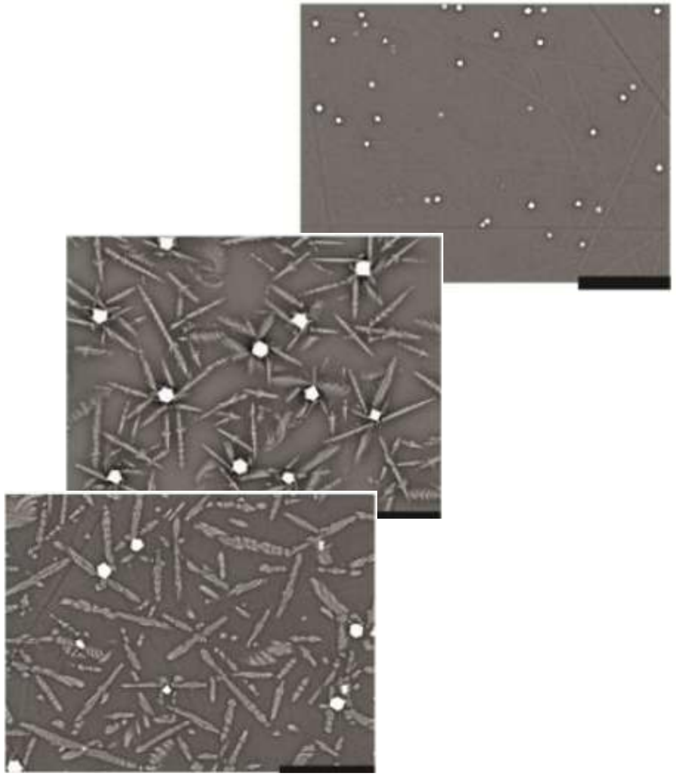


→ Mechanical/optical properties

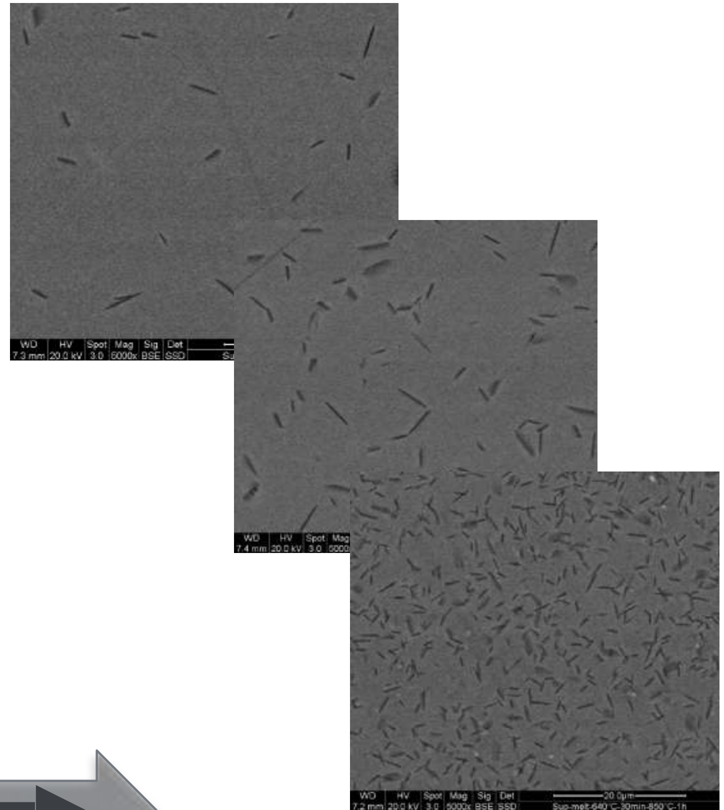
Rocks

Melt/glass

GC



T, time



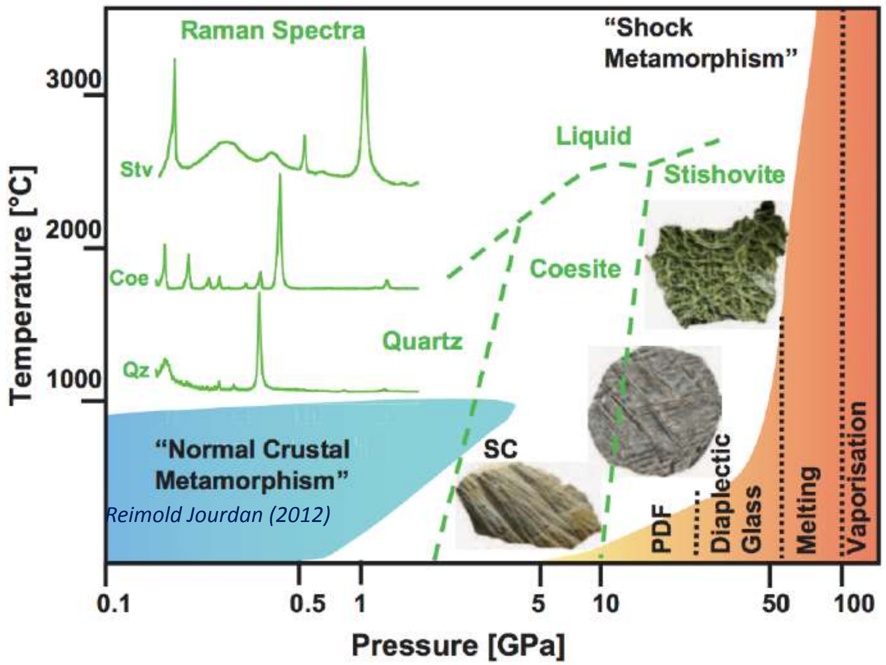
→ History of the volcanic area

→ Mechanical/optical properties

Investigation of glasses formed under extreme conditions

Hyperquenching, meteorite impacts, lunar glasses and irradiation

Obsidian



Images from: *Cicconi & Neuville 2019: Natural glasses. Springer Handbook of Glasses*
Cicconi et al. 2021: Non-Magmatic Glasses . Review in Mineralogy and Geochemistry

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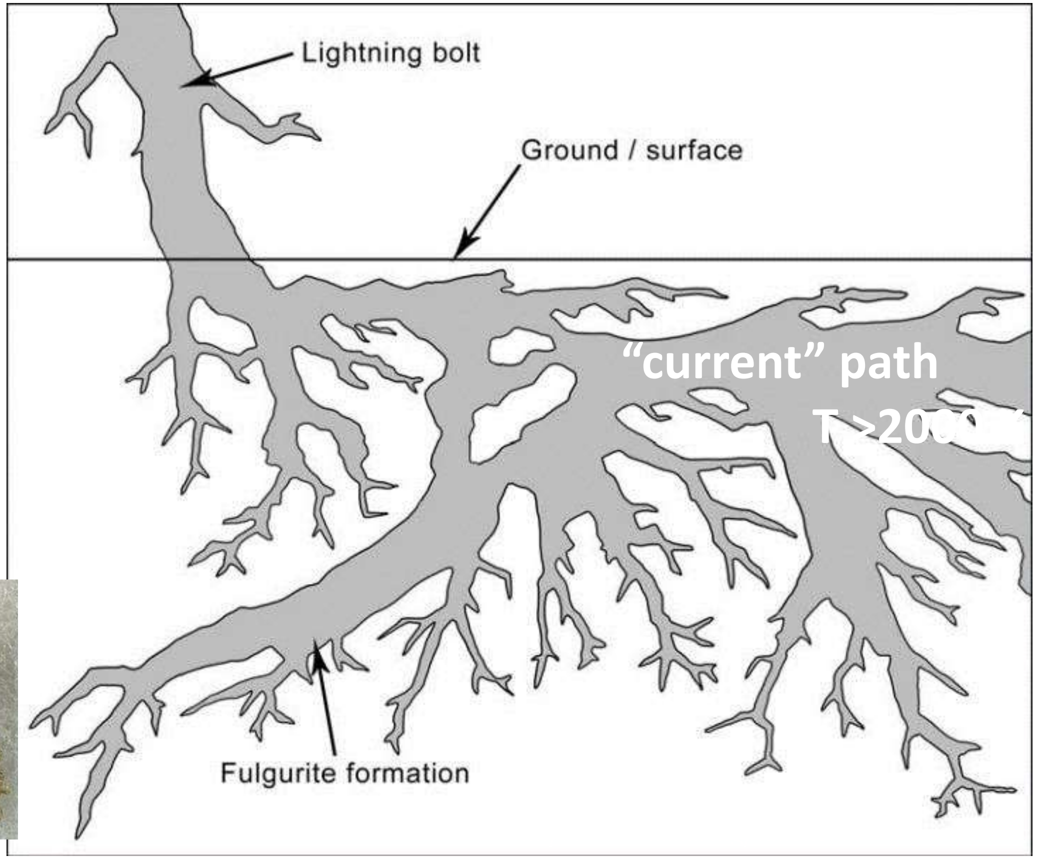
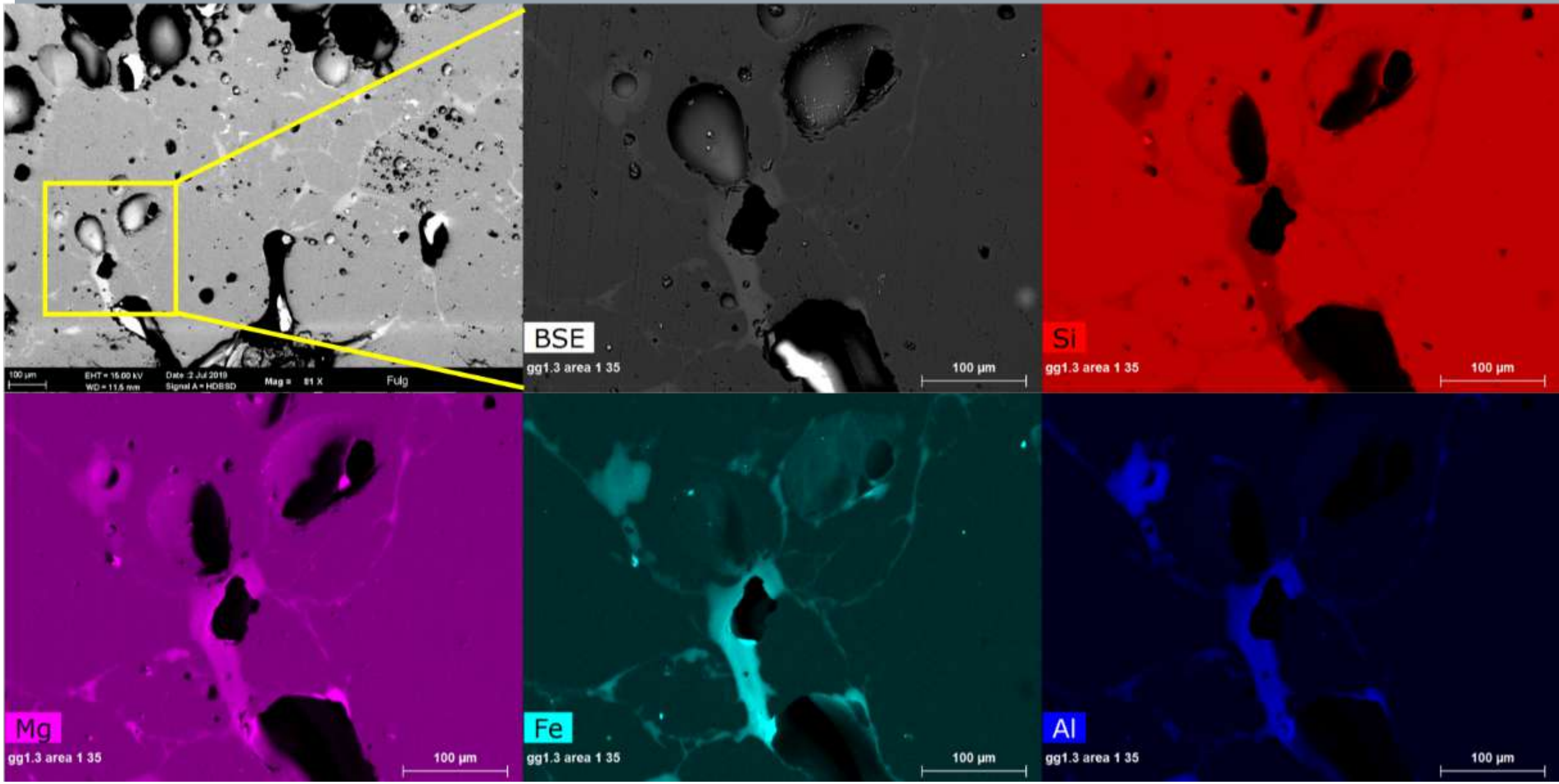

Lightning bolt
Ground / surface
"current" path
T >200
Fulgurite formation

Fulgurites



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