Composition of the First Solid Cumulates in a Deep Pyrolitic Magma Ocean

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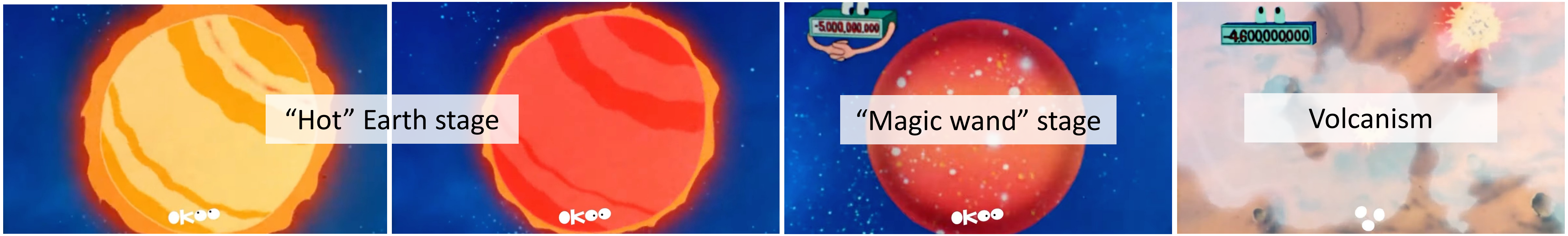
STEP'UP ÉCOLE DOCTORALE

CDD 2024

Earth's formation ….



Earth's formation as described for kids
Credit: Et la Terre fut…, *Il était une fois l'homme*

… A very simplified version!

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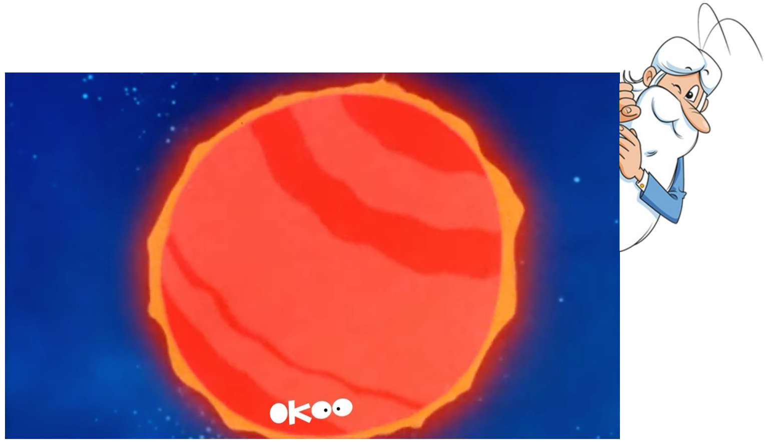
Terrestrial Magma Ocean (MO) - Formation



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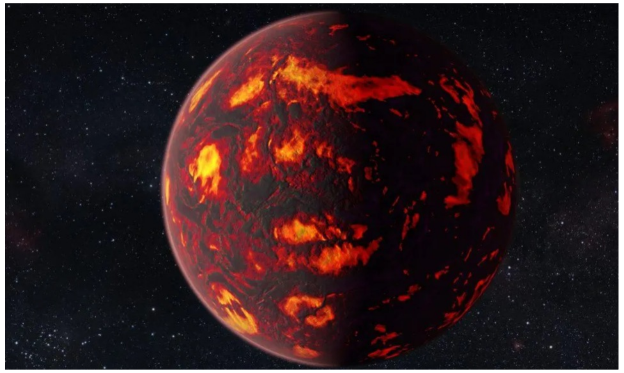
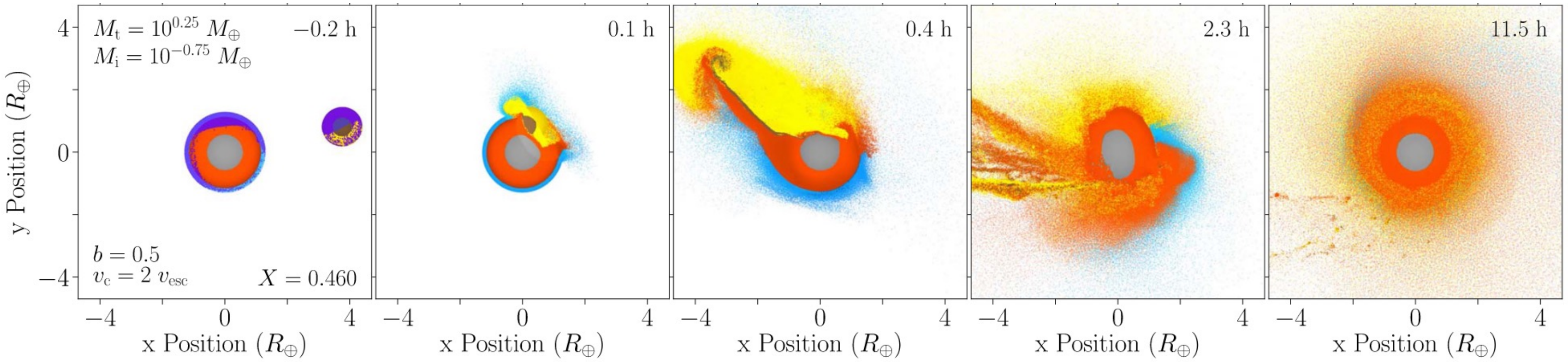


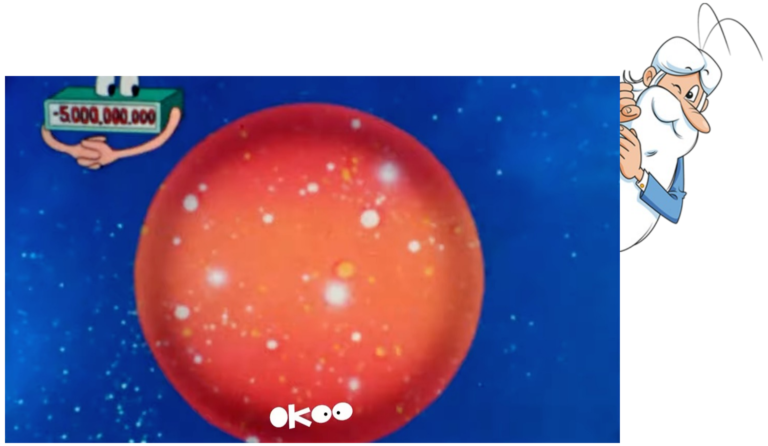
Artistic view of a magma ocean
Credit: ESA/Hubble, M. Kornmesser



3D smoothed particle hydrodynamics of a giant impact
Kegerreis *et al.* (2020)

- Earth extensively molten after the Moon forming impact (Nakajima and Stevenson, 2015; Piet *et al*., 2017): its surface is covered by a global **magma ocean** that could have extended down to the core-mantle boundary

Terrestrial Magma Ocean (MO) - Crystallization



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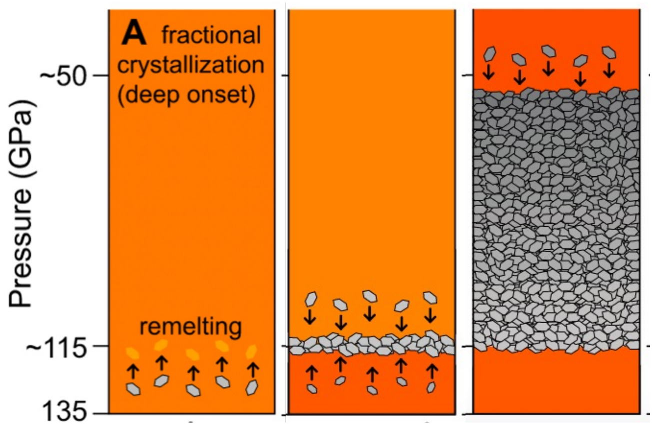


Formation of a basal magma ocean
Caracas et *al.* (2019)

- Earth extensively molten after the Moon forming impact (Nakajima and Stevenson, 2015; Piet *et al.*, 2017): its surface is covered by a global **magma ocean** that could have extended down to the core-mantle boundary
- As the Earth cools down, this magma ocean starts **crystallizing**
- Different scenarios of Earth magma ocean crystallization:

  "*Bottom-up*" (surface magma ocean) (Solomatov and Stevenson, 1993)

  "Top-down" (Labrosse *et al.*, 2007; Caracas et *al.*, 2019) with formation of a **basal magma ocean**

Terrestrial Magma Ocean (MO) - Crystallization

- What is the composition of the first solid cumulates that form at depth in a crystallising pyrolitic magma ocean?

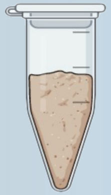
- How do these minerals behave in the magma ocean: Do they float, sink, remelt?

Influences the properties and behaviour of the crystallizing magma ocean

This study:

- **High-pressure high-temperature experiments in laser-heated diamond anvil cells (LH-DAC) that reproduce the crystallization of the primitive terrestrial magma ocean**

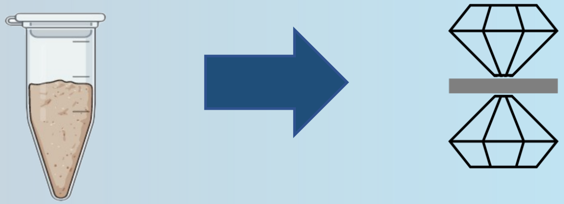
- Crystallization experiments in laser-heated diamond anvil cells (LH-DAC)



Pyrolite

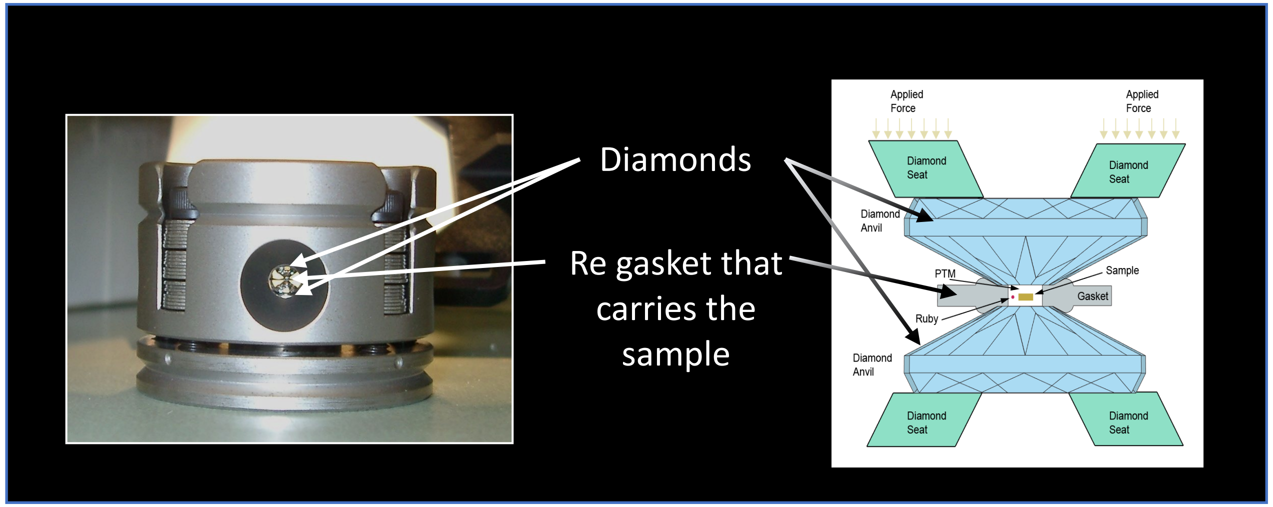
Model composition of the Earth's mantle

- Crystallization experiments in laser-heated diamond anvil cells (LH-DAC)



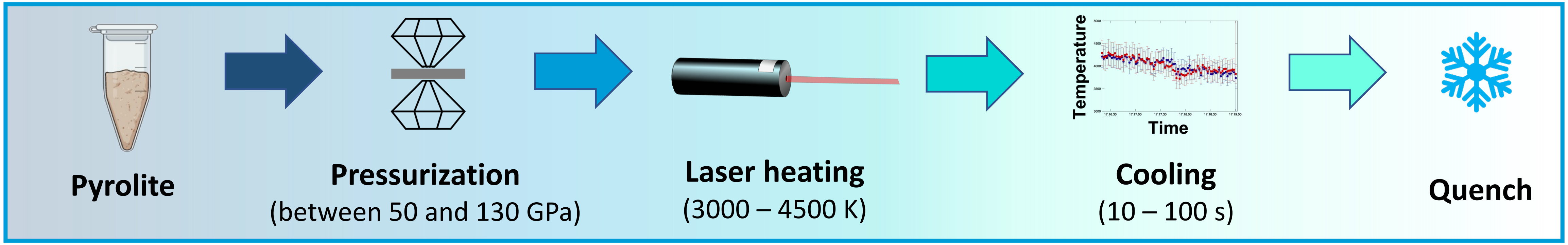
Pyrolite

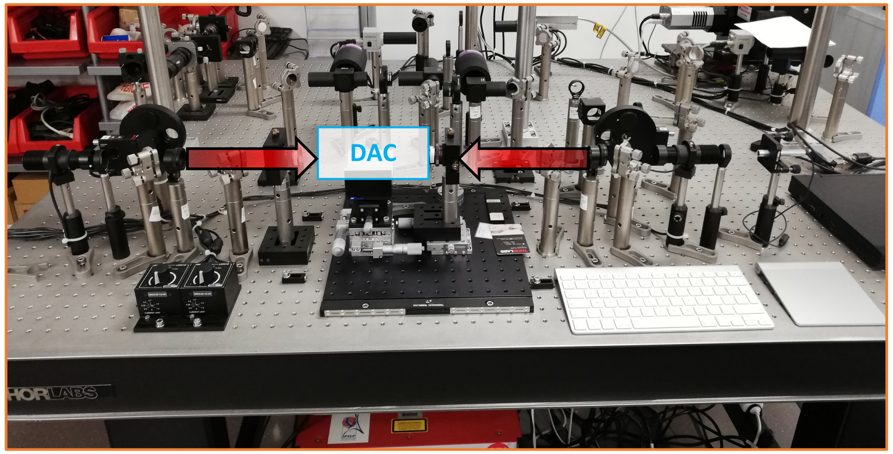
Pressurization
(between 50 and 130 GPa)



The starting material (pyrolite) is loaded in a Re gasket and further compressed in a diamond anvil cell (DAC) to reach lower mantle pressures. Once pressurized, the DAC is heated using a laser to melt the sample.

- Crystallization experiments in laser-heated diamond anvil cells (LH-DAC)

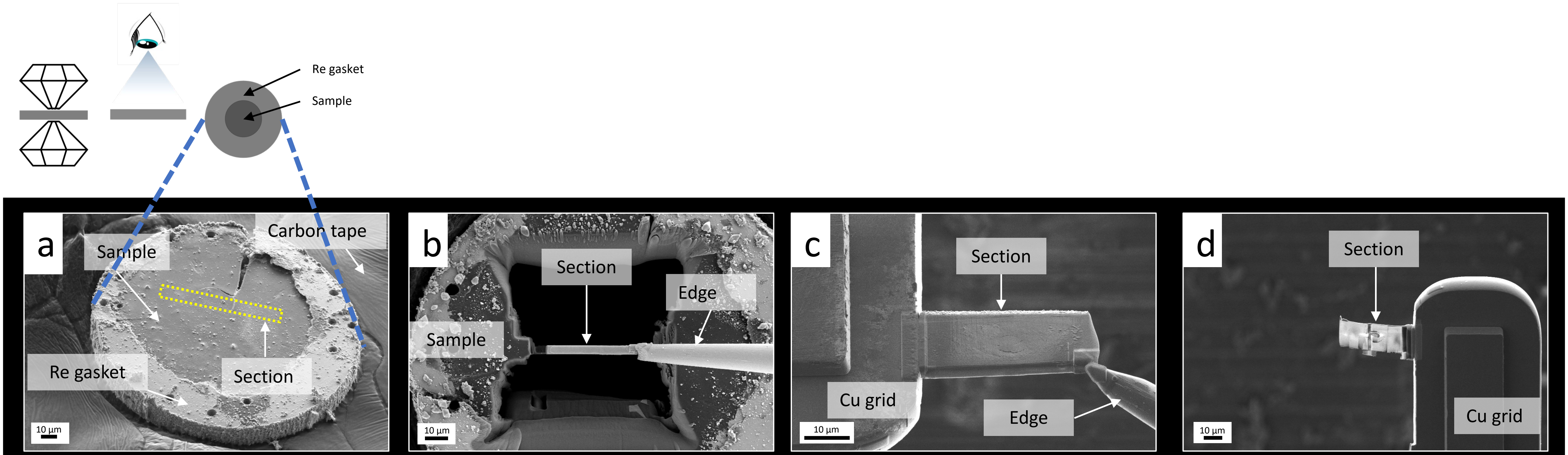




Optical setup used to heat the samples. The position of the DAC is identified with a blue rectangle. The two red arrows illustrate the laser beam.

- Crystallization experiments in laser-heated diamond anvil cells (LH-DAC)

- **Focused ion beam (FIB) preparation of the recovered samples for further analysis**



a. DAC sample after being depressurized.

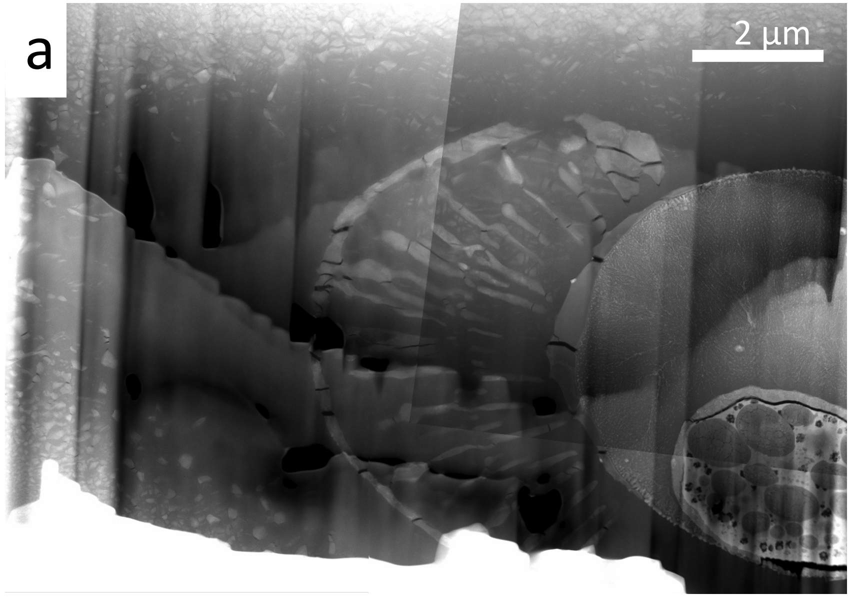
b. Thin section extraction out of the sample.

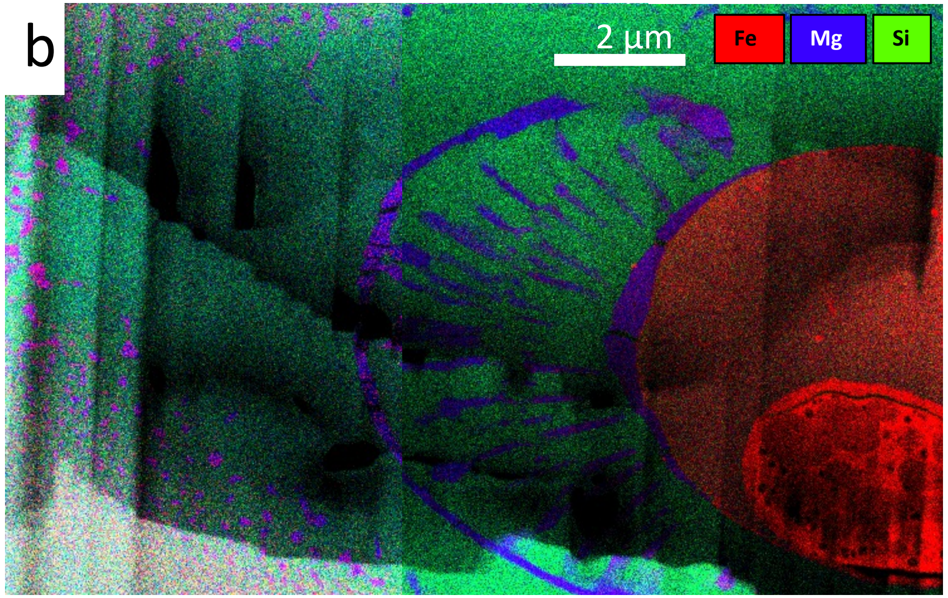
c. Soldering of the section on a Cu grid.

d. Further thinning down of the lammela until it is electron transparent.

A FIB thin section is further extracted out of each sample to further analyse the structure and composition of the various phases in a transmission electron microscope (TEM).

- Crystallization experiments in laser-heated diamond anvil cells (LH-DAC)
- Focused ion beam (FIB) preparation of the recovered samples for further analysis
- STEM-EDXS analysis (structure and composition) of the specimens at EPFL (Lausanne, Switzerland)





a) Secondary electrons picture (STEM) of one of the FIB thin sections.

b) STEM-EDXS chemical map of the thin section. Fe-rich regions appear in red, Mg-rich in blue and Si-rich in green.

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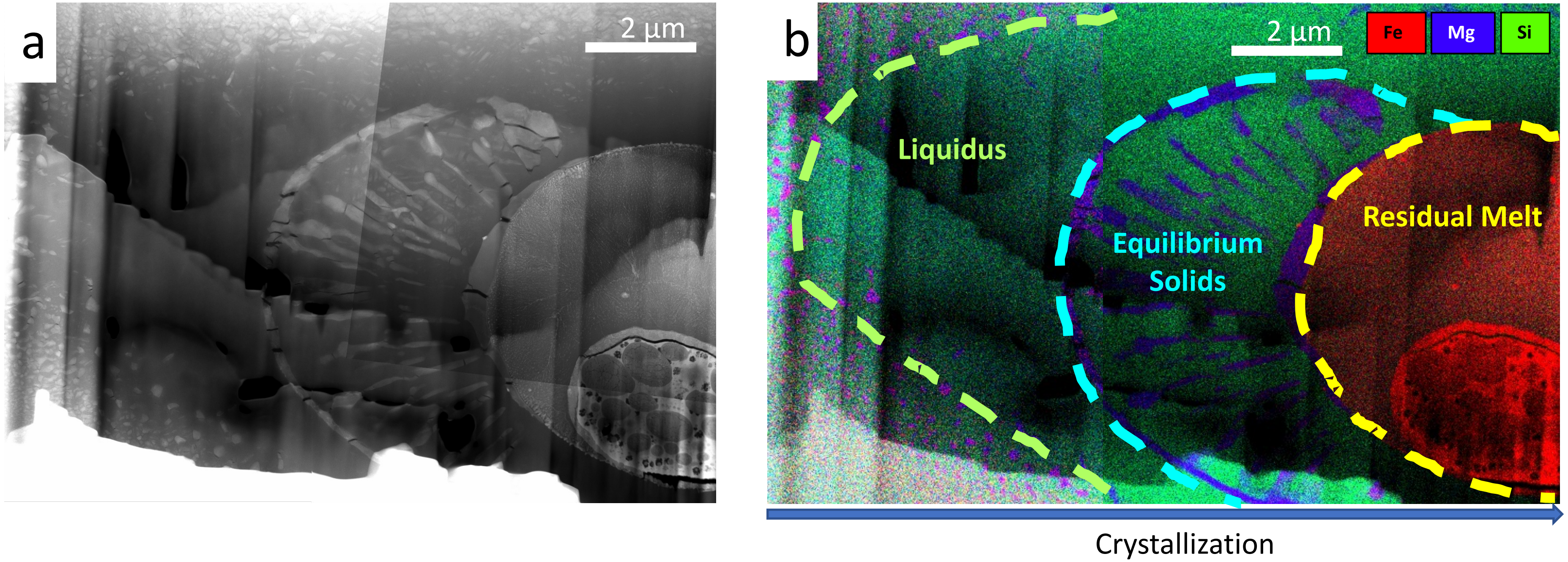

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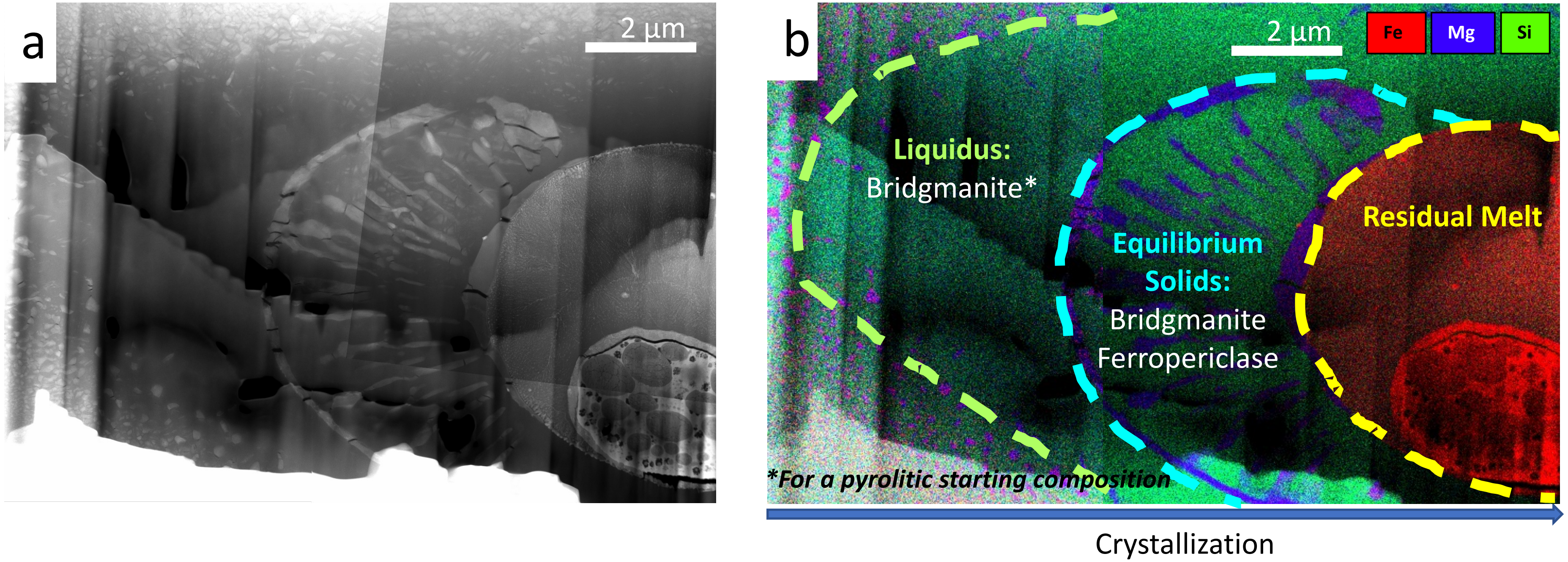
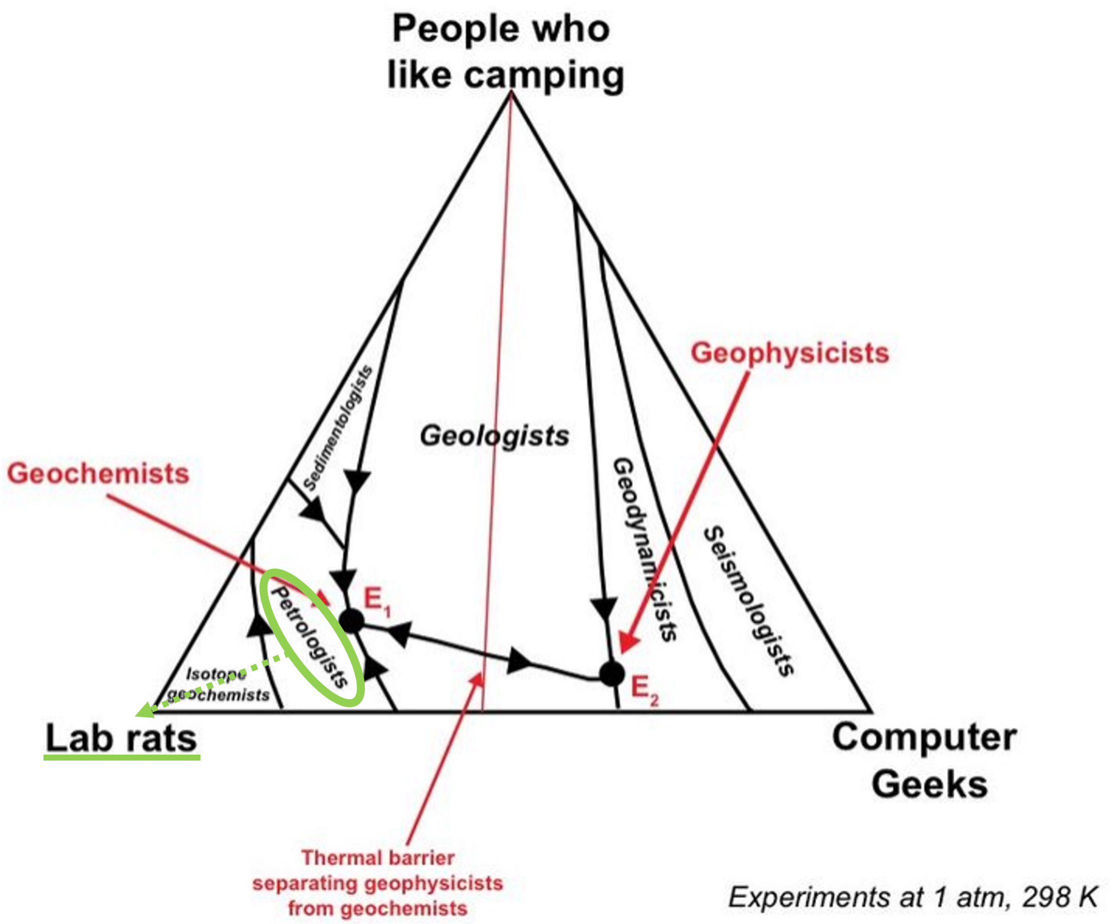


a) Secondary electrons picture (STEM) of one of the FIB thin sections.

b) STEM-EDXS chemical map of the thin section. Fe-rich regions appear in red, Mg-rich in blue and Si-rich in green. From left to right: crystallization sequence of a deep pyrolitic magma ocean in which bridgmanite (green areas) is the first mineral to crystallize followed by ferropericlase (purple rays). The residual melt (red pocket) corresponds to the region of the sample that is still molten once quenching.

Confronting experimental results with thermodynamics

How to read a ternary diagram



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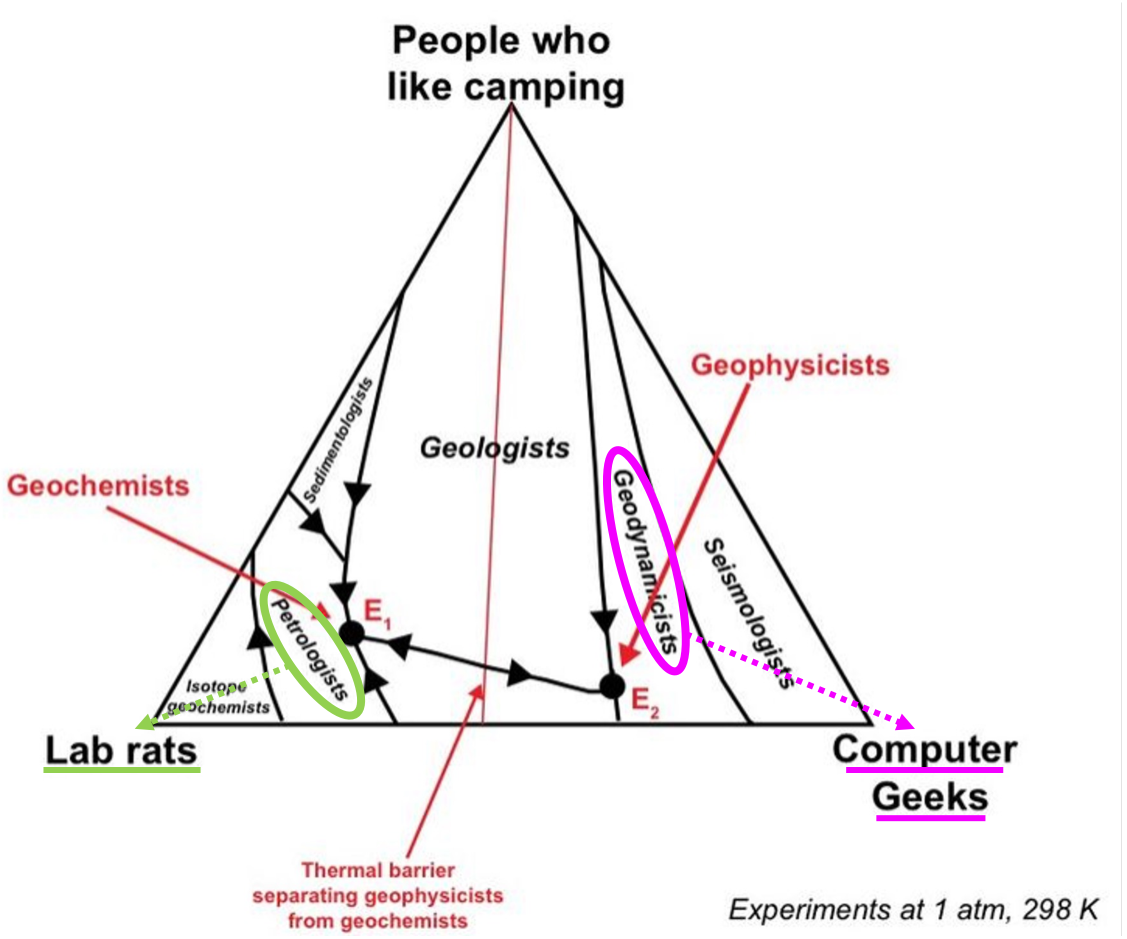

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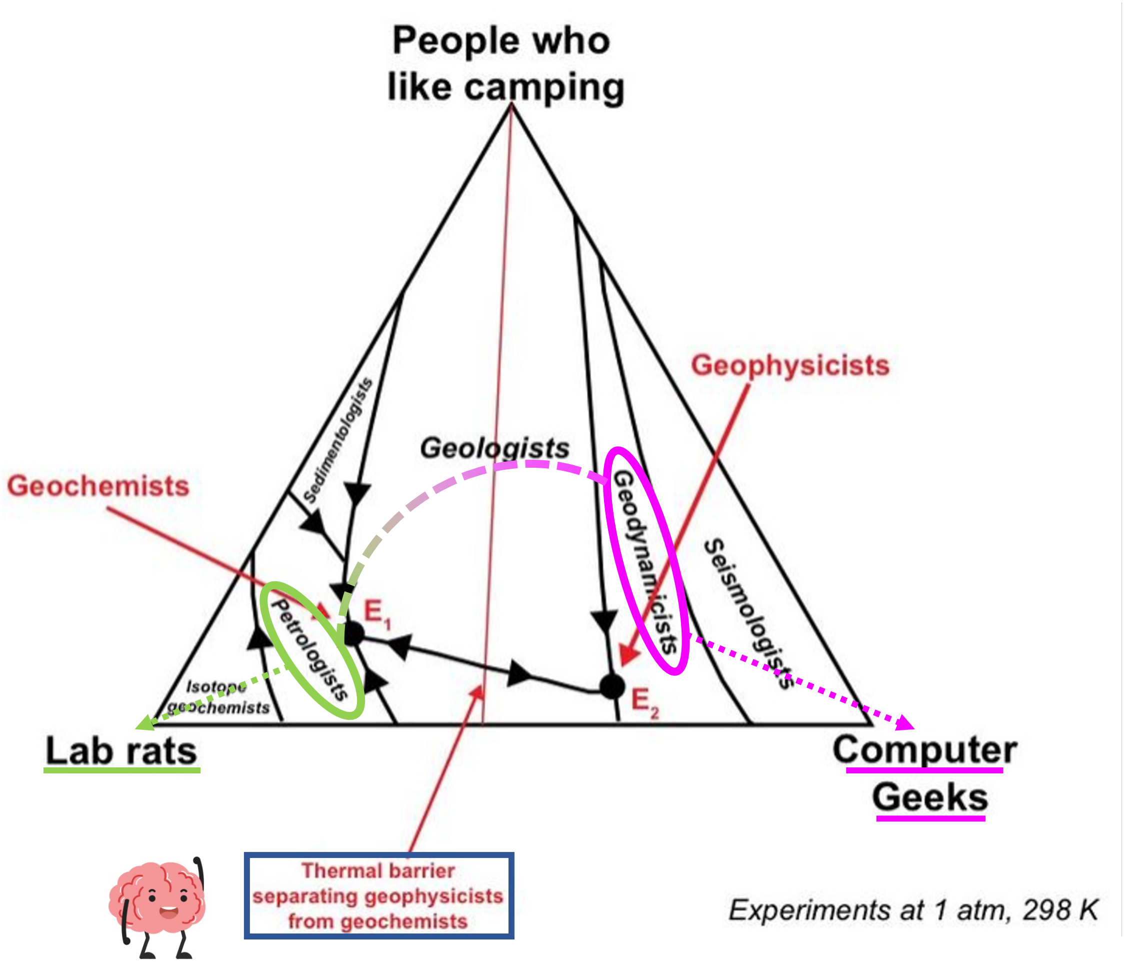
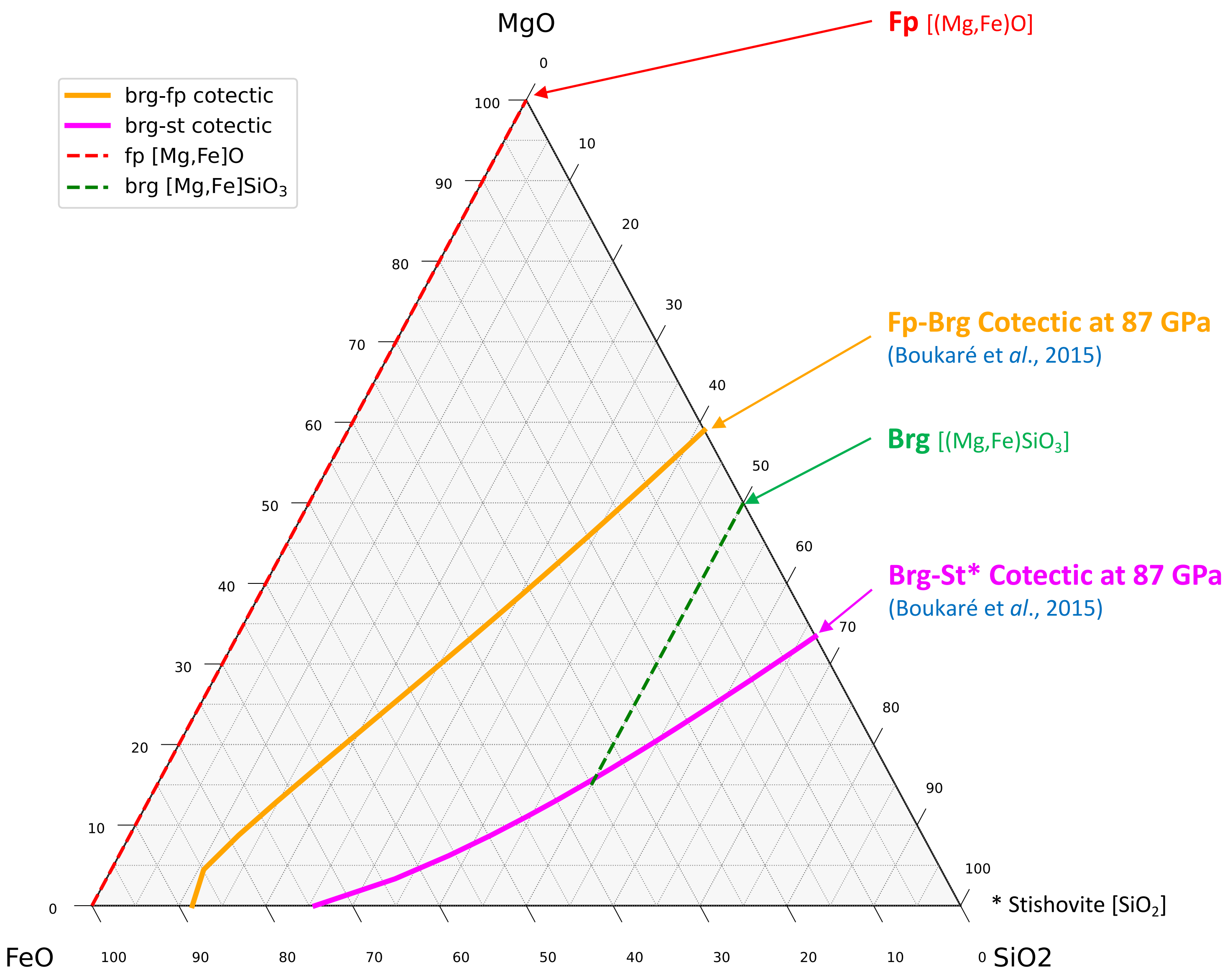


Experiments at 1 atm, 298 K

Confronting experimental results with thermodynamics



Confronting experimental results with thermodynamics

Ternary diagram

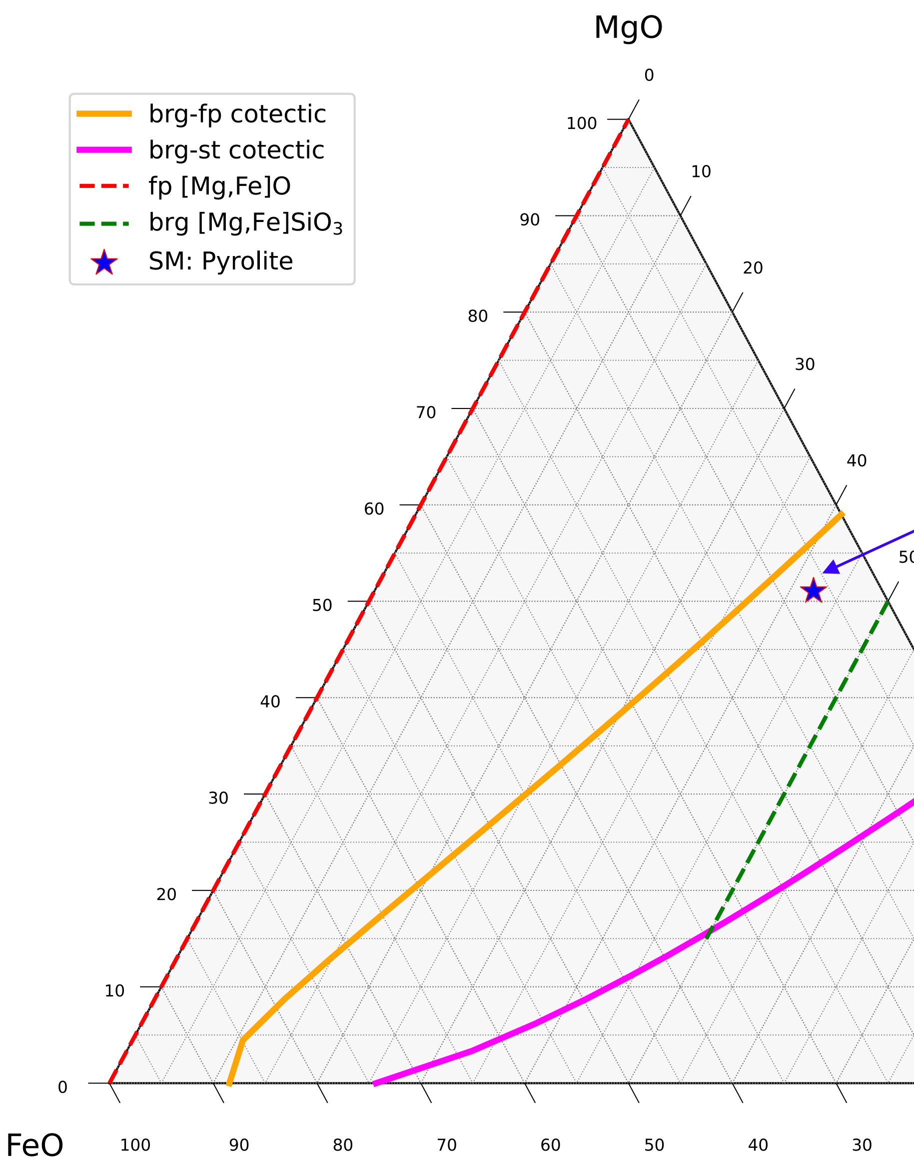
Magma Ocean

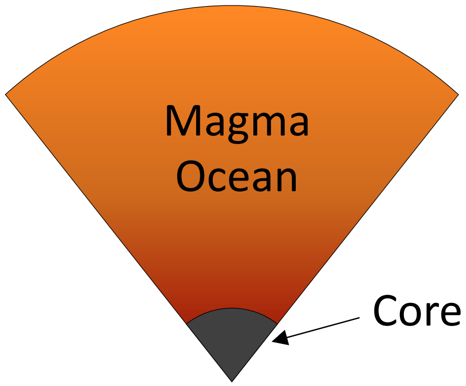
Description

DAC sample

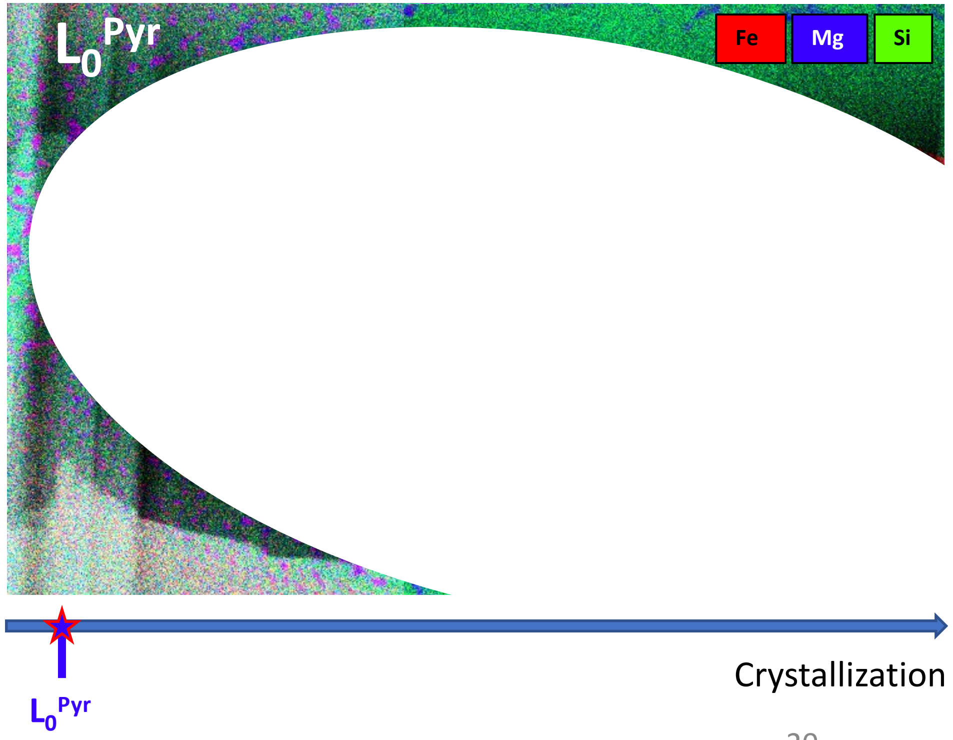
Crystallization

Confronting experimental results with thermodynamics





The DAC sample is laser-heated so that to melt: it is a microscopic magma ocean.



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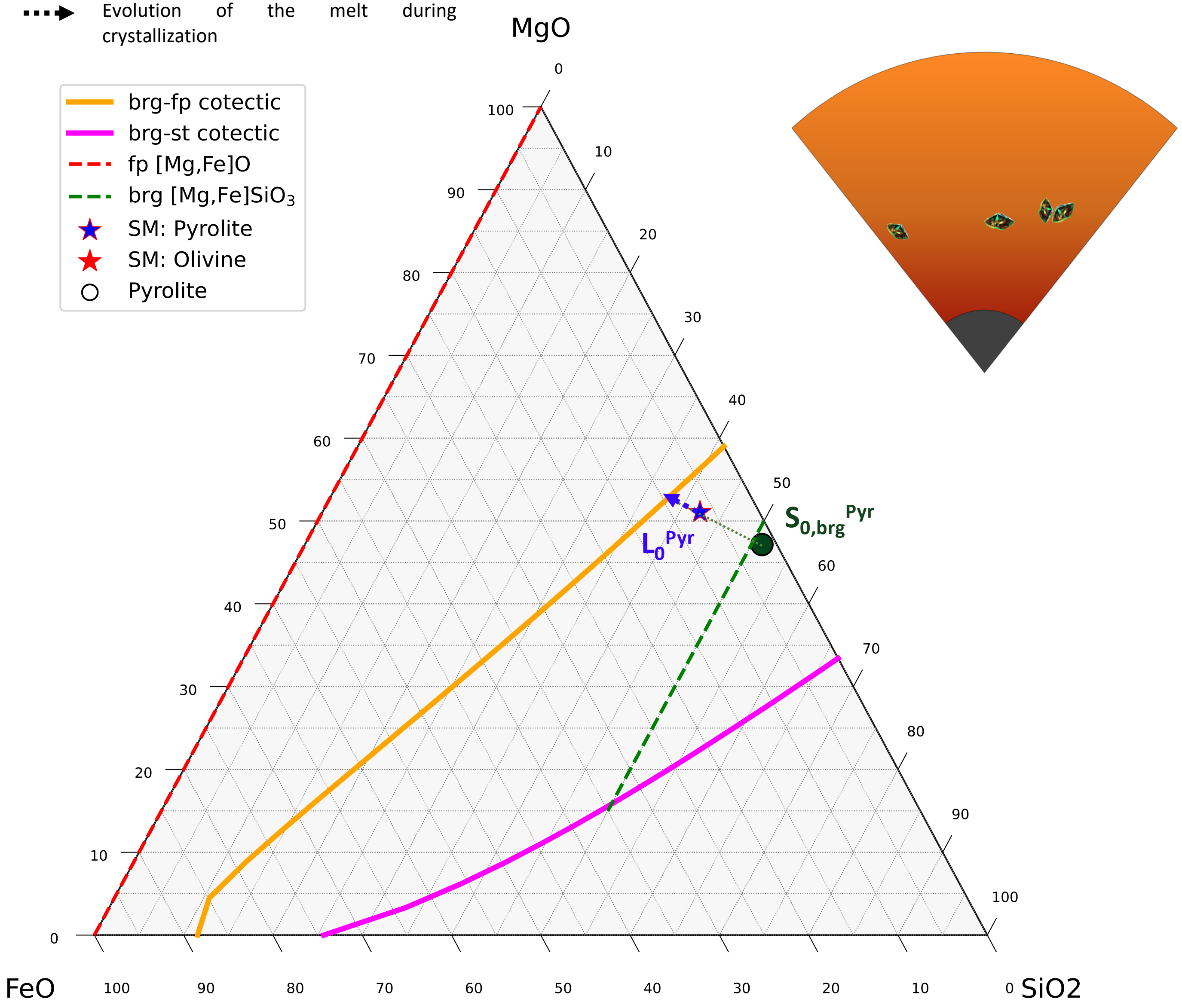
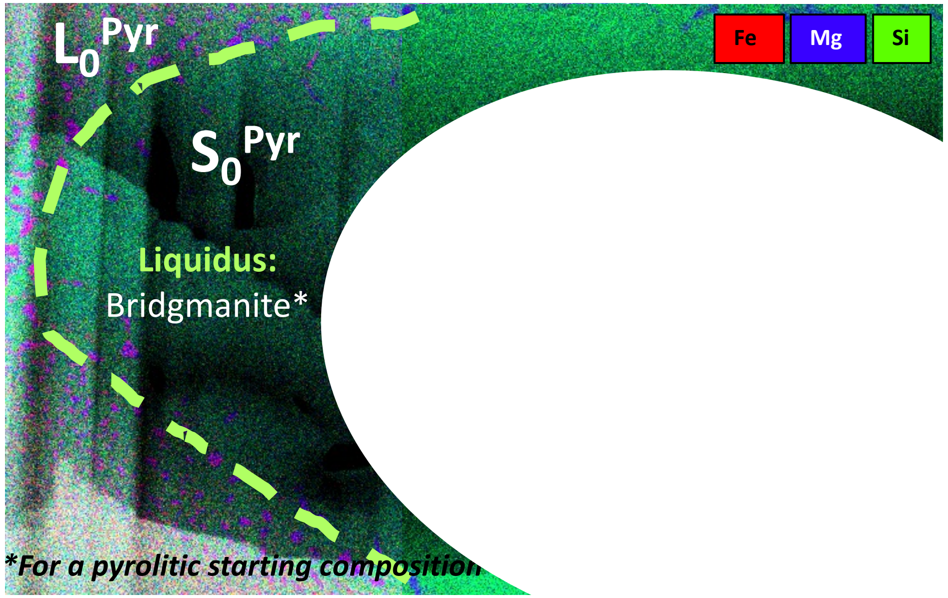


After being fully molten in the DAC (through laser-heating), the sample is slowly being cooled down. As temperature decreases the pyrolitic melt L_0^{Pyr} reaches the liquidus and starts crystallizing bridgmanite $S_{0,brg}^{Pyr}$.



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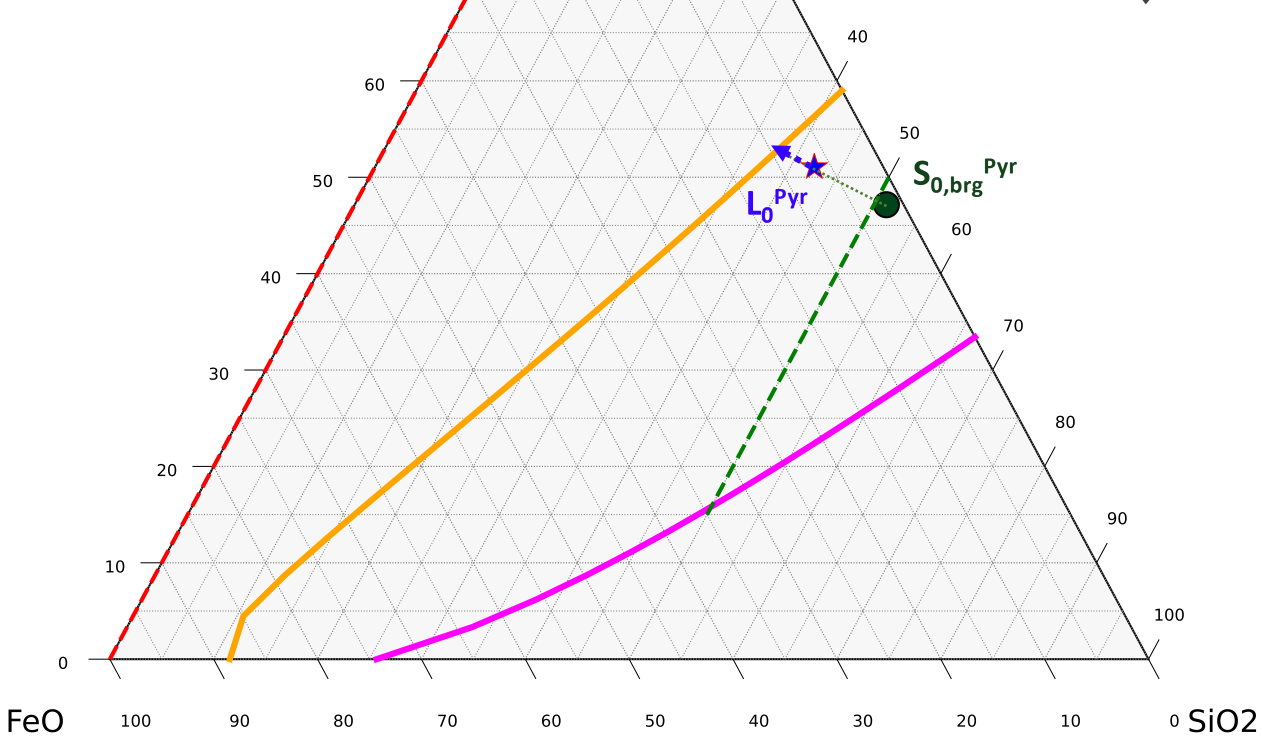

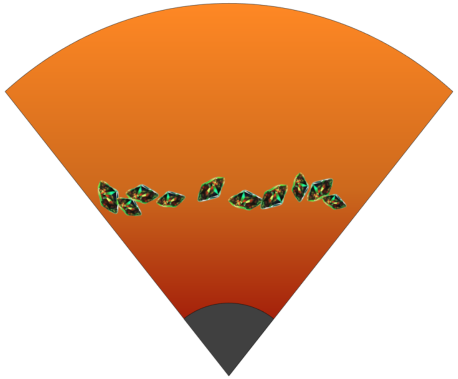

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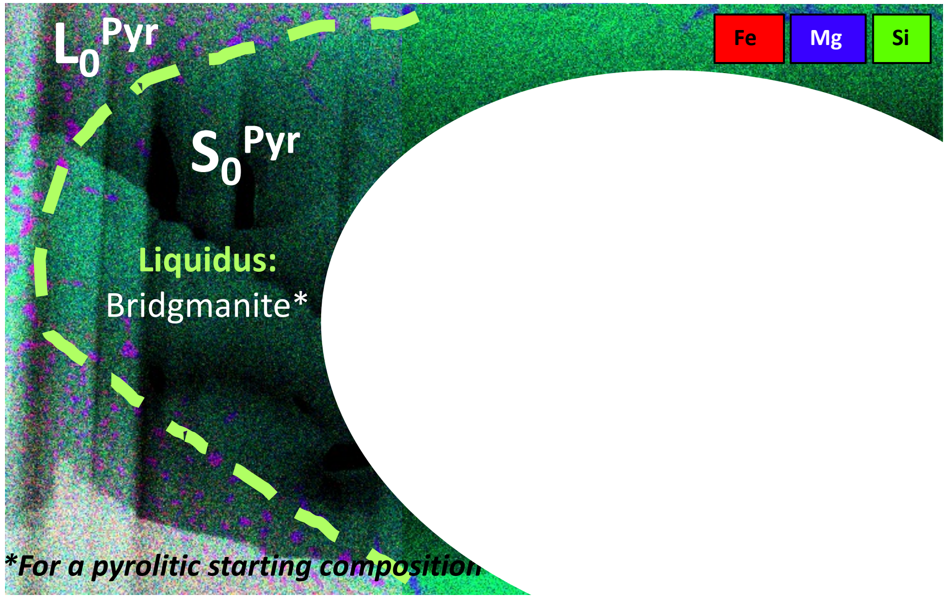

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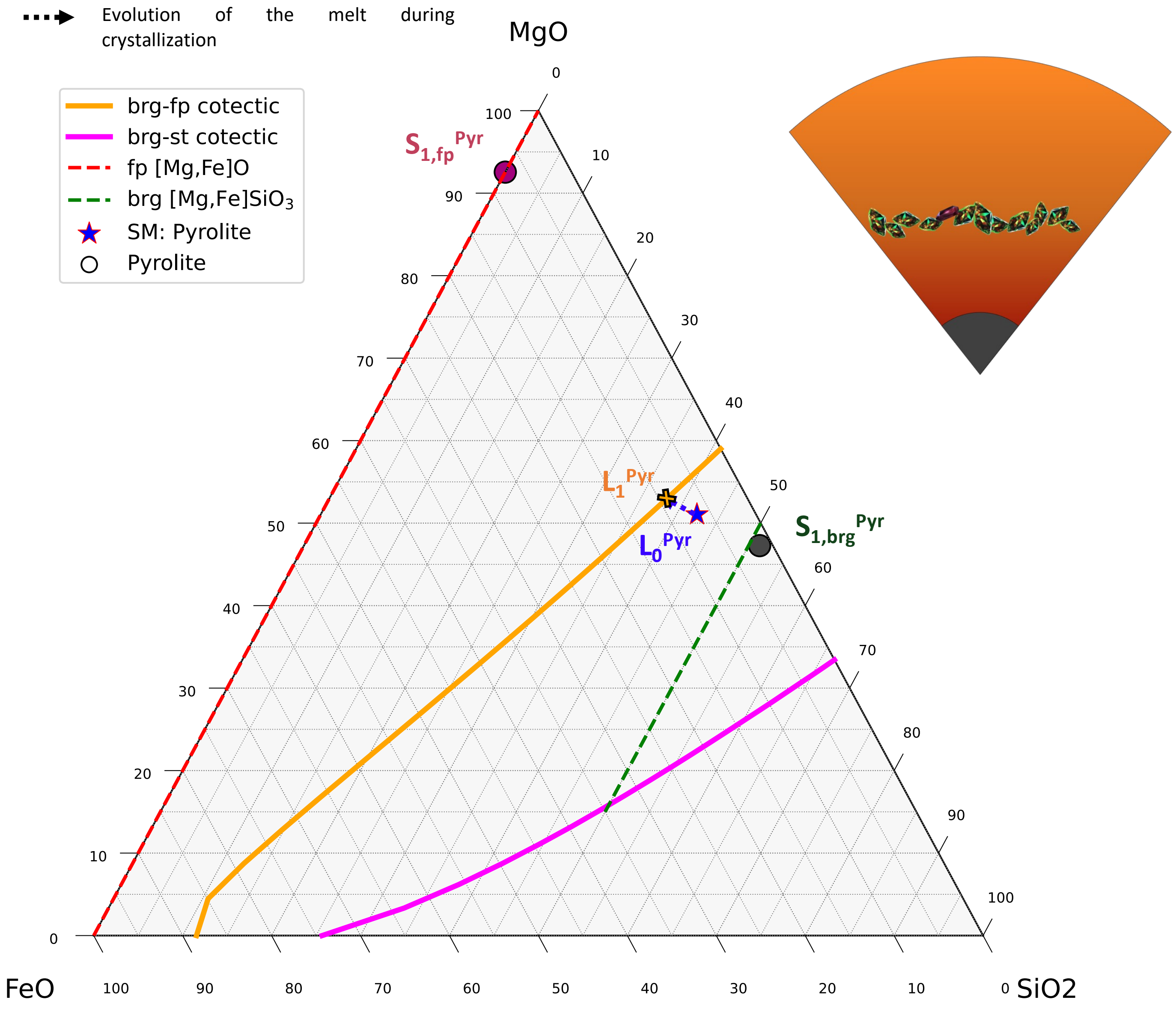
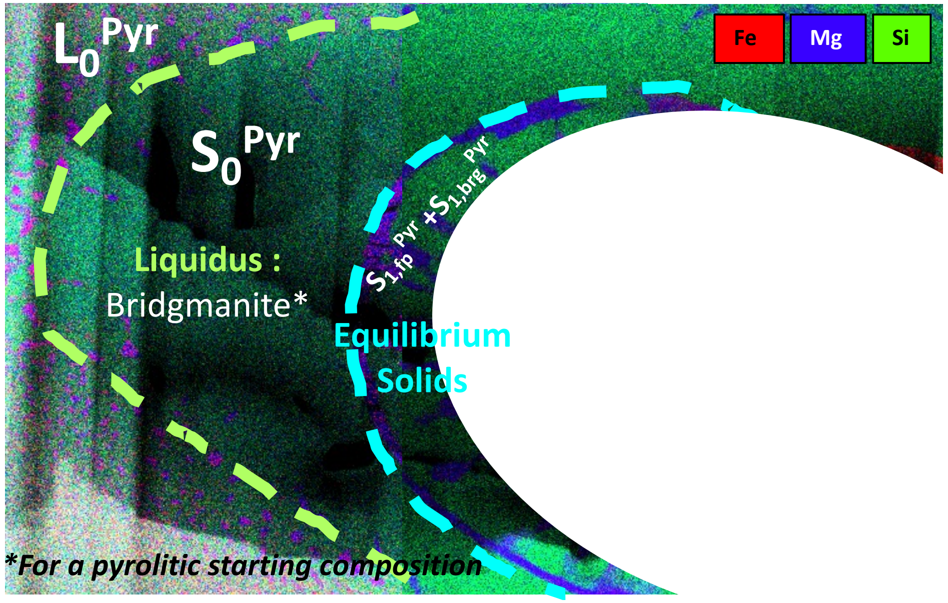
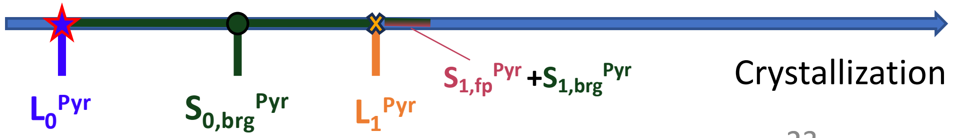


Focus on a pyrolitic fractional crystallization sequence

i. As crystallization proceeds, the liquid finally reaches the cotectic (L_1^{Pyr}) and a second solid starts forming: ferropericlase ($S_{1,fp}^{Pyr}$) along with bridgmanite that keeps forming ($S_{1,brg}^{Pyr}$).





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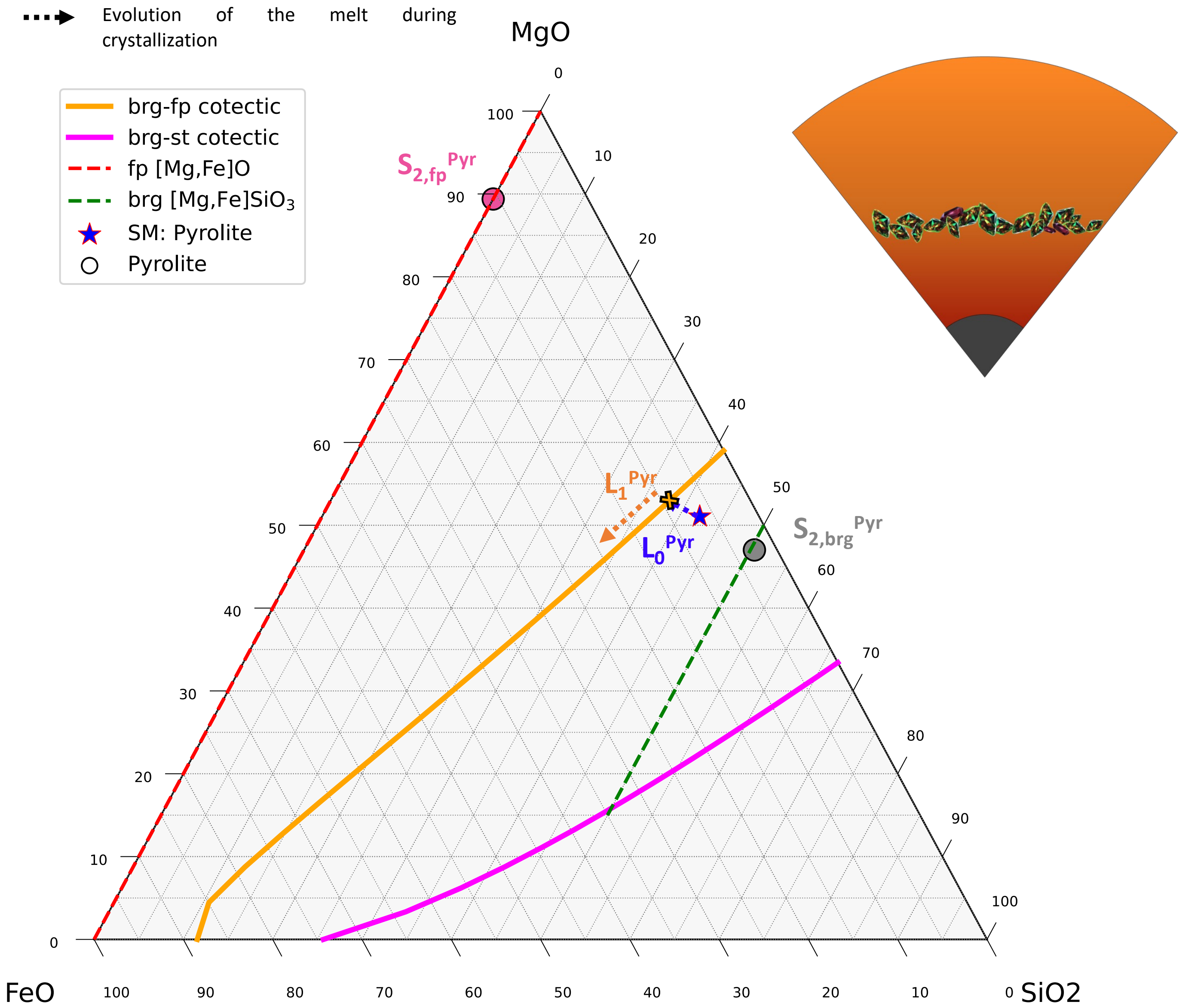
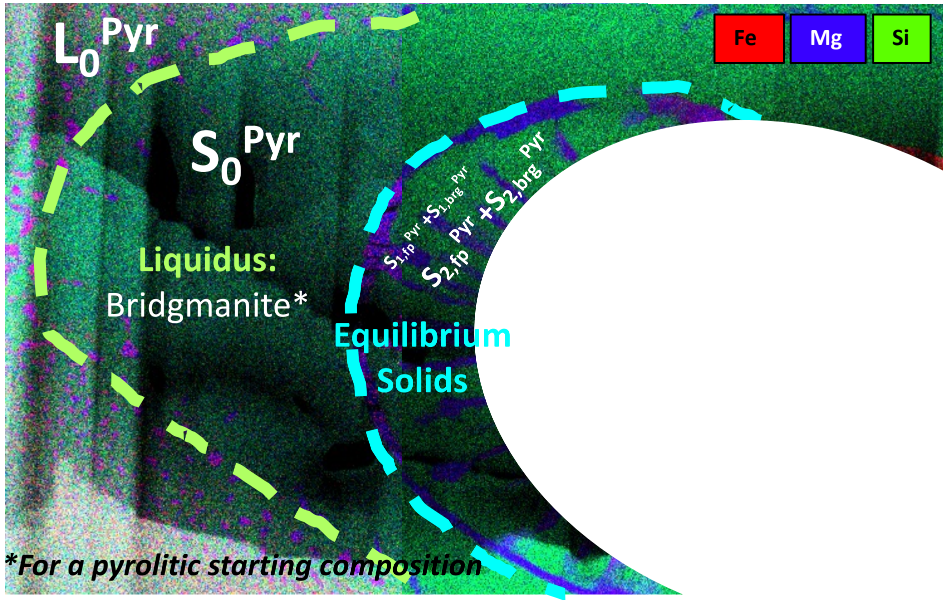
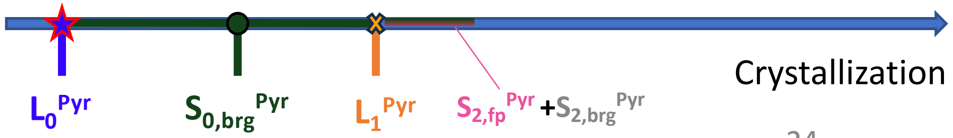


Focus on a pyrolitic fractional crystallization sequence

ii. Once the cotectic is reached, the liquid evolves along the line while ferropericlase and bridgmanite both keep forming until the experiment is quenched. As crystallization proceeds, all the different phases get enriched in iron but the compositional evolution of bridgmanite is much less pronounced than for ferropericlase and the residual melt.





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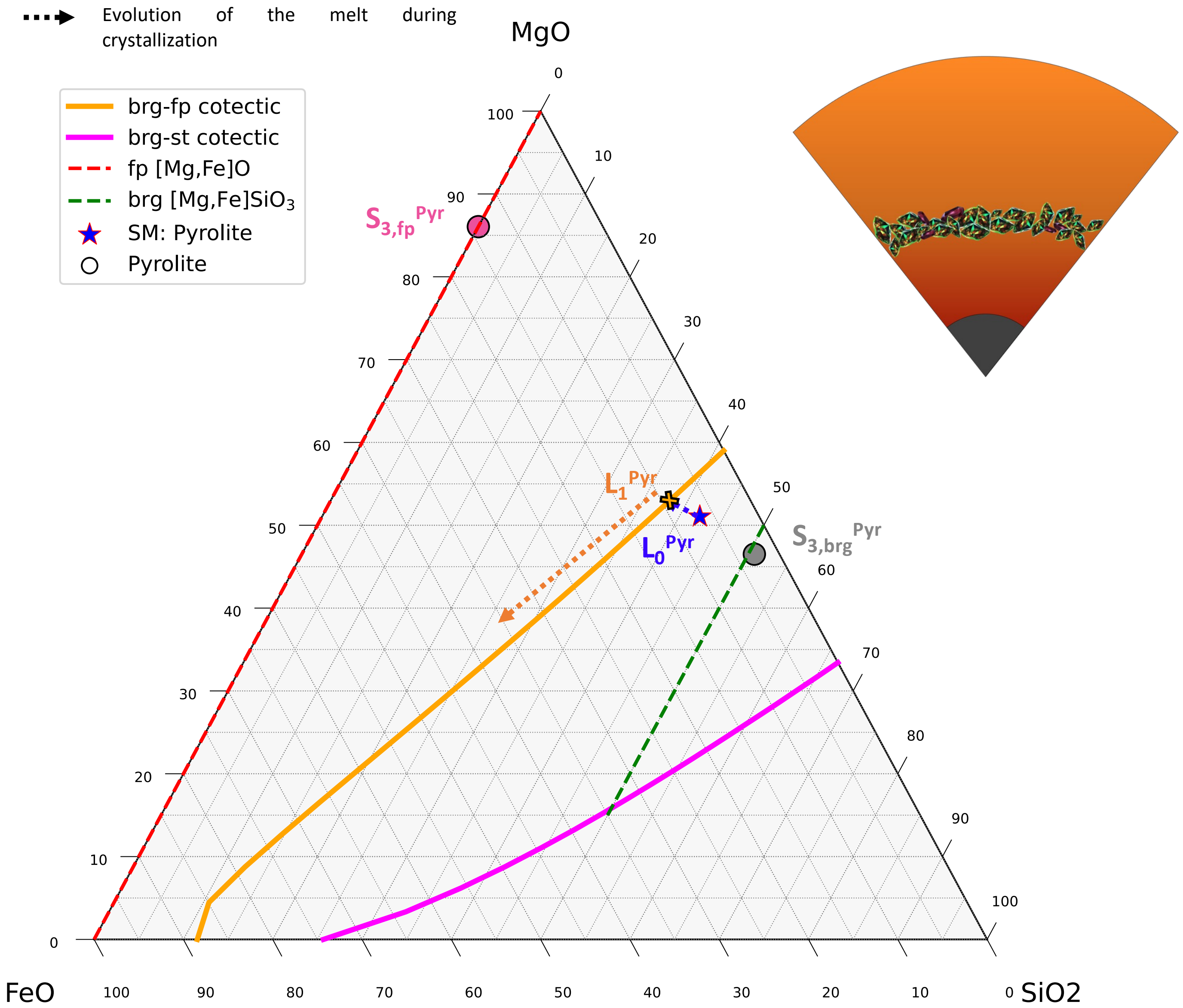

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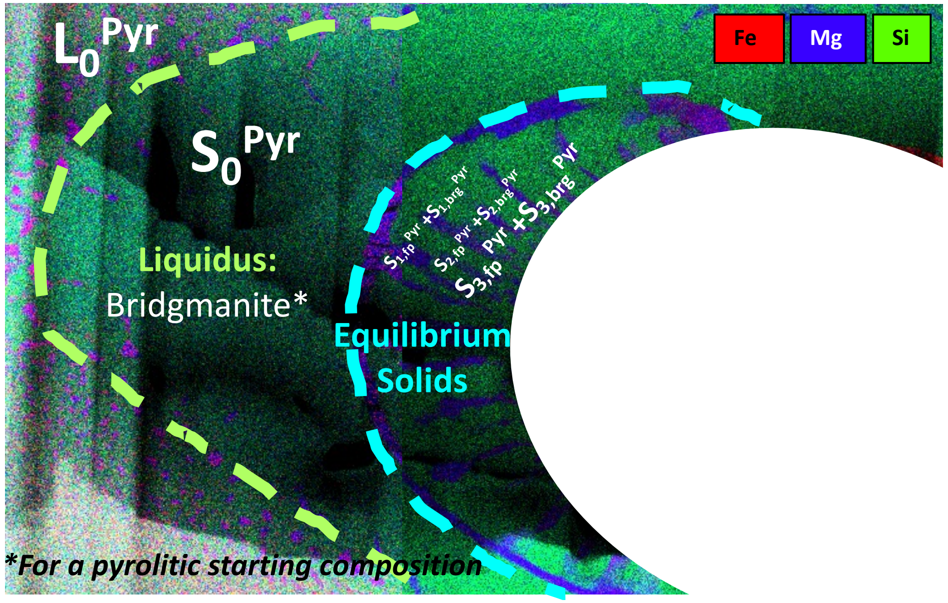

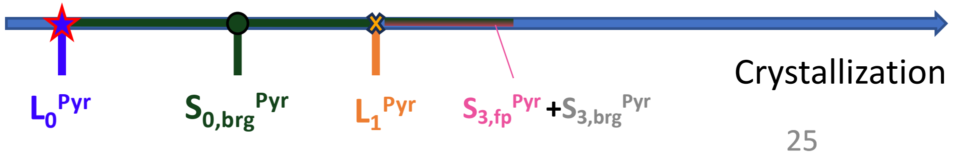

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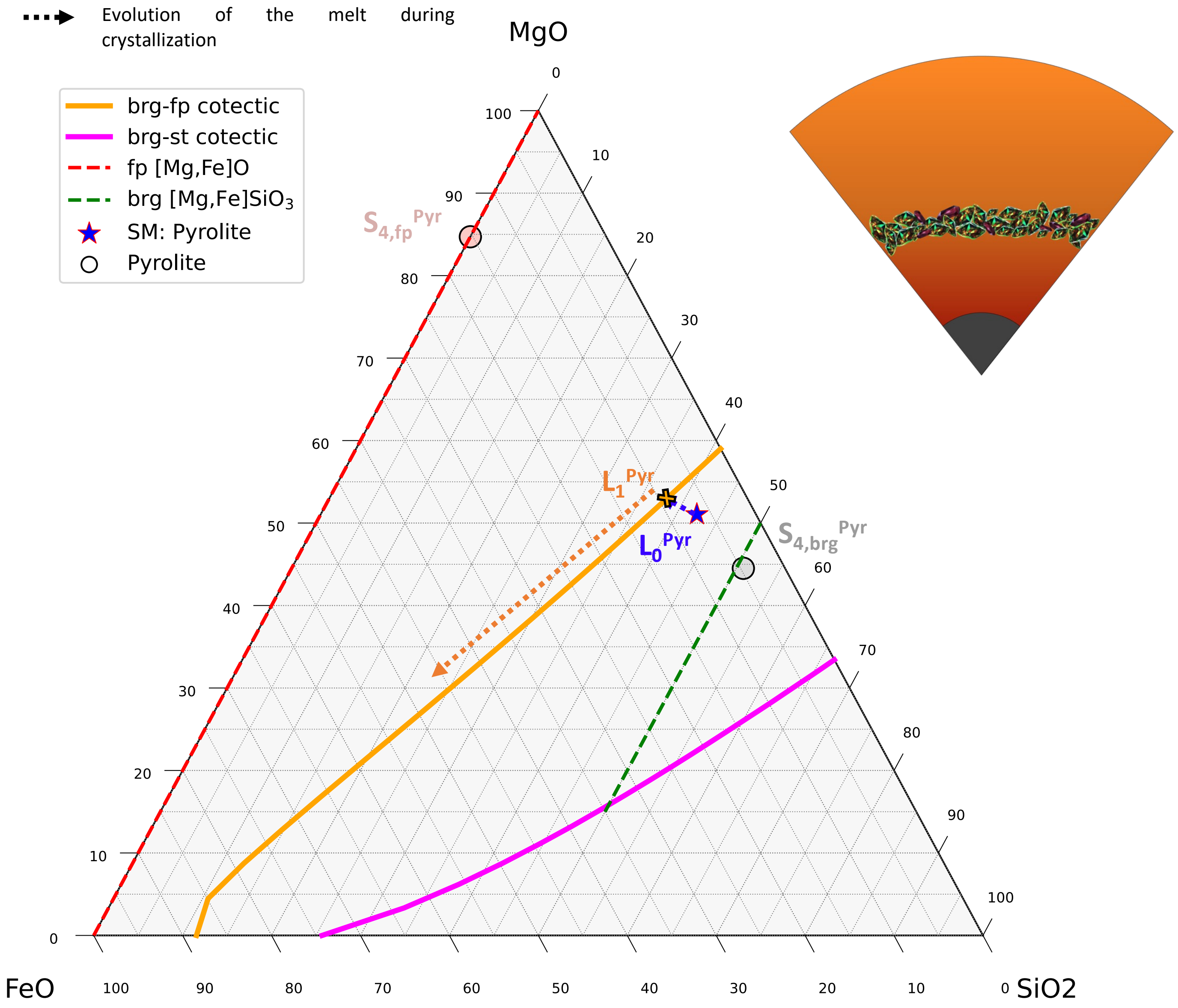

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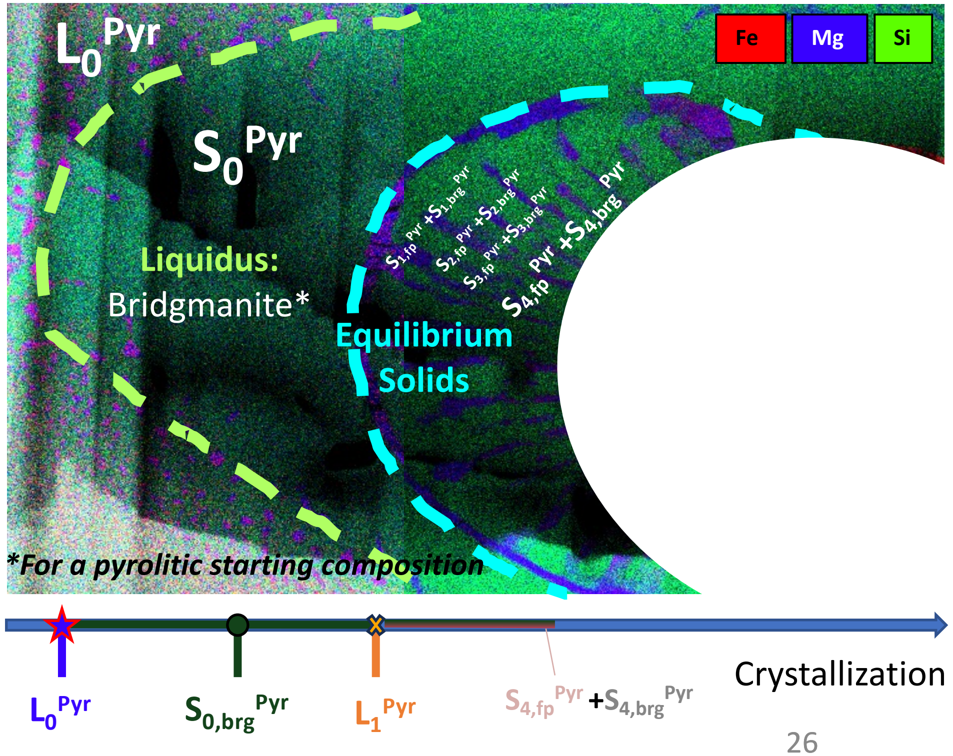

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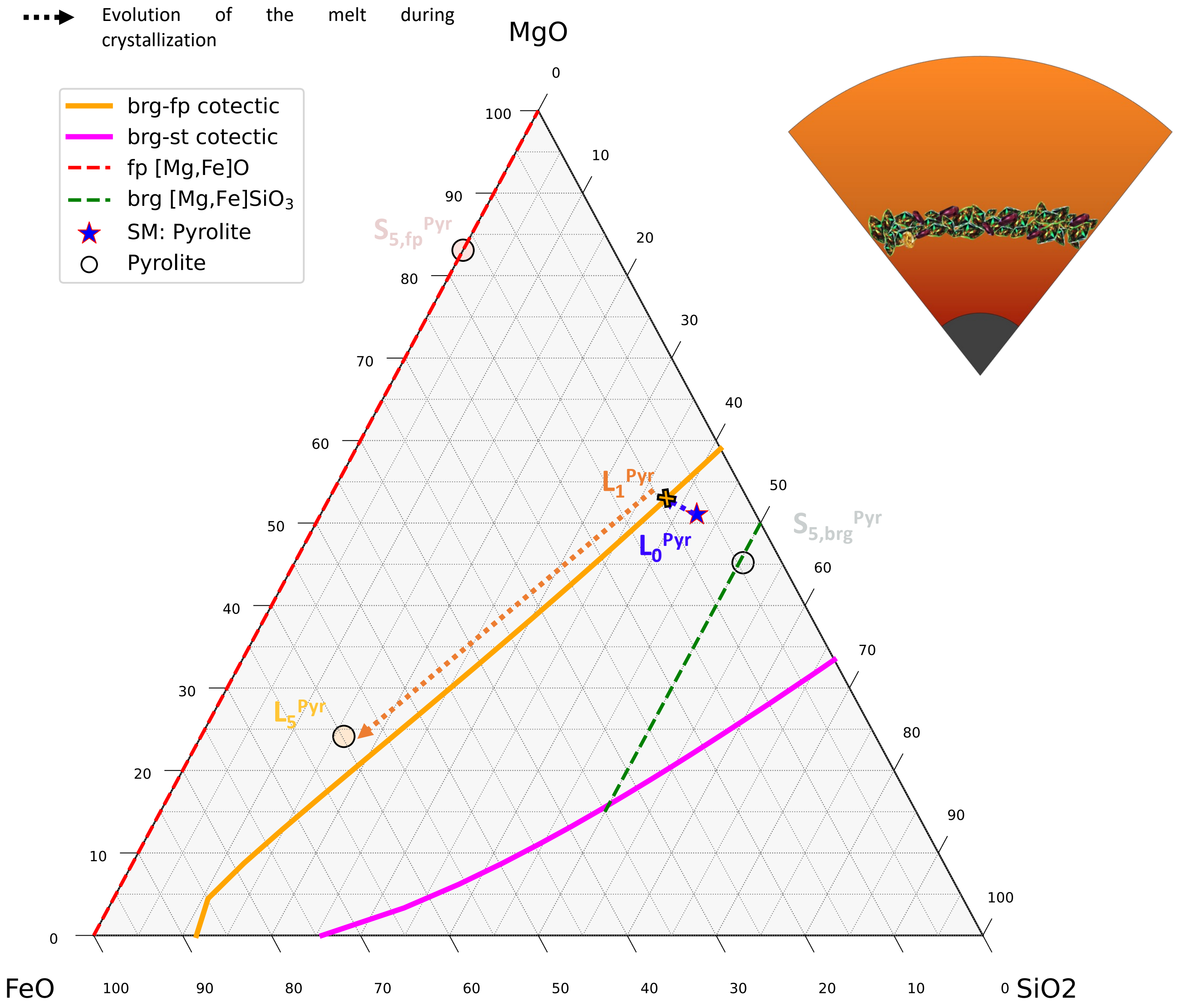

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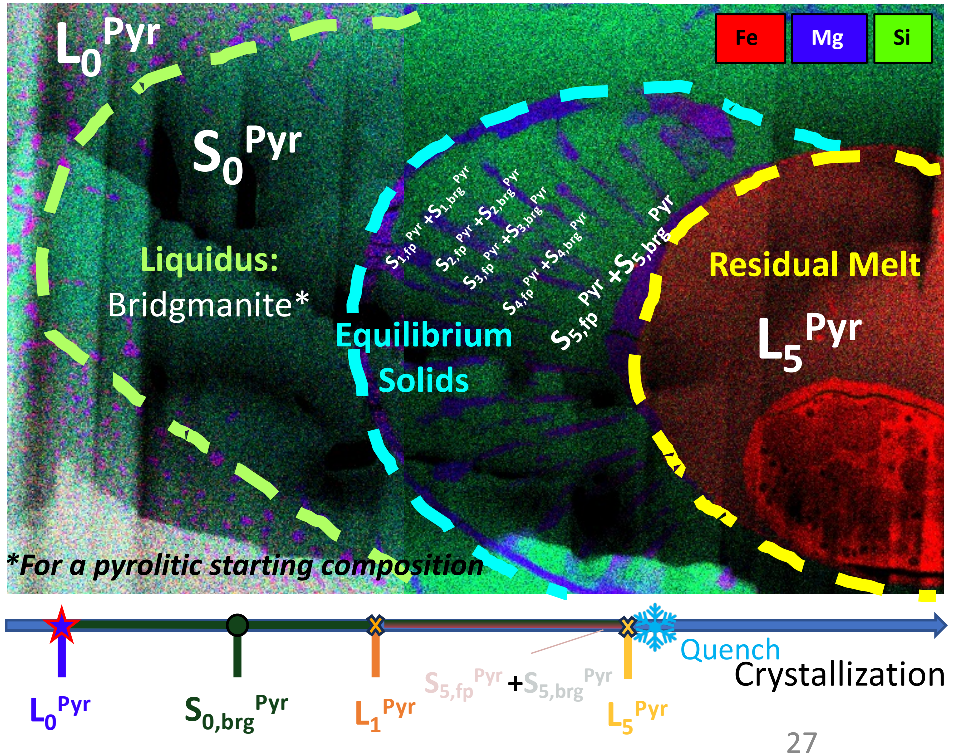
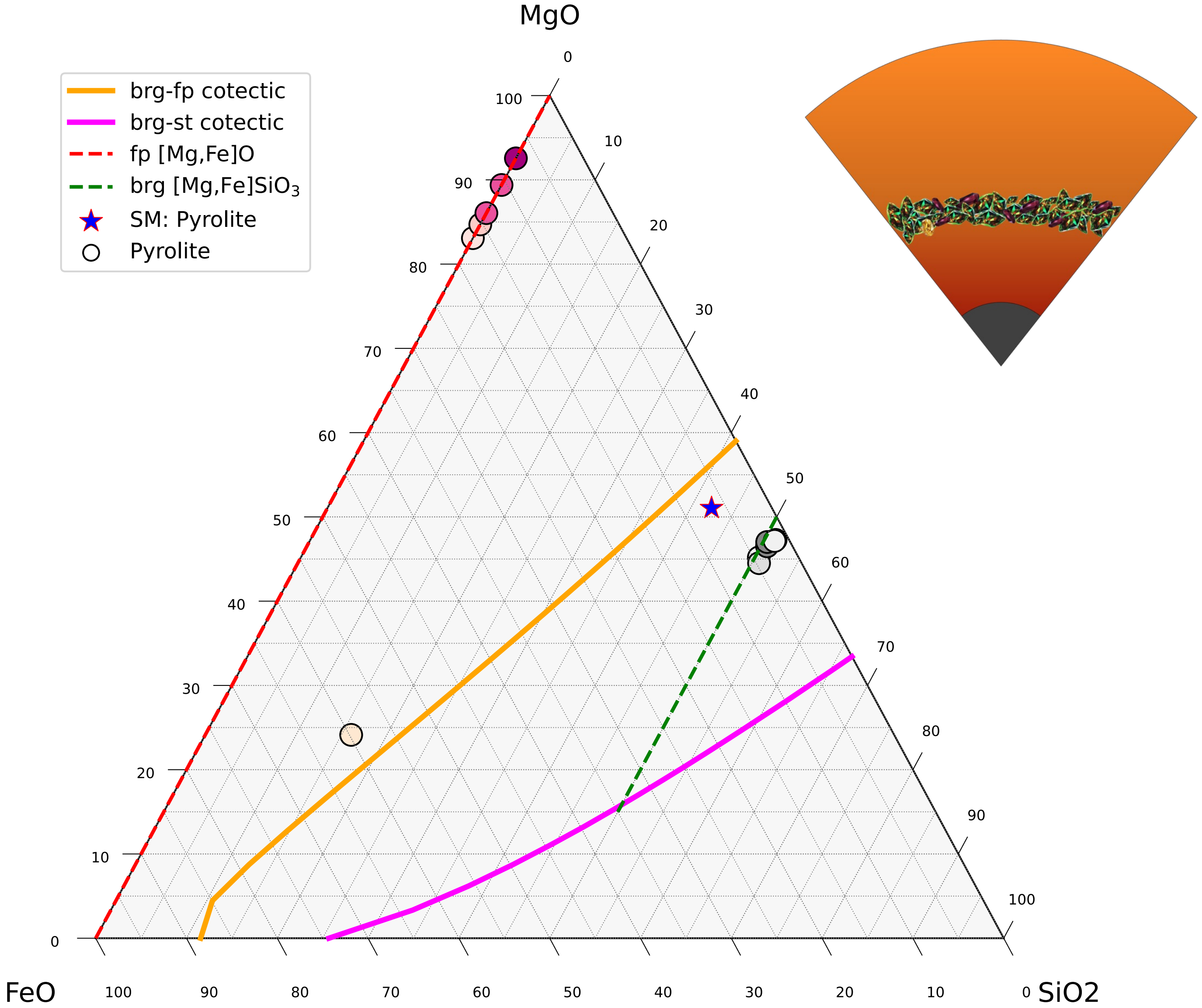
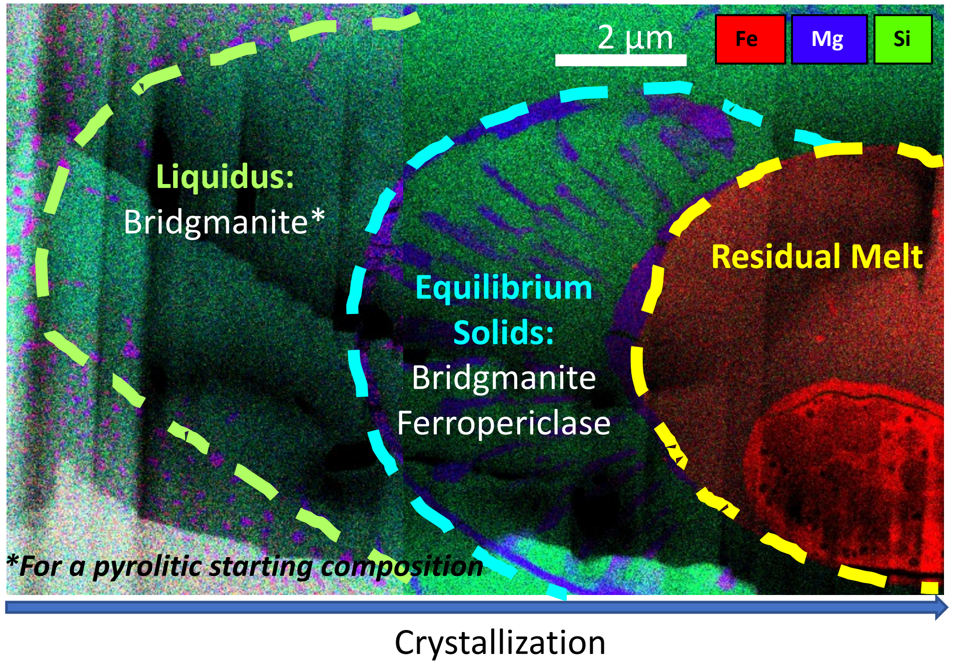
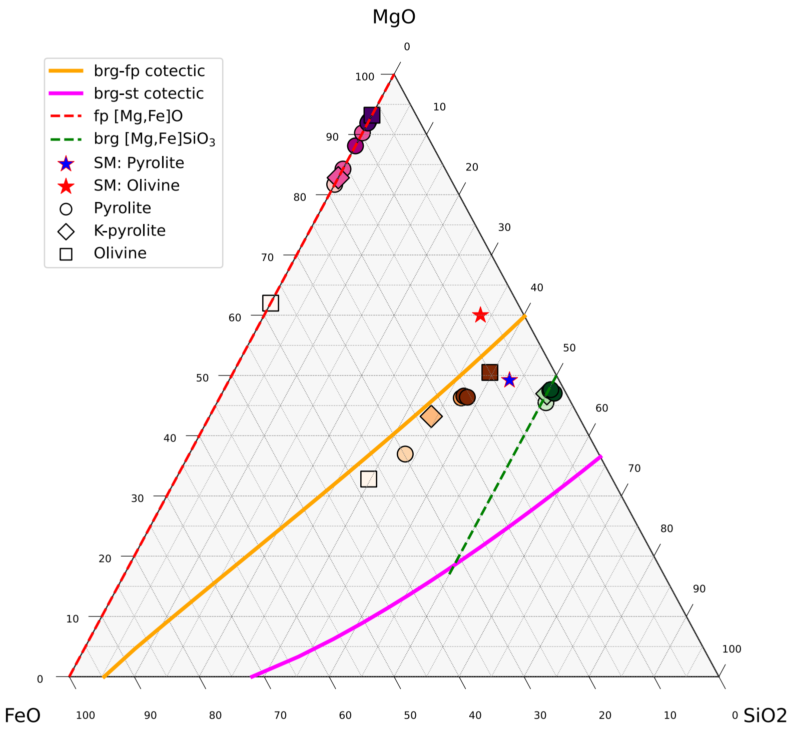


1 sample at 1 pressure (87 GPa)

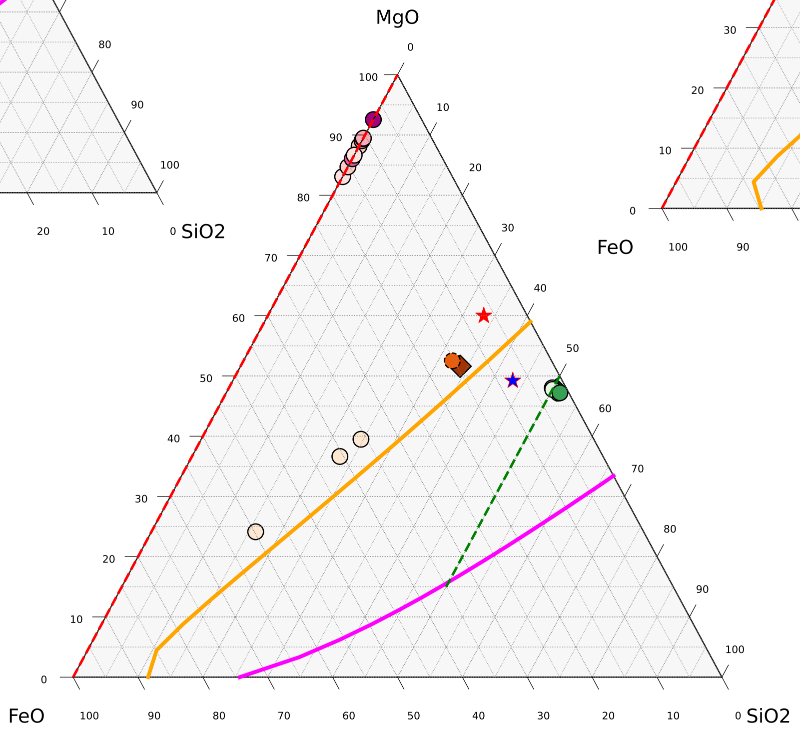


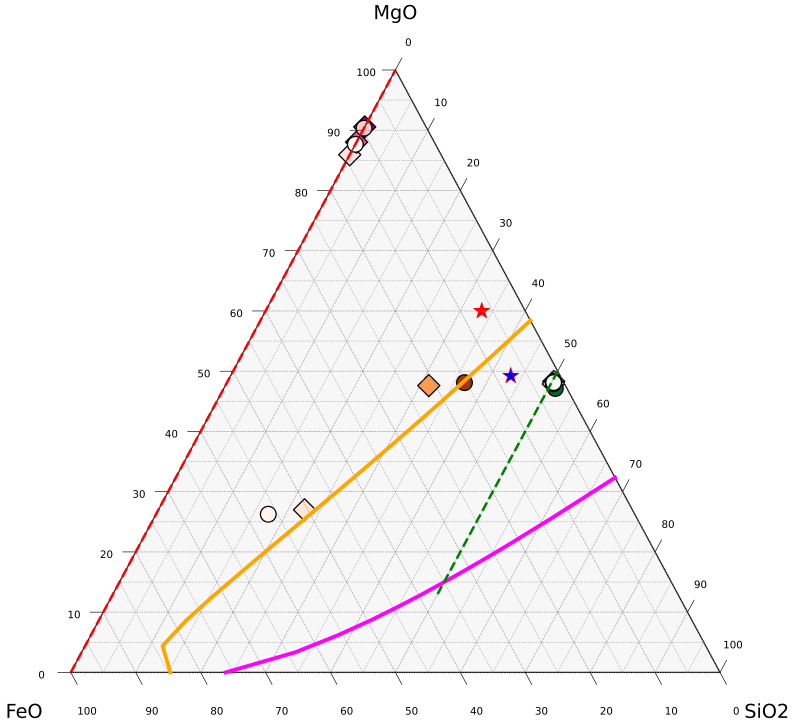




55 GPa

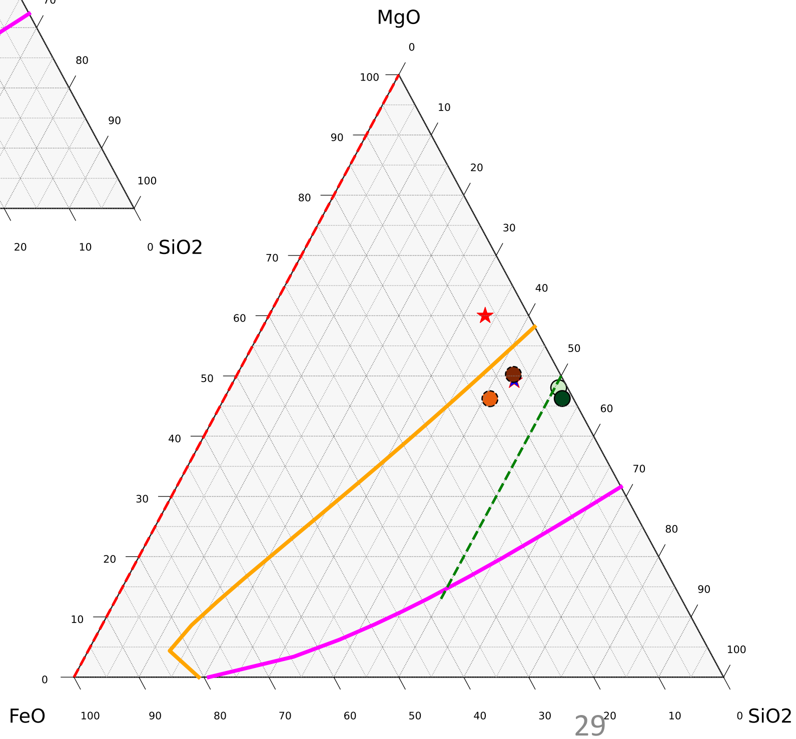
87 GPa





107 GPa

130 GPa



Main conclusions

- High-pressure high-temperature experiments in **diamond anvil cells** at 4 different pressures (55, 87, 107, 130 GPa) to constrain terrestrial magma ocean crystallization
- **Bridgmanite is the 1st mineral to form** in a deep pyrolitic magma ocean followed by ferropericlase
- **Residual melts**, which correspond to the final remnants of the magma ocean, are **very enriched in Fe**
- Determining the **melting phase diagram** allows to simulate the full **crystallization sequence of the magma ocean, at all depths**

Did This Really Happen?!

1.Did this really happen?!. 2018. *Did this really happen?!*. [ONLINE] Available at: https://didthisreallyhappen.net/. [29th March 2024].
2.Alice Adenis. 2018. *Entrelacs*. [ONLINE] Available at: https://entrelacsbd.wordpress.com/. [29th March 2024].