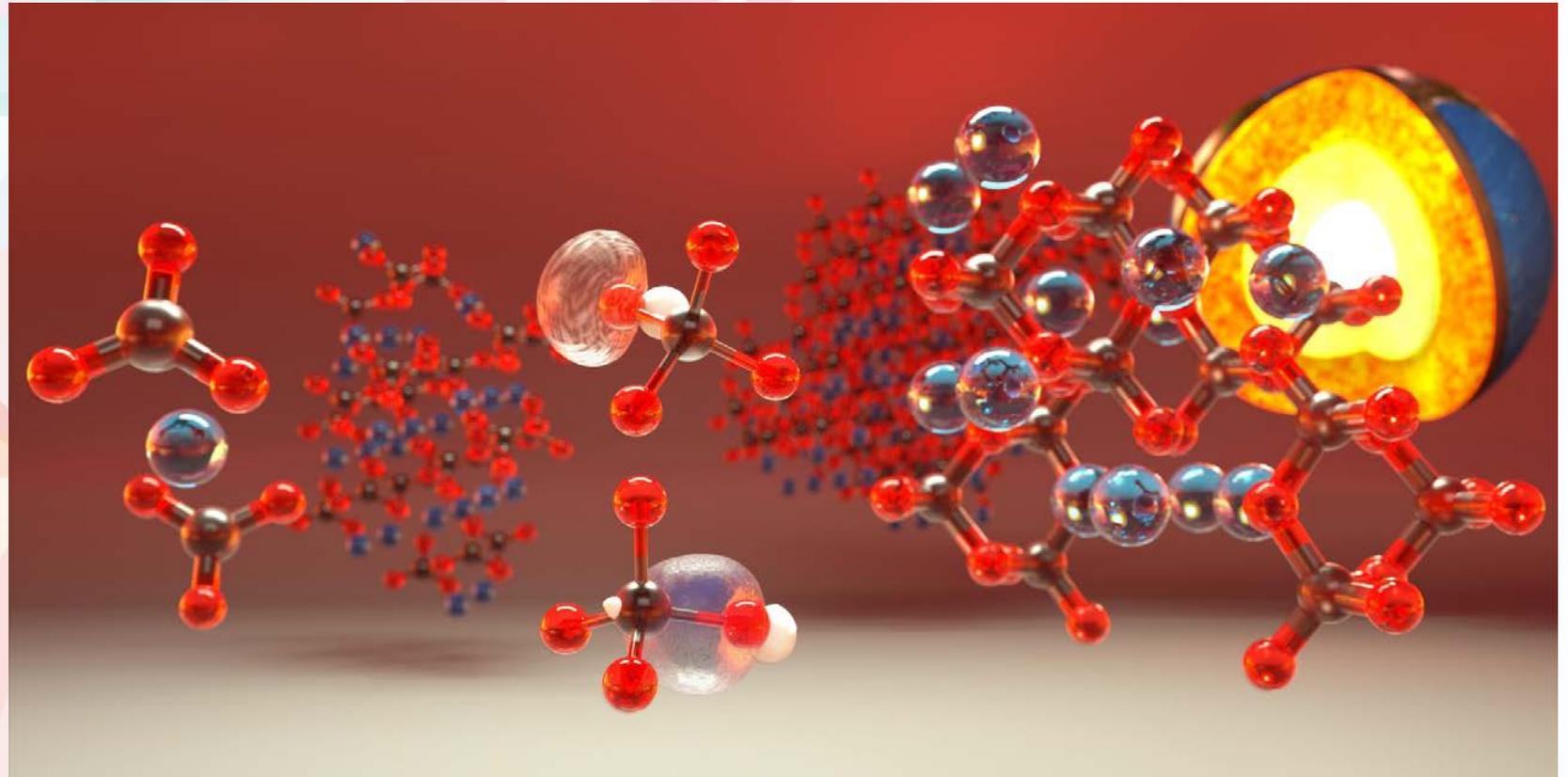
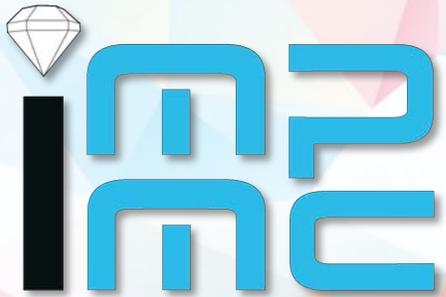


# Minéralogie de la Terre Profonde

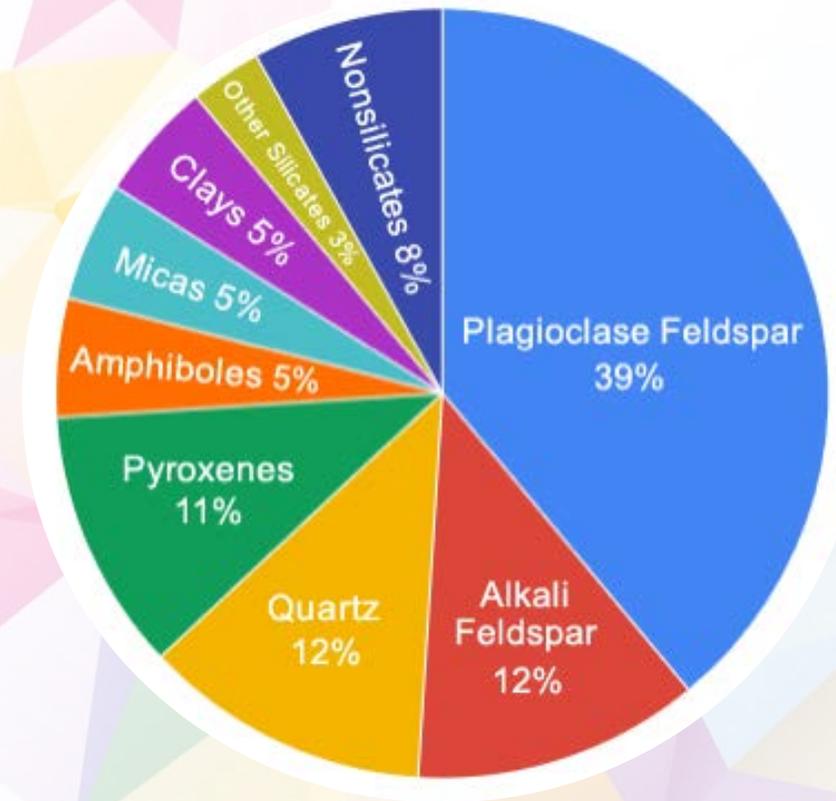
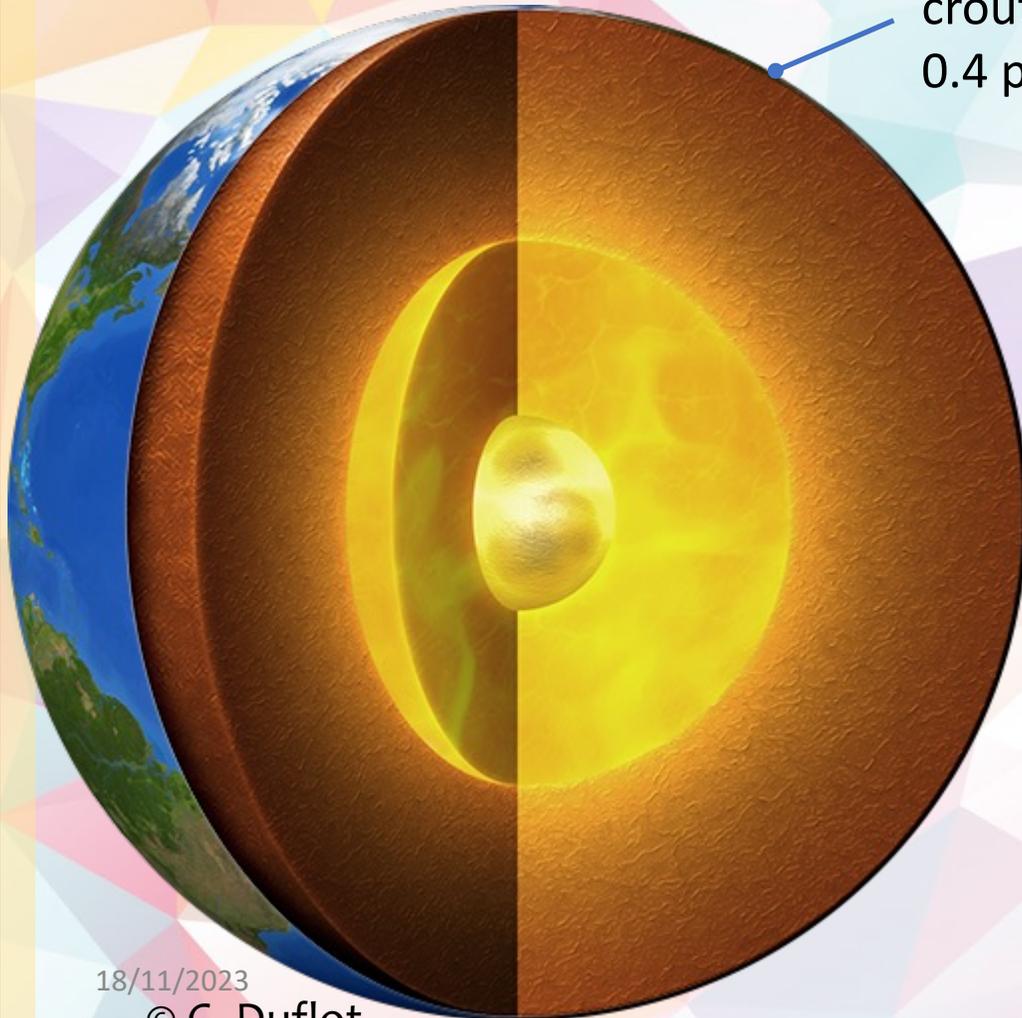
Eglantine Boulard

*Institut de Minéralogie, de Physique des Matériaux et de Cosmochimie (IMPMC), Sorbonne  
Université, CNRS UMR 7590, 75252 Paris Cedex 05, France*

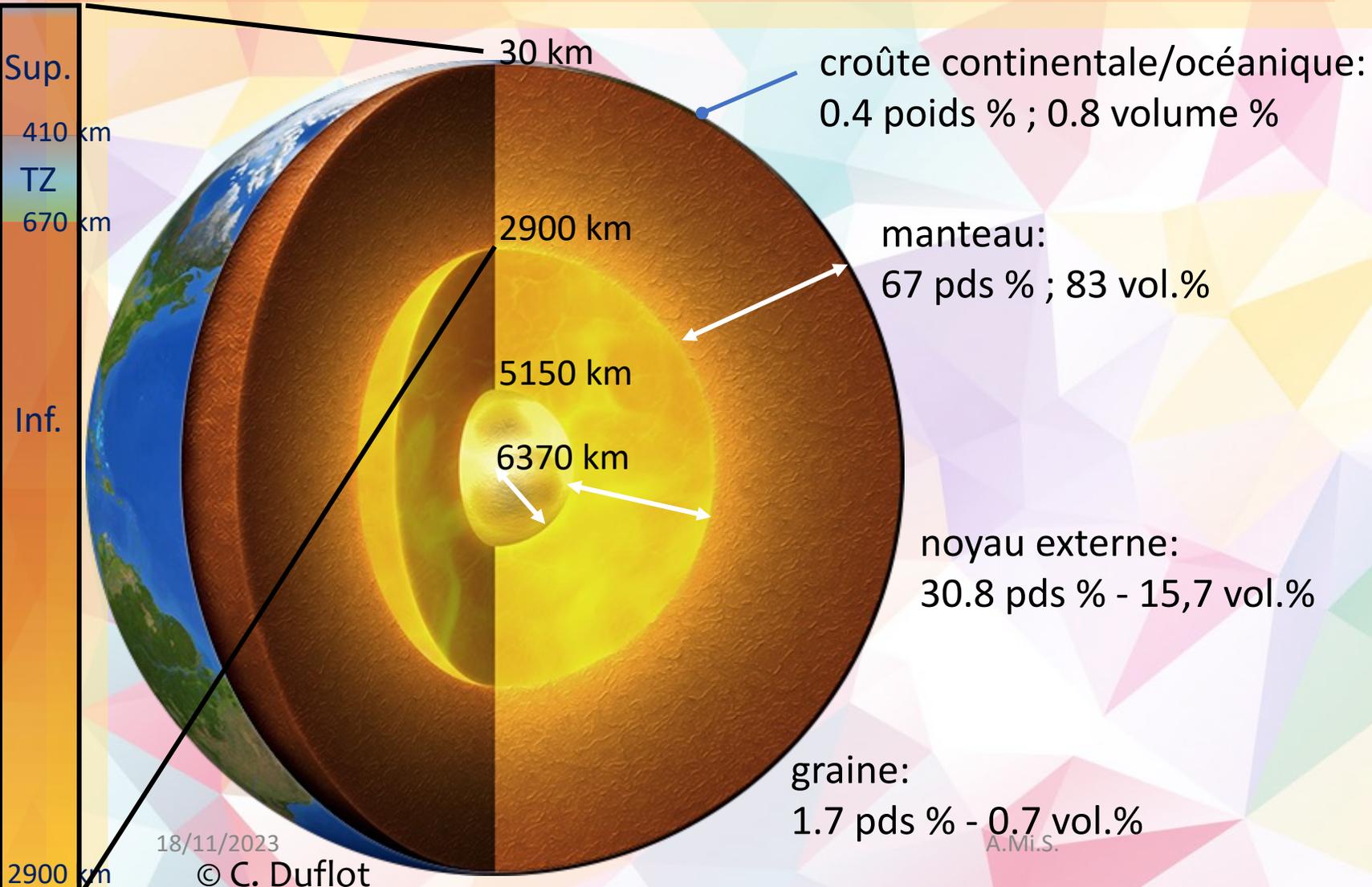


# Structure Simplifiée de la Terre :

croûte continentale/océanique:  
0.4 poids % ; 0.8 volume %



# Structure Simplifiée de la Terre :



# Accéder à la Terre Profonde



Sup.

410 km

TZ

670 km

Inf.



Deepest drilling S3G –Kola peninsula (Russia) – 12262 m



Depuis 2023, Basin Tarim, Chine : objectif 11 km

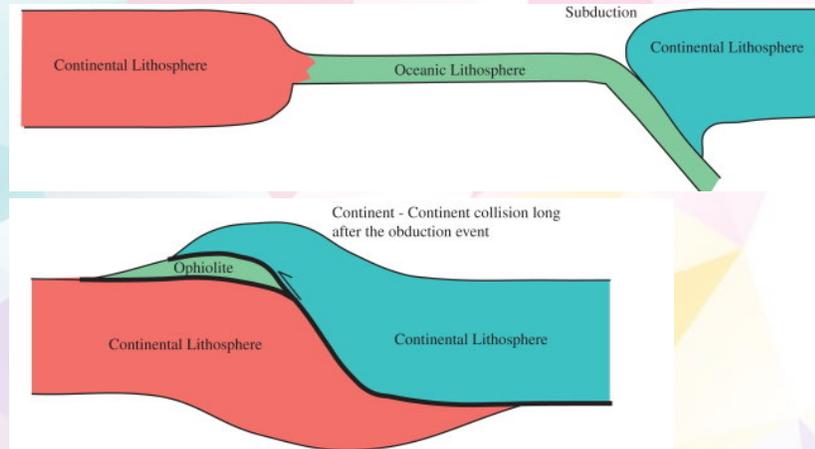
# Echantillons de la Terre Profonde

Sup.  
410 km  
TZ  
670 km  
Inf.  
2900 km

## Ophiolite



©James St Johns



## Eclogite



18/11/2023

©James St Johns

## Schiste Bleu



A.Mi.S.

< 60 km  
Roches qui ont subi un  
métamorphisme ou de l'altération

# Echantillons de la Terre Profonde

Sup.  
410 km  
TZ  
670 km  
Inf.  
2900 km

Laves



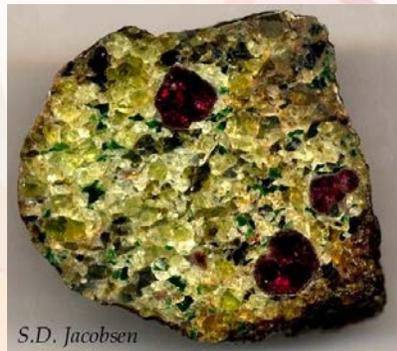
©Eglantine Boulard

< 300 km  
Fusion partielle

Péridotite & Péridotite à grenat



18/11/2023



S.D. Jacobsen

< 300 km

A.Mi.S.

Diamants avec inclusions du début du manteau inférieur



©Evan Smith

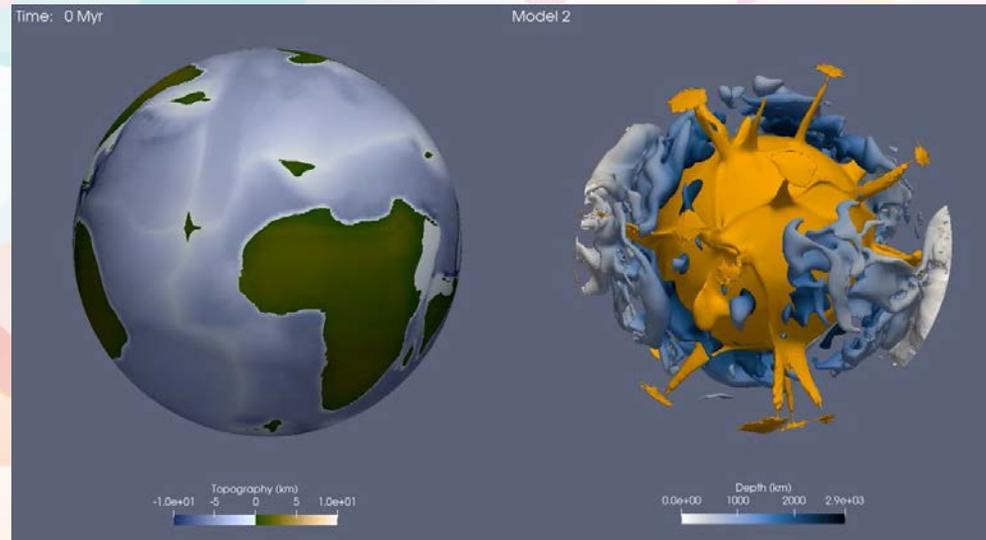
500µm

Jusqu'à 800 – 900 km  
Zone localisée

# Notre approche

## OBSERVATIONS:

Géochimie – Cosmochimie  
Géodésie, Gravimétrie,  
Sismologie



## MODELES & INTERPRETATIONS:

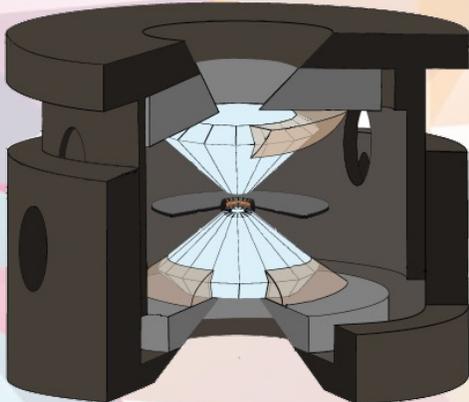
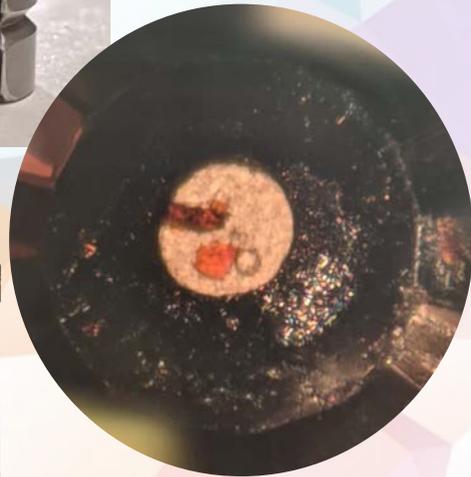
Chaque hypothèse mène à une origine,  
évolution ou géochimie profonde différente

**PETROLOGIE  
EXPERIMENTALE:**  
Propose des Candidats

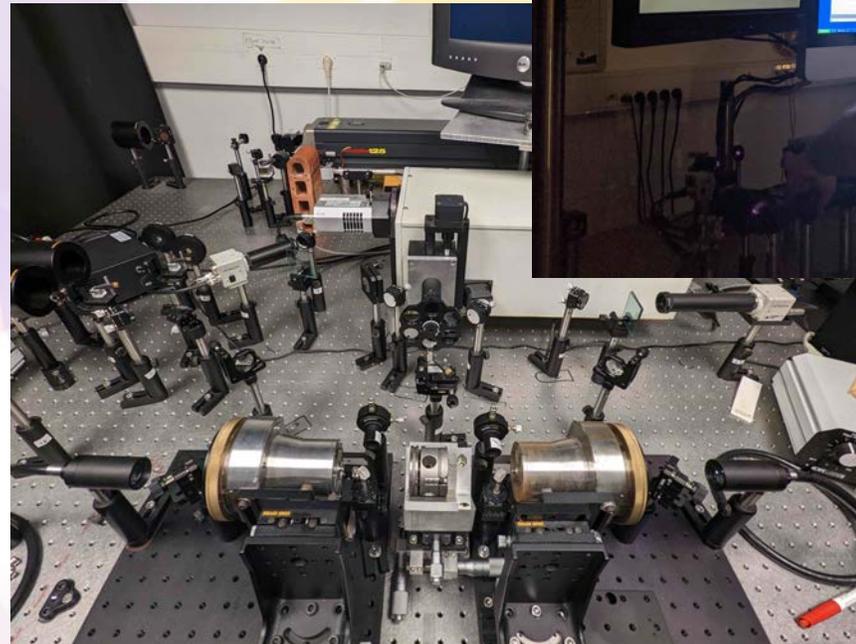
# Reproduire les Conditions Extrêmes



Cellule à enclume de diamant  
avec chauffage laser

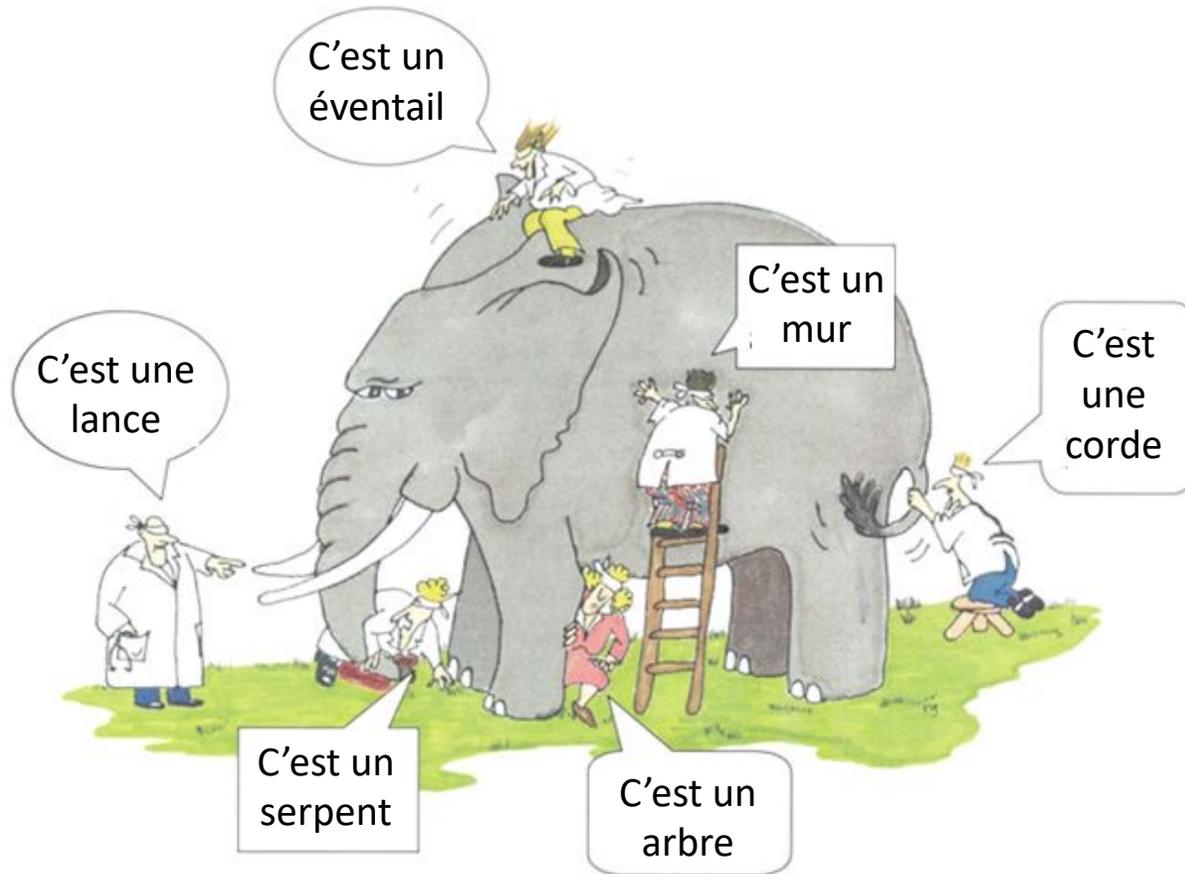


Shen & Mao, 2017

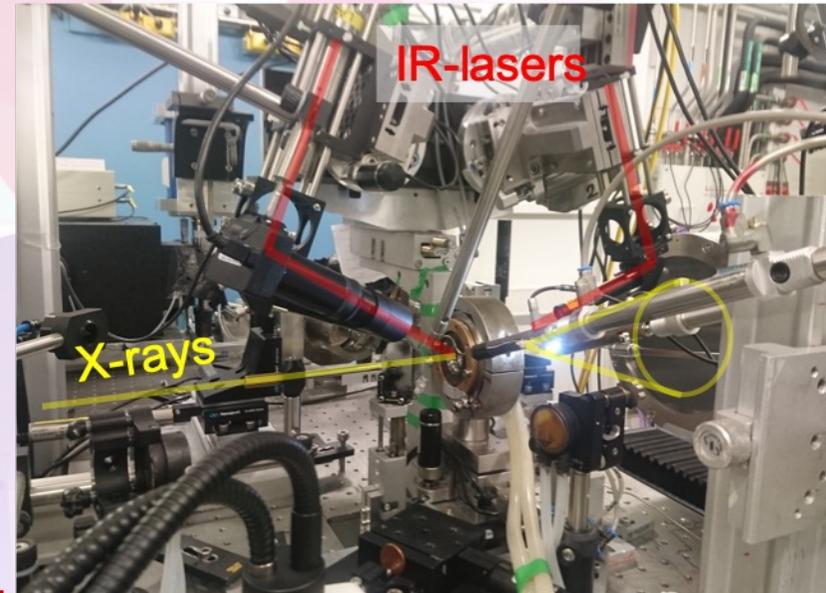
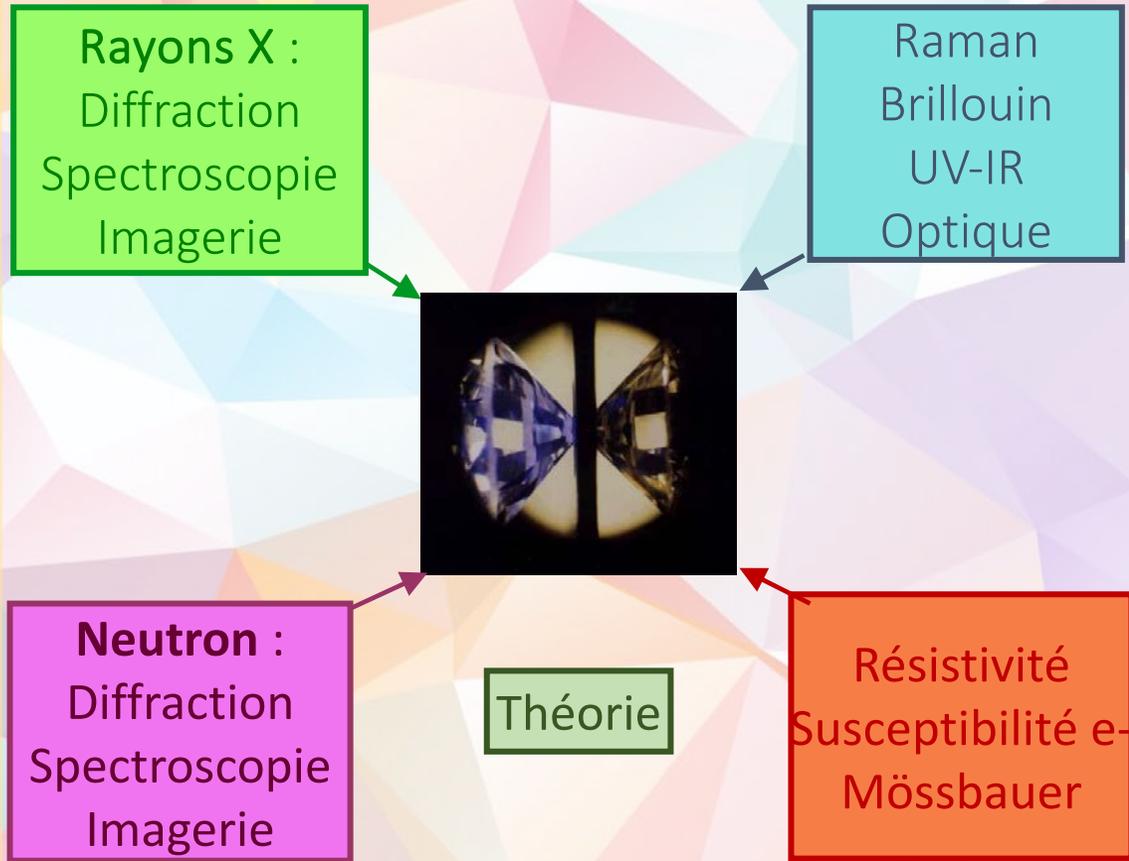


A.Mi.S.

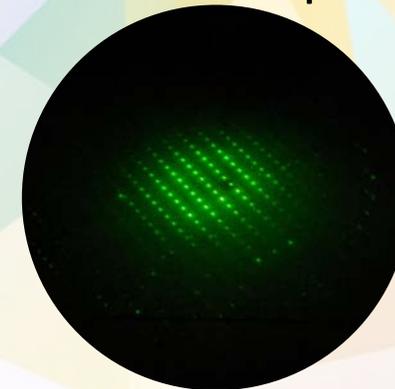
# Echantillons Synthétisés : Les six aveugles et l'éléphant



# Multiplier les Analyses



+ Microscopie électronique :



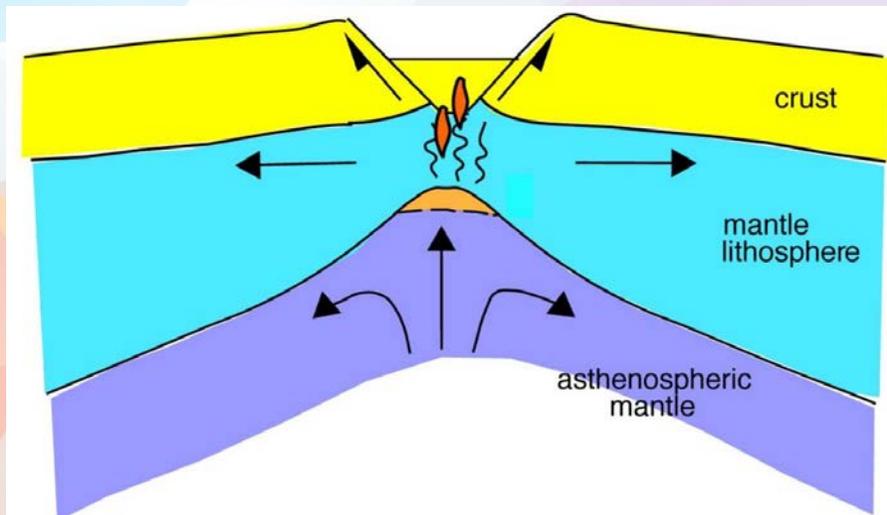
# Modèle d'un Manteau Pyrolitique

Ringwood, JGR, 1962 : **PY**roxene **OL**ivine :

Péridotite (Dunite/Harzburgite)

+

Basalte tholéitique



Compositions Chimiques:

	Pyrolite <sup>a</sup>	Harzburgite <sup>a</sup>	MORB <sup>b</sup>
SiO <sub>2</sub>	38.9	36.4	52.2
Al <sub>2</sub> O <sub>3</sub>	2.2	0.7	10.2
CaO	3.1	0.9	14.8
MgO	50.0	56.6	15.8
FeO	5.8	5.4	7.0
Mg/Si	1.29	1.55	0.30
Fe/Si	0.15	0.15	0.13
Ca/Si	0.08	0.02	0.28
Al/Si	0.11	0.04	0.39

# Minéralogie Mantélique Pyrolitique 0-20 km

Sup.

410 km

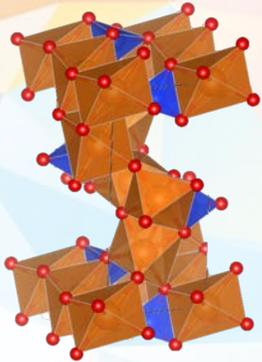
TZ

670 km

Inf.

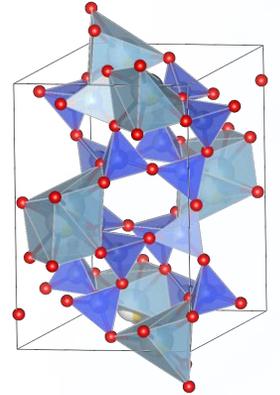
2900 km

## Olivine

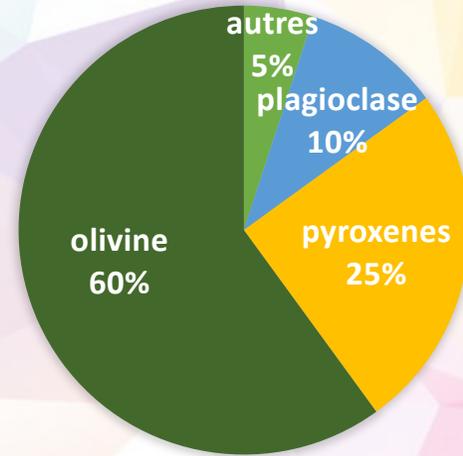


Nésosilicate

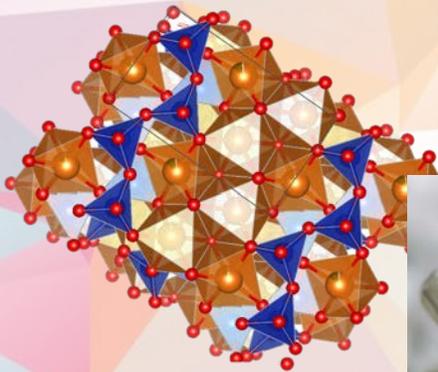
## Plagioclase



Tectosilicate

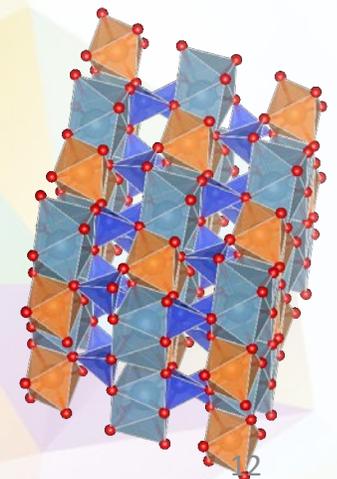
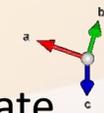


## Orthopyroxene



Inosilicate

## Clinopyroxene



Inosilicate

18/11/2023

Pictures: mindat.org

A.Mi.S.

# Minéralogie Mantélique Pyrolitique 0-20 km

## Olivine ( $(\text{Fe},\text{Mg})_2\text{SiO}_4$ )

Forsterite (Mg),  
Fayalite (Fe)  
Fe : 8-12%  
Ca => Profondeur



## Plagioclase ( $\text{Ca}[\text{Al}_2\text{Si}_2\text{O}_8]-\text{Na}[\text{AlSi}_3\text{O}_8]$ )

Anorthite - Albite



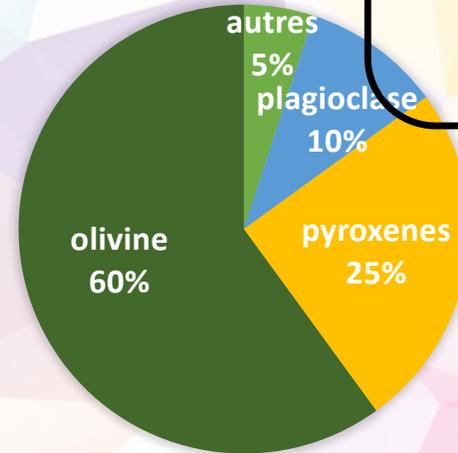
## Orthopyroxene ( $(\text{Fe},\text{Mg})_2\text{Si}_2\text{O}_6$ )

Enstatite (Mg), Ferrosilite (Fe)



## Clinopyroxene ( $(\text{Ca},\text{Fe},\text{Mg})_2\text{Si}_2\text{O}_6$ )

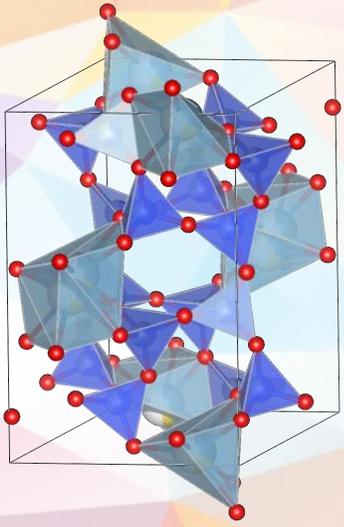
Pigeonite, Diopside,  
Hedenbergite .....



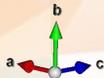
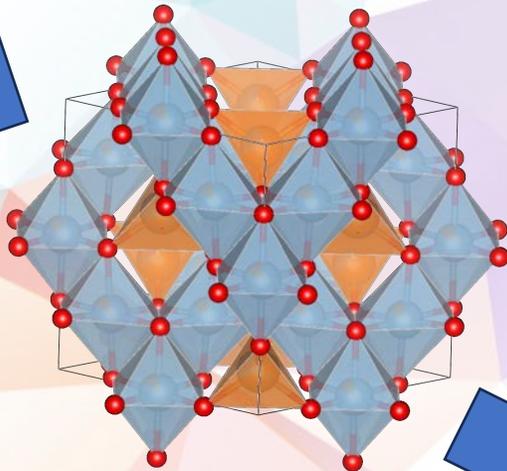
# Phase Alumineuse à Haute Pression

Sup.  
410 km  
TZ  
670 km  
Inf.  
2900 km

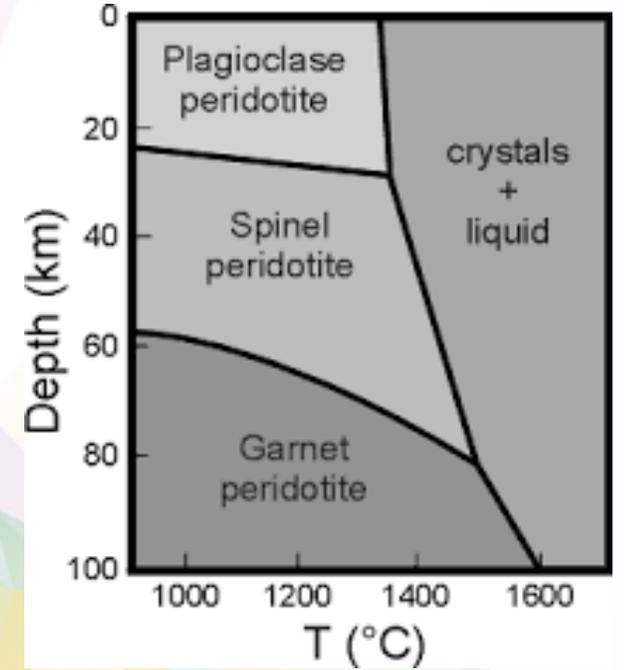
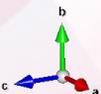
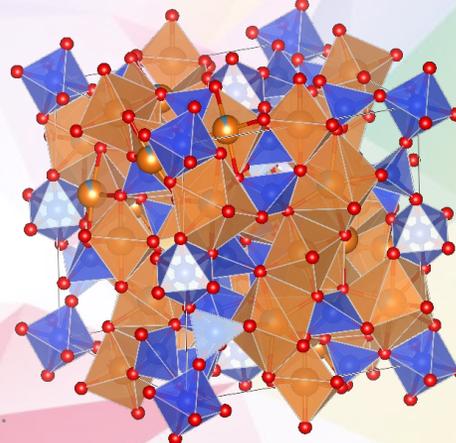
Plagioclase ( $\text{Ca}[\text{Al}_2\text{Si}_2\text{O}_8]\text{-Na}[\text{AlSi}_3\text{O}_8]$ )



Spinel  $\text{MgAl}_2\text{O}_4$



Grenat Pyrope  $\text{Mg}_3\text{Al}_2(\text{SiO}_4)_3$

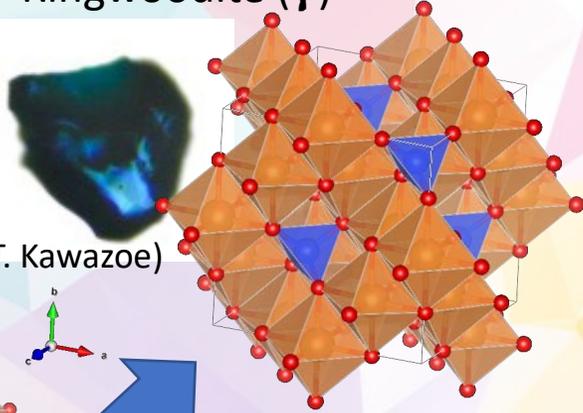


# Transitions de Phase de l'Olivine

Sup.  
410 km  
TZ  
670 km

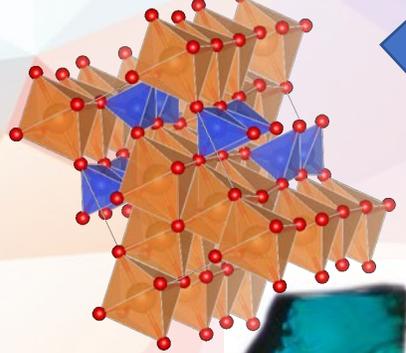
Inf.

Ringwoodite ( $\gamma$ )



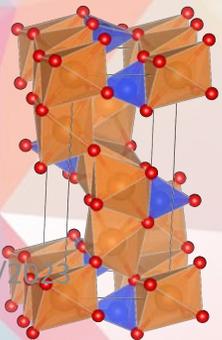
(T. Kawazoe)

Wadsleyite ( $\beta$ )



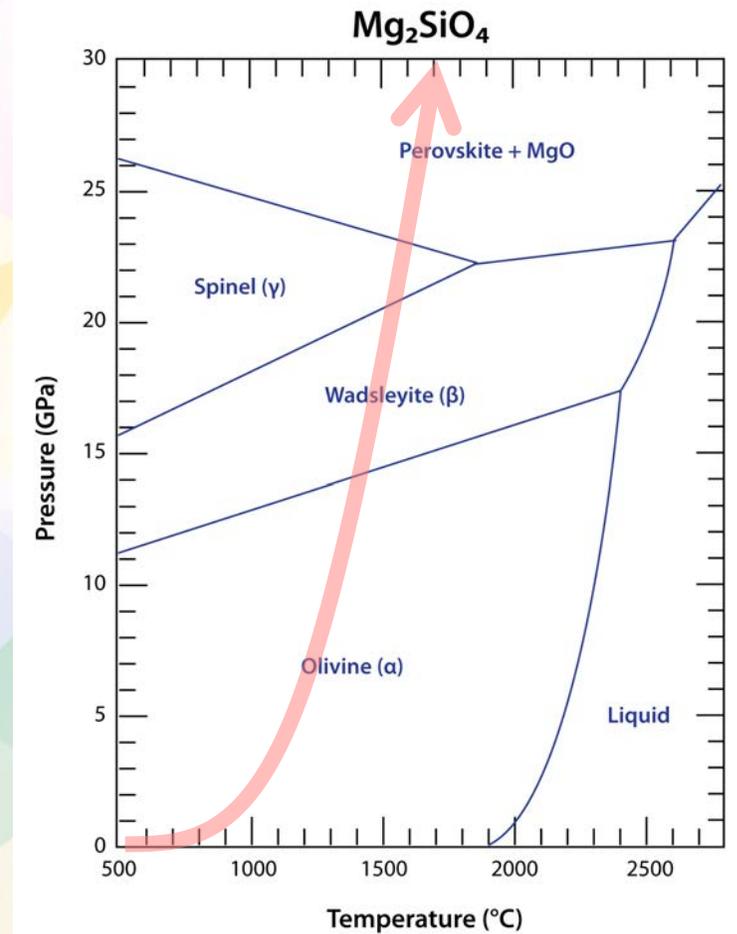
(T. Kawazoe)

Forsterite ( $\alpha$ )



18/11/2011

2900 km



P. Burnley SERC  
Modifié d'après Fei and Bertka, 1999

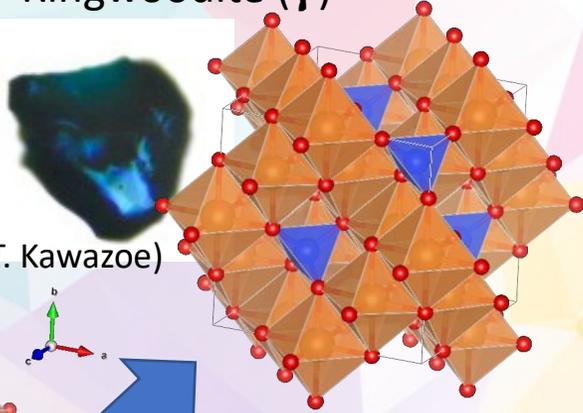
A.Mi.S.

# Transitions de Phase de l'Olivine

Sup.  
410 km  
TZ  
670 km

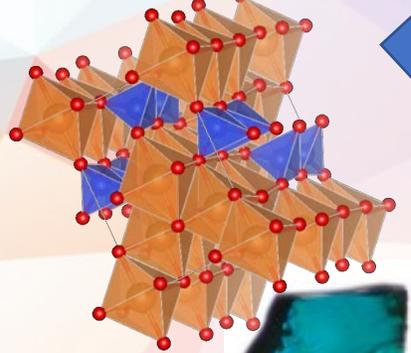
Inf.

Ringwoodite ( $\gamma$ )



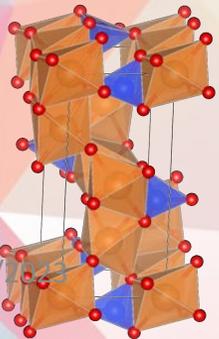
(T. Kawazoe)

Wadsleyite ( $\beta$ )

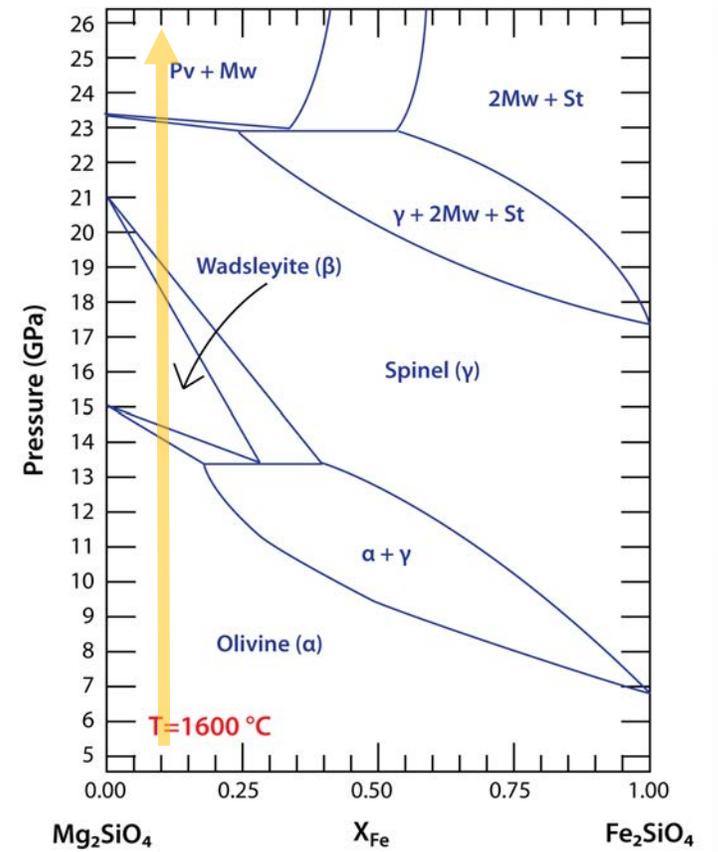


(T. Kawazoe)

Forsterite ( $\alpha$ )



(Mg,Fe)<sub>2</sub>SiO<sub>4</sub>



18/11/2011

A.Mi.S.

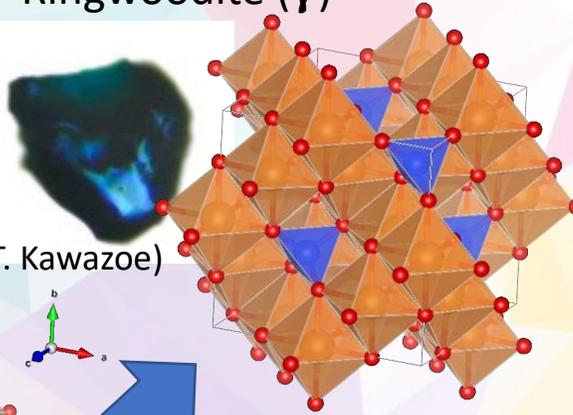
P. Burnley SERC  
Modifié d'après Fei and Bertka, 1999

# Transitions de Phase de l'Olivine

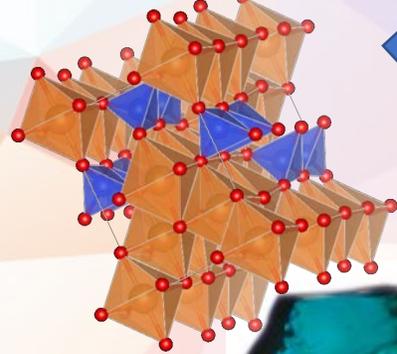
Sup.  
410 km  
TZ  
670 km

Inf.

Ringwoodite ( $\gamma$ )

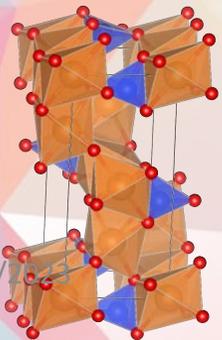


Wadsleyite ( $\beta$ )



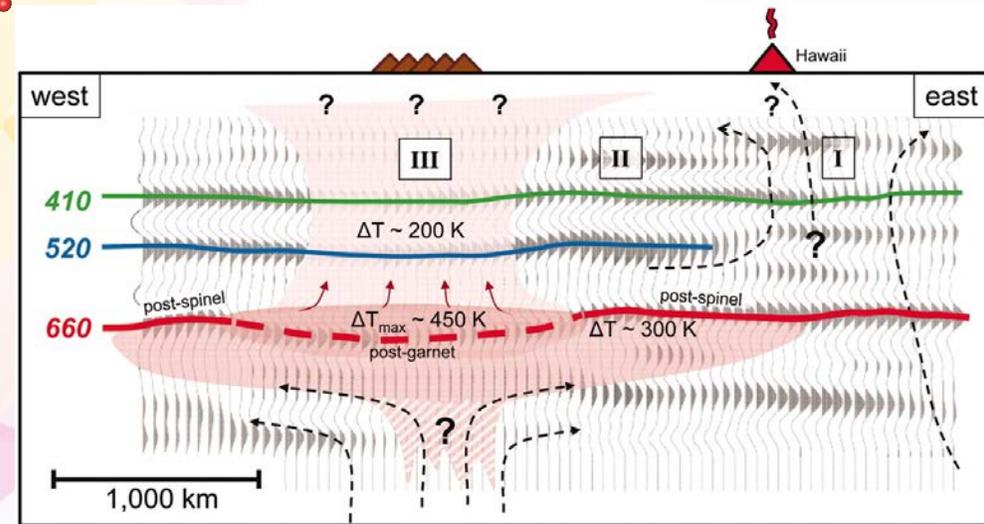
(T. Kawazoe)

Forsterite ( $\alpha$ )



18/11/2011

2900 km

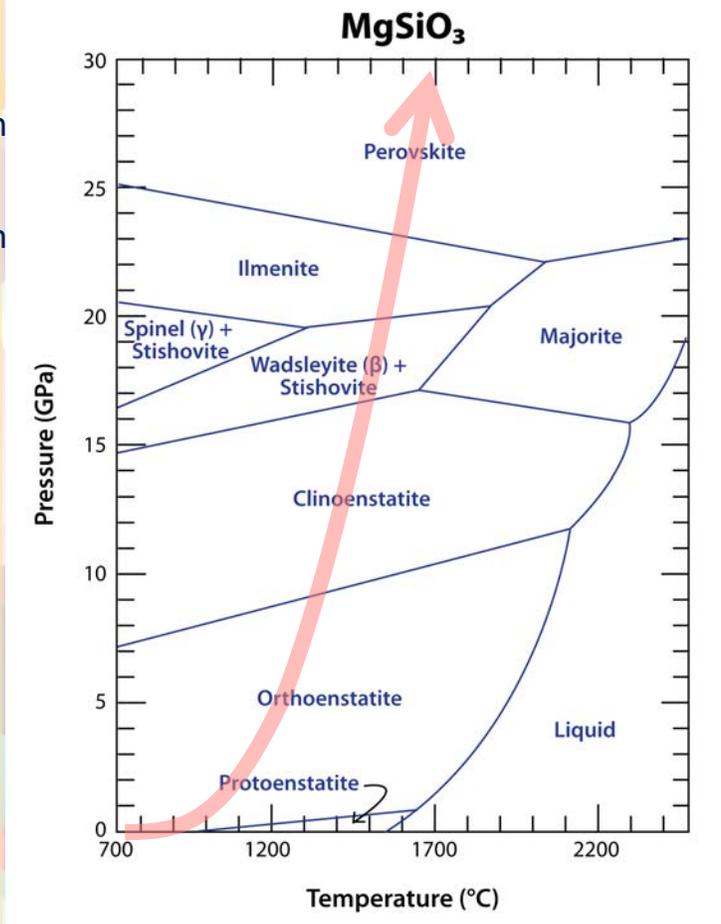


Changement de phases aux pressions correspondant aux discontinuités sismiques observées.

Cao et al., 2011

# Transitions de Phase des Pyroxenes

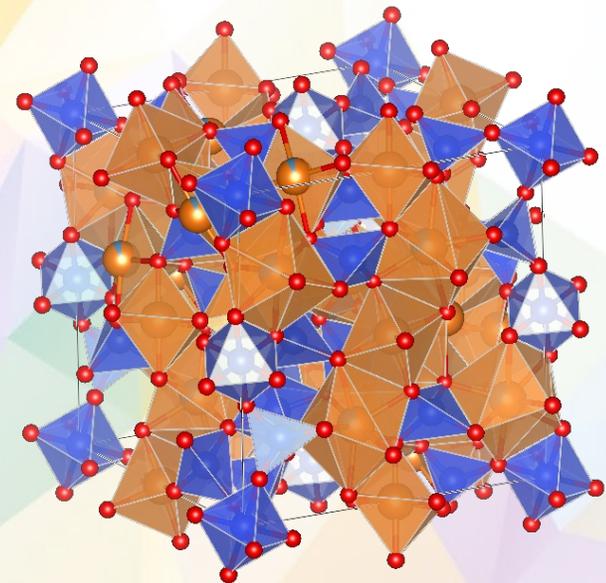
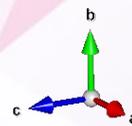
Sup.  
410 km  
TZ  
670 km  
Inf.  
2900 km



Pyroxènes incorporent Na, Ca, etc..

Majorite

$Mg_3(MgSi)(SiO_4)_3$  Incorpore Fe, Ca, Al ...



P. Burnley SERC

Modifié d'après Fei and Bertka, 1999

A.Mi.S.

# Passage au Manteau Inférieur

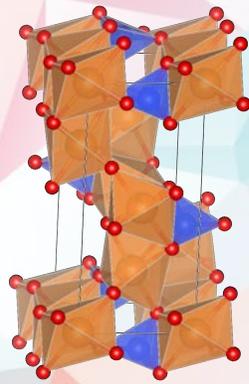
Sup.

410 km

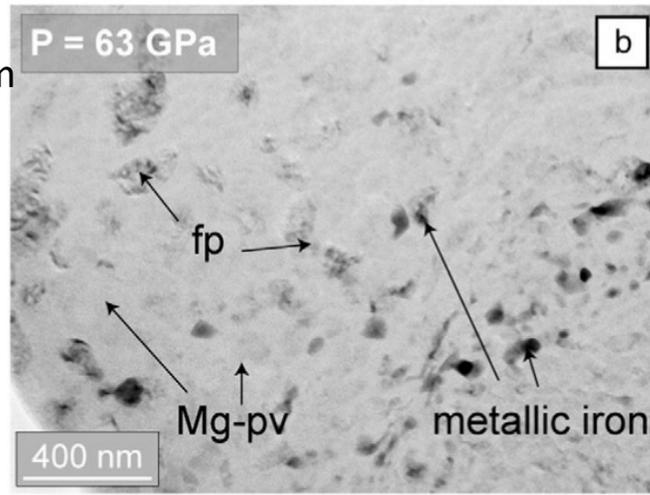
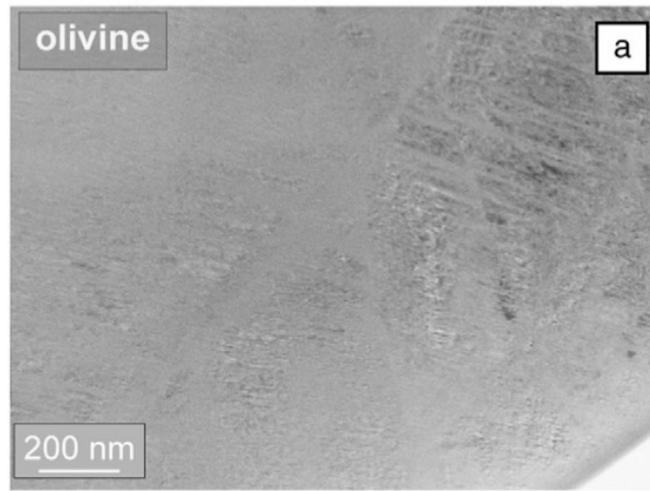
TZ

670 km

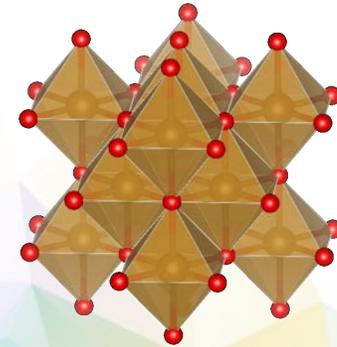
Inf.



Coordinance 4 du Silicium

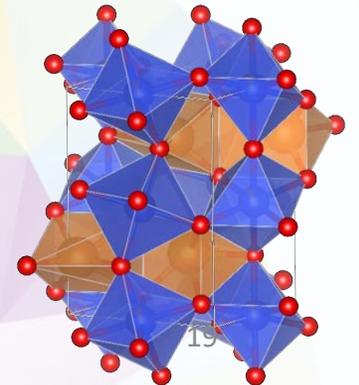


Ferropericlase  $(\text{Mg,Fe})\text{O}$



Mg-Perovskite  $(\text{Mg,Fe})\text{SiO}_3$

Coordinance 6 du Silicium



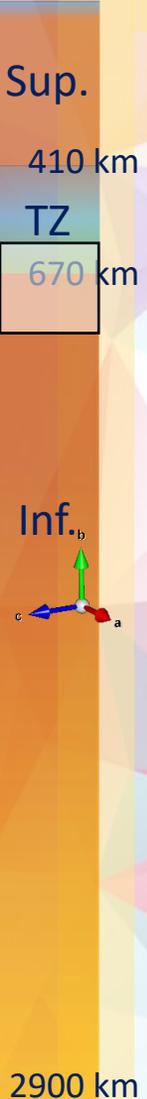
18/11/2023

Auzende et al. 2008

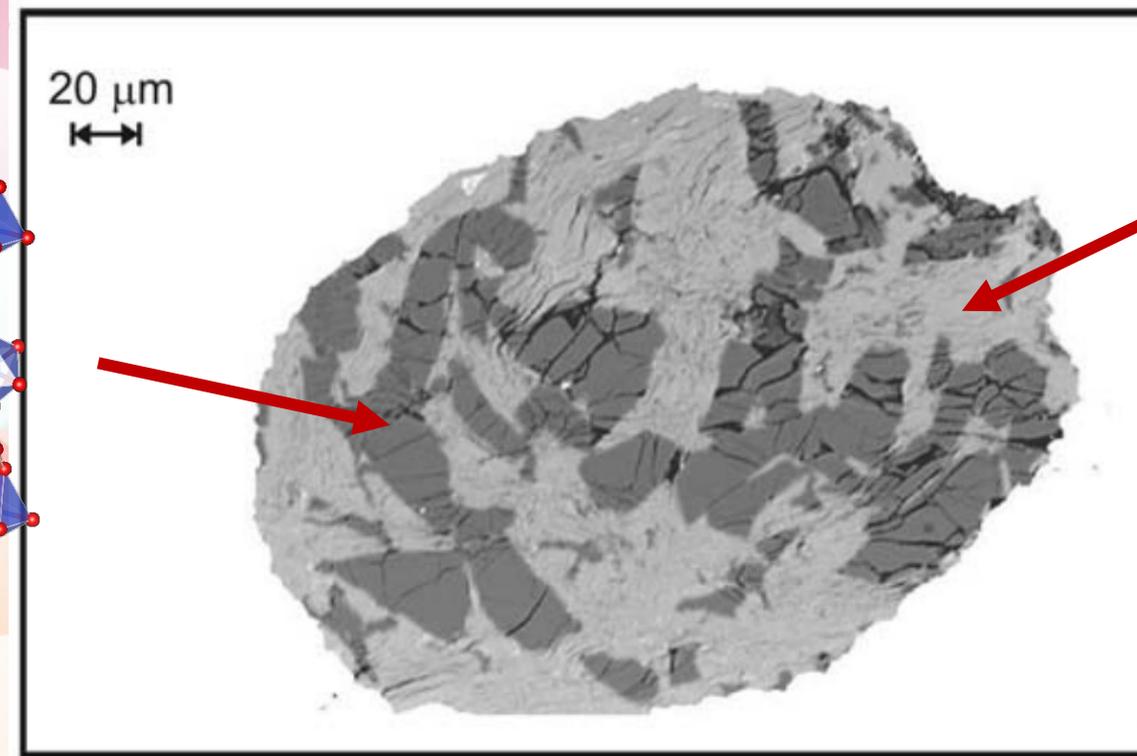
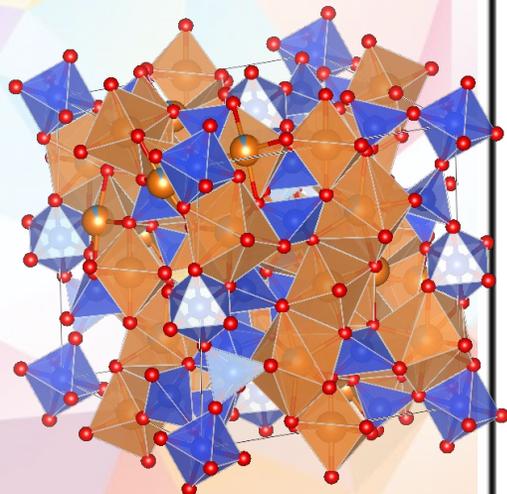
A.Mi.S.

2900 km

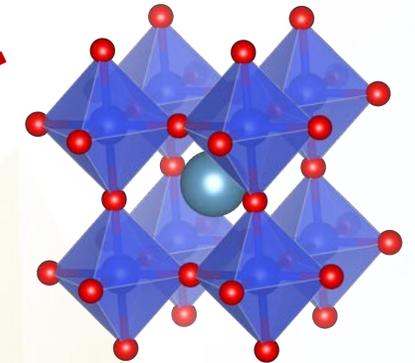
# Passage au Manteau Inférieur



Majorite



Pérovskite  $\text{CaSiO}_3$



Saikia et al., 2008

Le Calcium diffuse petit à petit dans la phase majorite qui éventuellement devient saturée et se transforme en  $\text{CaSiO}_3$   
 $\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$  Grenat +  $\frac{3}{4}(\text{Mg,Fe})_4\text{Si}_4\text{O}_{12}$  Grenat =  $3\text{CaSiO}_3$  Pérovskite +  $(\text{Mg,Fe})_3\text{Al}_2\text{Si}_3\text{O}_{12}$  Grenat

# De la Physique des Minéraux à la Minéralogie

## Bridgmanite (Mg)SiO<sub>3</sub>

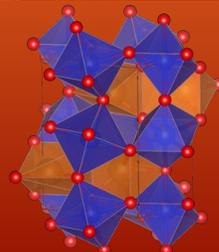
MINERALOGY

Science 2014

### Discovery of bridgmanite, the most abundant mineral in Earth, in a shocked meteorite

Oliver Tschauner,<sup>1\*</sup> Chi Ma,<sup>2</sup> John R. Beckett,<sup>2</sup> Clemens Prescher,<sup>2</sup> Vitali B. Prakapenka,<sup>3</sup> George R. Rossman<sup>2</sup>

Meteorites exposed to high pressures and temperatures during impact-induced shock often contain minerals whose occurrence and stability normally confine them to the deeper portions of Earth's mantle. One exception has been MgSiO<sub>3</sub> in the perovskite structure, which is the most abundant solid phase in Earth. Here we report the discovery of this important phase as a mineral in the Tenham L6 chondrite and approved by the International Mineralogical Association (specimen IMA 2014-017). MgSiO<sub>3</sub>-perovskite is now called bridgmanite. The associated phase assemblage constrains peak shock conditions to ~ 24 gigapascals and 2300 kelvin. The discovery concludes a half century of efforts to find, identify, and characterize a natural specimen of this important mineral.



## Hiroseite FeSiO<sub>3</sub>

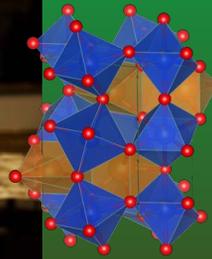
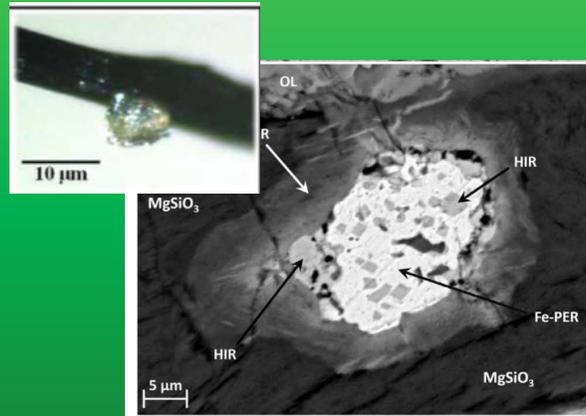
SCIENCE | GEOLOGY

Science Advances, 2020

### Evidence for the charge disproportionation of iron in extraterrestrial bridgmanite

Luca Bindi<sup>1\*</sup>, Sang-Heon Shim<sup>2</sup>, Thomas G. Sharp<sup>2</sup>, Xiande Xie<sup>3</sup>

Bridgmanite, MgSiO<sub>3</sub> with perovskite structure, is considered the most abundant mineral on Earth. On the lower mantle, it contains Fe and Al that strongly influence its behavior. Experimentalists have debated whether iron may exist in a mixed valence state, coexistence of Fe<sup>2+</sup> and Fe<sup>3+</sup> in bridgmanite, through charge disproportionation. Here, we report the discovery of Fe-rich aluminous bridgmanite coexisting with metallic iron in a shock vein of the Suizhou meteorite. This is the first direct evidence in nature of the Fe disproportionation reaction, which so far has only been observed in some high-pressure experiments. Furthermore, our discovery supports the idea that the disproportionation reaction would have played a key role in redox processes and the evolution of Earth.



## Davemaoite CaSiO<sub>3</sub>

RESEARCH

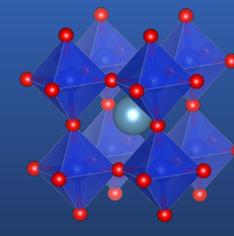
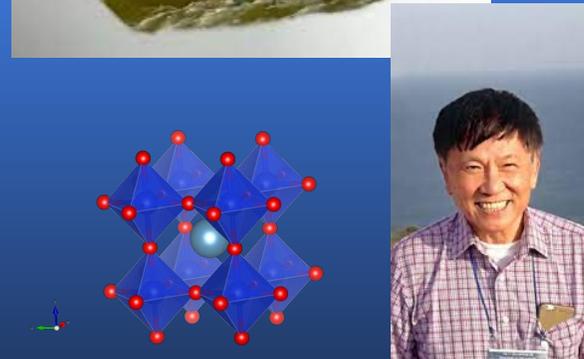
Science, 2021

MINERALOGY

### Discovery of davemaoite, CaSiO<sub>3</sub>-perovskite, as a mineral from the lower mantle

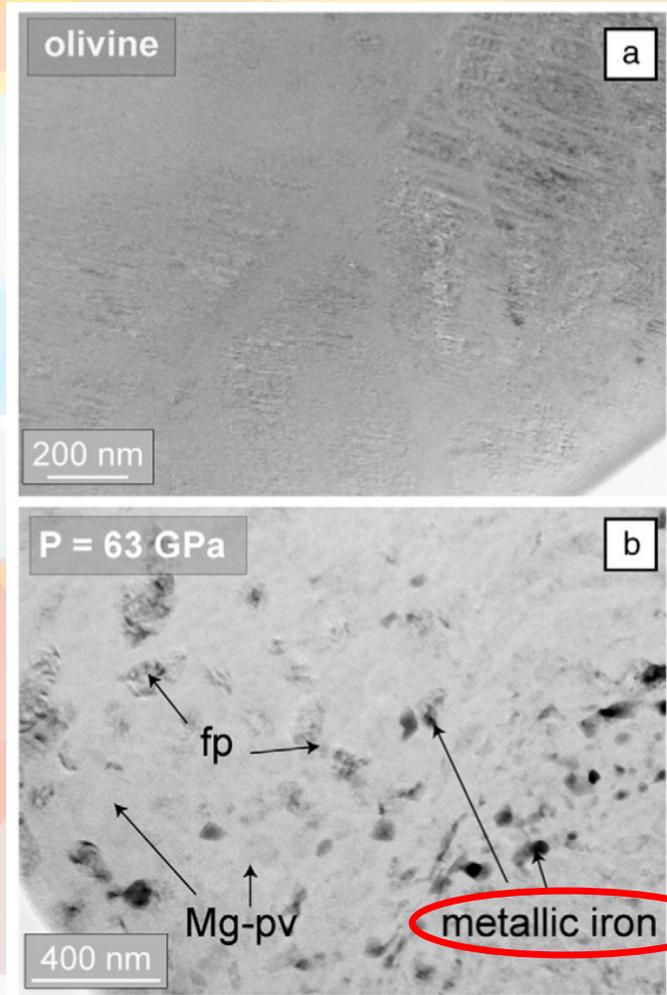
Oliver Tschauner<sup>1\*</sup>, Shichun Huang<sup>1</sup>, Shuying Yang<sup>2</sup>, Munir Humayun<sup>2</sup>, Wenjun Liu<sup>1</sup>, Stephanie N. Gilbert Corder<sup>4</sup>, Hans A. Bechtel<sup>4</sup>, Jon Tischler<sup>3</sup>, George R. Rossman<sup>5</sup>

Calcium silicate perovskite, CaSiO<sub>3</sub>, is arguably the most geochemically important phase in the lower mantle, because it concentrates elements that are incompatible in the upper mantle, including the heat-generating elements thorium and uranium, which have half-lives longer than the geologic history of Earth. We report CaSiO<sub>3</sub>-perovskite as an approved mineral (IMA2020-012a) with the name davemaoite. The natural specimen of davemaoite proves the existence of compositional heterogeneity within the lower mantle. Our observations indicate that davemaoite also hosts potassium in addition to uranium and thorium in its structure. Hence, the regional and global abundances of davemaoite influence the heat budget of the deep mantle, where the mineral is thermodynamically stable.



# Le Fer Dans le Manteau Inférieur

Sup.  
410 km  
TZ  
670 km  
Inf.  
2900 km



Bridgmanite  $(\text{Mg,Fe})(\text{Si,Al})\text{O}_3$



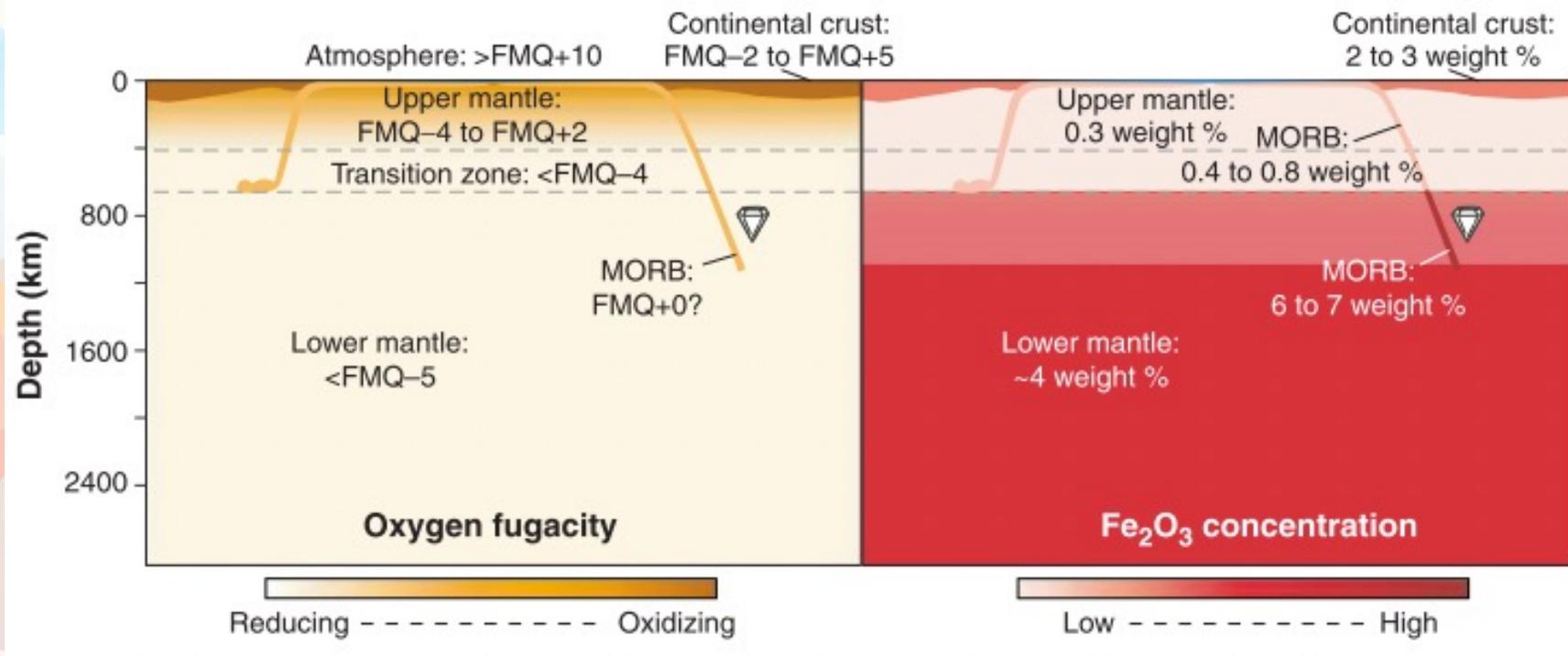
La quantité de  $\text{Fe}^{3+}$  n'est plus sensible à la fugacité d'oxygène mais à la quantité d'aluminium :

➤ Le manteau inférieur est saturé en Fer métal

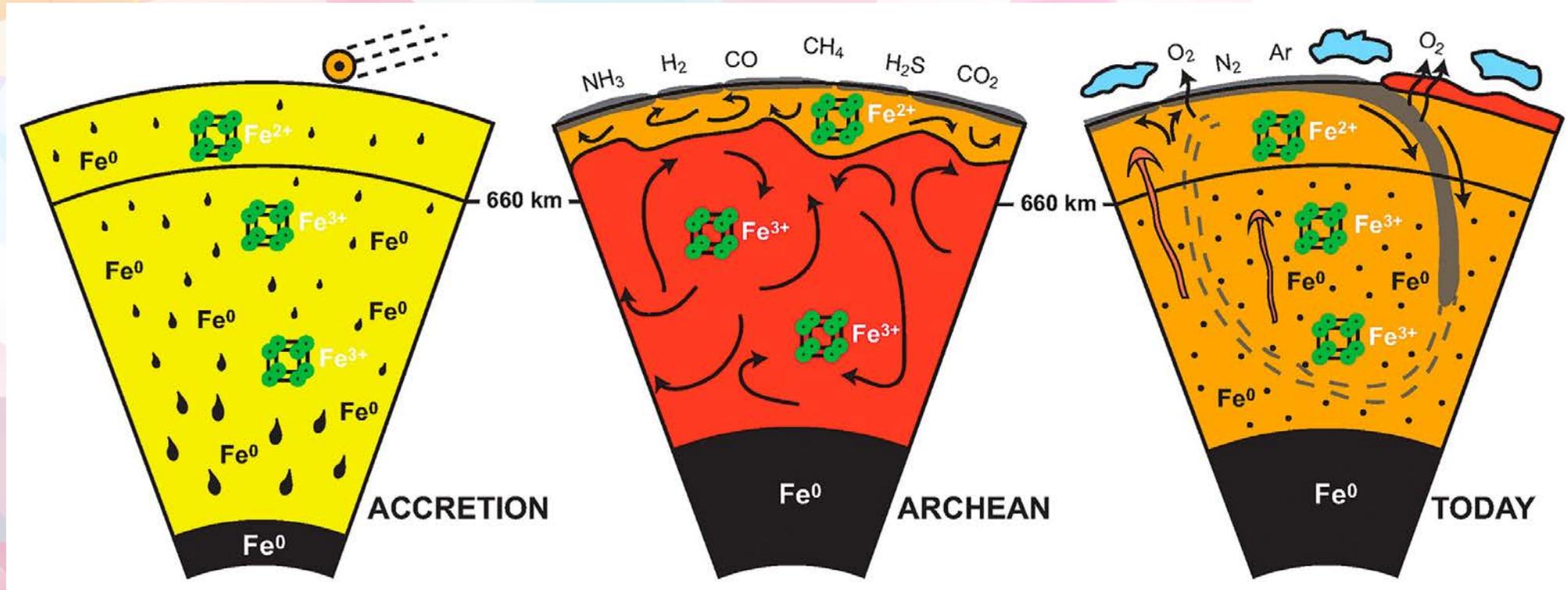
# Paradoxe du Redox Mantellique

Sup.  
410 km  
TZ  
670 km  
Inf.  
2900 km

FMQ : fayalite-magnétite-quartz  
 $3 \text{Fe}_2\text{SiO}_4 + \text{O}_2 = 2 \text{Fe}_3\text{O}_4 + 3 \text{SiO}_2$



# Paradoxe du Redox Mantellique : Un Peu de GéoPoésie

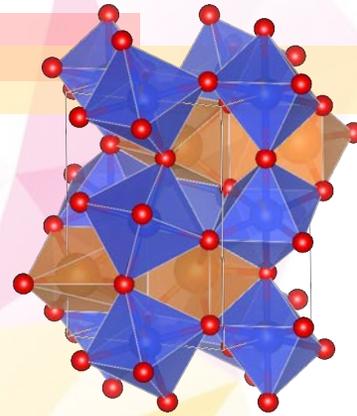
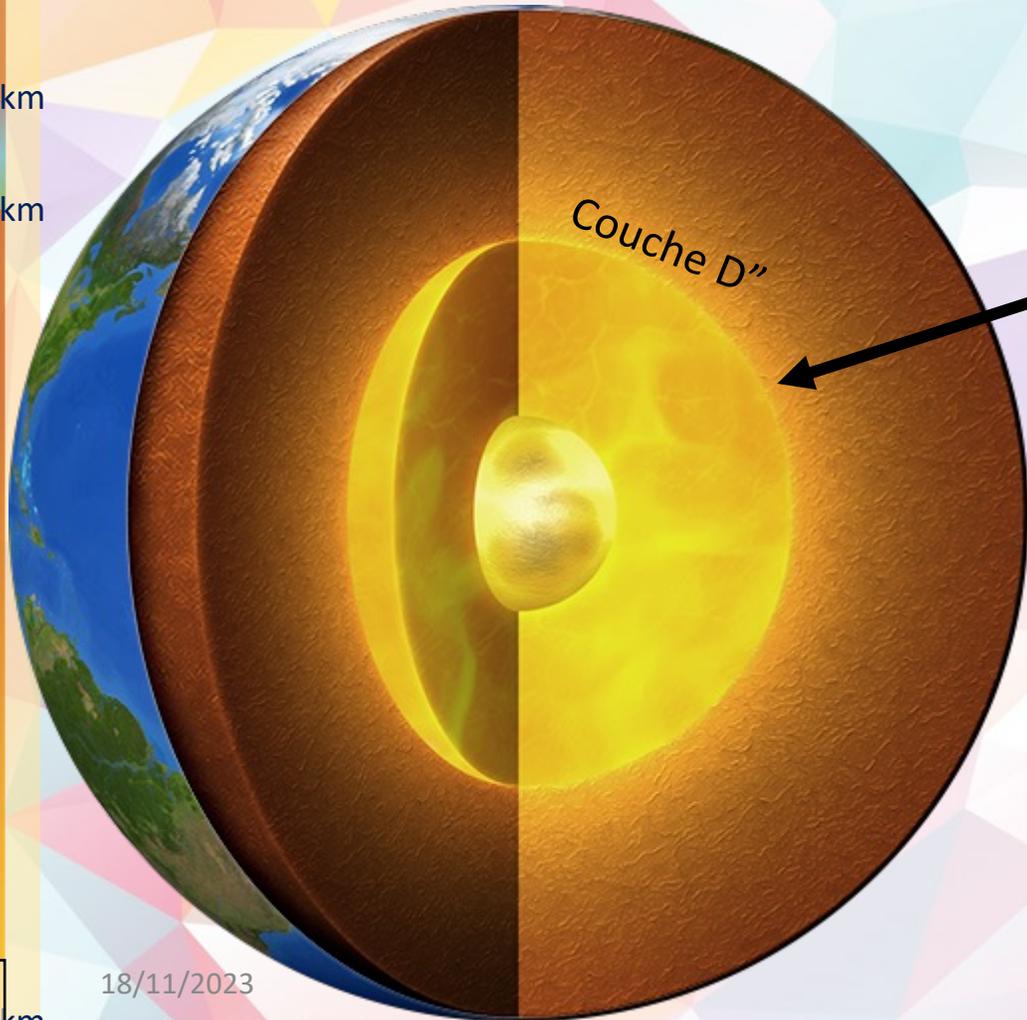


Andrault et al., 2017

# Limite Noyau Manteau

Sup.  
410 km  
TZ  
670 km

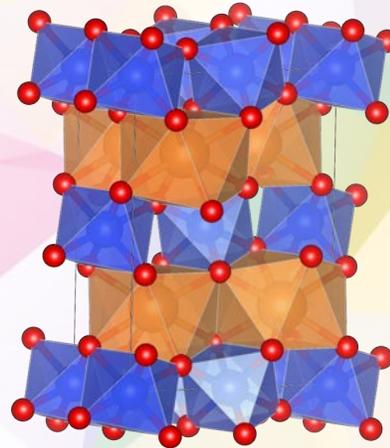
Inf.



Bridgmanite

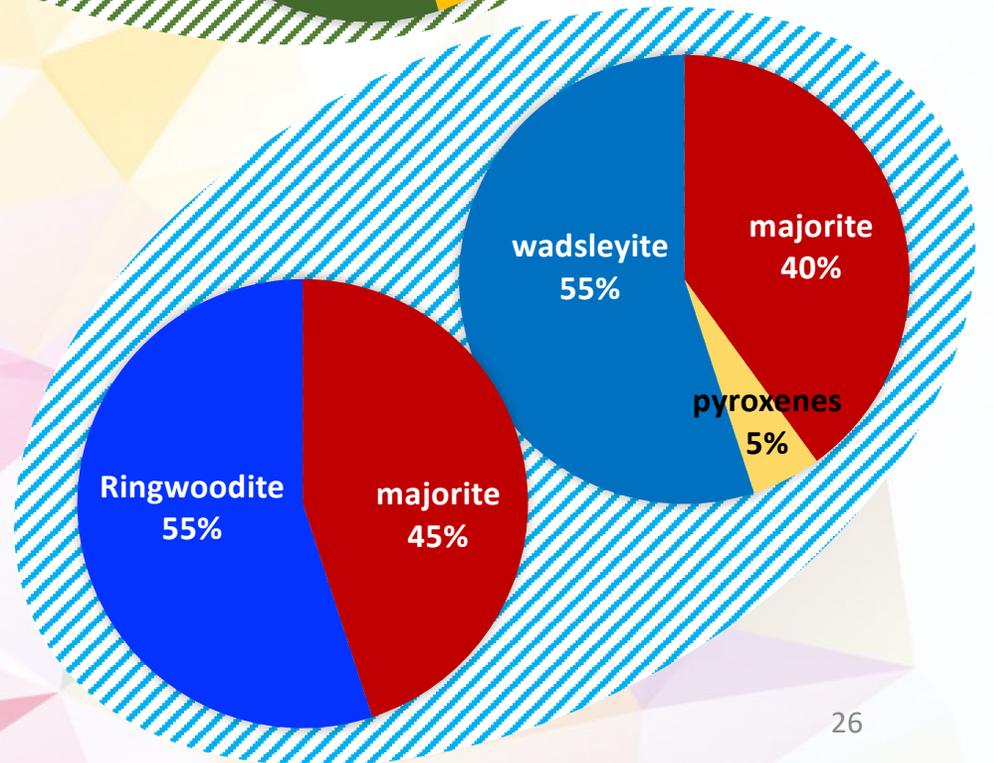
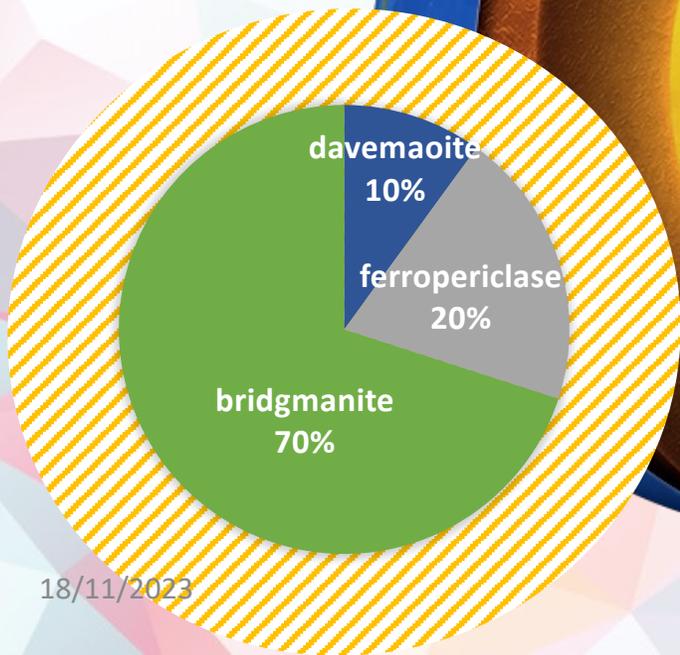
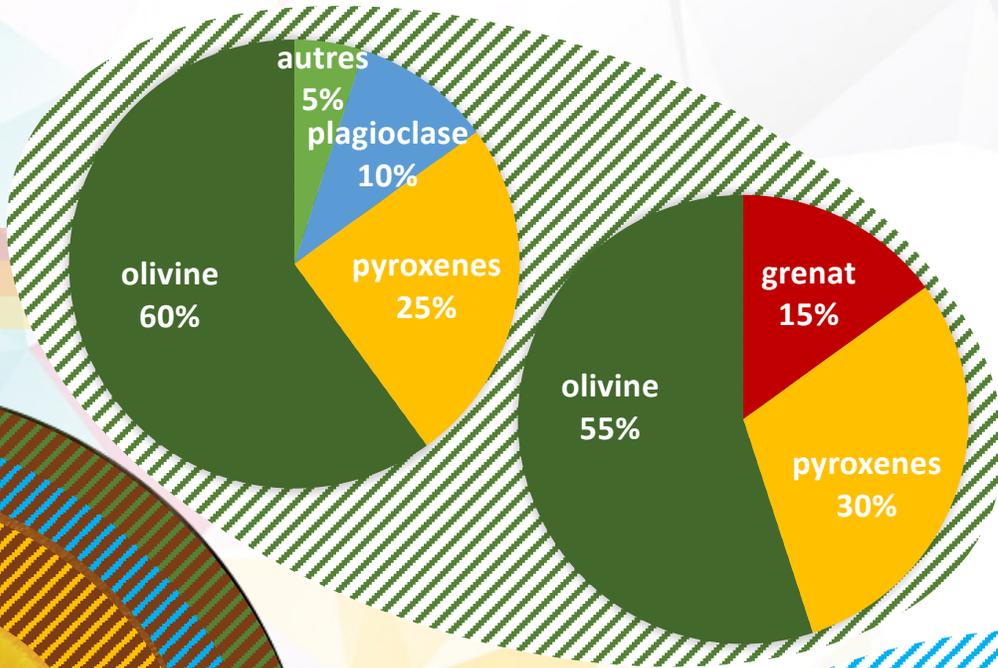
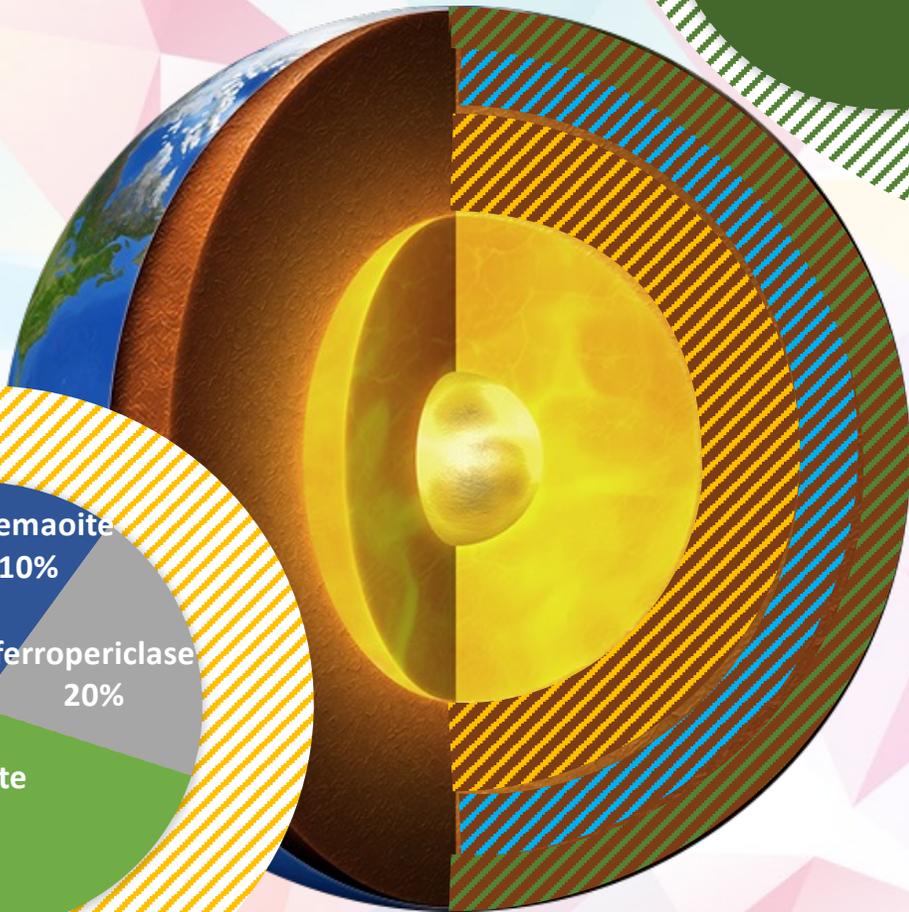


Post-Perovskite (Mg,Fe)SiO<sub>3</sub>

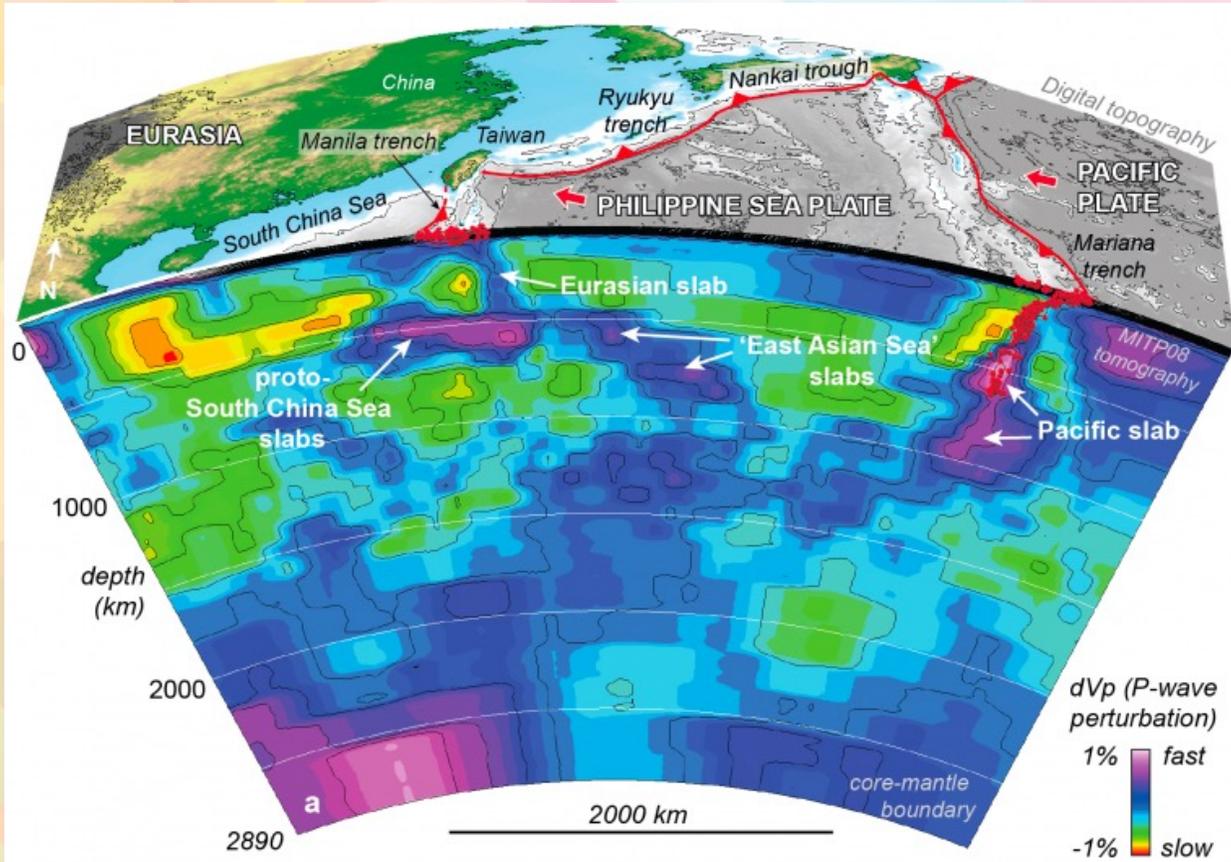


Orientation préférentielle  
dans un slab en subduction  
=> anisotropie sismique



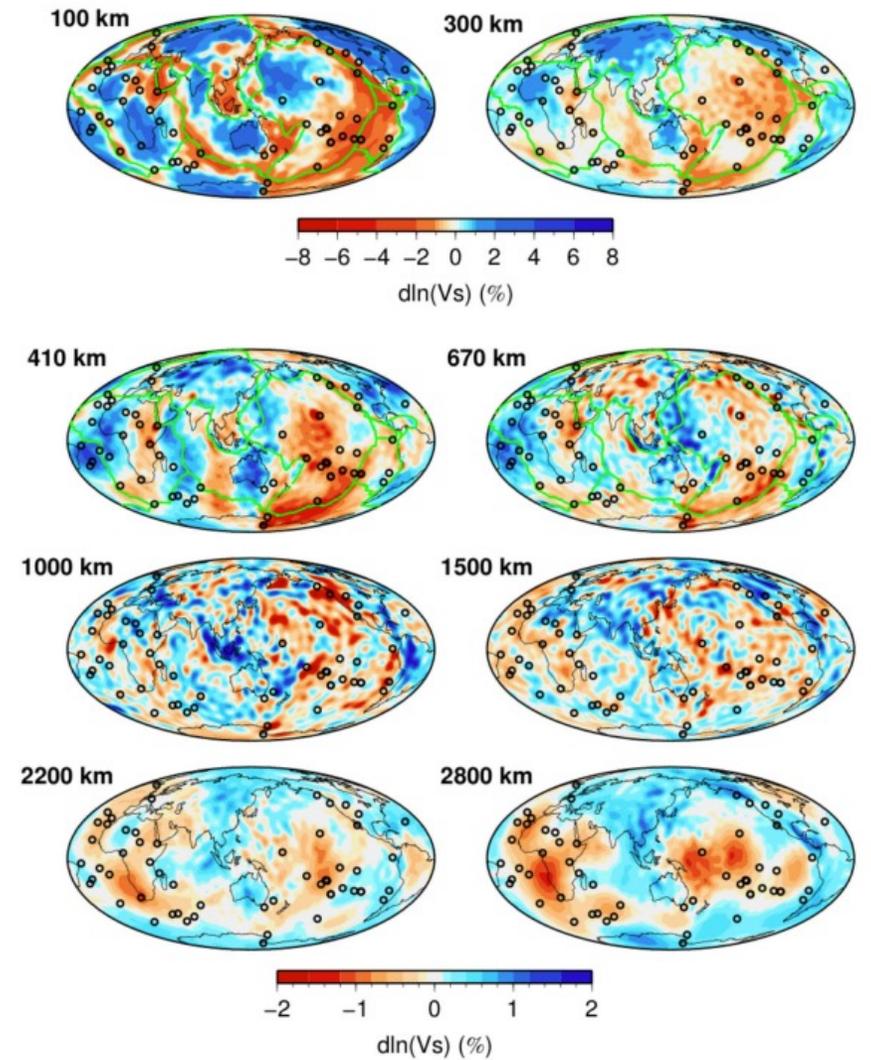


# Sauf Que ...



Li et al., 2008

## SEISGLOB2



Durand et al., 2017

# Transport de L'Eau Dans le Manteau

Sup.

410 km

TZ

670 km

Inf.

2900 km

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Contact: [Karen McNully Walsh](#), (631) 344-8350, or [Peter Genzer](#), (631) 344-3174

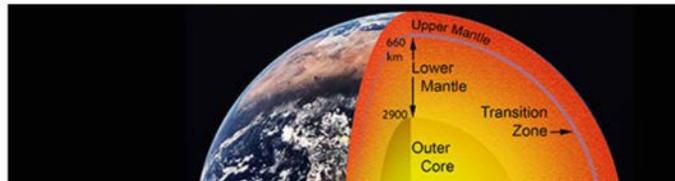
share: [f](#) [t](#) [in](#) [p](#)

The following news release on a paper published today in the journal *Science* was issued by Northwestern University. The research was conducted, in part, at the National Synchrotron Light Source at the U.S. Department of Energy's Brookhaven National Laboratory.

## New Evidence for Oceans of Water Deep in the Earth

Water bound in mantle rock alters our view of the Earth's composition

June 13, 2014



notre-planete.info

ACTUALITES DOSSIERS FAKE NEWS INDICATEURS AGENDA

Mis à jour le 29 septembre 2022, 11:52 121 K lectures / 9 réactions

### Des océans gigantesques dans les profondeurs de la Terre ?



-> Au sein de phases hydratées

-> Au sein de phases nominalemeent anhydres

Home > World News > Scientists Discover Massive "Ocean" Near Earth's Core

## Scientists Discover Massive "Ocean" Near Earth's Core

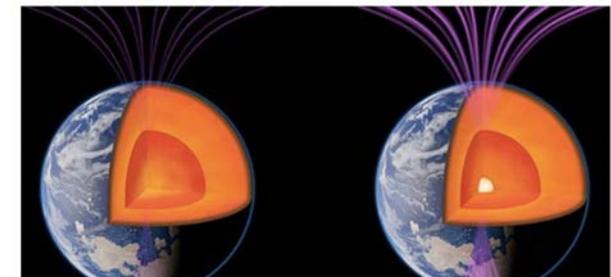
The study confirmed something that it was only a theory, namely that ocean water accompanies subducting slabs and thus enters the transition zone.

World News | Edited by Anjali Thakur | Updated: October 02, 2022 7:51 am IST

TRENDING

Watch: Epic No-Ball Drama On Last Delivery Of Bangladesh vs Zimbabwe Match

"Want Uniform Civil Code But BJP Is Bluffing": Arvind Kejriwal In Gujarat



18/11/2023



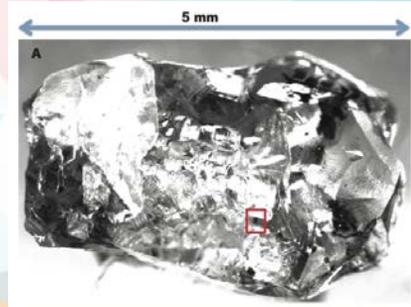
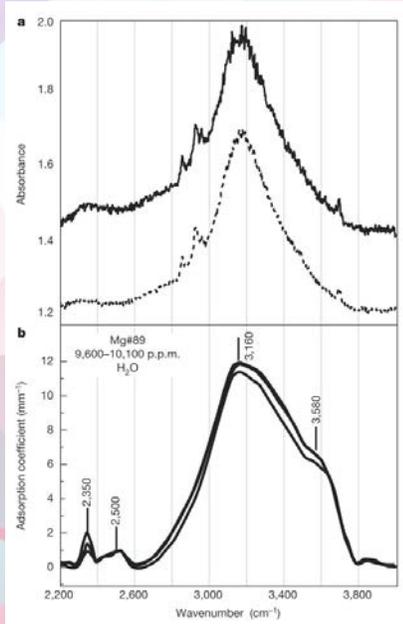
A.Mi.S.

28

# Phases Nominalement Anhydres en Zone de Transition

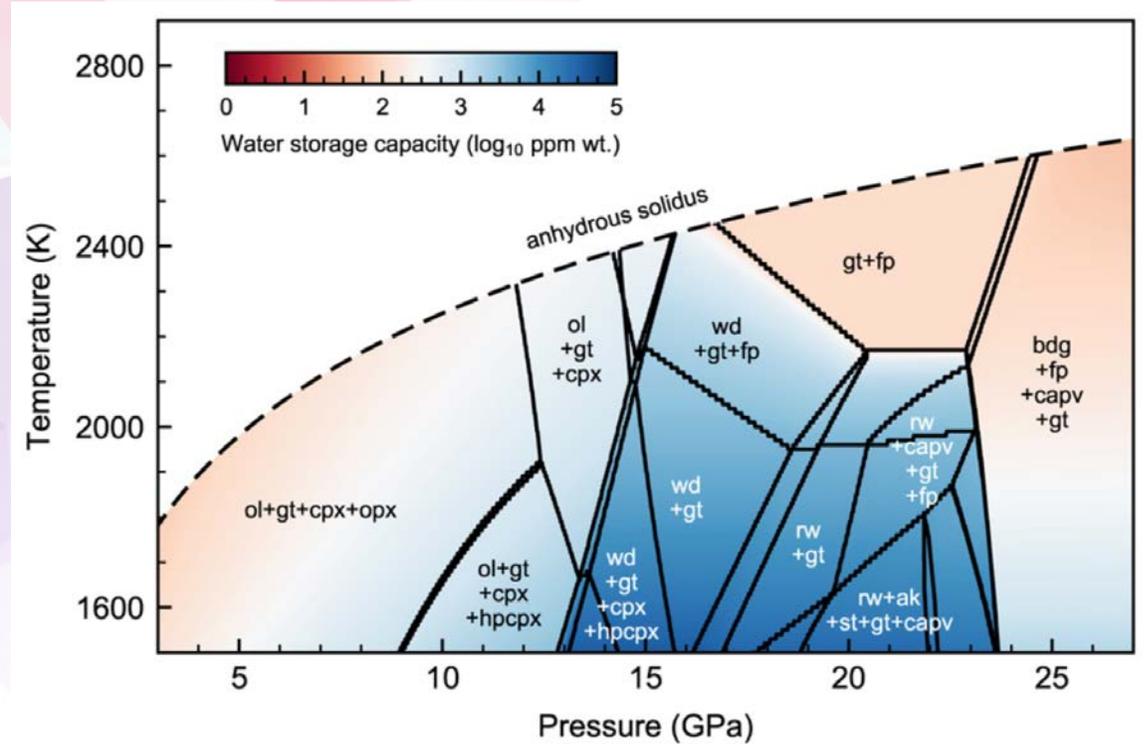
Sup.  
410 km  
TZ  
670 km

Inclusion de Ringwoodite  
dans des diamants naturels



1.5 wt% H<sub>2</sub>O

Pearson et al., 2014

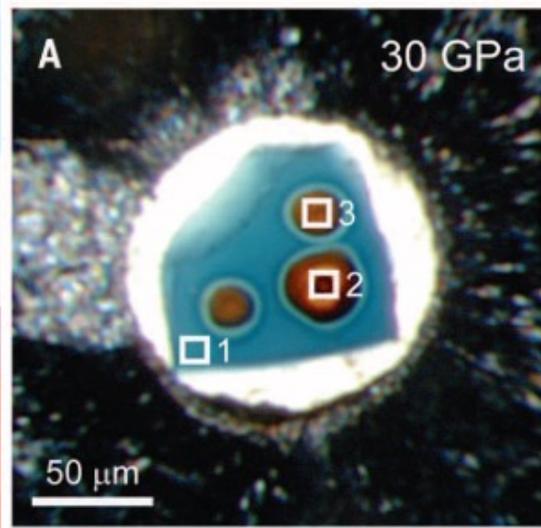


Dong et al., 2012

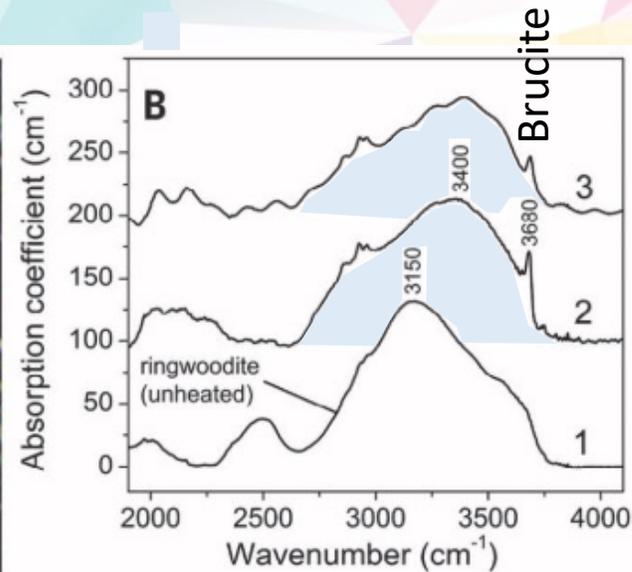
# Passage de la Zone de Transition au Manteau Inférieur

Sup.  
410 km  
TZ  
670 km

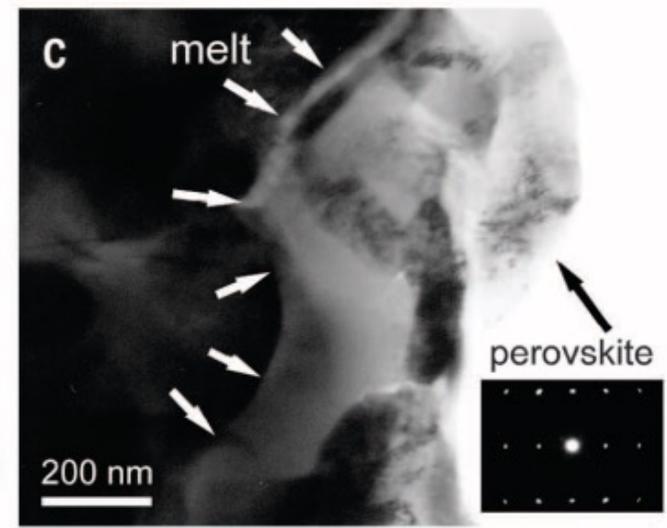
Echantillon de Ringwoodite en cellule à enclume de diamants



Analyses IR au sein des spot de chauffe



Analyse en microscopie électronique sur l'échantillon récupéré



-OH dans le liquide silicaté

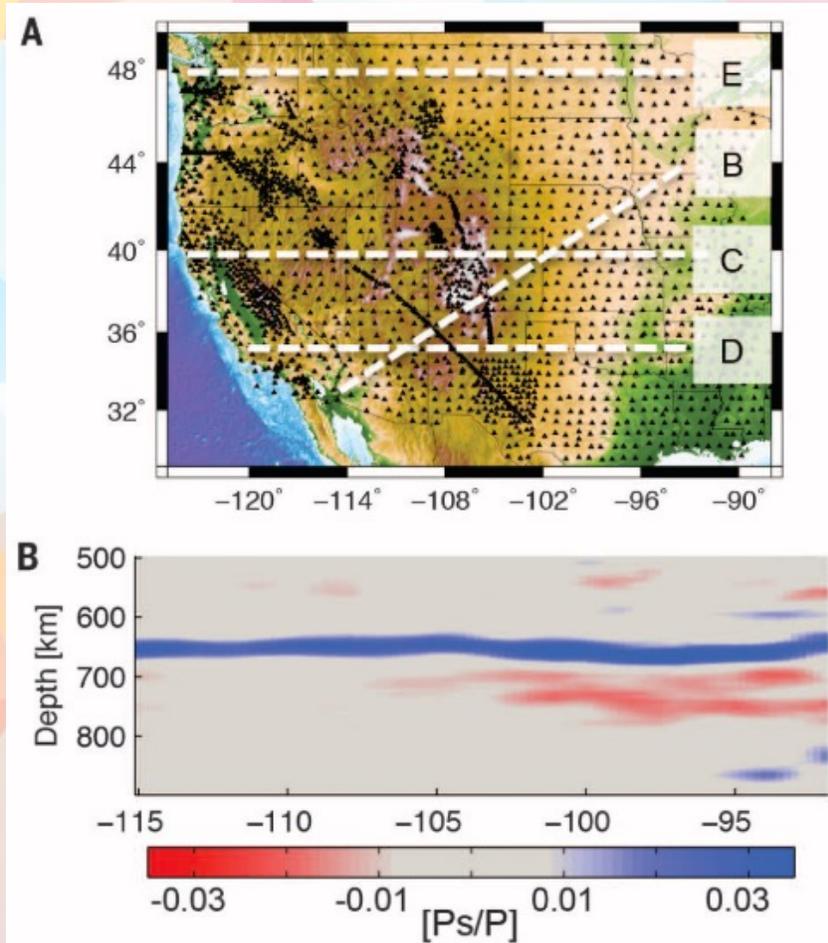
-Présence de liquide silicaté

Schmandt et al., 2014

# Passage de la Zone de Transition au Manteau Inférieur

Sup.  
410 km  
TZ  
670 km

Inf.

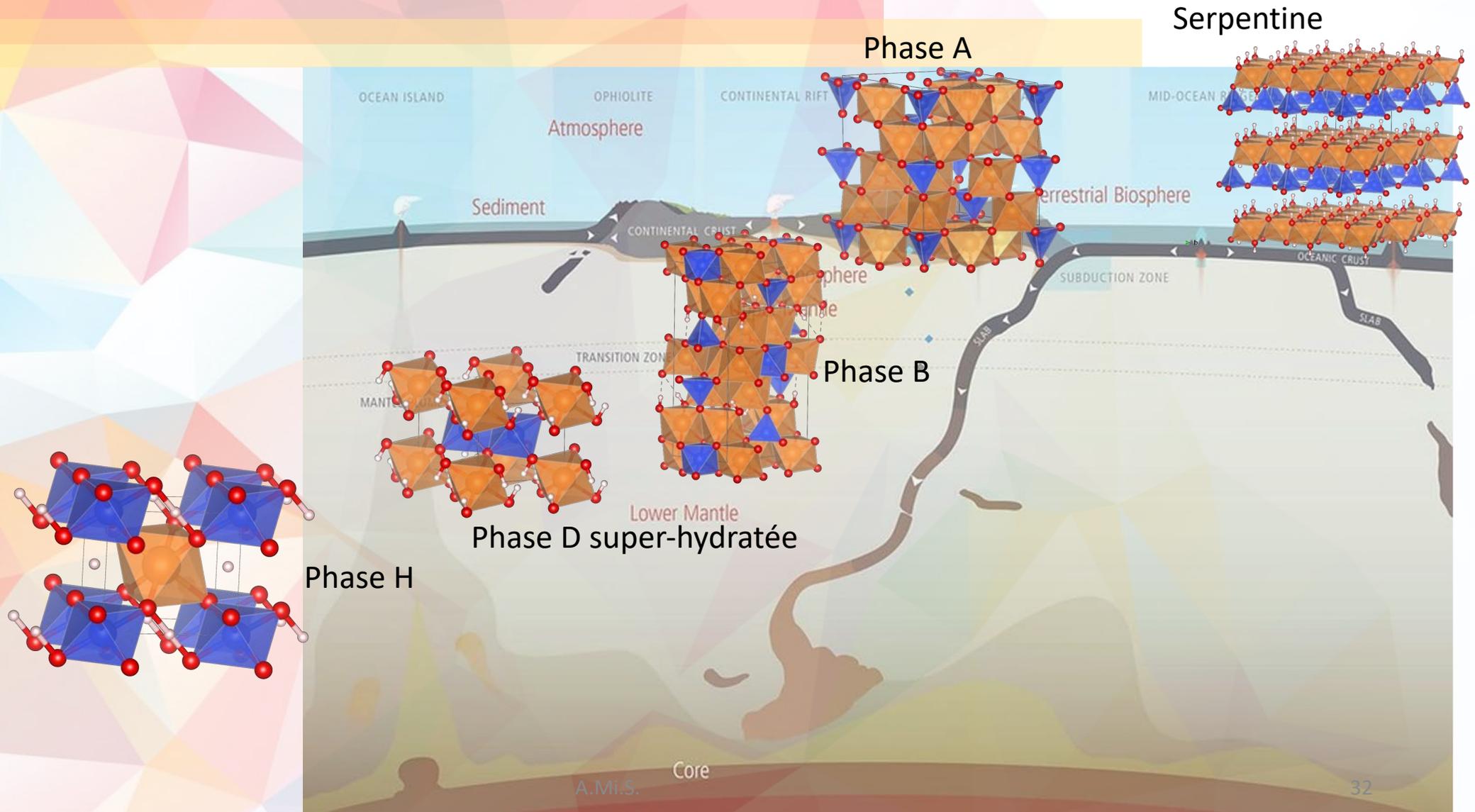


➤ 0.68 to 1% de fusion partielle qui pourrait expliquer la réduction des  $V_p$  et  $V_s$

Schmandt et al., 2014

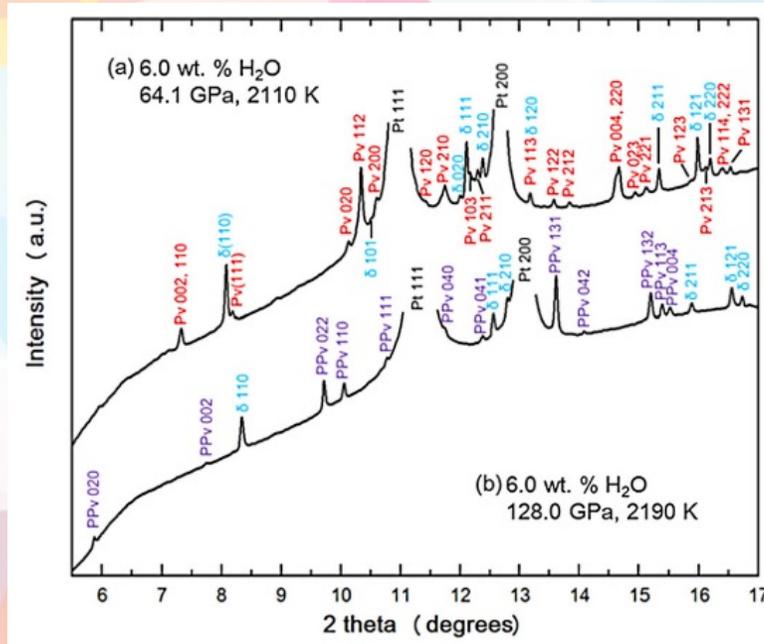
# Phases Denses Hydratées Silicatées et Magnésiennes

Sup.  
410 km  
TZ  
670 km  
Inf.

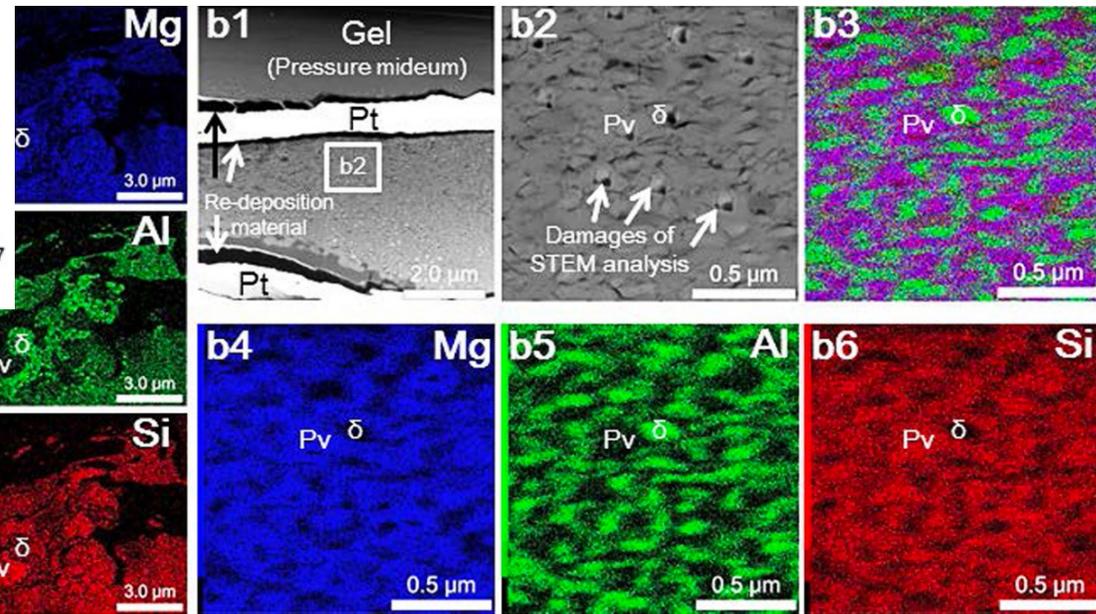


# Phases Denses Hydratées Silicatées et Magnésiennes et Alumineuses!

70 mol% MgSiO<sub>3</sub> – 30 mol% Al<sub>2</sub>O<sub>3</sub> et 6 wt% H<sub>2</sub>O



➤ L'Aluminium stabilise la structure de la Phase H, voir delta-AlOOH



Sup.  
410 km  
TZ  
670 km

Inf.

# Phases Denses Hydratées Alumineuses

Sup.

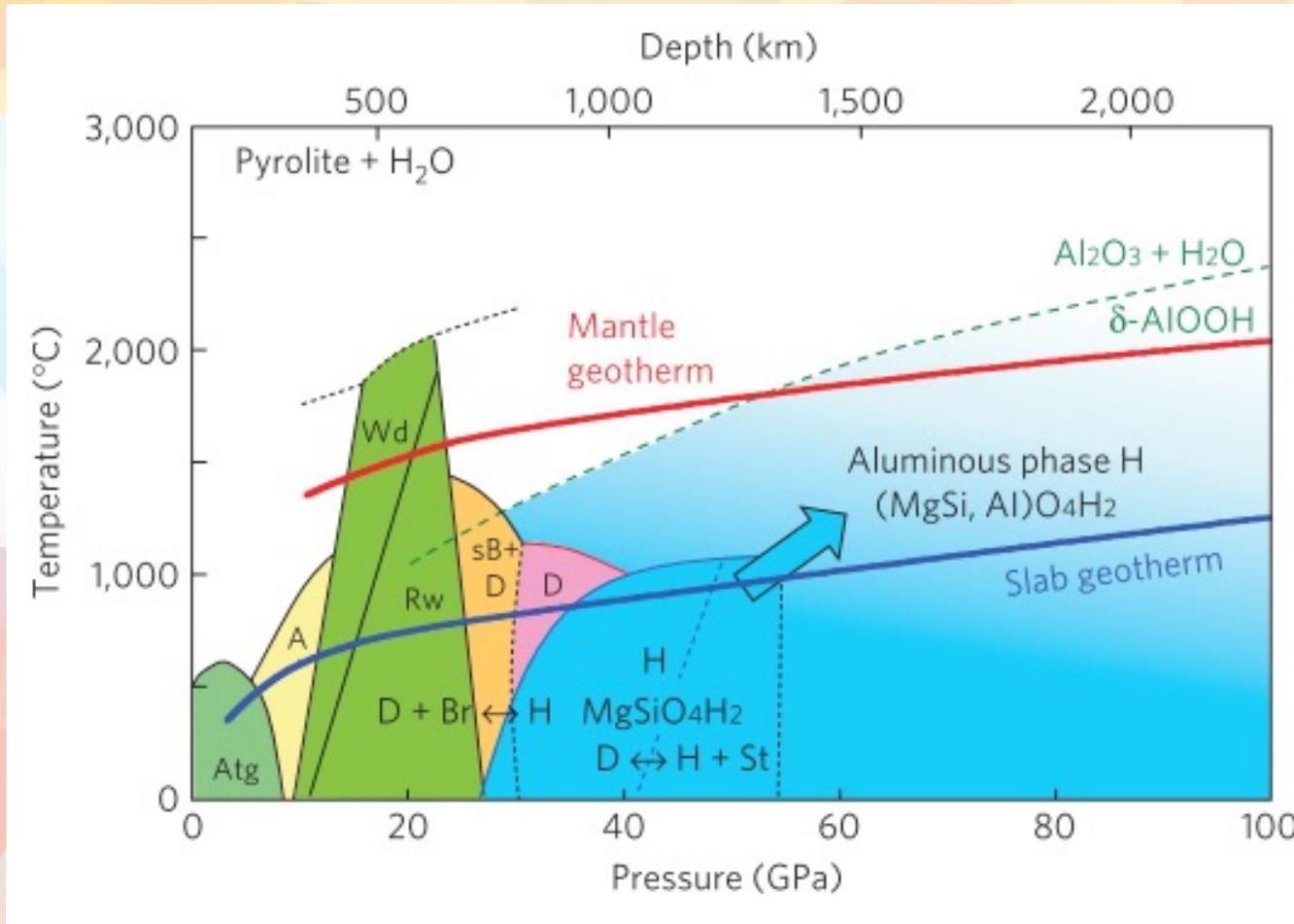
410 km

TZ

670 km

Inf.

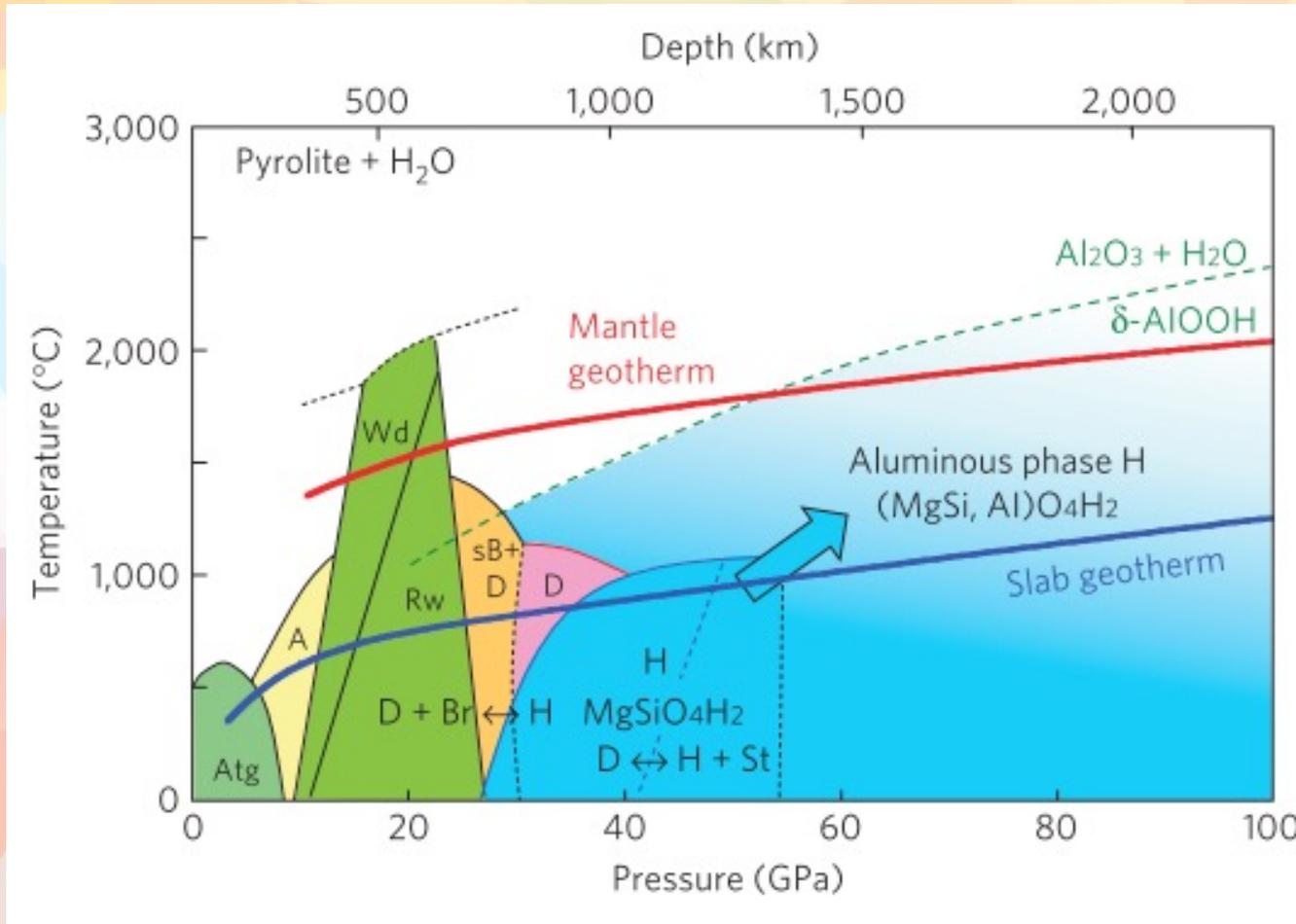
2900 km



Nishi et al., 2014

# Phases Denses Hydratées Alumineuses et Ferreuses !

Sup.  
410 km  
TZ  
670 km  
Inf.  
2900 km



Nishi et al., 2014

+ FeO<sub>2</sub>Hx (py-phase)

Hu et al. 2016

+ (Fe,Al)OOH

Zhang et al. 2018

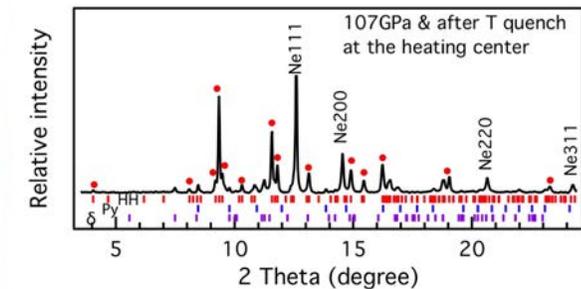
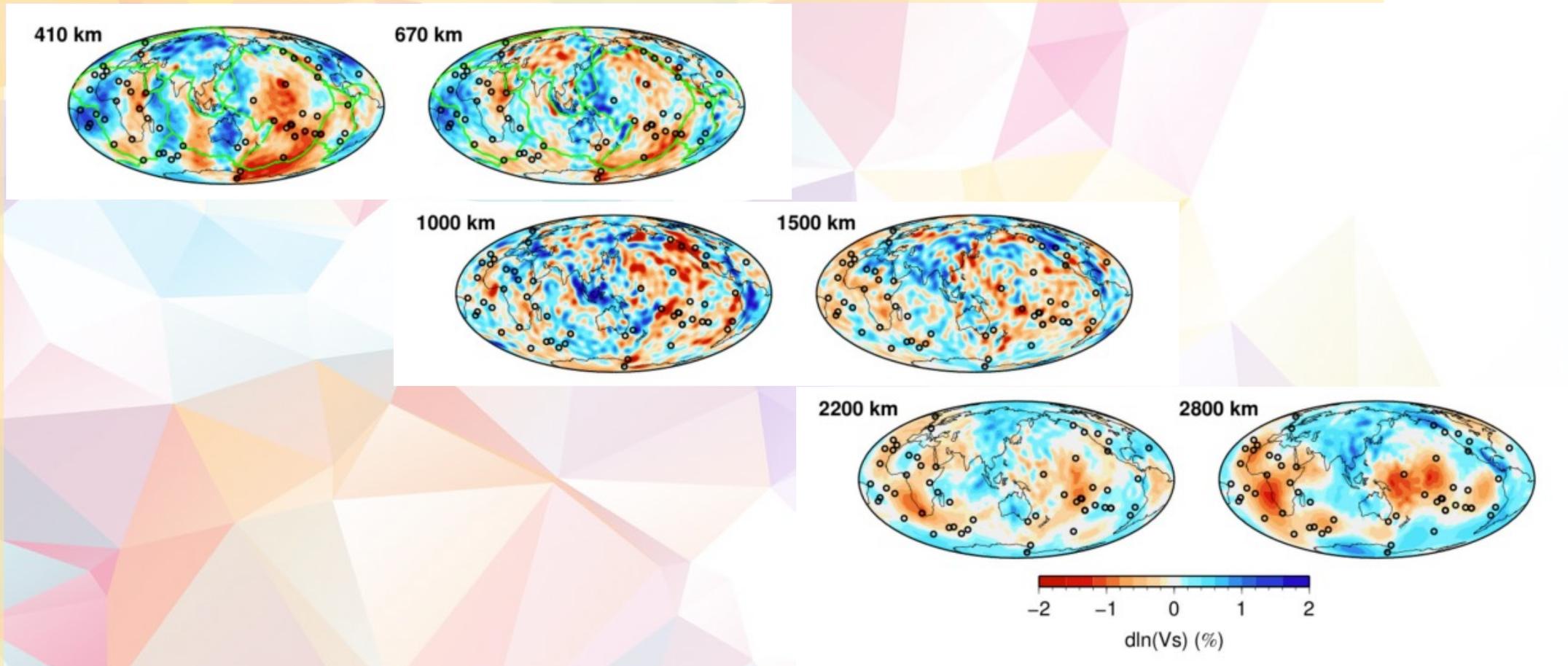


Fig. 3. Powder XRD pattern of the HH phase in A20 collected in region C. The HH phase (marked with red dots) was dominant under *P-T* conditions of 107.0 GPa and 2,000–2,400 K (X-ray wavelength: 0.3738 Å). The calculated peak positions of the HH phase, Py phase, and δ-phase are indicated by small ticks, showing coexistence of small amount of both P-phase and δ-phase.

# Que se Passe t'il Autour de 1500 km ?



Durand et al., Geophys. J. Int., 2017

# Changement de Configuration Electronique du Fer

Sup.

410 km

TZ

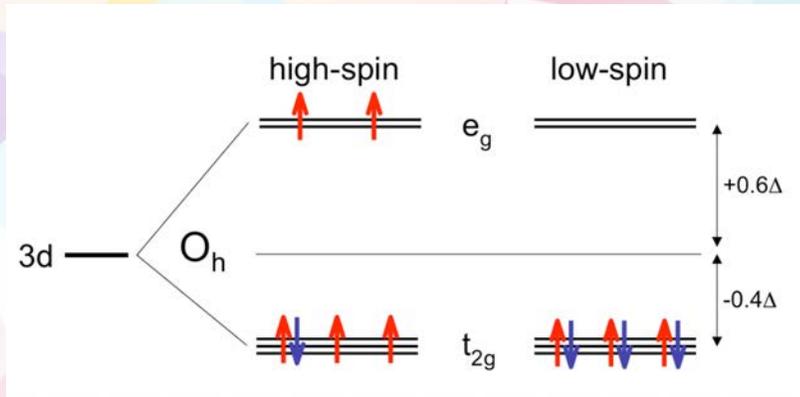
670 km

Inf.

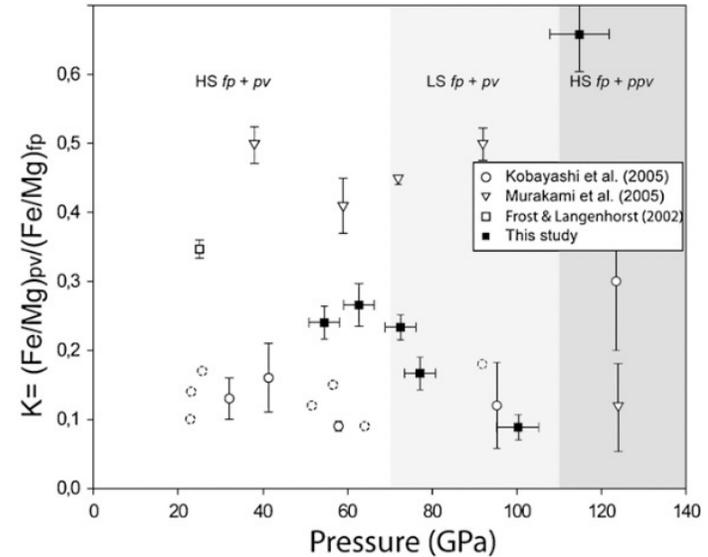
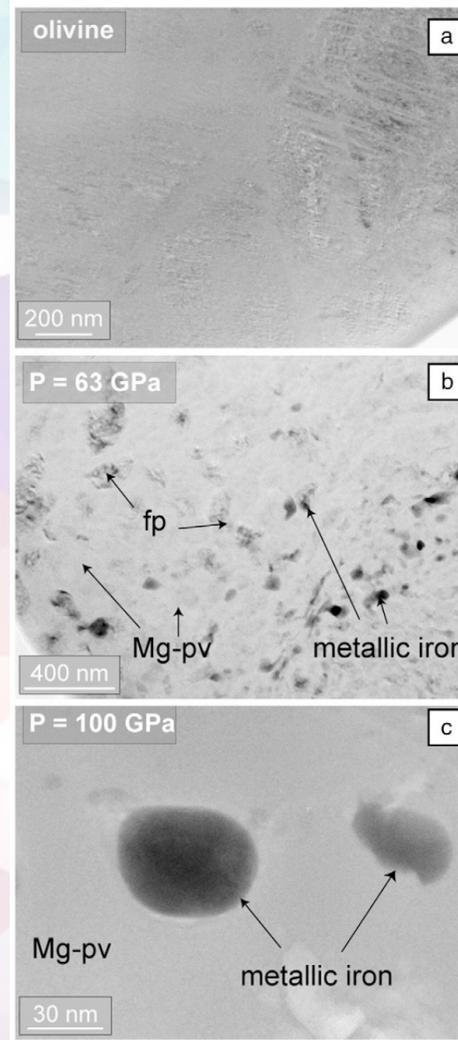


2900 km

Transition de spin induite par la pression :



Badro et al., 2003 et 2004  
(Bridgmanite et Ferropericlasé)



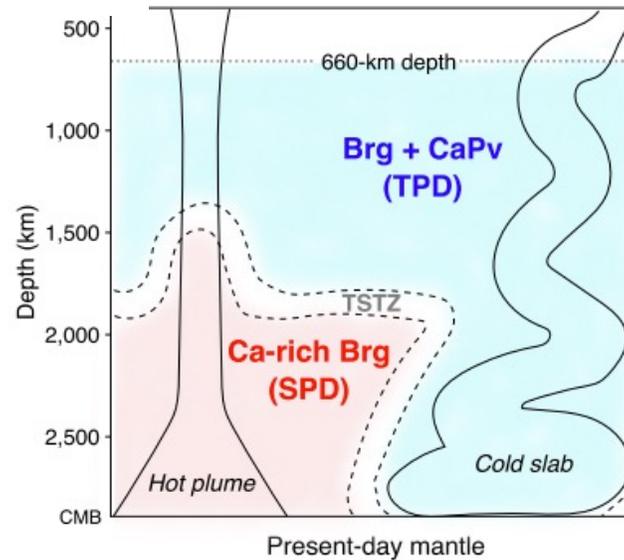
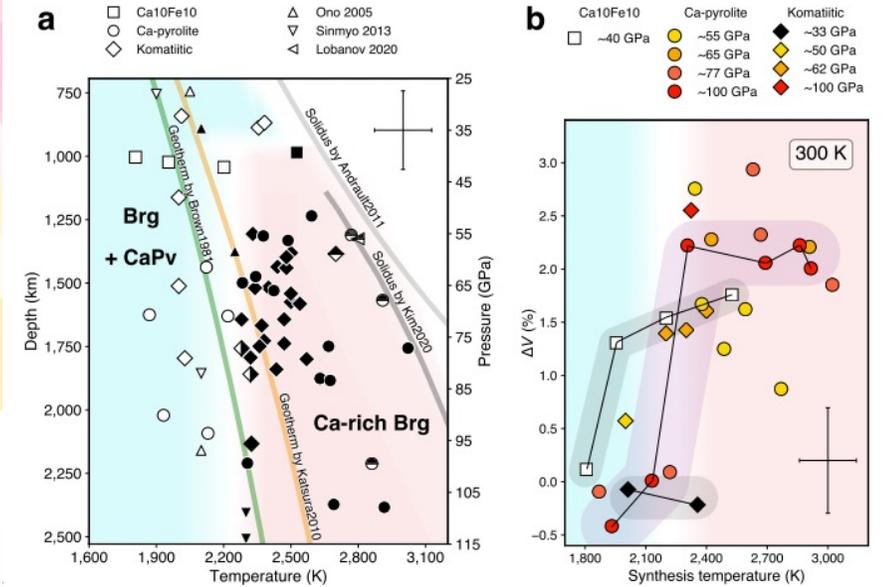
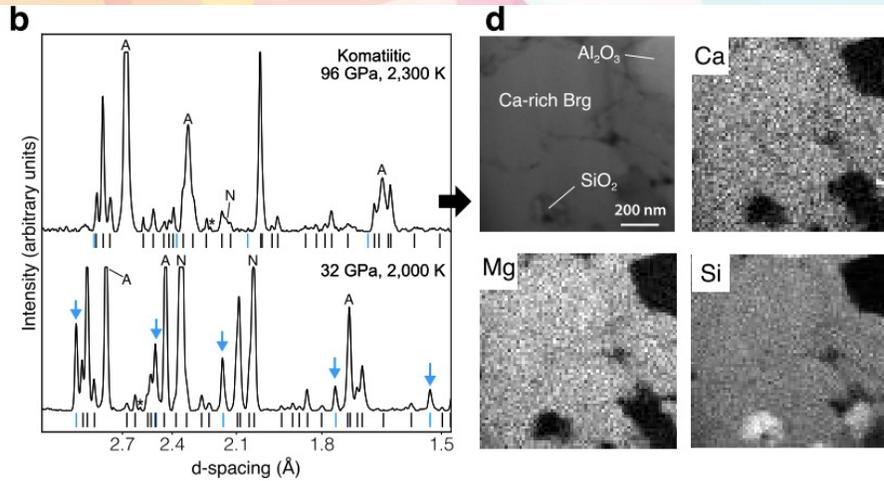
Auzende et al., 2008

- Modifie le coefficient de partage du fer
- augmente la conductivité thermique

# Dissolution de la Davemaoite Dans la Bridgmanite

Sup.  
410 km  
TZ  
670 km

Inf.



Ko et al., 2022

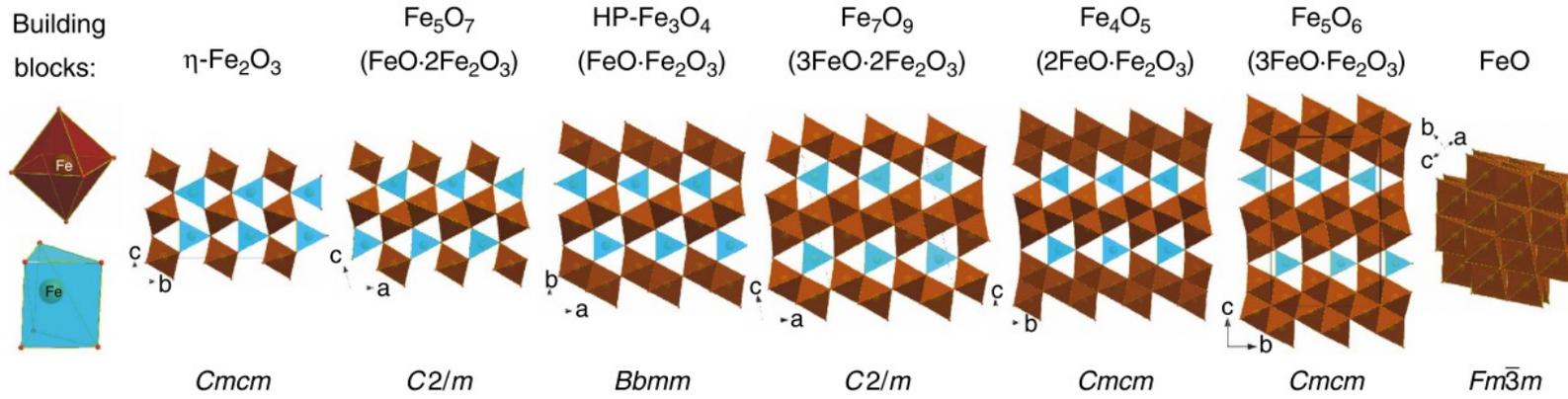
18/11/2023

38

2900 km

# Nouveaux Oxydes de Fer à Partir de 1500 km

Sup.  
410 km  
TZ  
670 km



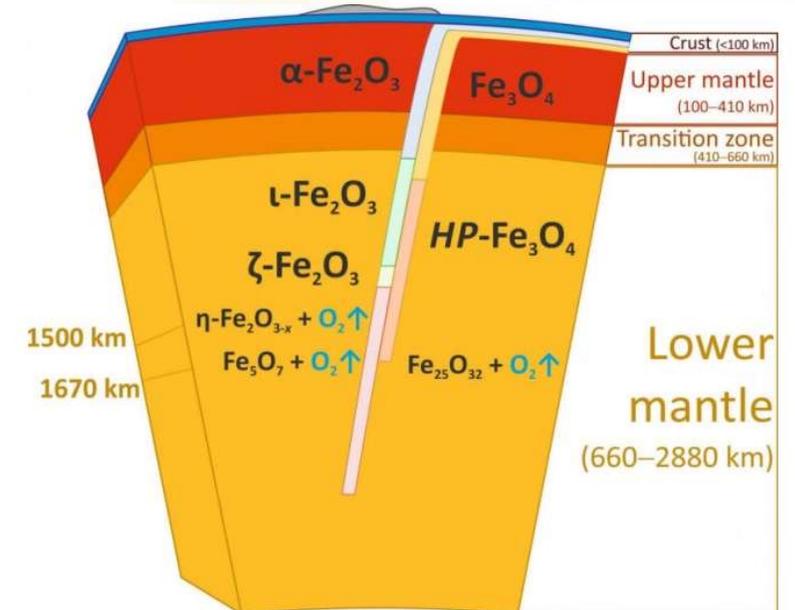
Inf.  
2900 km

➤ production d'oxygène

Bykova et al., 2016

18/11/2023

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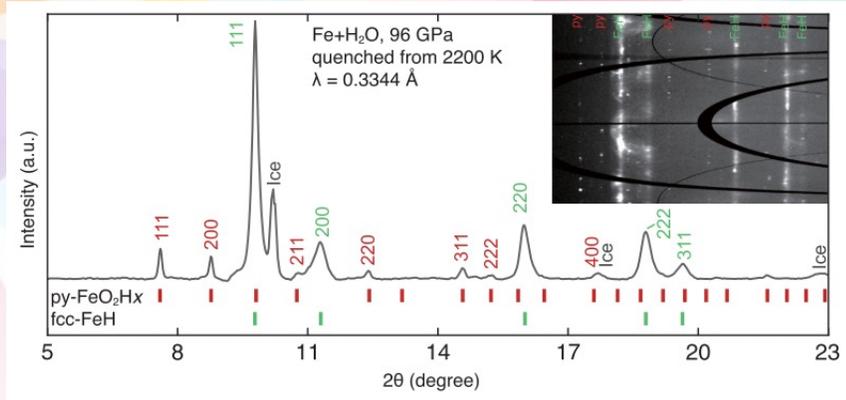


# Nouvelle Valence de l'Oxygène

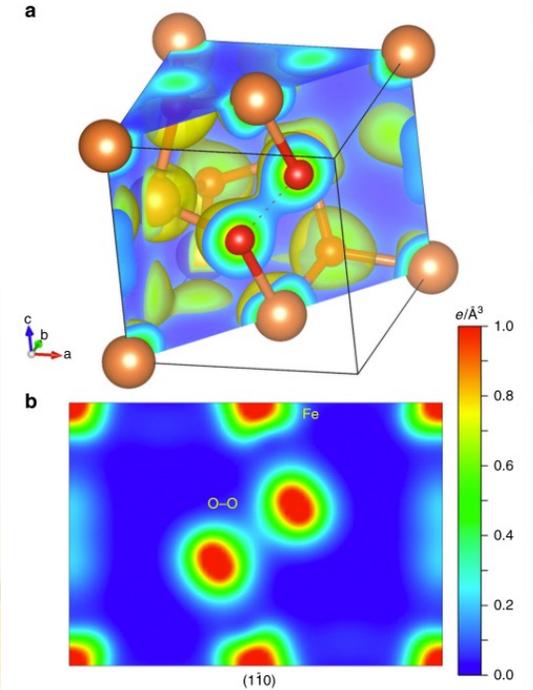
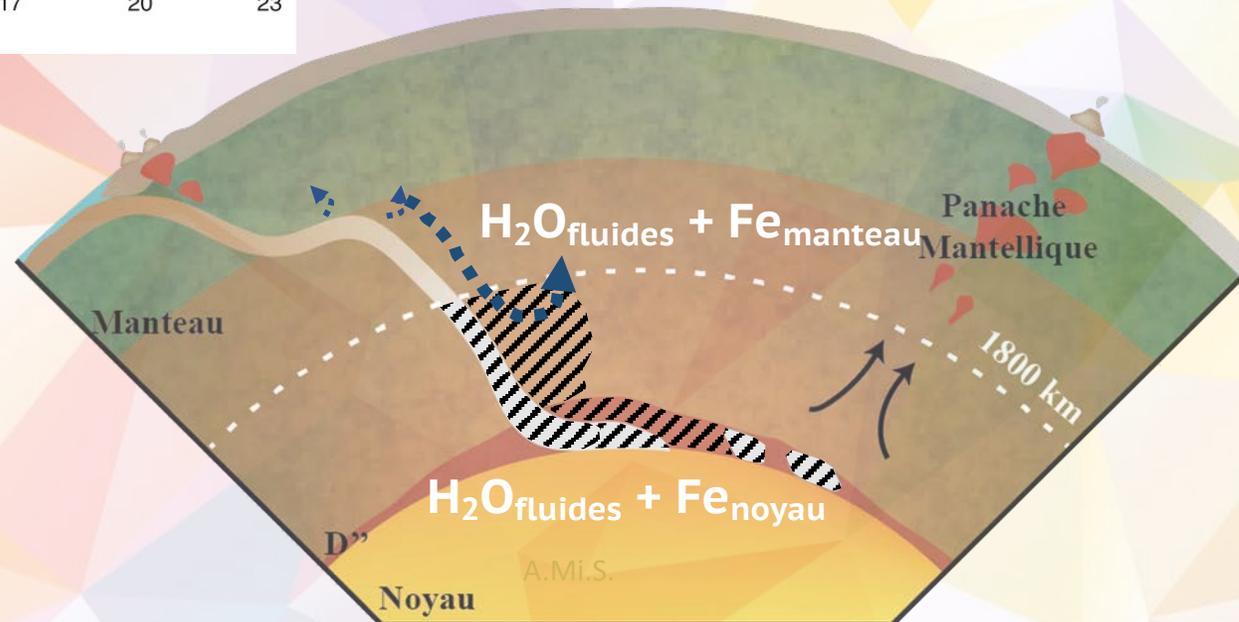
Sup.  
410 km  
TZ  
670 km

## FeO<sub>2</sub>Hx (py-phase)

Hu et al., 2016



Mao et al., 2018



Liu et al., 2019  
Boulard et al., 2019

Inf.

# L'Hydrogène Devient Superionique

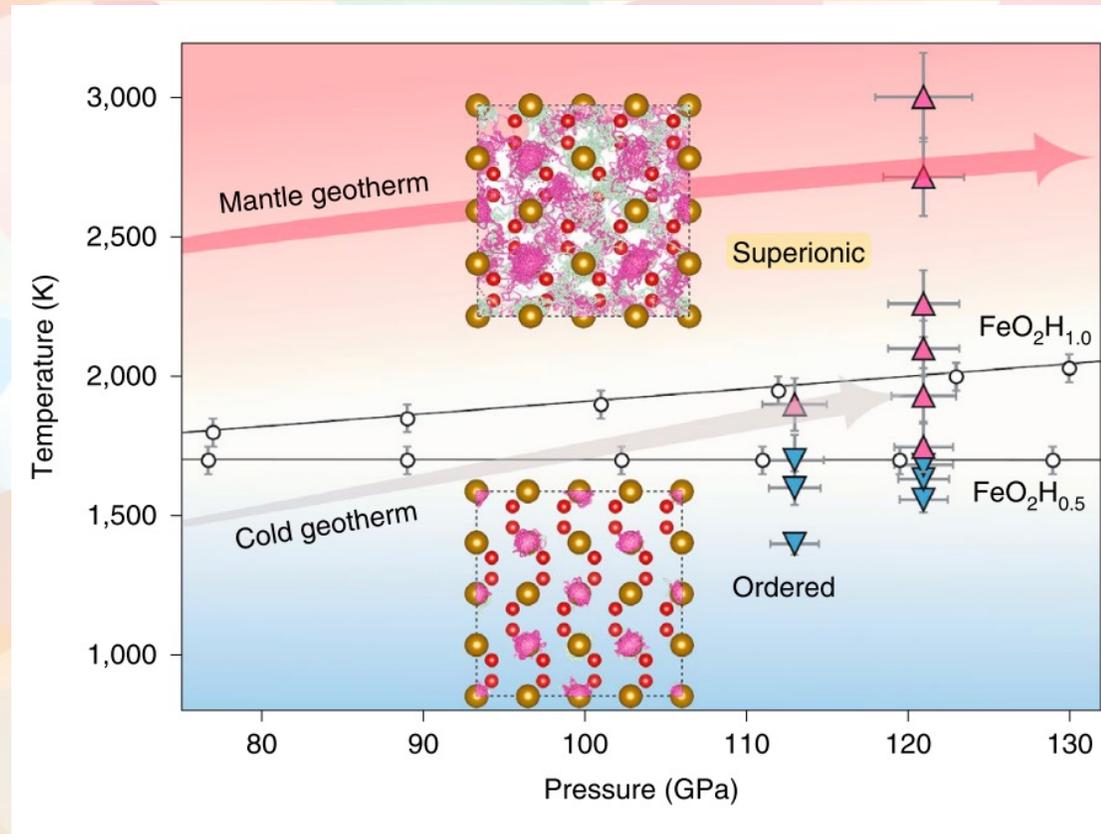
Sup.

410 km

TZ

670 km

Inf.



Hou et al., 2021

Haute diffusivité de l'hydrogène => Modifie les mécanismes de transport de charge and masse: (conductivité électrique, magnétisme, oxydo-réduction, la circulation de l'hydrogène et mélange isotopique dans la terre profonde)

18/11/2023

A.Mi.S.

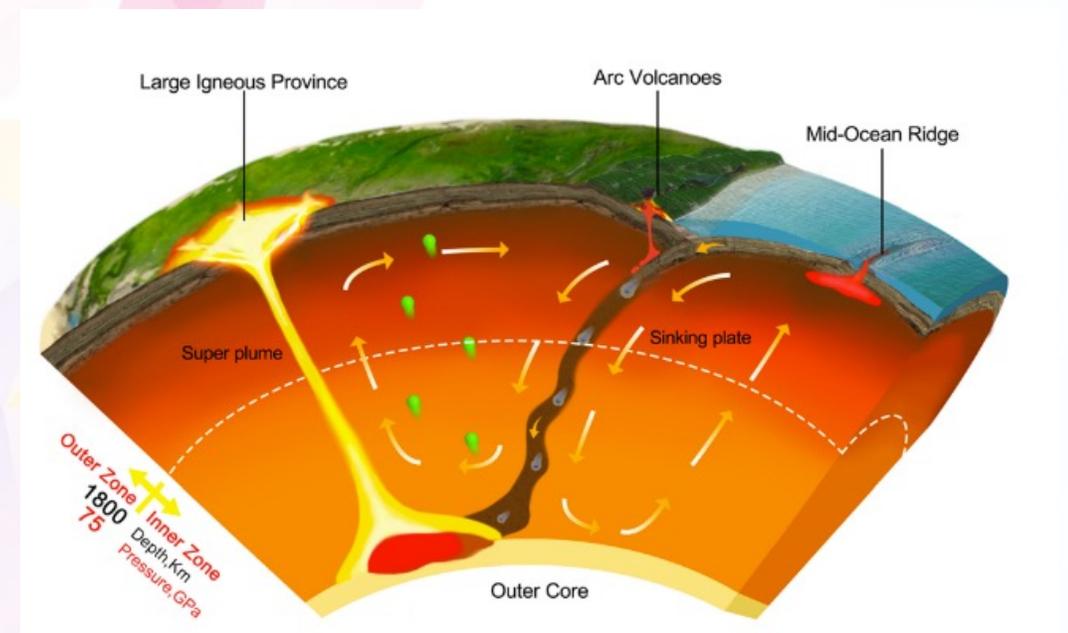
41

2900 km

# Nouvelle Vision du Manteau Inférieur

Au-delà de 1500-1800 km de profondeur :

- nouvelles stoechiométries d'oxyde de fer et production d'oxygène
- Changement de configuration électronique des éléments de transitions : modification de la conductivité thermique et du partage du fer
- passage à un domaine à une seule pérovskite : Bridgmanite riche en Calcium
- Hydrogène superionique
- valence de l'oxygène possible à -1 dans les phases hydratées
- Stoechiométrie des minéraux basée sur la valence ionique de  $\text{Na}^+$ ,  $\text{Mg}^{2+}$ ,  $\text{Fe}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Al}^{3+}$ ,  $\text{Cl}^-$ ,  $\text{O}^{2-}$ , etc. n'existe plus



Mao et Mao, 2020