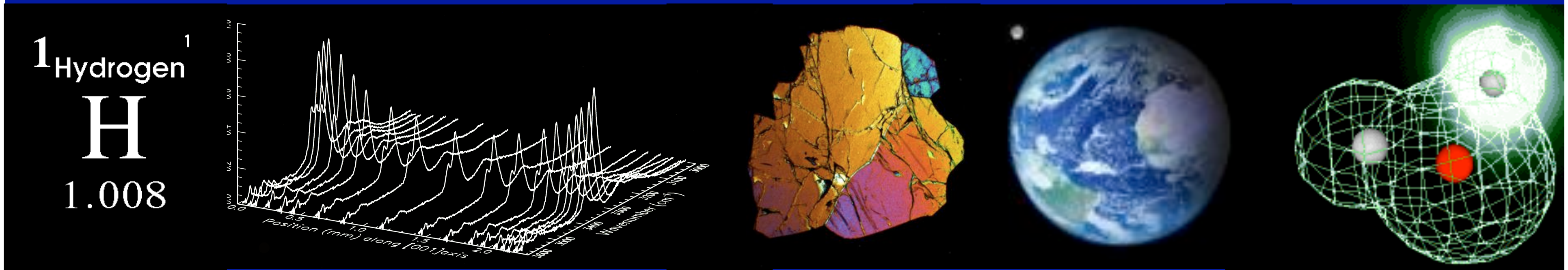
Water in the upper mantle: consequences to rheology



Sylvie Demouchy
CNRS, Geosciences Montpellier, France

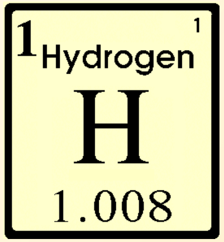
- *What is «water»* H_2O, OH^-, H^+, H^2

- *Where is this «water » in the mantle?*

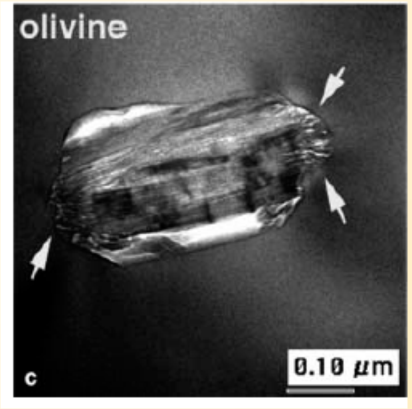
- *Water & Deformation*

Where ????

- **Hydrogen as an impurity at the atomic scale in point defect:**
  Hydrogen occupy a vacant site or is interstitial



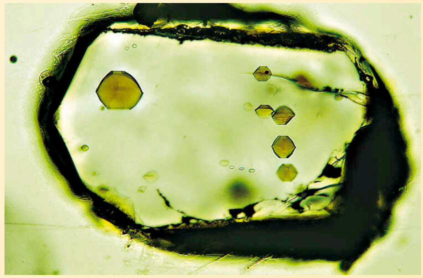
- **Microscopic scale (2 dimensions defect):**
  OH or H_2O in hydrous phase
  Amphiboles lamellae in pyroxenes,
  Chlorite, humites or serpentines in olivine.



(Khisina et al, 2001)

- **Macroscopic scale (3 dimensions defect):**
  H_2, OH, H_2O in fluid and/or glass inclusions.

Hydrogen is <u>an incompatible element</u> : it prefers to be in the magma than in the mineral !



(Sobolev's web sitel)

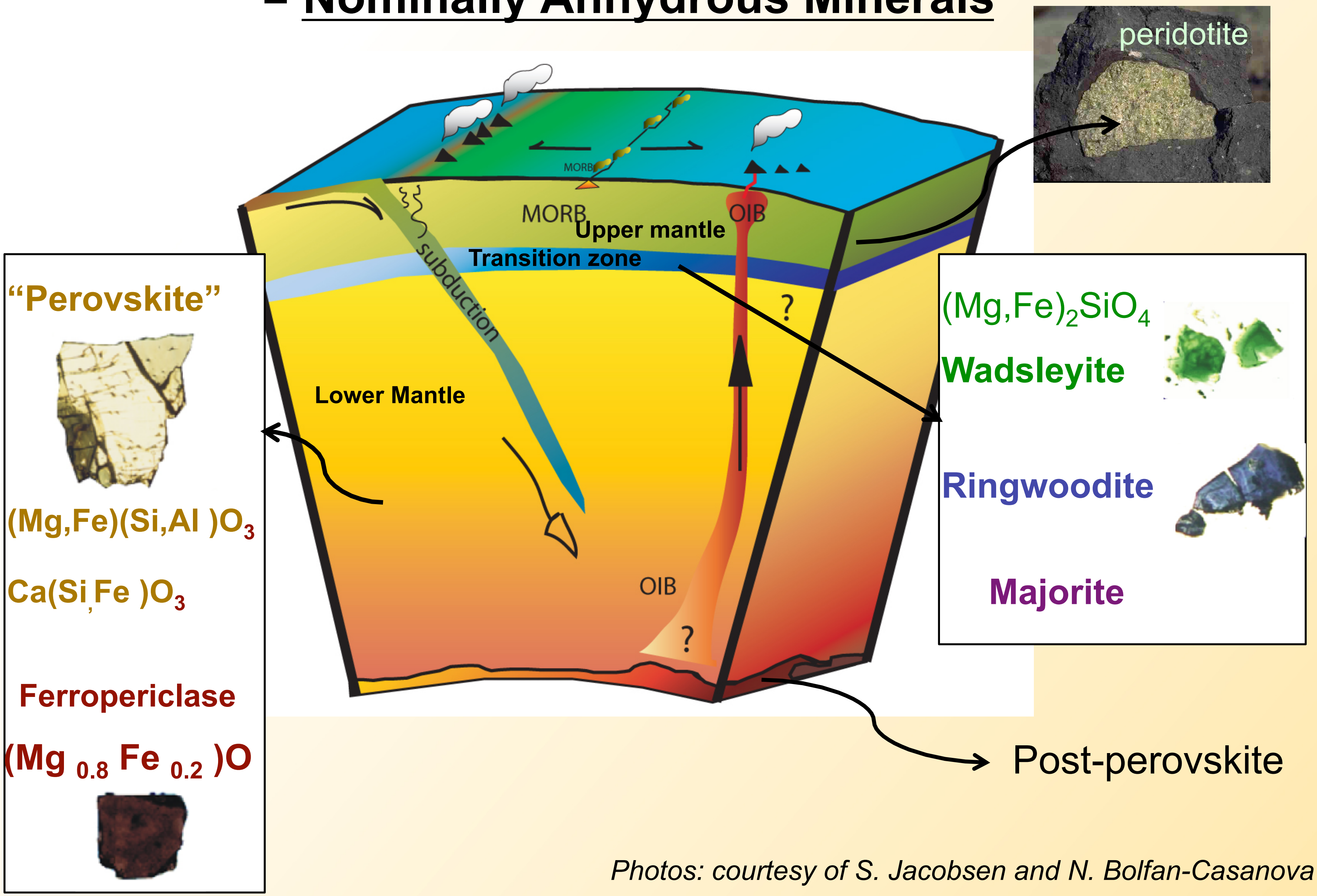
- No molecular water in the minerals of the deep Earth
  But, we will call it « water » anyway !

- "Water" solubility or "water" capacity is the maximum amount of hydrogen you can put into a mineral structure. It is determined experimentally.
  f(T, P, chemical composition, fO_2, a_{sio2}, co-existing phases)

- The water solubility is NOT equal to the **REAL** hydrogen concentration in the mantle

Where?

= <u>Nominally Anhydrous Minerals</u>



Photos: courtesy of S. Jacobsen and N. Bolfan-Casanova

Real water

MORB magma = 0.1 wt% H_2O
OIB magma= 0.3-1.0 wt% H_2O

Extrapolation

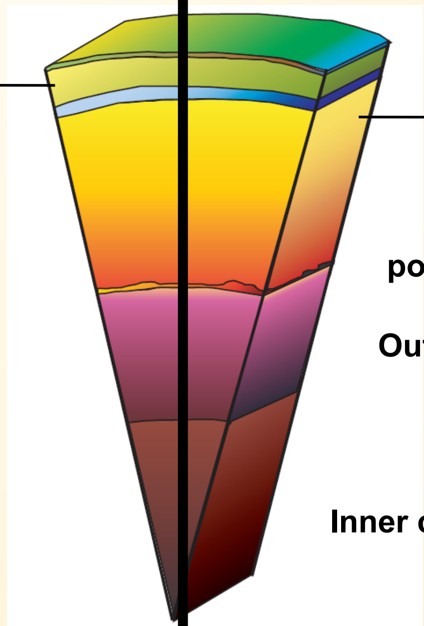
MORB source= 50-450 wt ppm H_2O
OIB source= 400-1000 wt ppm H_2O

UM xenoliths= 100-250 wt ppm H_2O

Water solubility

Fonction of T, P, chemistry, etc

UM= 250-800 wt ppm H_2O
TZ = 10 000 wt ppm H_2O = 1 wt%
LM= ~ 10 wt ppm H_2O



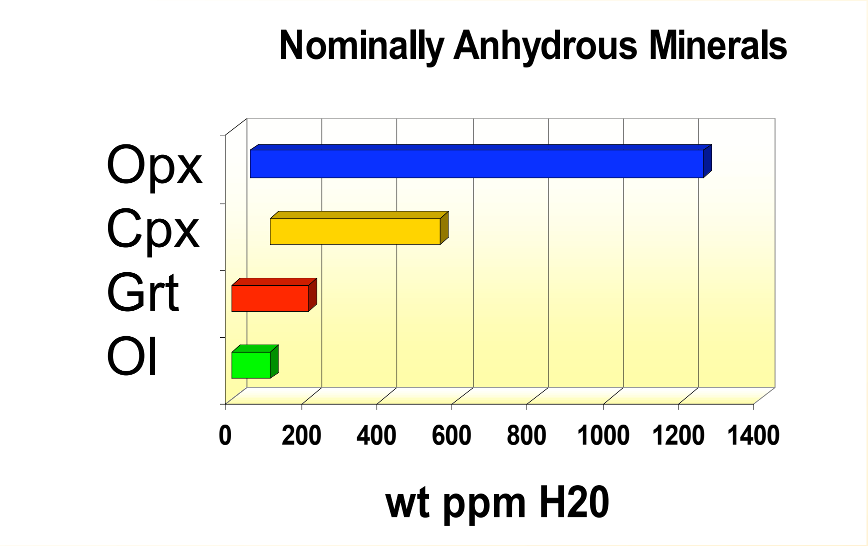
From Bolfan-Casanova, 2000; Dixon et al., 2004 ; Hirschmann et al, 2005

<u>Nota:</u> 1 wt% H_2O=10 000 wt ppm H_2O
For olivine Fo_{90}, 1 wt ppm H_2O =16.35 $H/10^6Si$

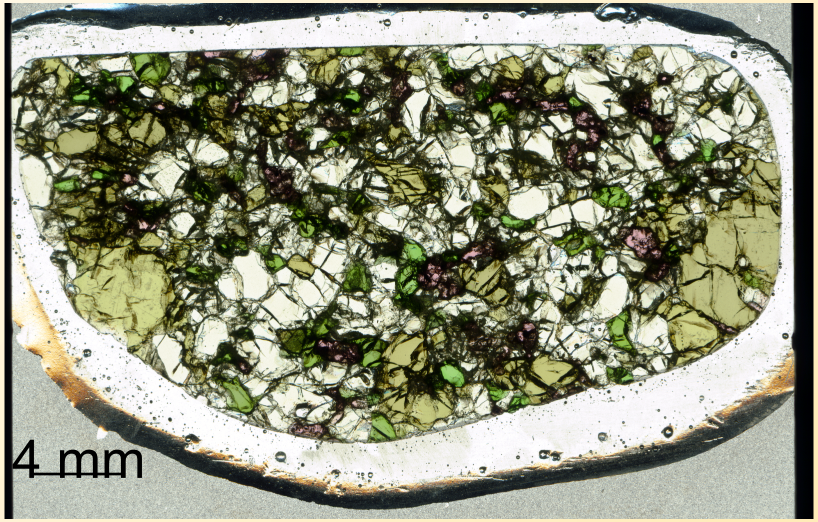
Close up

Water concentration of the upper mantle

- Between 0 wt ppm H_2O and 250 wt ppm H_2O

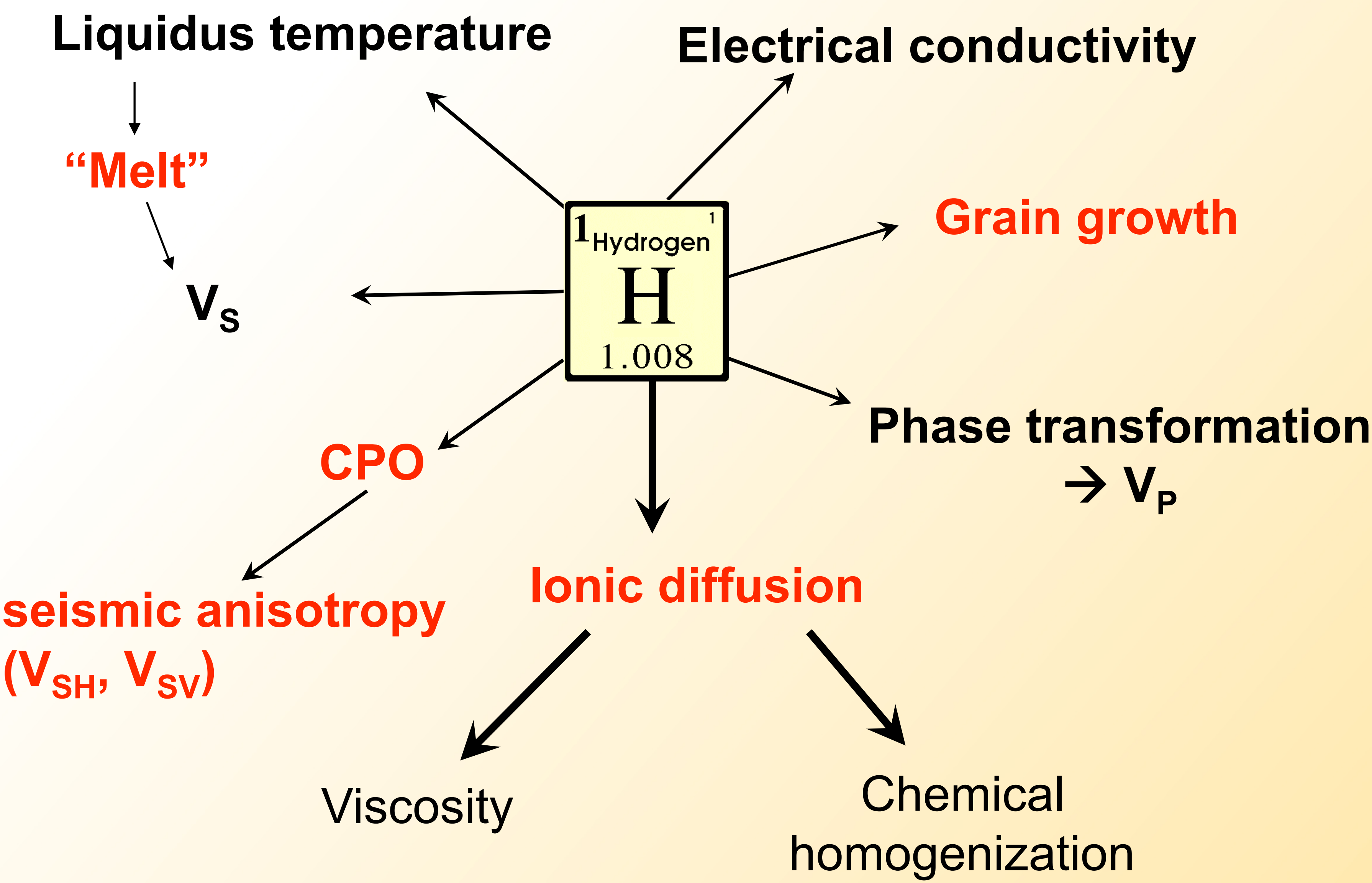


(Modifiied from Ingrin and Skogby, 2000)



Demouchy, 2004

EFFECT OF HYDROGEN



Water and deformation

To simplify, 2 deformation mechanisms
=> diffusion and dislocation

- *Effect of water in the diffusion creep regime*

  Transport of matter by ion diffusion

- *Effect of water in the dislocation creep regime*

  Transport of matter by dislocation motion
  Different styles of motion: glide, climb and cross-slip....
  We will see dislocation climb and glide

Power flow laws:

Empirical equations to describe deformation processes

$$\dot{\varepsilon} = A\, f_{H_2O}^{r}\, \frac{\sigma^{n}}{d^{p}} \exp\left(-\frac{E+PV}{RT}\right)$$

$$for\ diffusion\ creep\quad n = 1$$

$$\dot{\varepsilon} = B\, f_{H_2O}^{r}\, \frac{\sigma^{n}}{d^{p}} \exp\left(-\frac{E+PV}{RT}\right)$$

$$for\ dislocation\ creep\quad n \approx 3$$

Effect of water in the diffusion creep regime

Hydrogen uses point defect in the structure
Those point defect are moving → transport of matter

- From point defect (0 dimension defect in the lattice)

$$D_{ion} = C_{vacancy} \times D_{vacancy}$$

Effect of water in the diffusion creep regime

- The presence of H increases the concentration of vacancy due to eleconeutrality requiered by point defect theory to keep a crystal stable.

$$C_{\text{vacancy}}^{\text{hydrous conditions}} \neq C_{\text{vacancy}}^{\text{dry conditions}}$$

$$C_{\text{vacancy}}^{\text{hydrous conditions}} >> C_{\text{vacancy}}^{\text{dry conditions}}$$

$$D_{\text{ion}} = C_{\text{vacancy}} \times D_{\text{vacancy}}$$

$$D_{ion}^{\text{hydrous conditions}} > D_{ion}^{\textit{an}\text{hydrous conditions}}$$

Viscosity in the diffusion creep regime

$$\frac{1}{\eta} = A \frac{\Omega}{RT} \frac{D_{eff}}{G^2} \quad or \quad \eta = \sigma / \dot{\varepsilon} = (stress / strain\,rate)$$

$$D_{eff} = 1 / \sum_i \left(n_i / D_i \right)$$

Controlled by the slowest species in the mineral

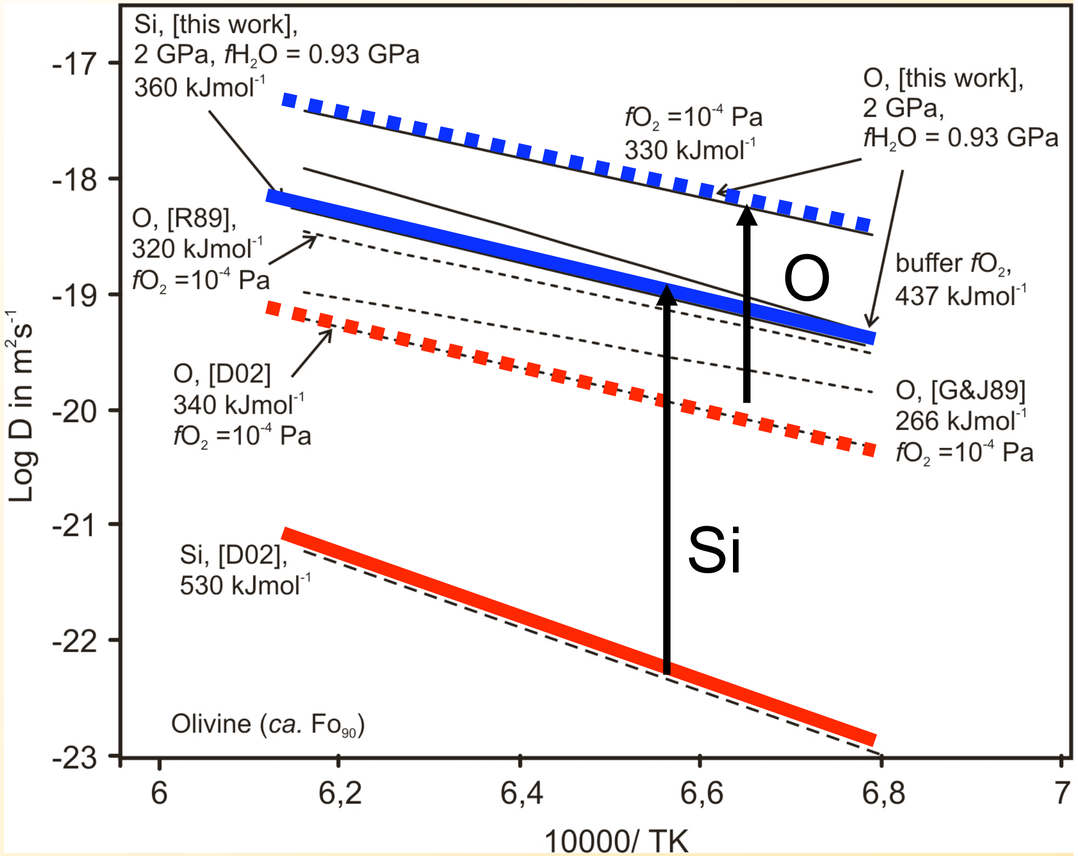
To test and quantify this hypothesis
→ **diffusion** experiments and **deformation** experiments

Diffusion experiments

- Si and O self-diffusion in olivine
- 2 to 4 orders of magnitude faster!

YES ! Diffusion is faster under hydrous conditions

Viscosity will be lower



Costa and Chakraborthy, 2008

Nabarro's model:

η = 9,8 x 10^{21} à 1,6 x 10^{18} Pa.s

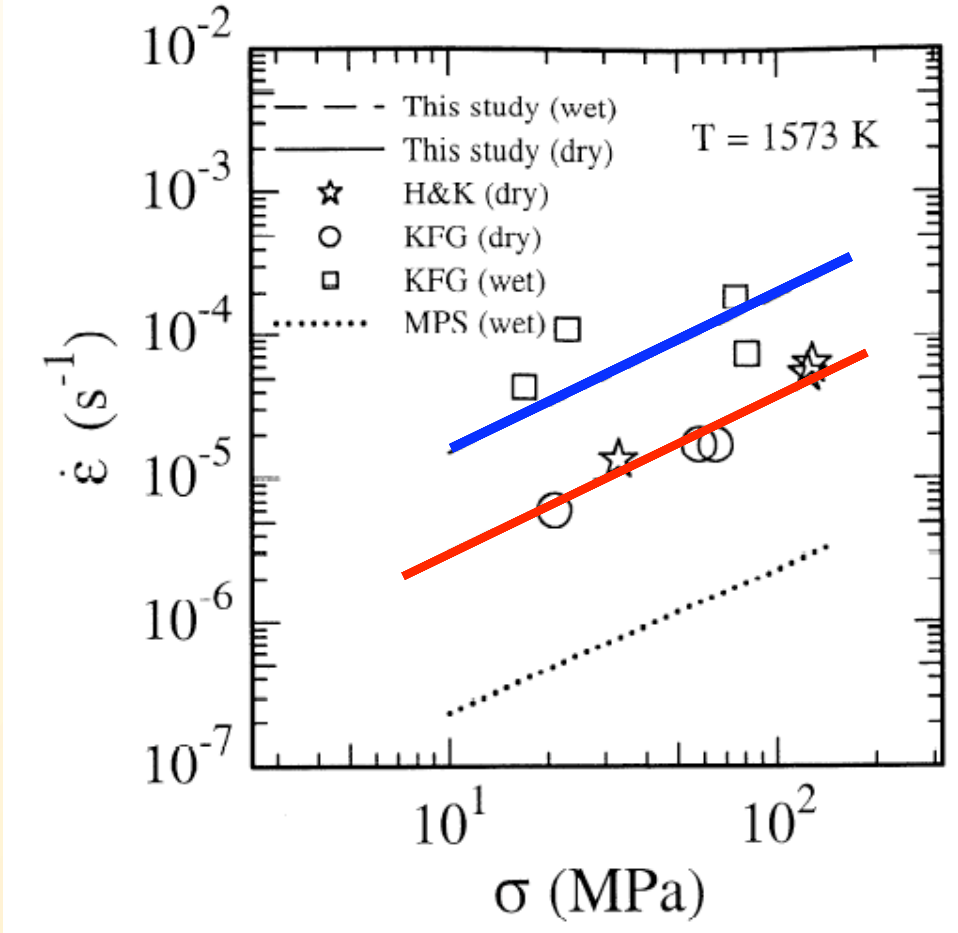
@ 1200°C, 2GPa

Deformation experiments in the diffusion creep regime

- YES ! Stress is weaker under hydrous conditions

$$\eta = \sigma / \dot{\varepsilon}$$

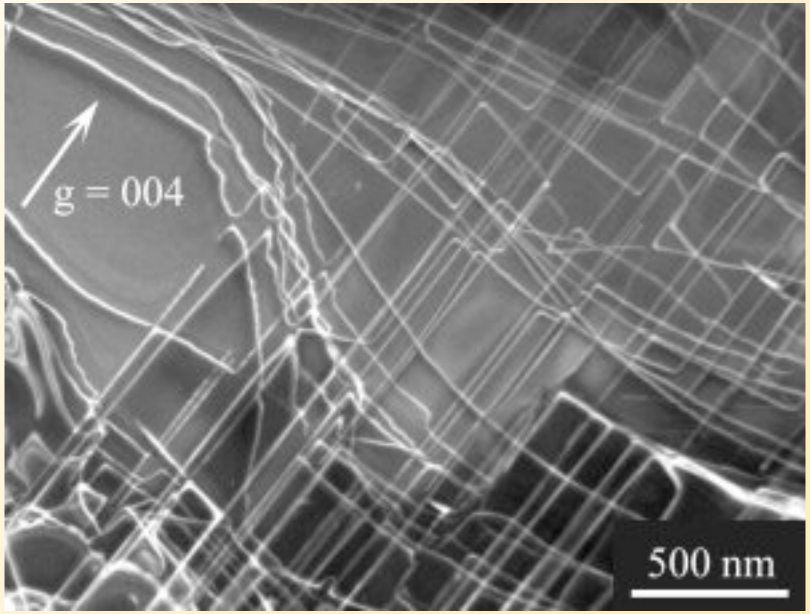
Viscosity will be lower !



Mei and Kohlstedt, 2000a

Effect of water in dislocation creep regime

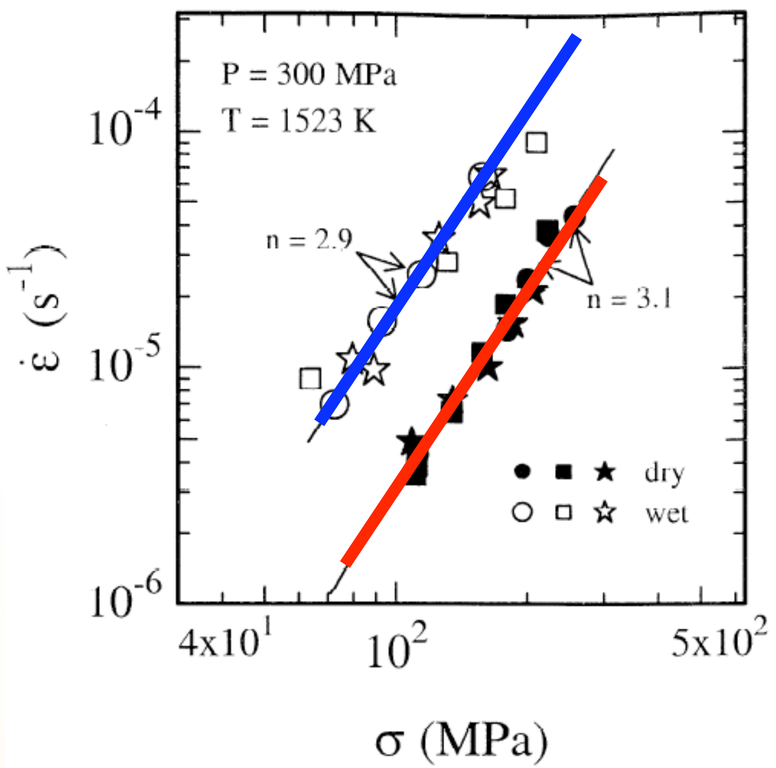
- Transport throught the lattice using dislocation
- Hydrogen as point defect
  0 dimension defect
- Dislocations are
  1 dimension defect

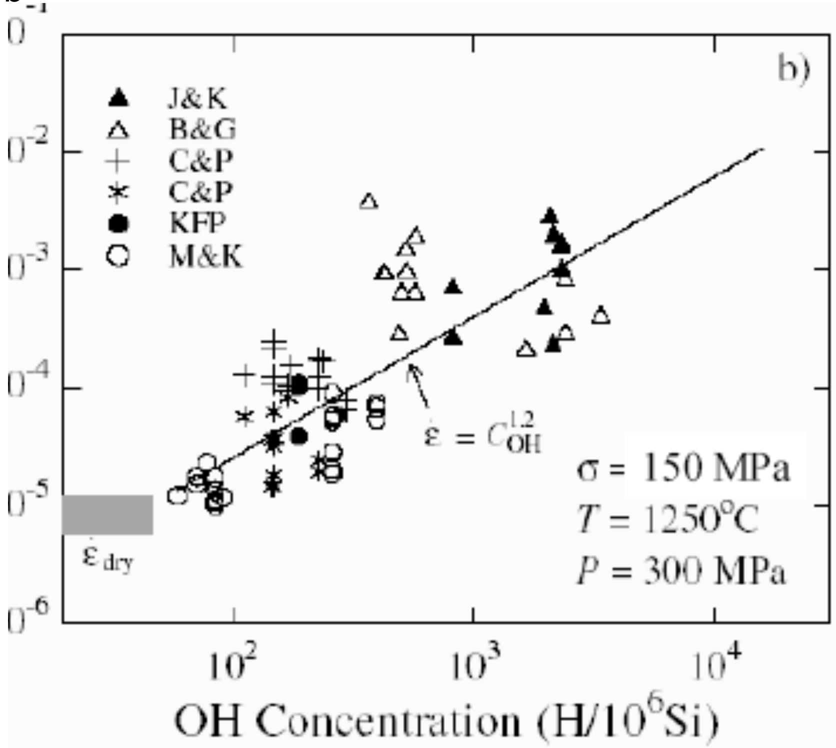


TEM image of deformed olivine

Deformation experiments

Mei and Kohlstedt, 2000b



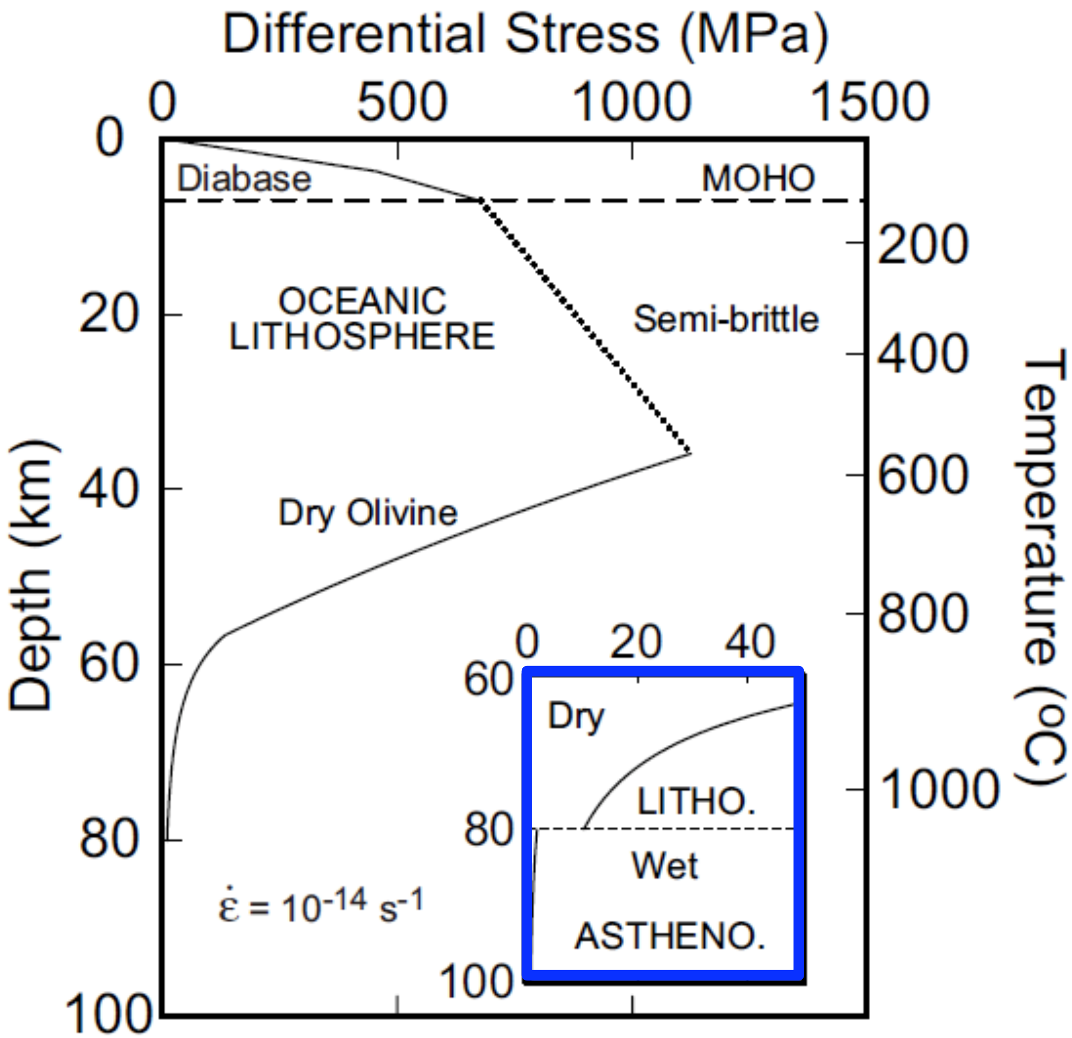


Hirth & Kohlstedt, 2003

Jung & Karato, 2001; Borch & Green, 1989; Chopra & Paterson, 1981; Karato et al., 1986; Mei & Kohlstedt, 2000

YES ! Stress is weaker under hydrous conditions Viscosity will be lower !

Effect of water in dislocation creep regime



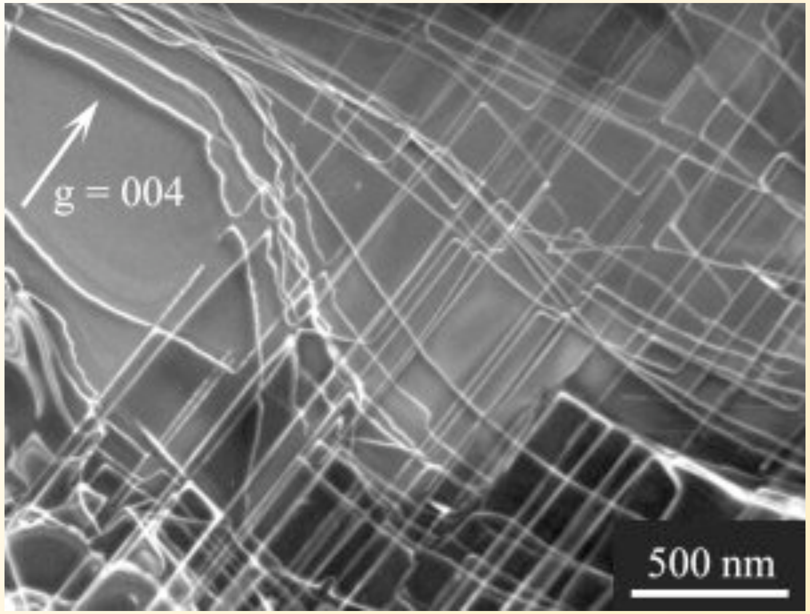
Kohlstedt and Mackwell, 2006

Effect of water in dislocation creep regime

Style of motion for dislocation:

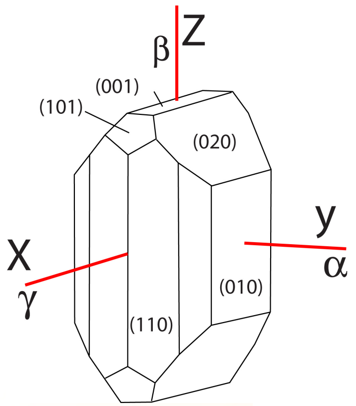
We saw the effect of water on <u>dislocation climb</u>

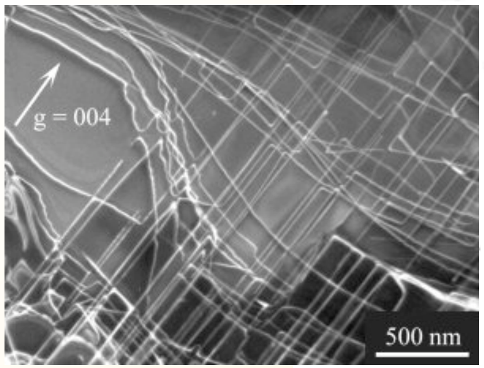
What's about <u>dislocation glide</u>?

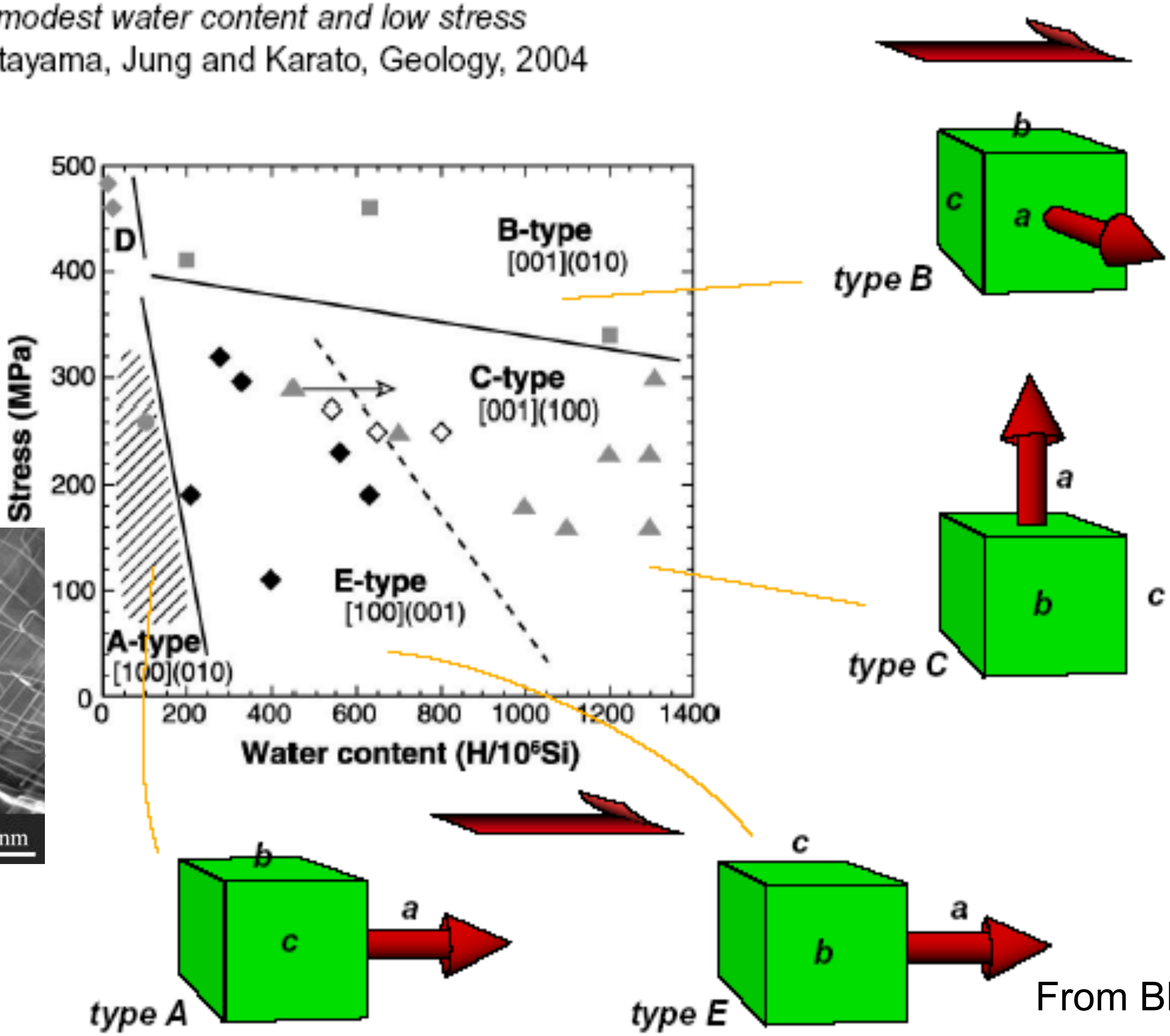


Hydrogen in the lattice may affect the dislocation glide system

New type of olivine fabric from deformation experiments at modest water content and low stress
Katayama, Jung and Karato, Geology, 2004



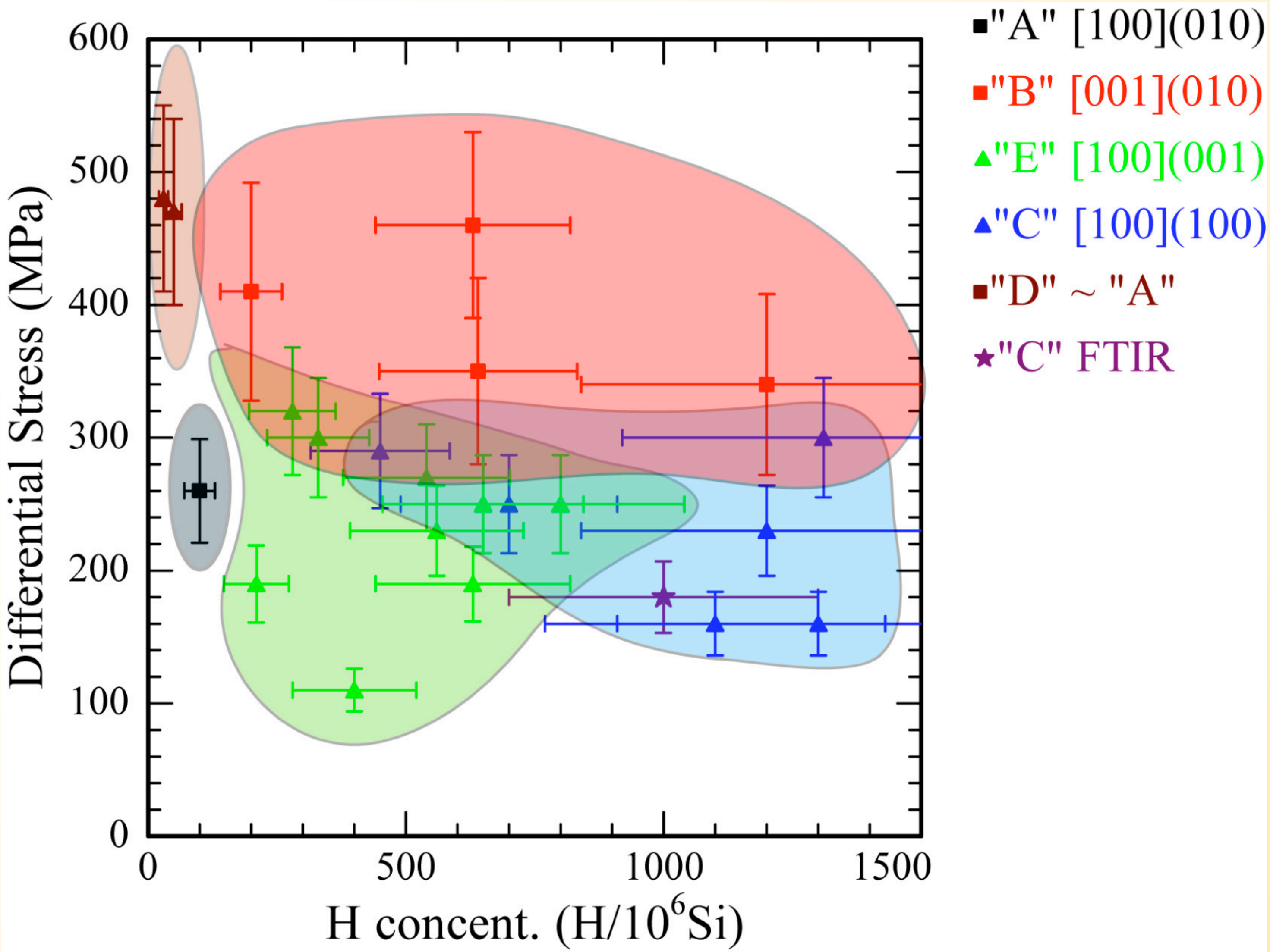




From BKH

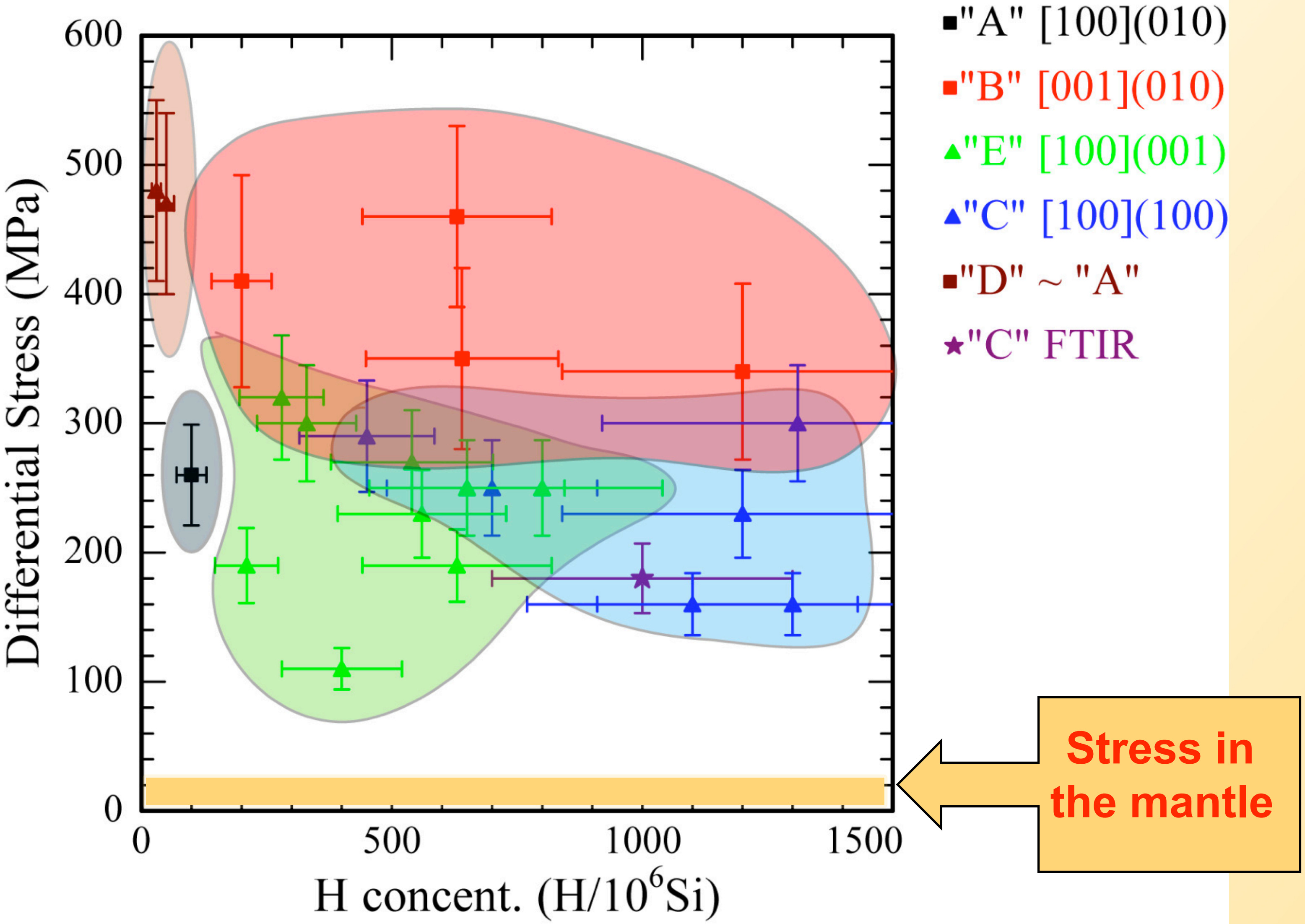
Effect of water in dislocation creep regime

With error bars……



Effect of water in dislocation creep regime

With error bars……



Conclusions

- Hydrogen is embeded in mantle minerals as impurities
  (and is fixed in the structure using **point defect**), **not molecular water !**

  Deep Earth bulk hydrogen concentration….still poorly contraint !

- Hydrogen enhances ionic diffusion,
  Then it weaken solids in the diffusion creep regime.

- Hydrogen affects dislocation velocity,
  then it weaken solids in the dislocation creep regime.

- Hydrogen <u>may</u> change the dislocation glide system…

But keep your eyes open !