Massachusetts Institute of Technology

The influence of water on rheology and seismic properties of olivine

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In collaboration with
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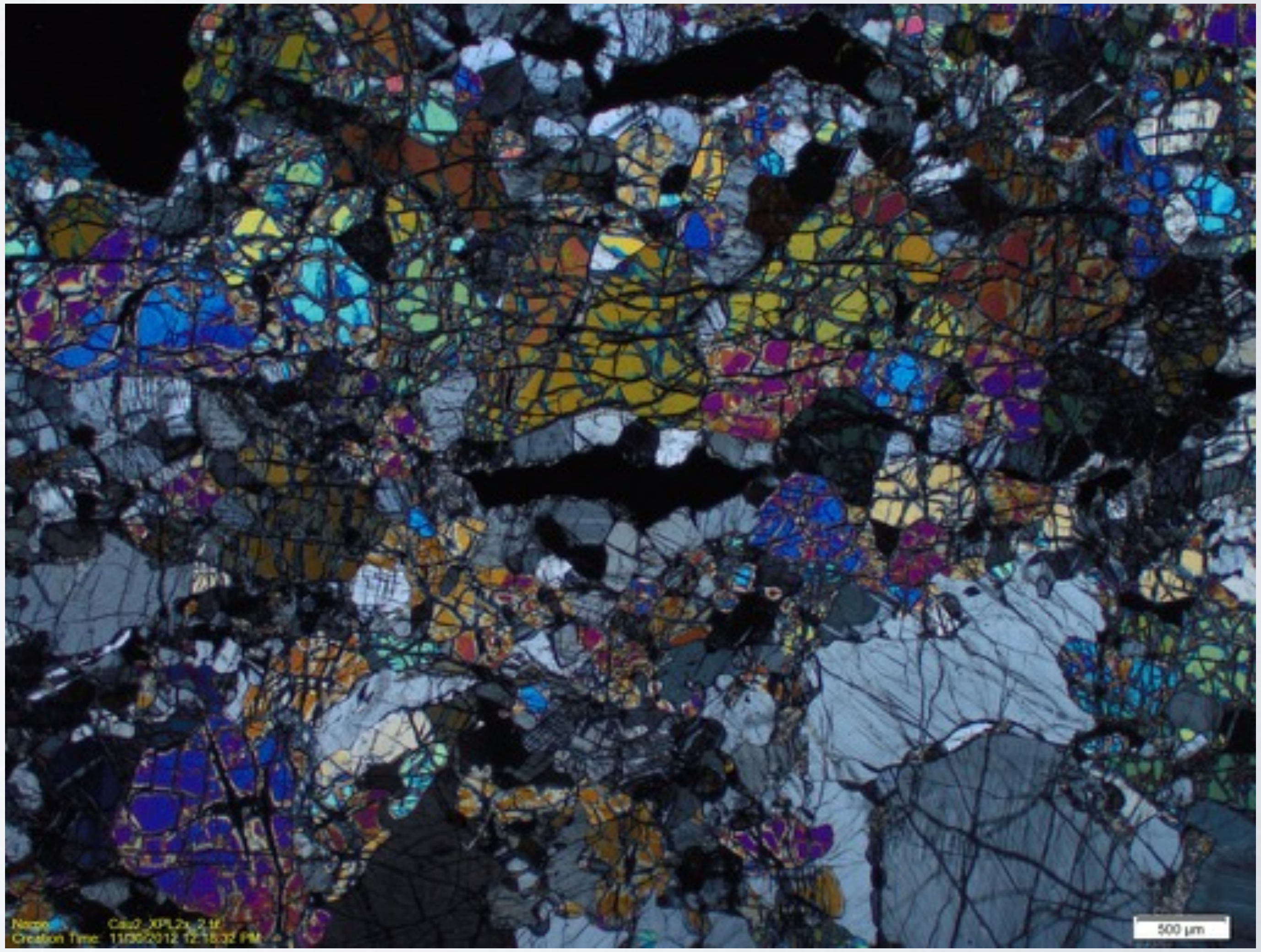
(Australian National University)

Outline

- large strain rheology (dislocation creep)
- water incorporation in olivine (extrinsic defects)
- oxygen fugacity
- seismic properties

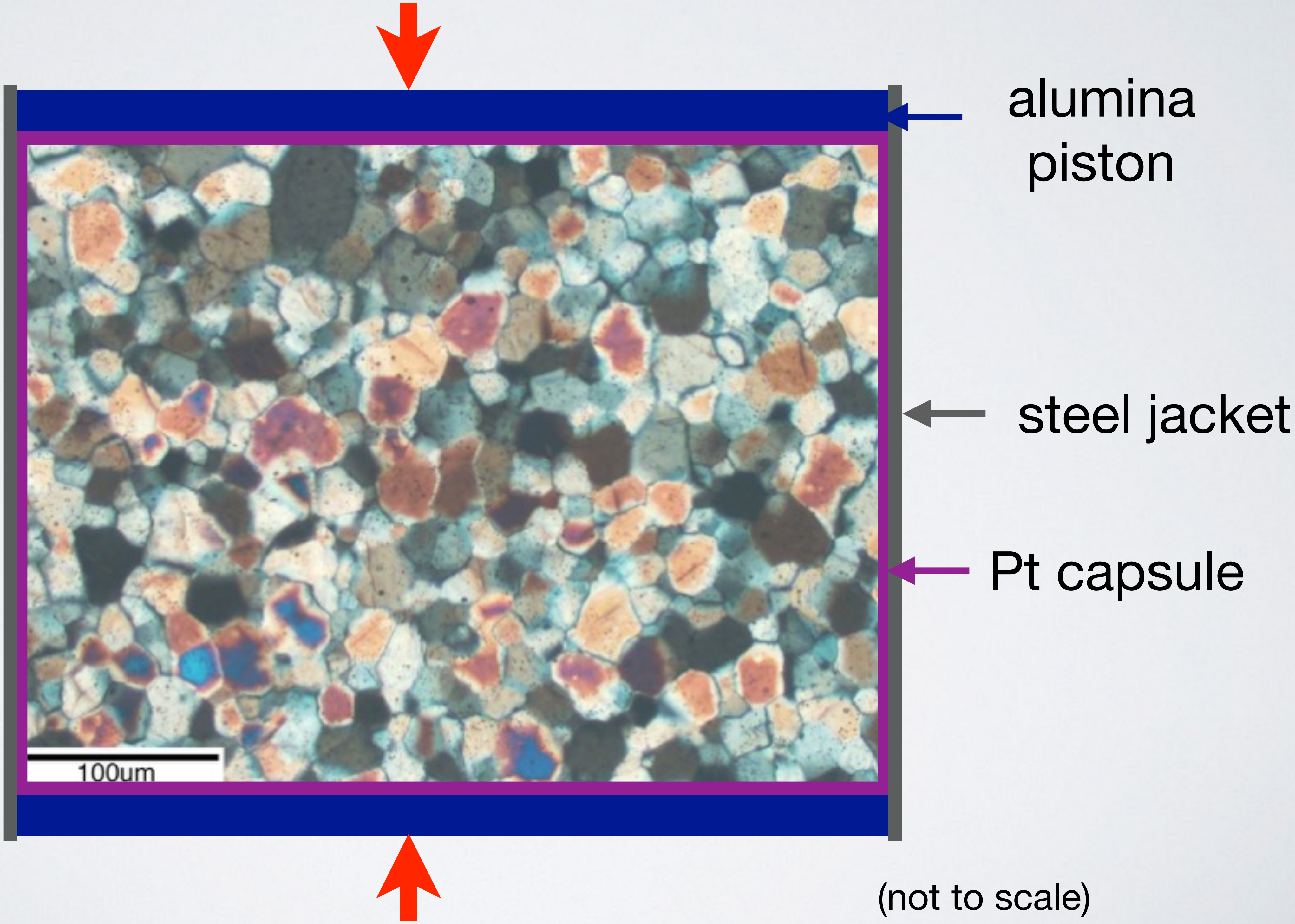


deformed plagioclase lherzolite,
Krivaja massif, Bosnia-Herzegovina

Deformation experiments

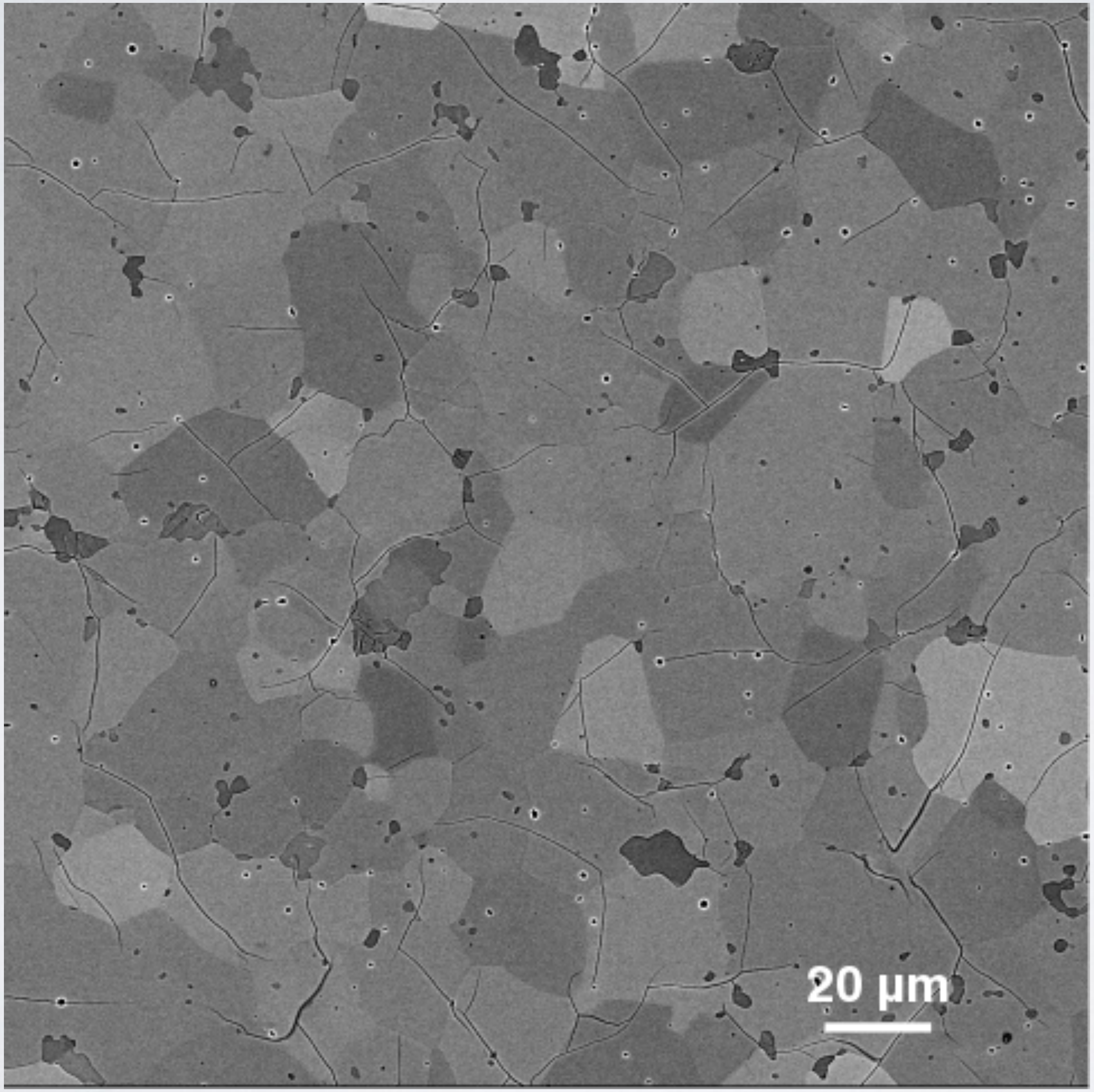
Experiments: gas medium (Paterson) app., P = 300 MPa

Samples surrounded by $Fe_{70}Ni_{30}$ or Pt metals, no water buffer



(not to scale)

Samples:
Solution-gelation derived Fo_{90} olivine doped with a range of Ti contents (0 - 0.04 wt. % TiO_2)



grain sizes ~ a few tens of μm

BSE image

Rheology: flow laws

general form: $$\dot{\varepsilon} = A\frac{\sigma^n}{d^p}\exp\left(\frac{-Q}{RT}\right)$$

$\dot{\varepsilon}$: strain rate, A: constant, $\boldsymbol{\sigma}$: stress (exponent n), d: grain size (exponent p), Q: activation energy, R: gas constant, T: temperature

Strain rate is the sum of two (or more) mechanisms:

$$\dot{\varepsilon}_{\text{total}} = \dot{\varepsilon}_{\text{dif}} + \dot{\varepsilon}_{\text{dis}} + \dot{\varepsilon}_{\text{GBS}}$$

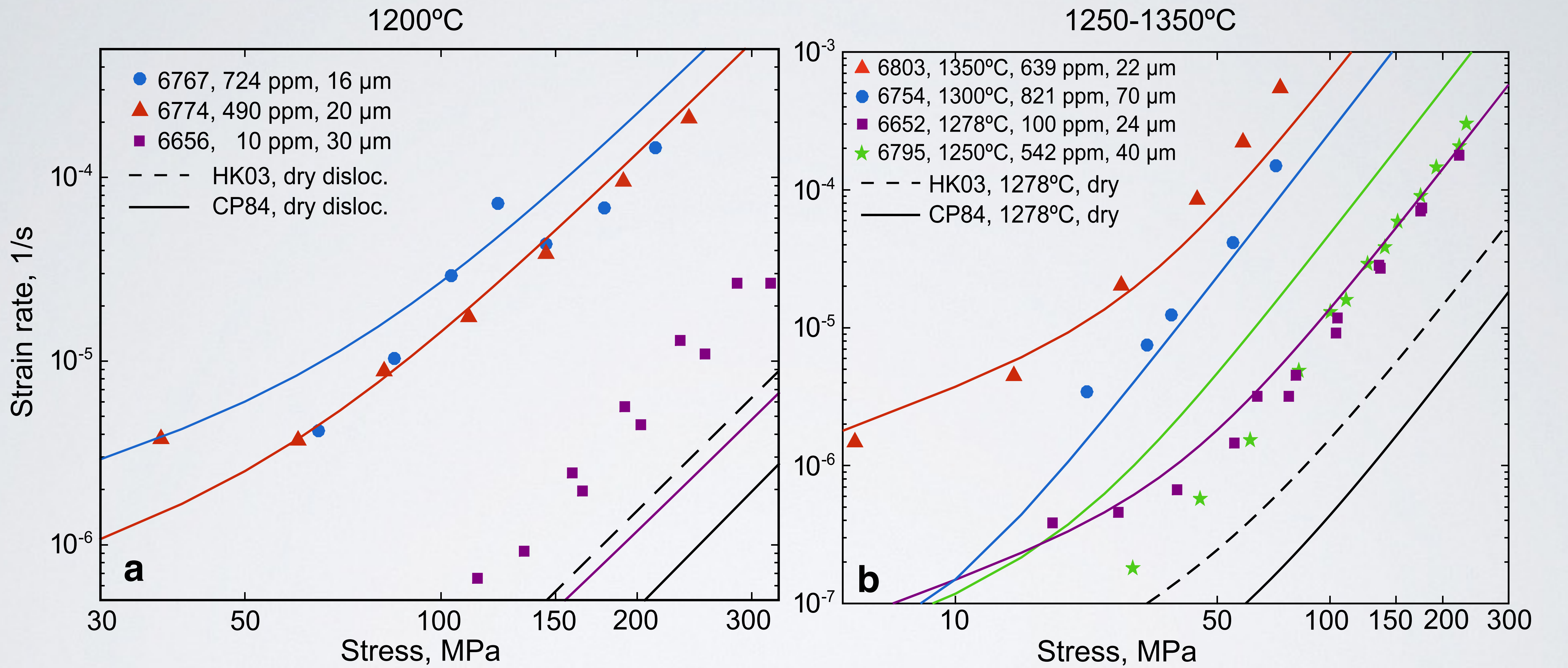
dif: diffusion creep, dis: dislocation creep, GBS: grain boundary sliding

dominant mechanism may change as a function of stress

diffusion creep: n ~ 1, p = 3; dislocation creep n ~ 3.5, p = 0

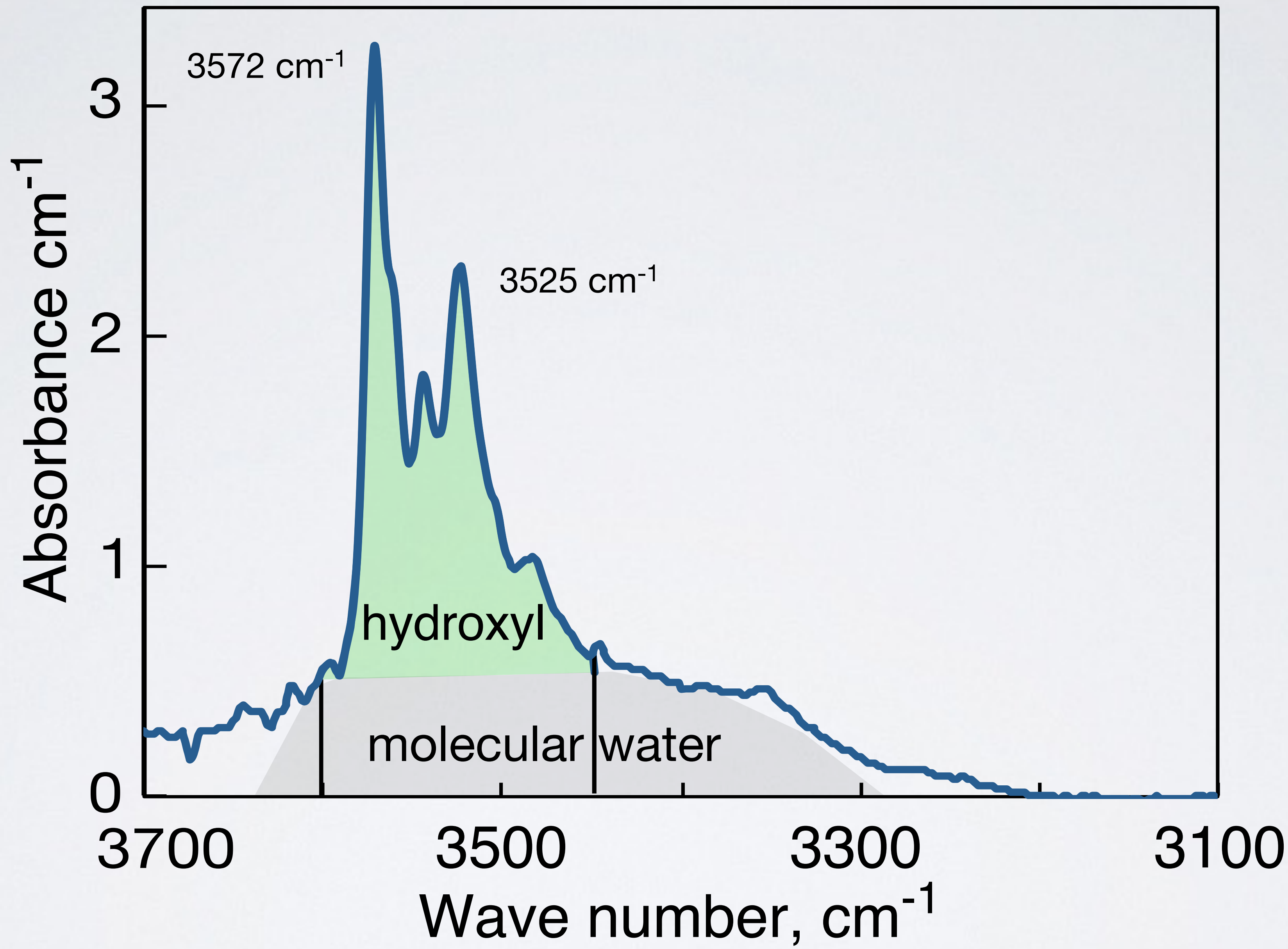
water present flow law: $$\dot{\varepsilon} = A\sigma^n\, d^{-p}\, fH_2O^r \exp\left(\frac{-Q}{RT}\right)$$

Results: ‘Wet’ samples become weaker with increasing water contents

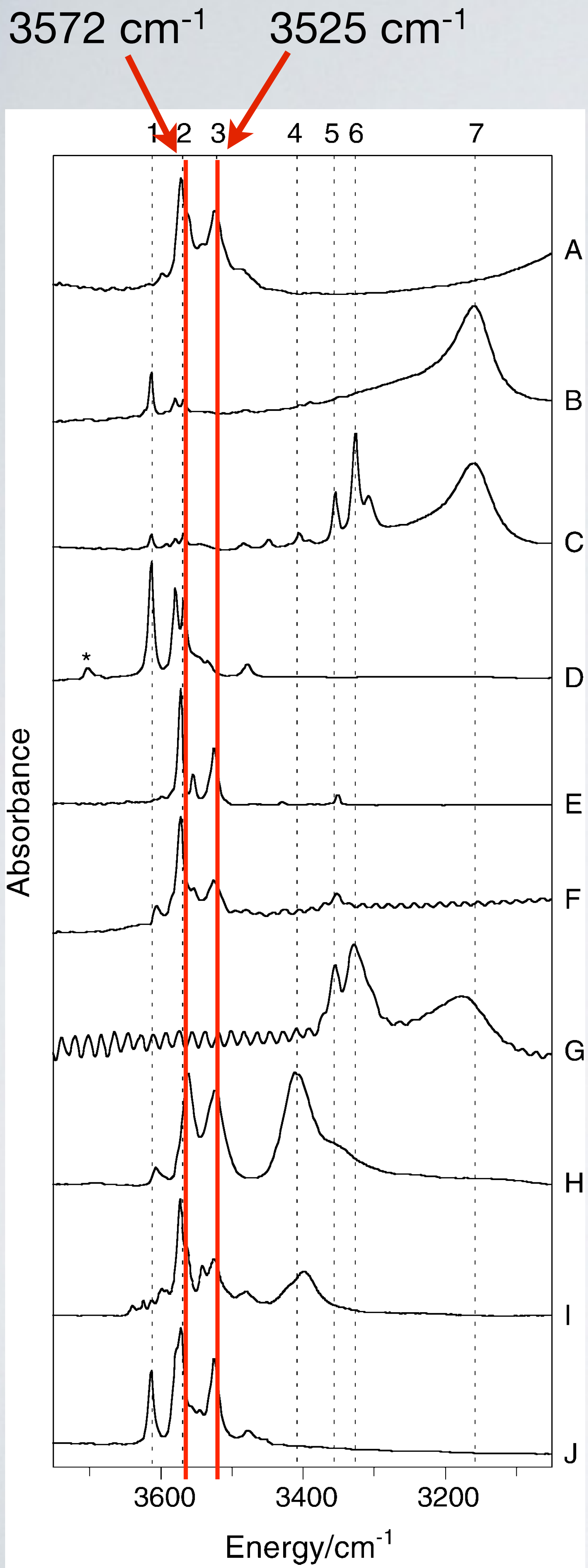


slope n = 3.5, activation energy Q = 480 kJ/mol

Key difference to previous experiments: water-undersaturated conditions (no buffer) - mantle is water-undersaturated



FTIR spectra show only two absorption bands + broad absorption region for molecular water



San Carlos olivine

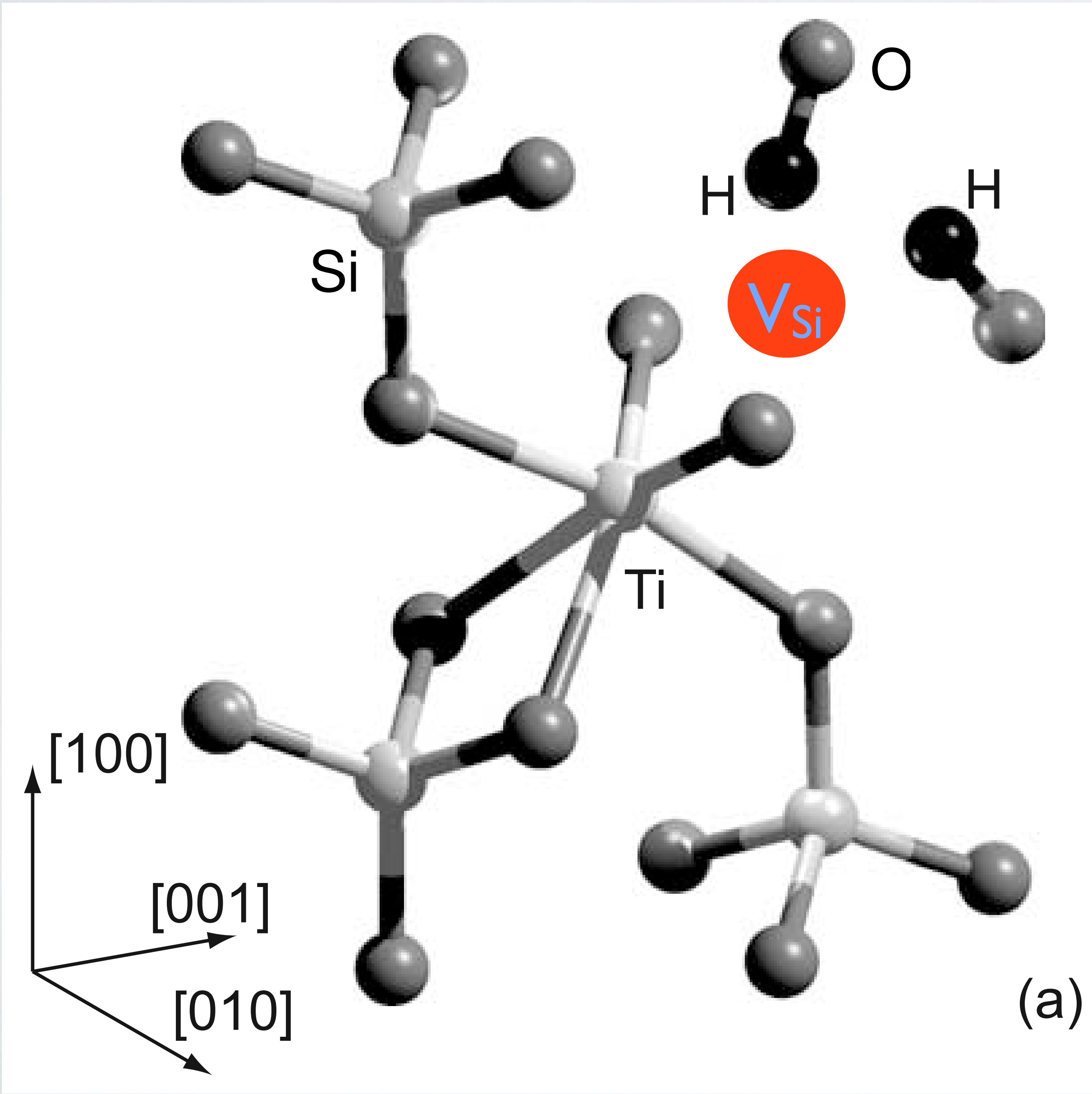
IR bands in (untreated) San Carlos olivine can only be reproduced in the presence of Ti.

rutile-buffered olivine (olivine contains Ti)

Piston cylinder experiments, Berry et al., 2005

Incorporation of hydrogen in olivine: Titanium clinohumite-like point defect

Coupled substitution of Ti on M1 site with 2 H on Si vacancy.
Energetically the most stable.



calculated OH - vibrational frequencies: 3572 and 3525 cm^{-1}

(The mineral Ti-clinohumite has additional bands, e.g. 3400 cm^{-1})

Walker et al., 2007

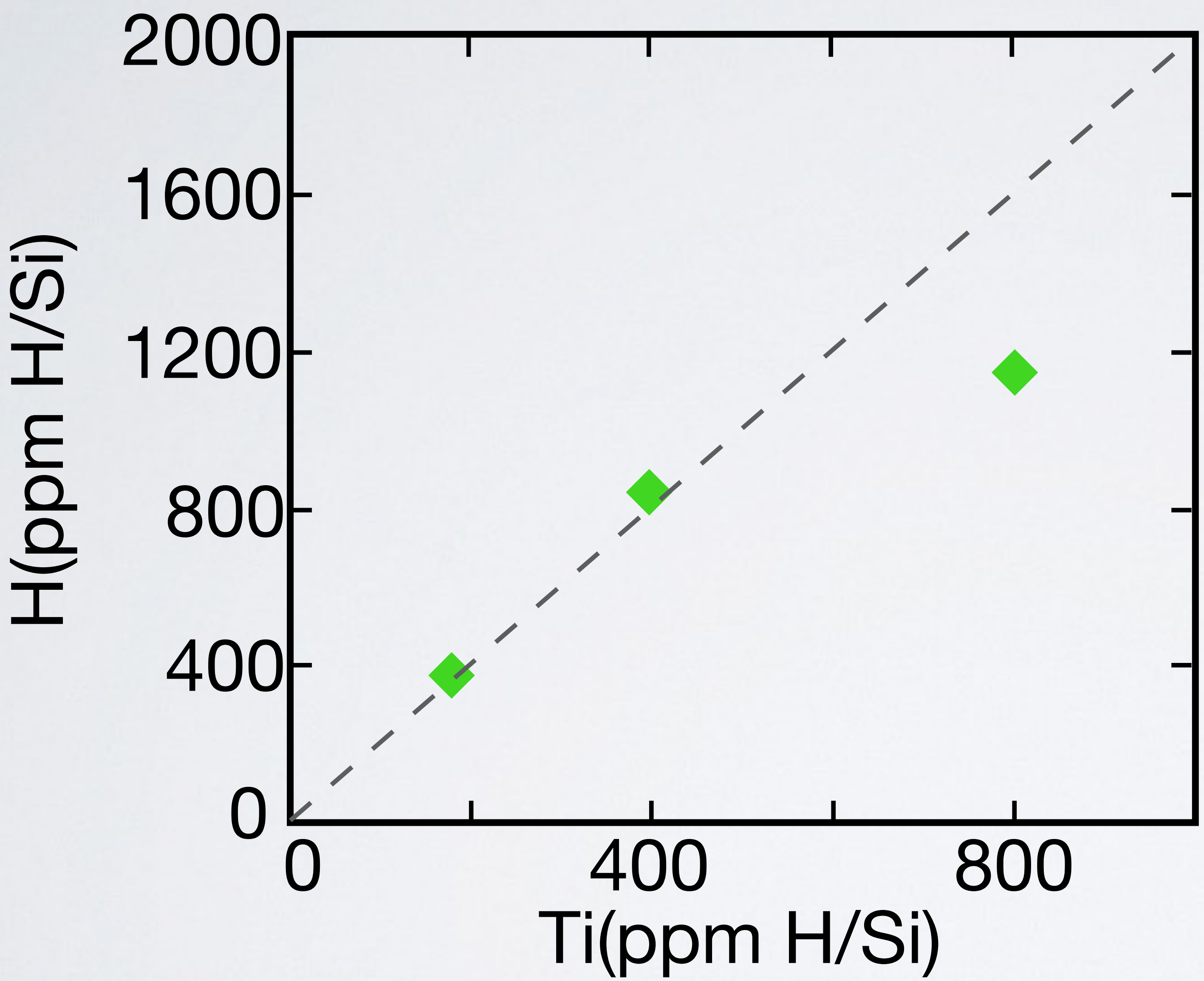
Hydrogen incorporation in olivine

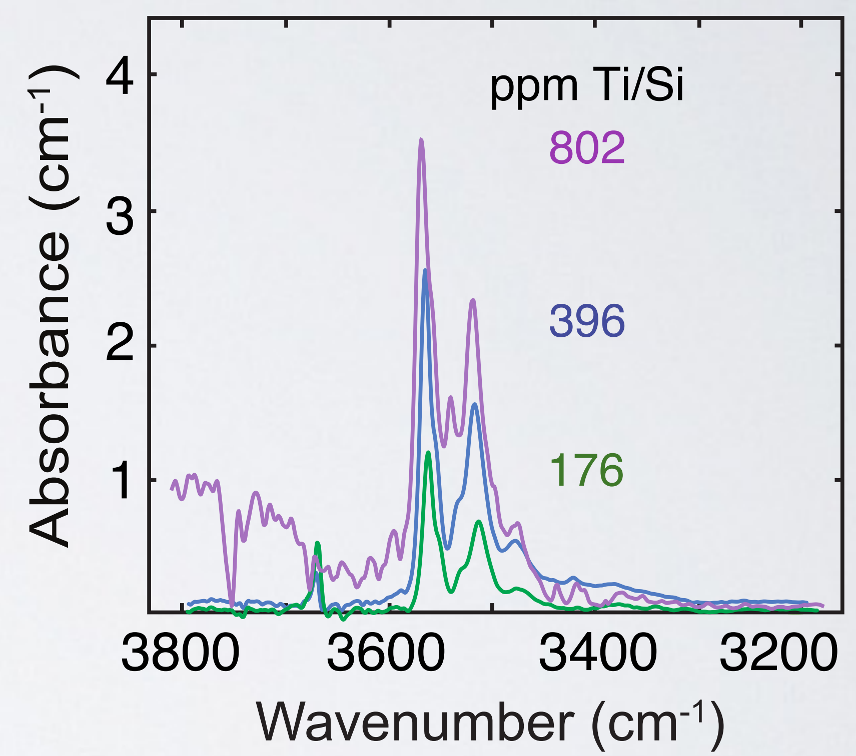
$$(\mathrm{Mg_2})_\mathrm{M}(\mathrm{Ti})_\mathrm{Si}\mathrm{O_4}(\mathrm{ol}) + \mathrm{H_2O} = (\mathrm{MgTi})_\mathrm{M}(\mathrm{H_2})_\mathrm{Si}\mathrm{O_4}(\mathrm{Ti-humite}) + \mathrm{MgO}.$$

$$\mathrm{MgO} + \mathrm{MgSiO_3} = \mathrm{Mg_2SiO_4}.$$

- independent of Si buffering
- concentration of (hydroxyl-related) tetrahedral defects dependent on extrinsic impurities.

Hydroxyl and titanium content satisfy 2:1 relationship (only hydroxyl in Ti-bands counted)



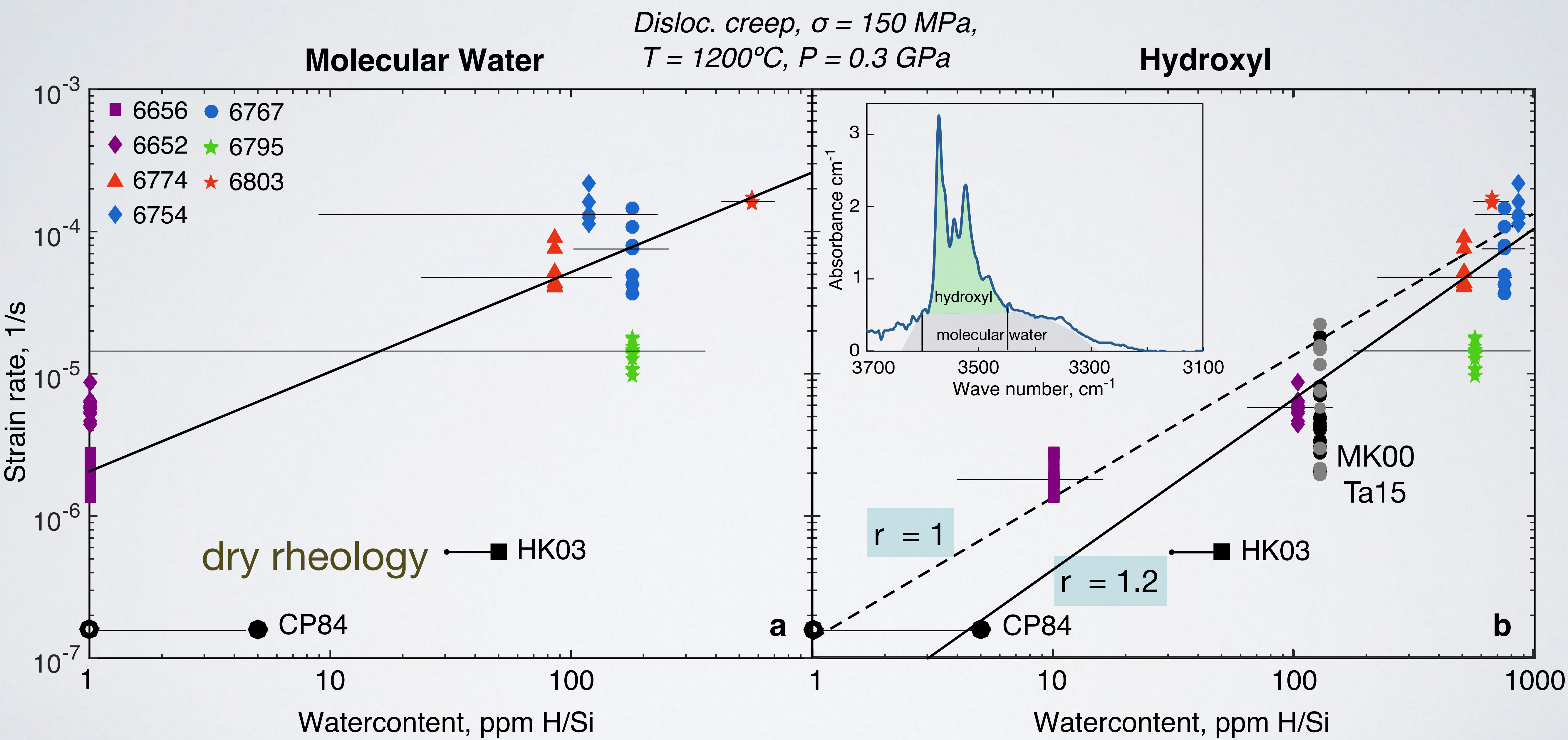


Cline et al., in prep

(not to be confused with storage capacity of olivine)

- rheology controlled by structurally bound water (hydroxyl)
- water incorporation linked to titanium:

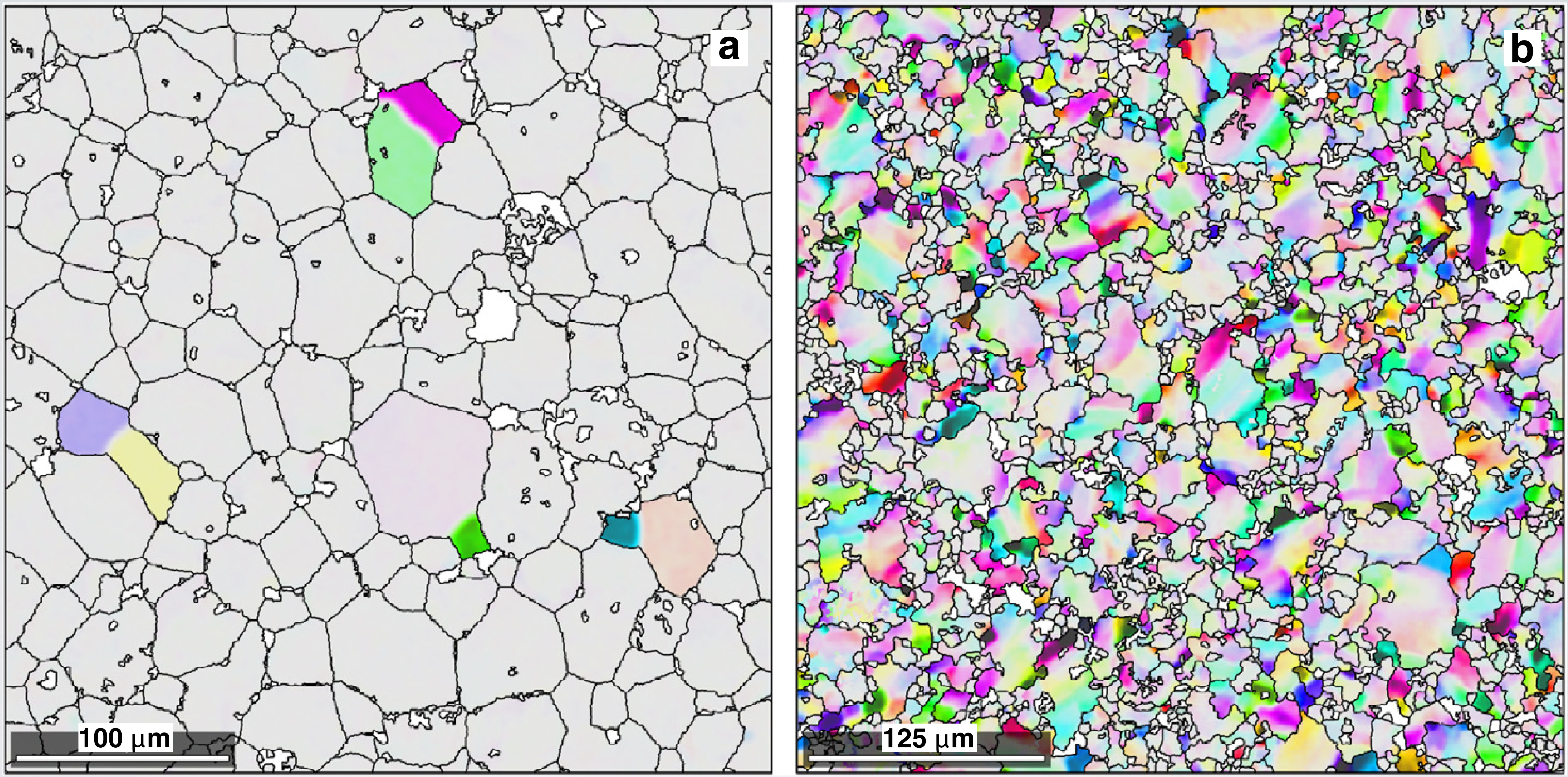
extrinsic defects control water incorporation and rheology



MK00: Mei & Kohlstedt, 2000
Ta15: Tasaka et al., 2015
CP84 Chopra & Paterson, 1984
HK03 Hirth & Kohlstedt, 2003

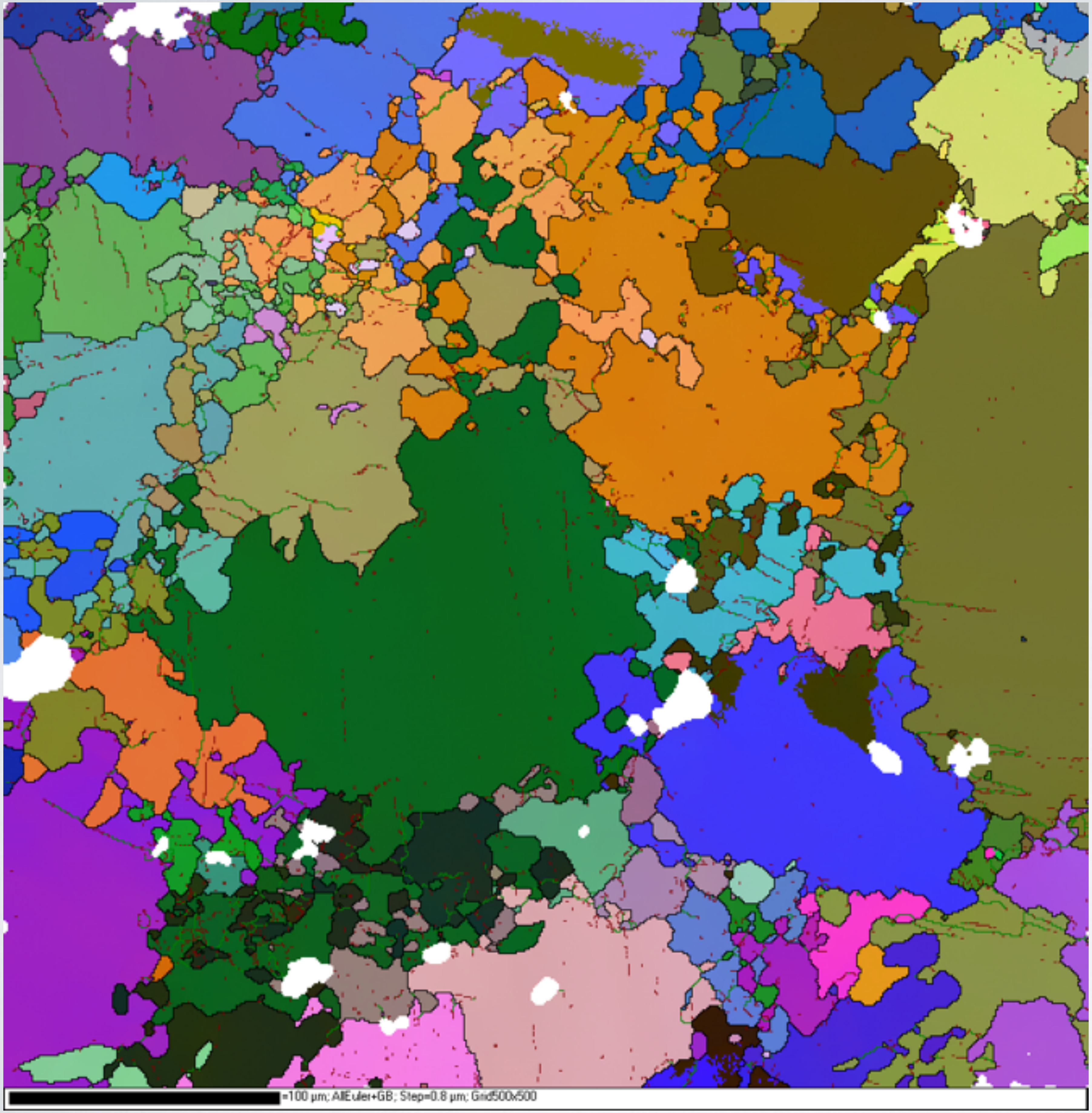
Faul et al., EPSL 2016

Intragranular deformation - dislocation creep



before after

$$\dot{\varepsilon} \sim \sigma^{3.5}$$

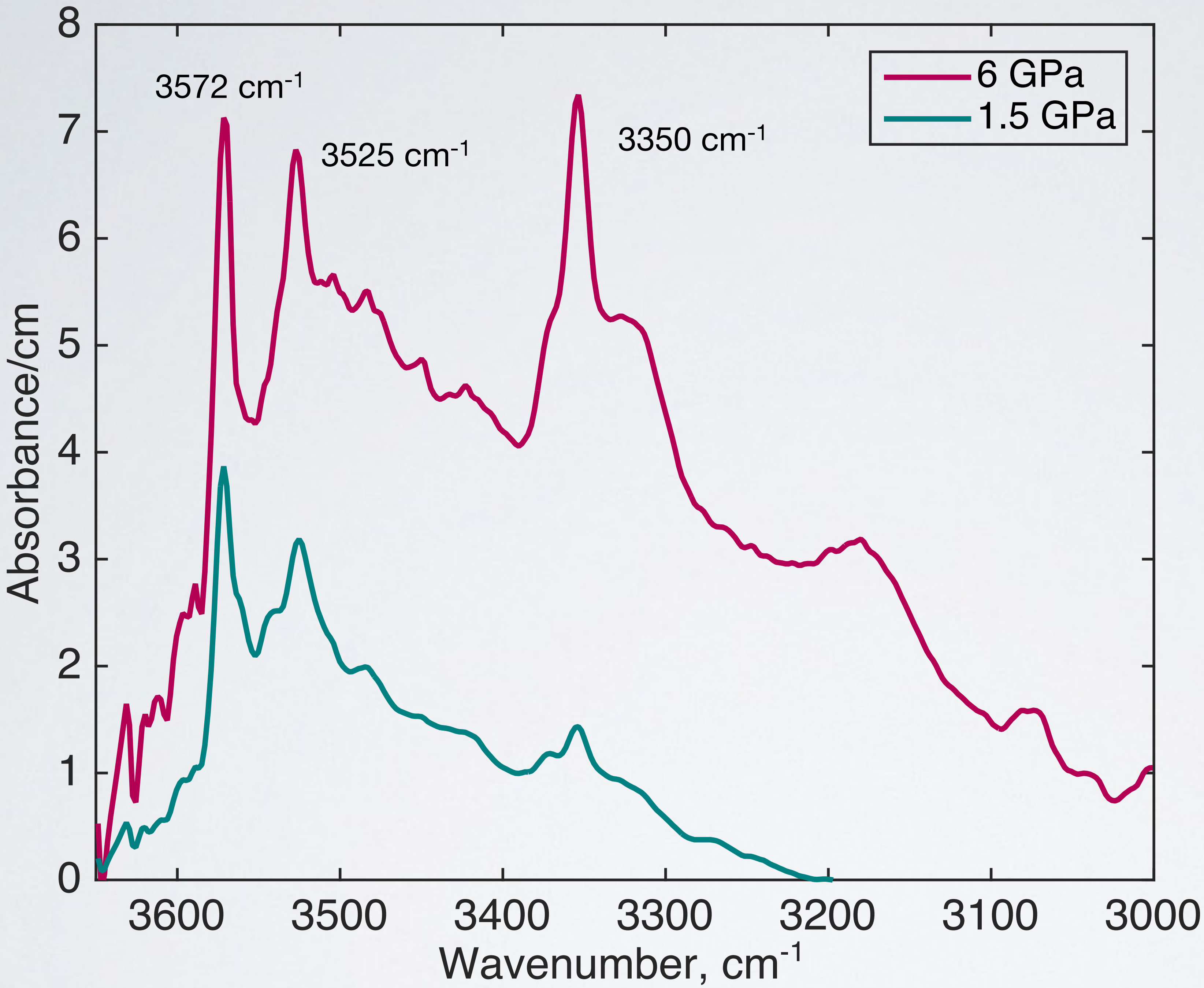


high grain boundary mobility

Large strain deformation

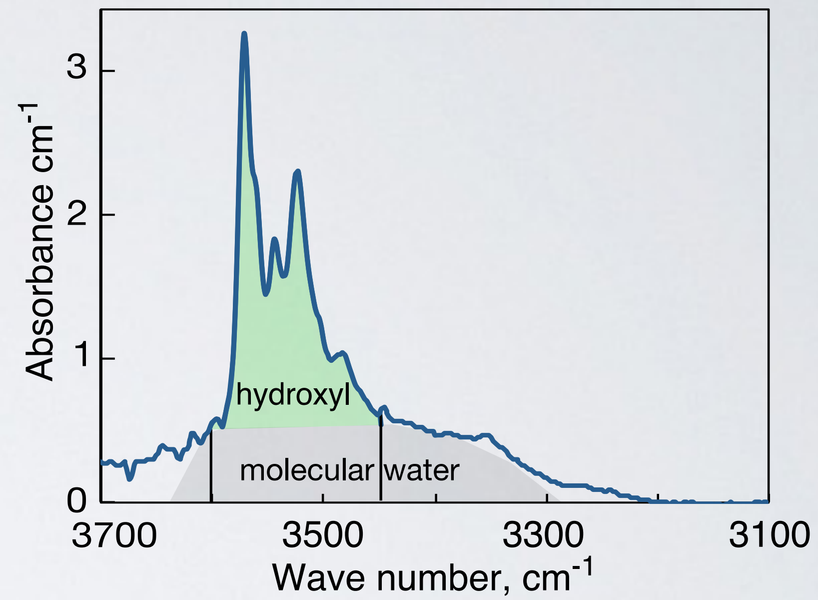
- ‘Wet’, coarse-grained samples deform in grain size-independent dislocation creep regime
- strain rate depends linearly on water content
- mechanism: increased Si diffusivity due to Ti-hydroxyl defect (enhanced disloc. climb)
- high grain boundary mobility
- no sign of grain boundary sliding (grain size sensitive)

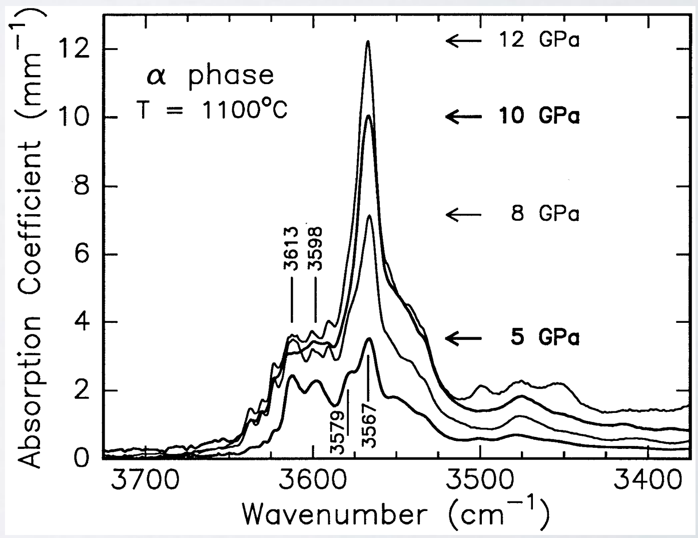
Extension to high pressure at water-undersaturated conditions



Experiments at BGI, Bayreuth

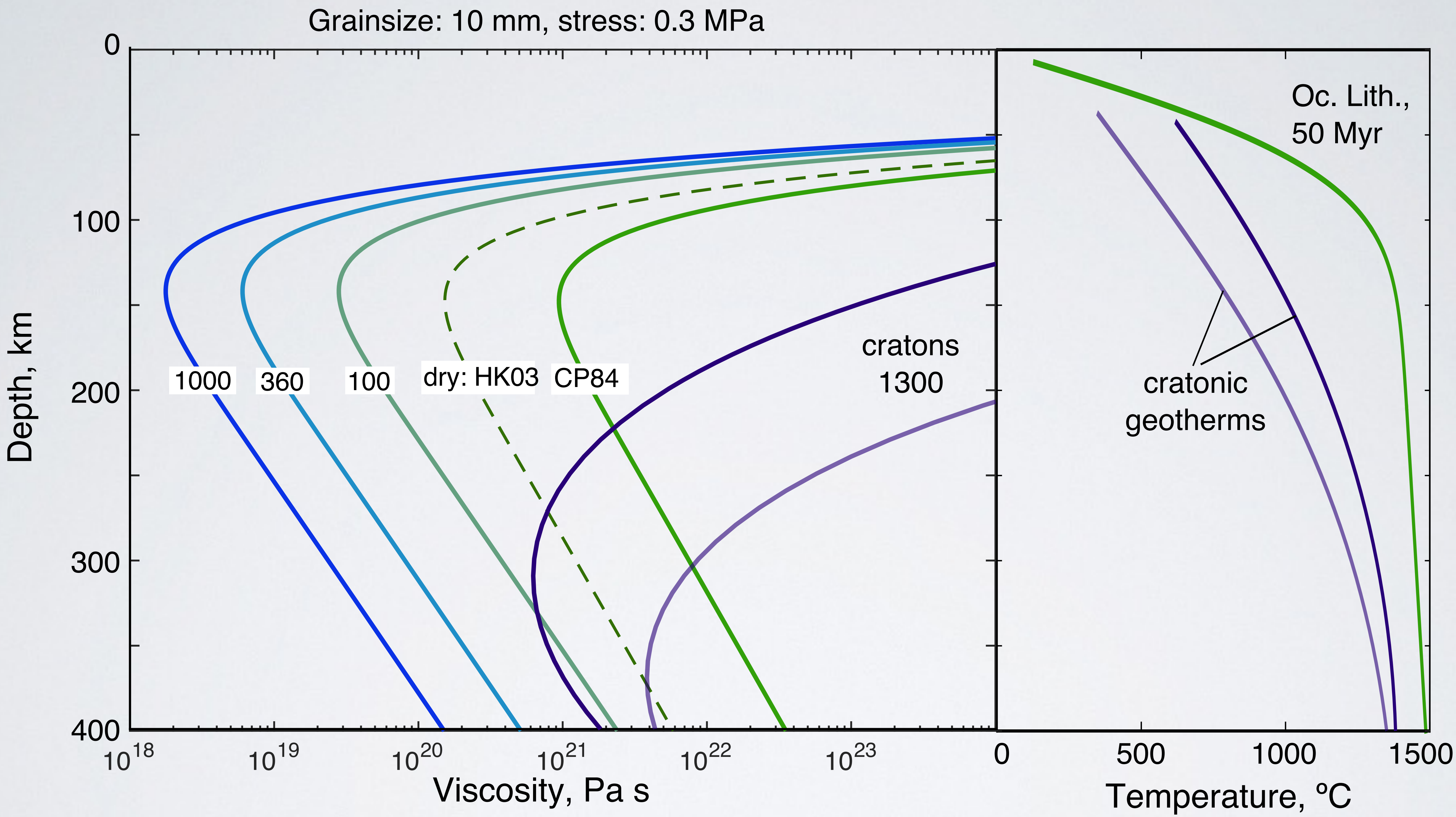
0.3 GPa





Kohlstedt et al., 1996

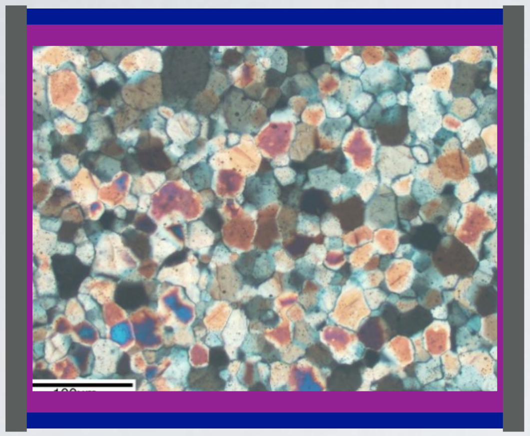
Upper mantle viscosity at water-undersaturated conditions



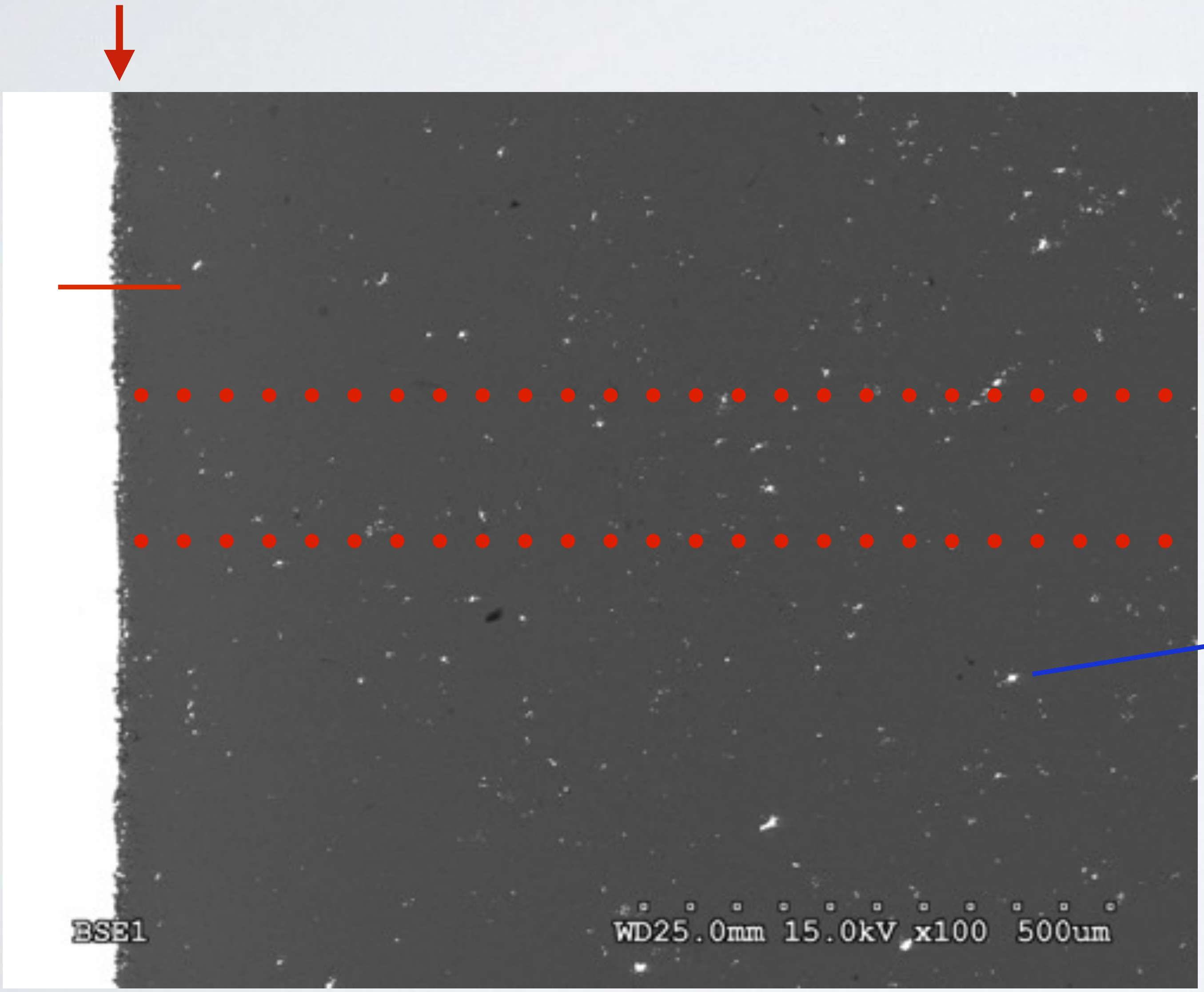
(water contents in ppm H/Si)

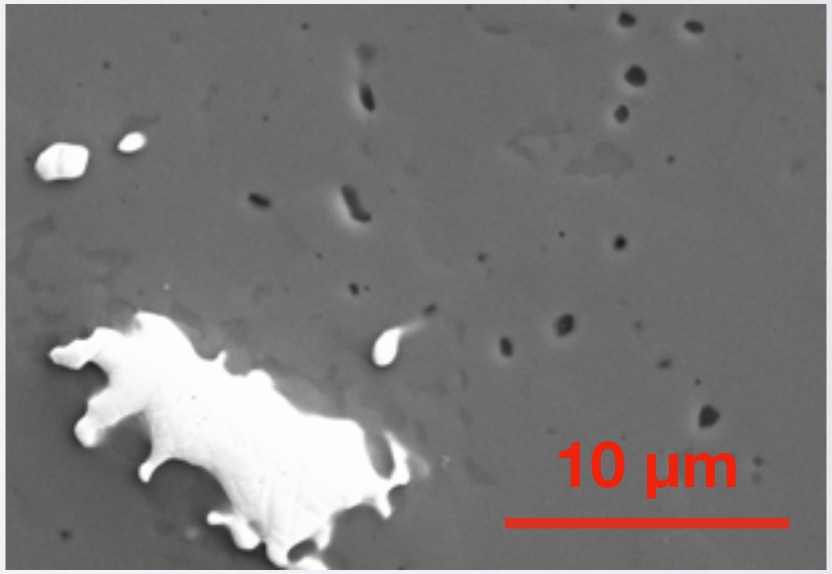
What is the fO_2 in the sample interior?

samples are 11+ mm in diameter, 25 - 30 mm long

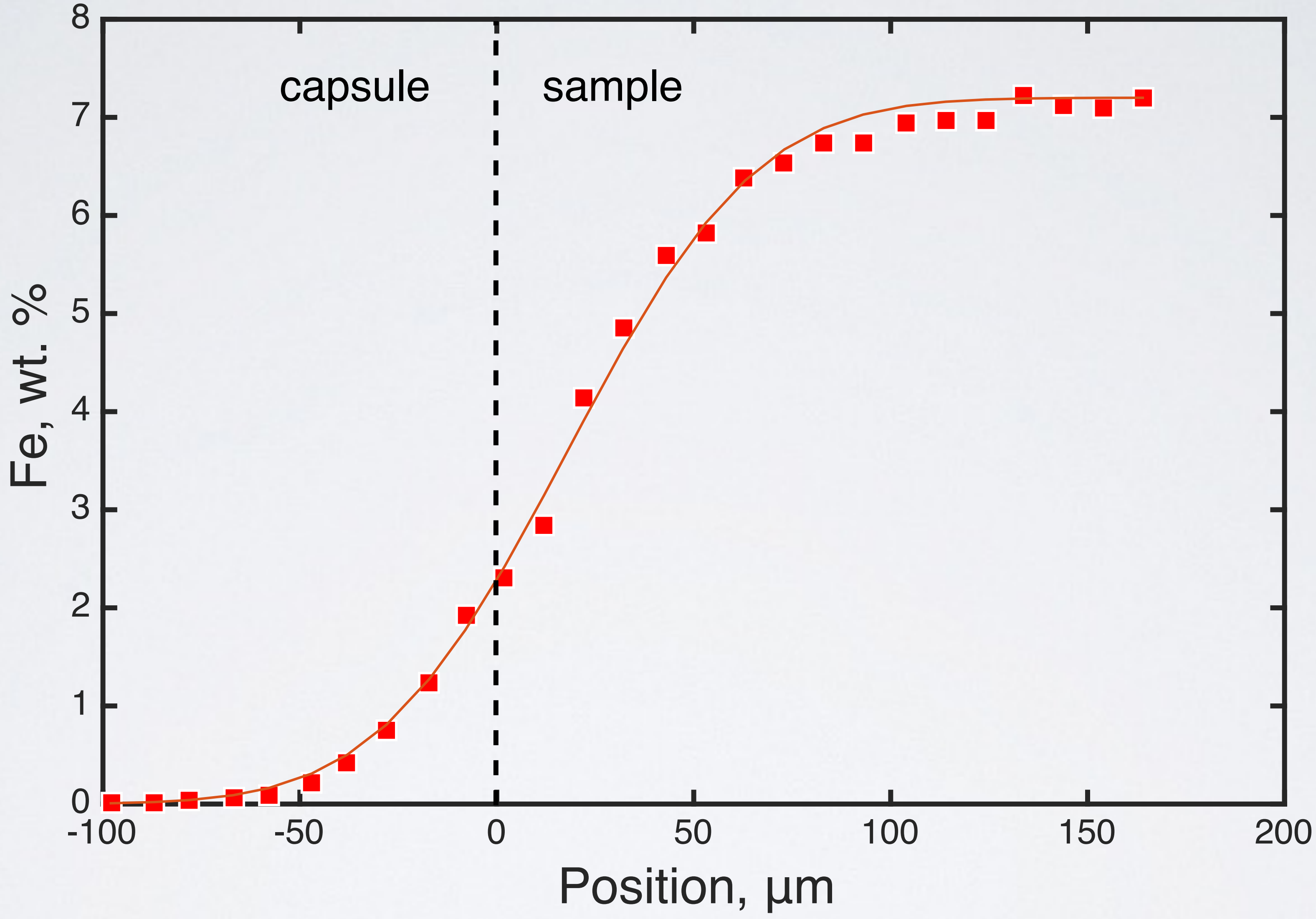


add small Pt particles to olivine powder, measure Fe content in PtFe blebs and olivine, calculate fO_2 (e.g. Rubie et al., 1993)



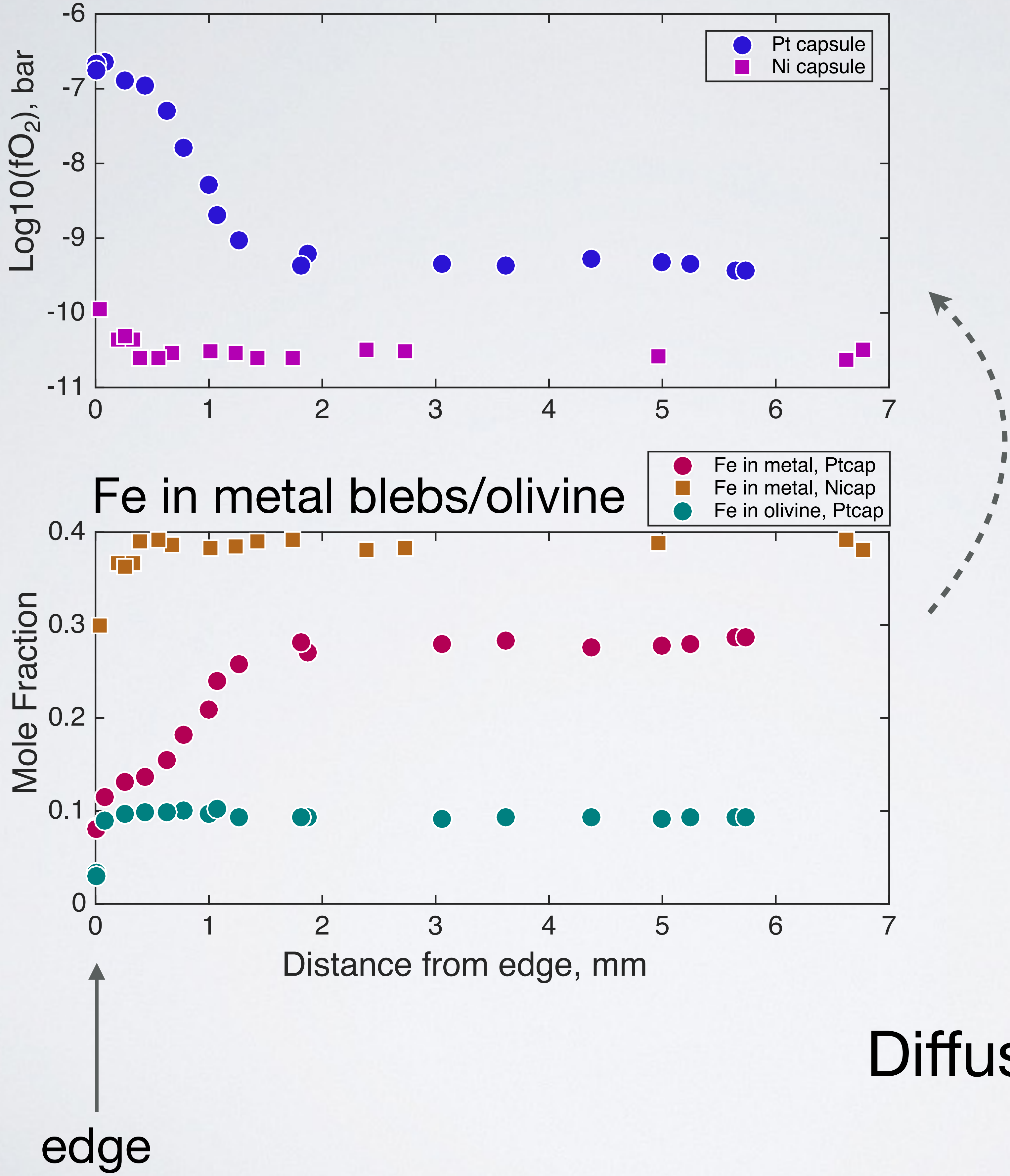


Diffusive loss of Fe into Pt capsule



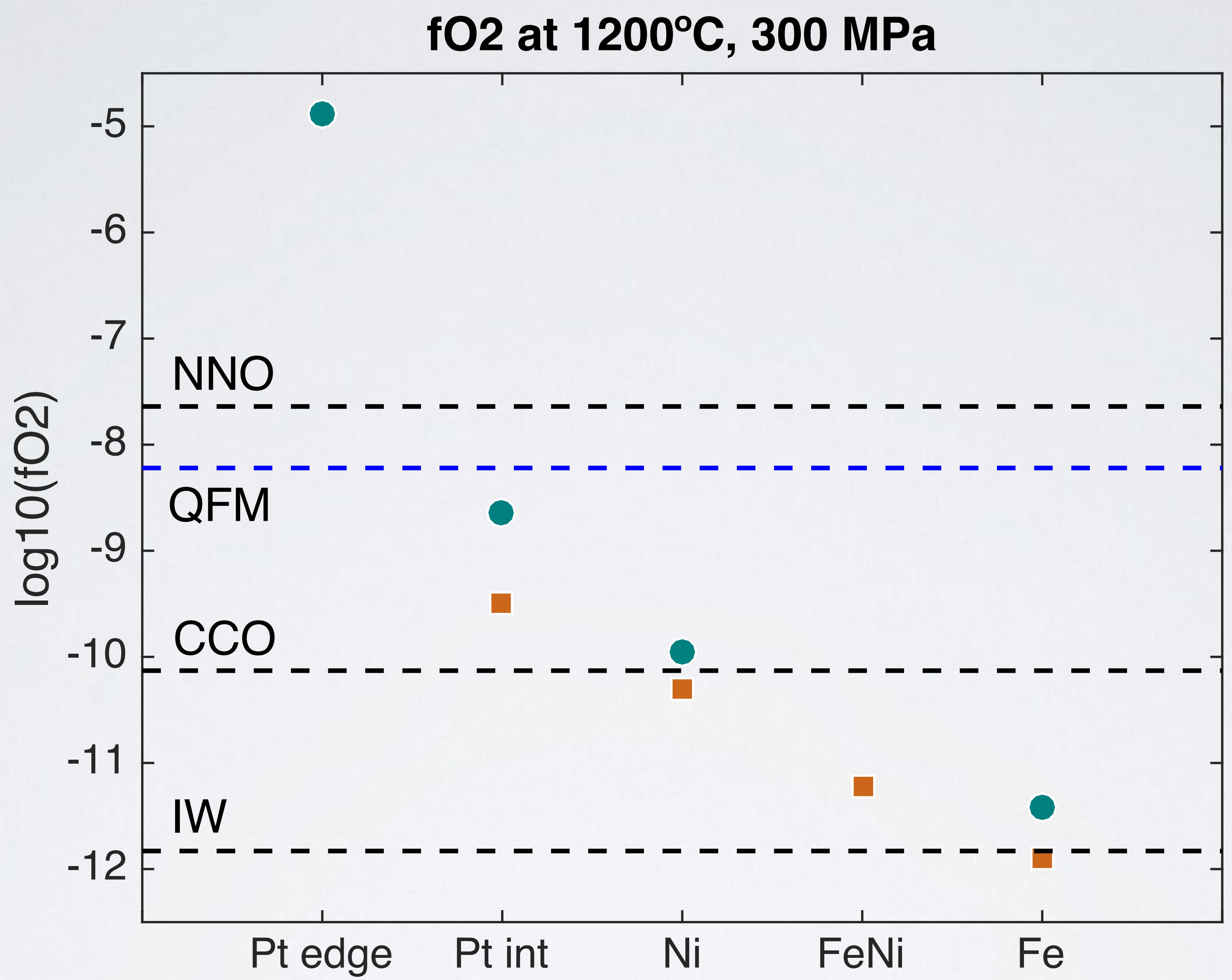
Diffusivity ~ 10^{-14} m^2/s

Fe/fO2 center to edge



Diffusivity ~ 10^{-12} m^2/s

Oxygen fugacity in the interior of large capsules
(11.5 mm diameter)

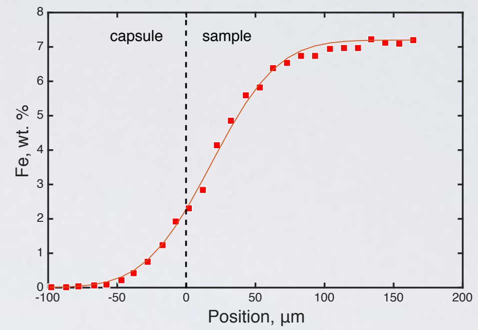


interior fO_2 dependent on capsule material, but not at metal-oxide buffer at higher fO_2 (sample self buffering)

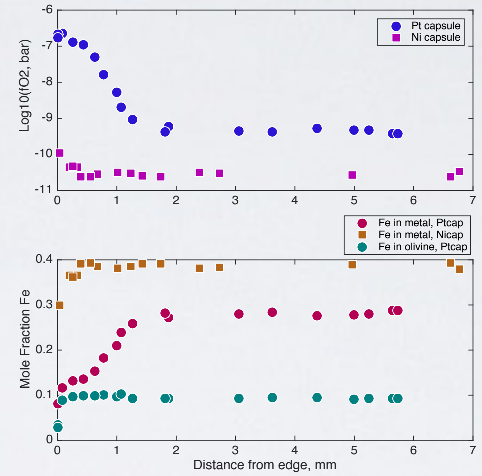
implied diffusivity ~ 10^{-10} m^2/s

Three diffusive regimes:

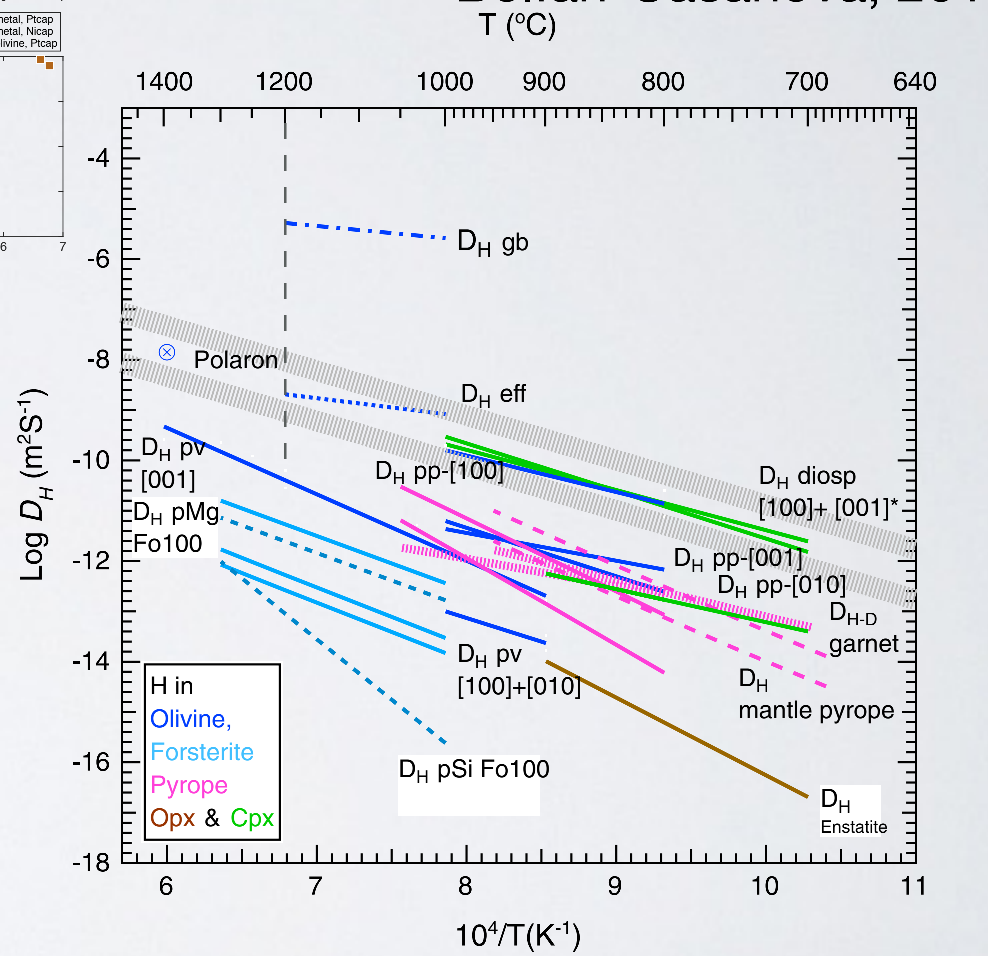
Fe loss ~ 100 µm, D ~ 10^{-14} m^2/s
(D_{GB}Fe ~ 10^{-13} m^2/s)



Fe3+ ~ 1.5 mm, D ~ 10^{-12} m^2/s
(D_{GB}O ~ 10^{-12} m^2/s)



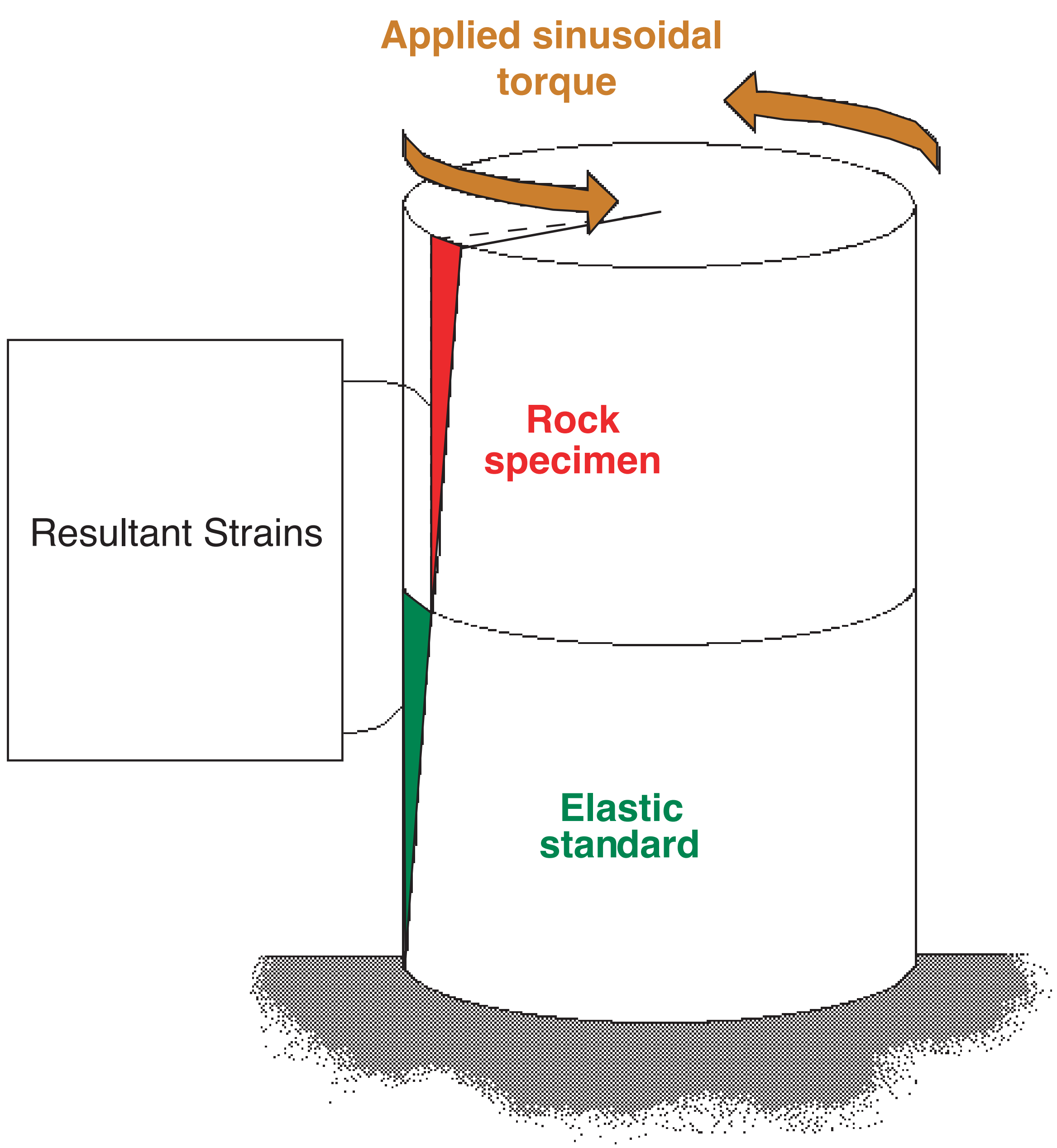
Demouchy & Bolfan-Casanova, 2016



interior fO2 > 5 mm, D ~ 10^{-10} m^2/s
(D_H ~ 10^{-10} m^2/s)

-> interior of samples in gas-medium apparatus are likely not at the respective metal-oxide buffer

Seismic property experiments: Measure shear modulus (G) and attenuation (1/Q)



Research School of Earth Sciences, Australian National University

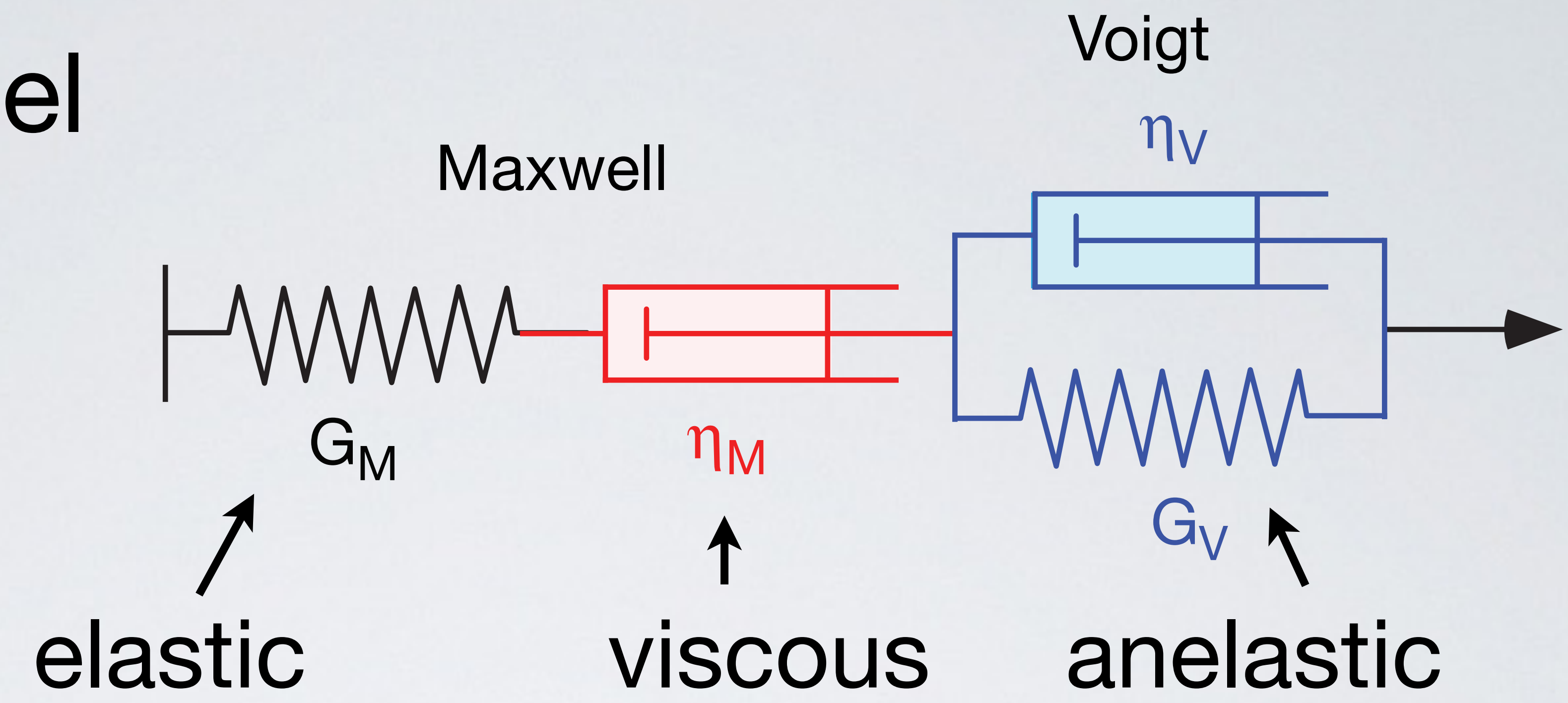
Experiments at

- temperatures to 1300ºC
- periods 1 - 1000s
- 200 MPa confining pressure
- strain: 10^{-8} - 10^{-5}

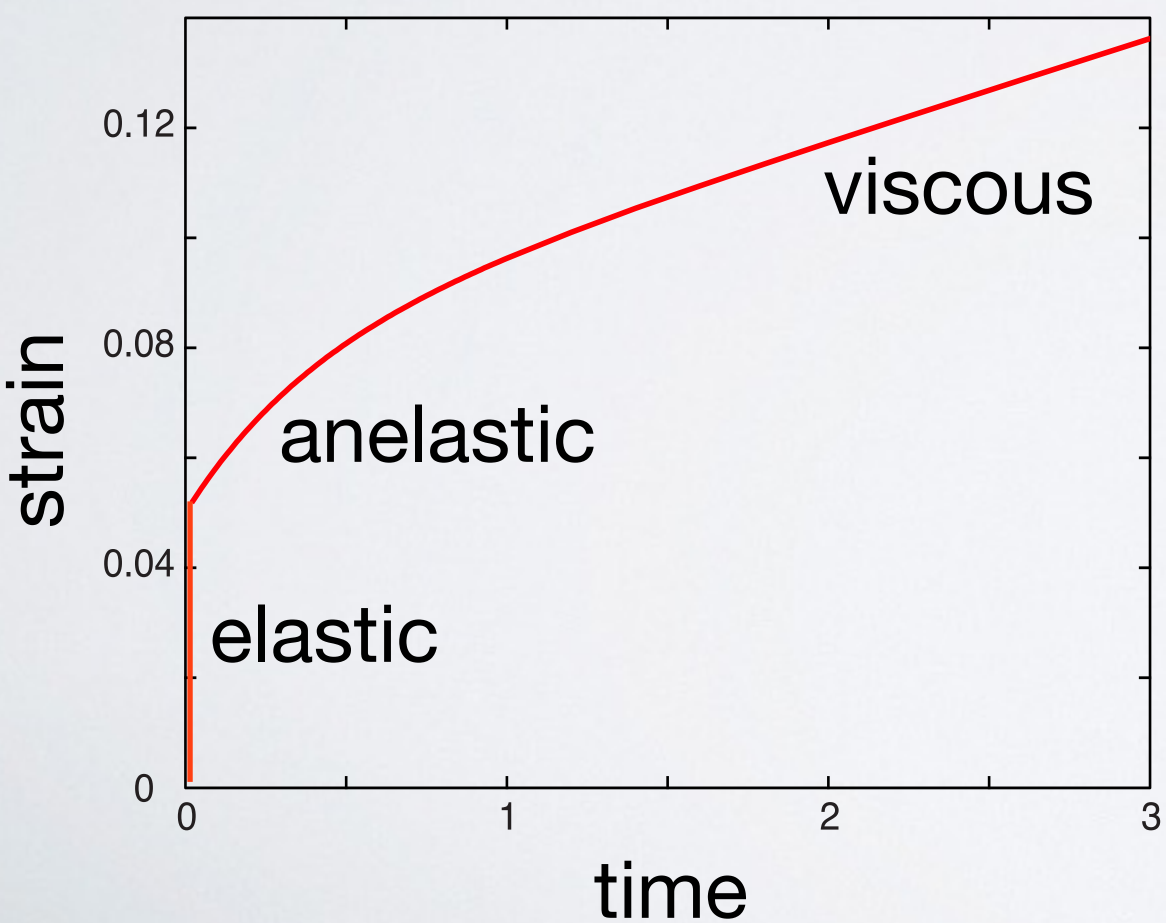
Measure shear modulus G and dissipation (attenuation)

Attenuation (1/Q): energy loss per cycle

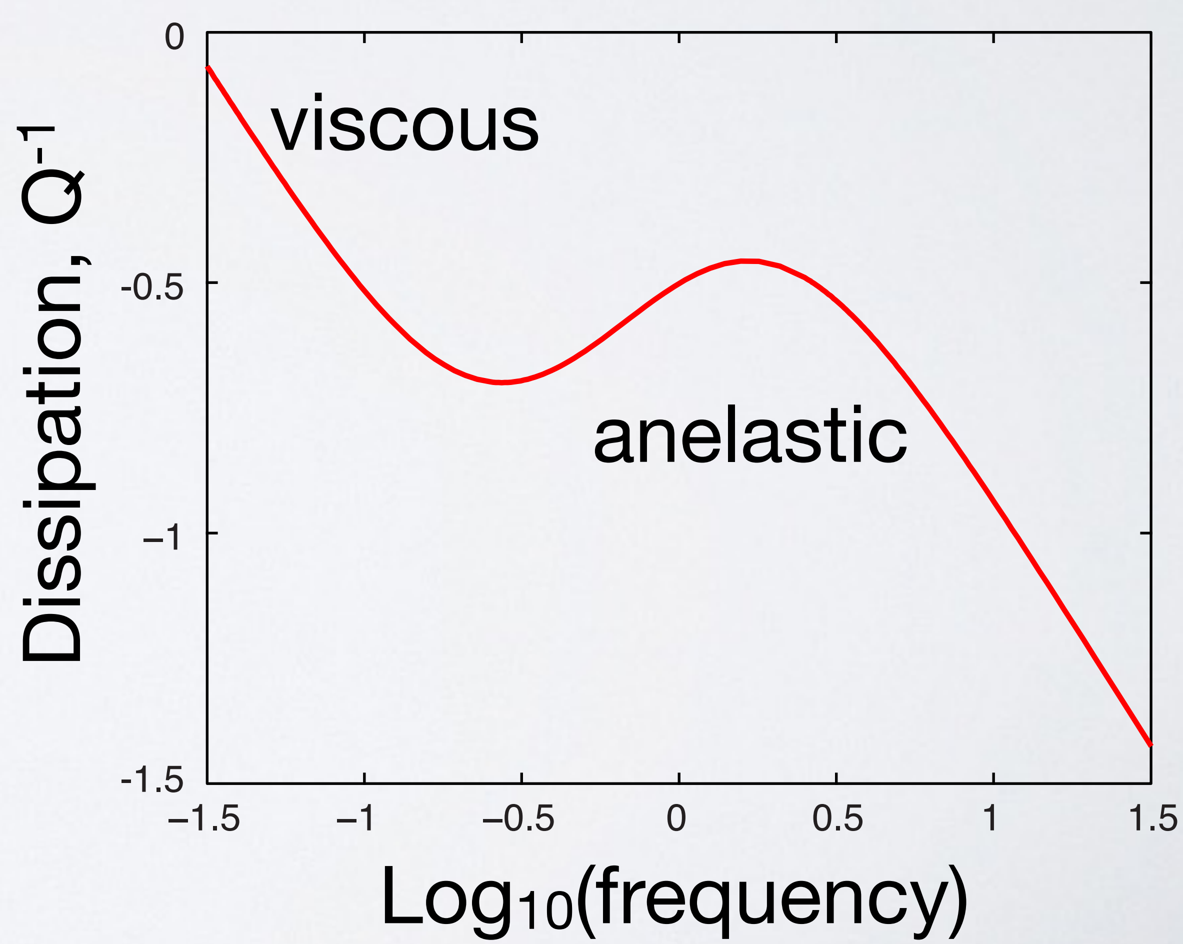
Burgers model



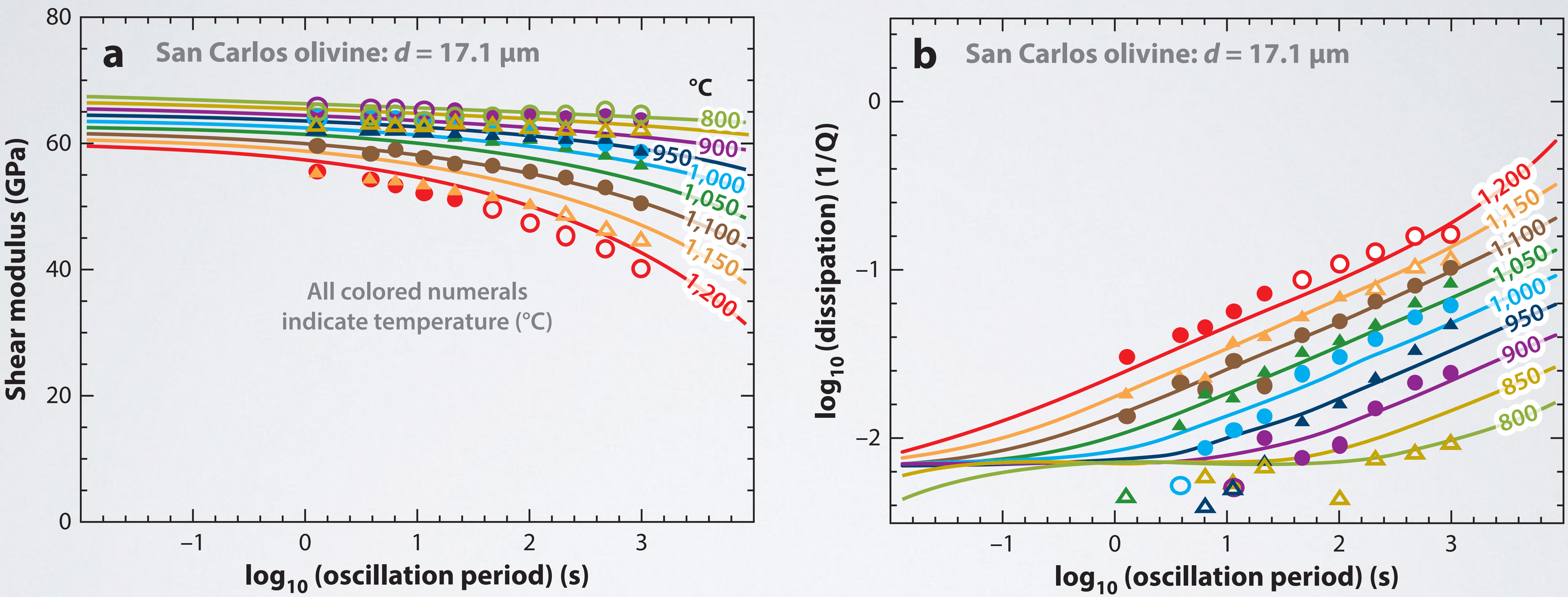
time domain



frequency domain



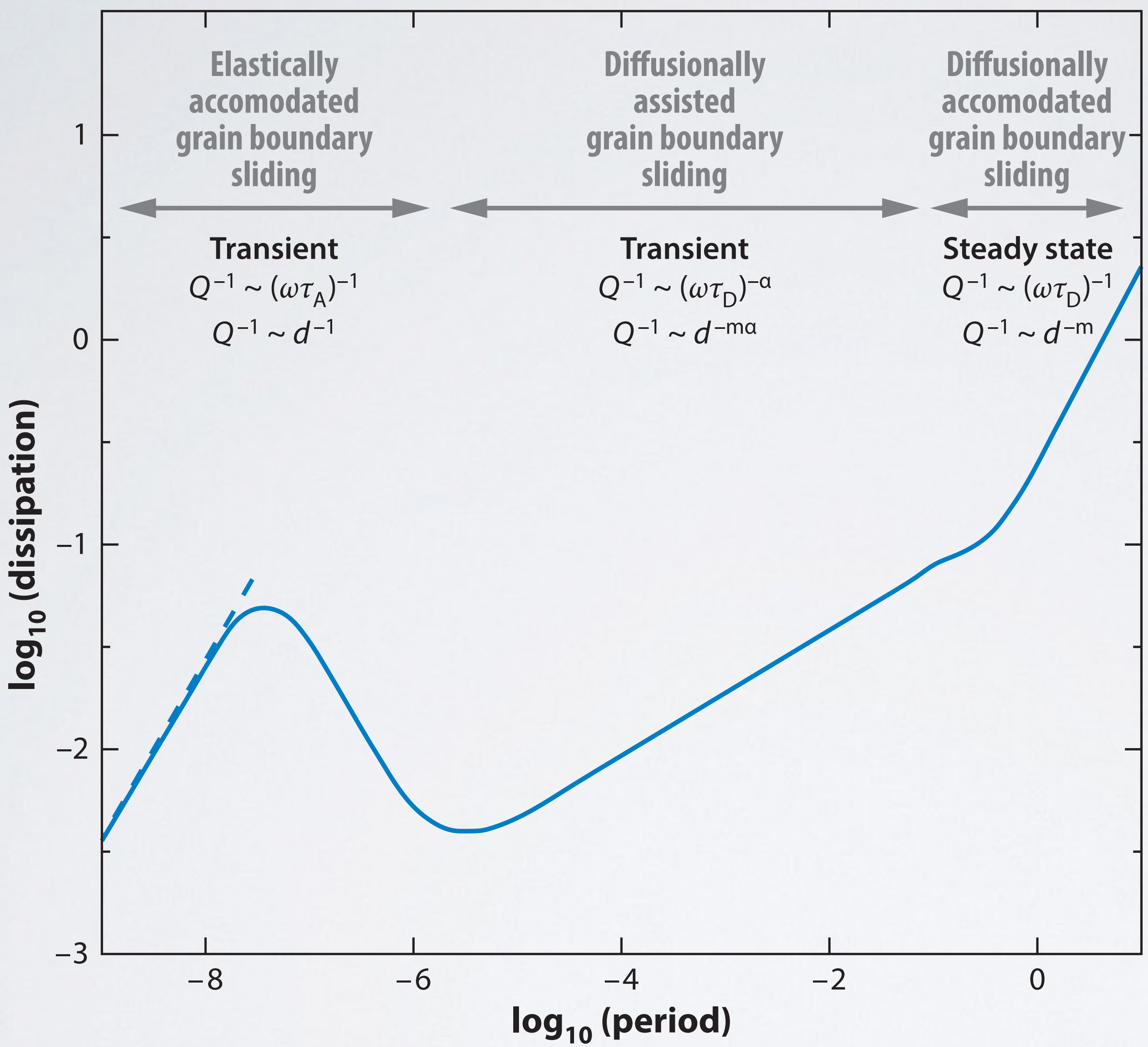
Frequency domain (forced torsional oscillation experiments): direct evidence for frequency dependence

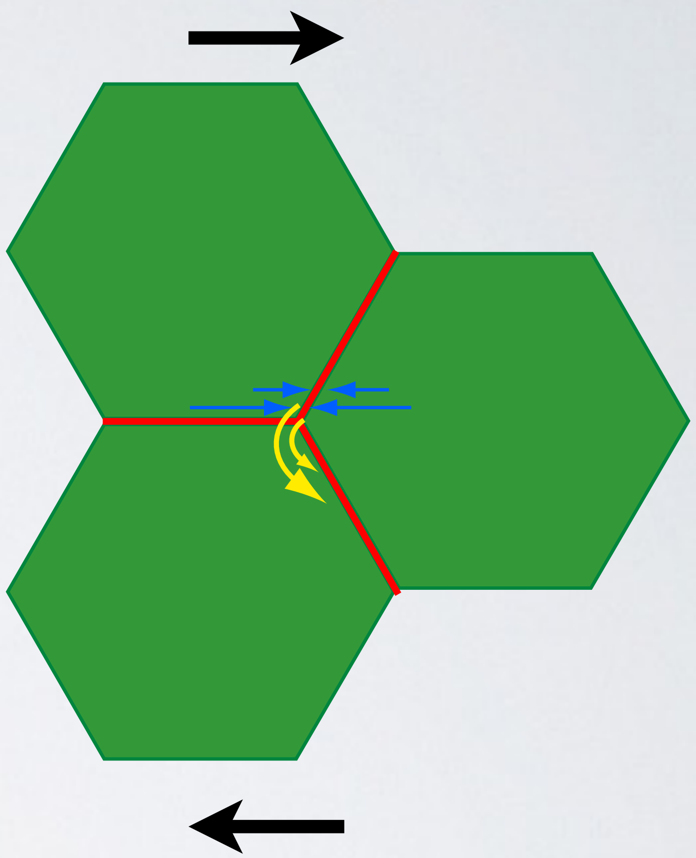


dry, melt-free polycrystalline olivine

Faul & Jackson, AREPS, 2015

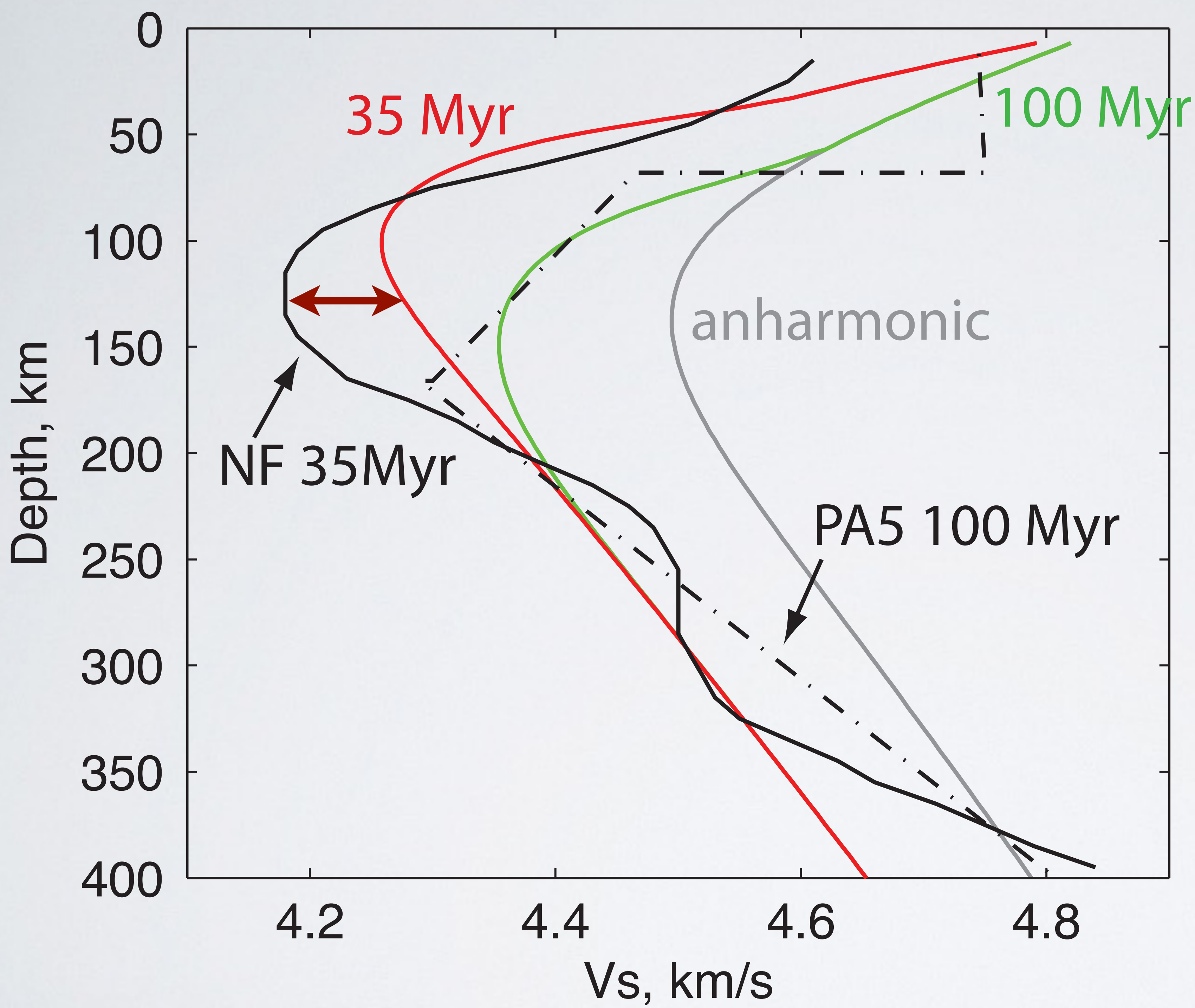
Microphysical model predicts continuum of relaxation times

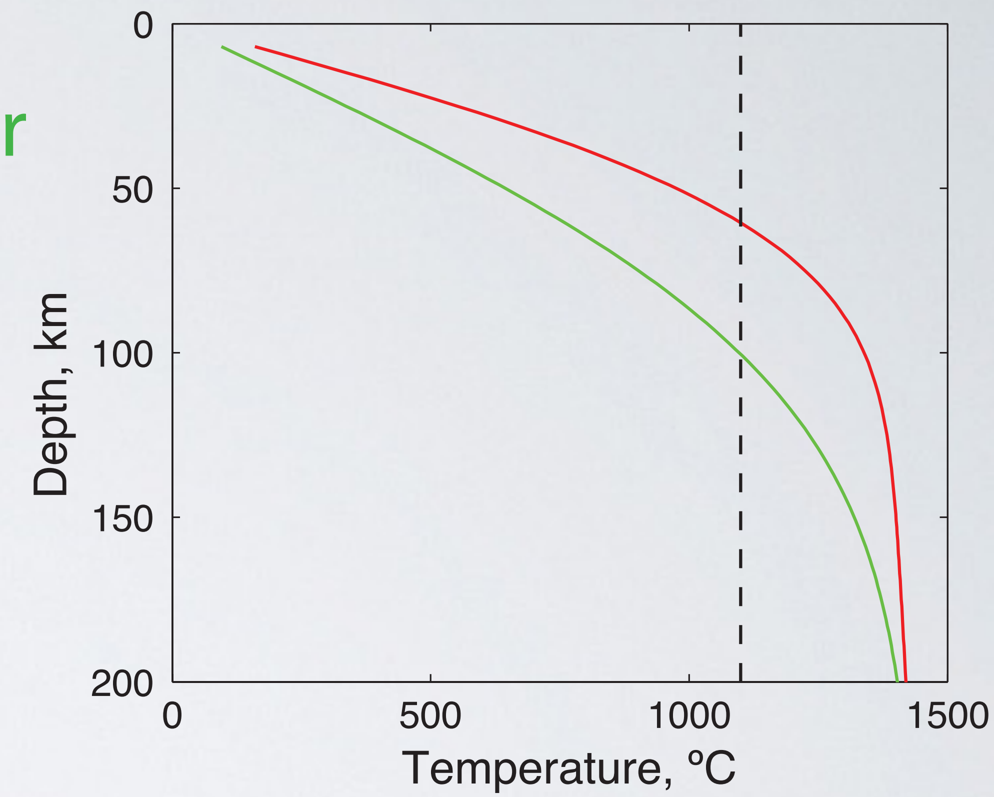




Raj & Ashby 71, Cooper 02, Morris & coworkers 09, Faul & Jackson, AREPS, 2015

Temperature only





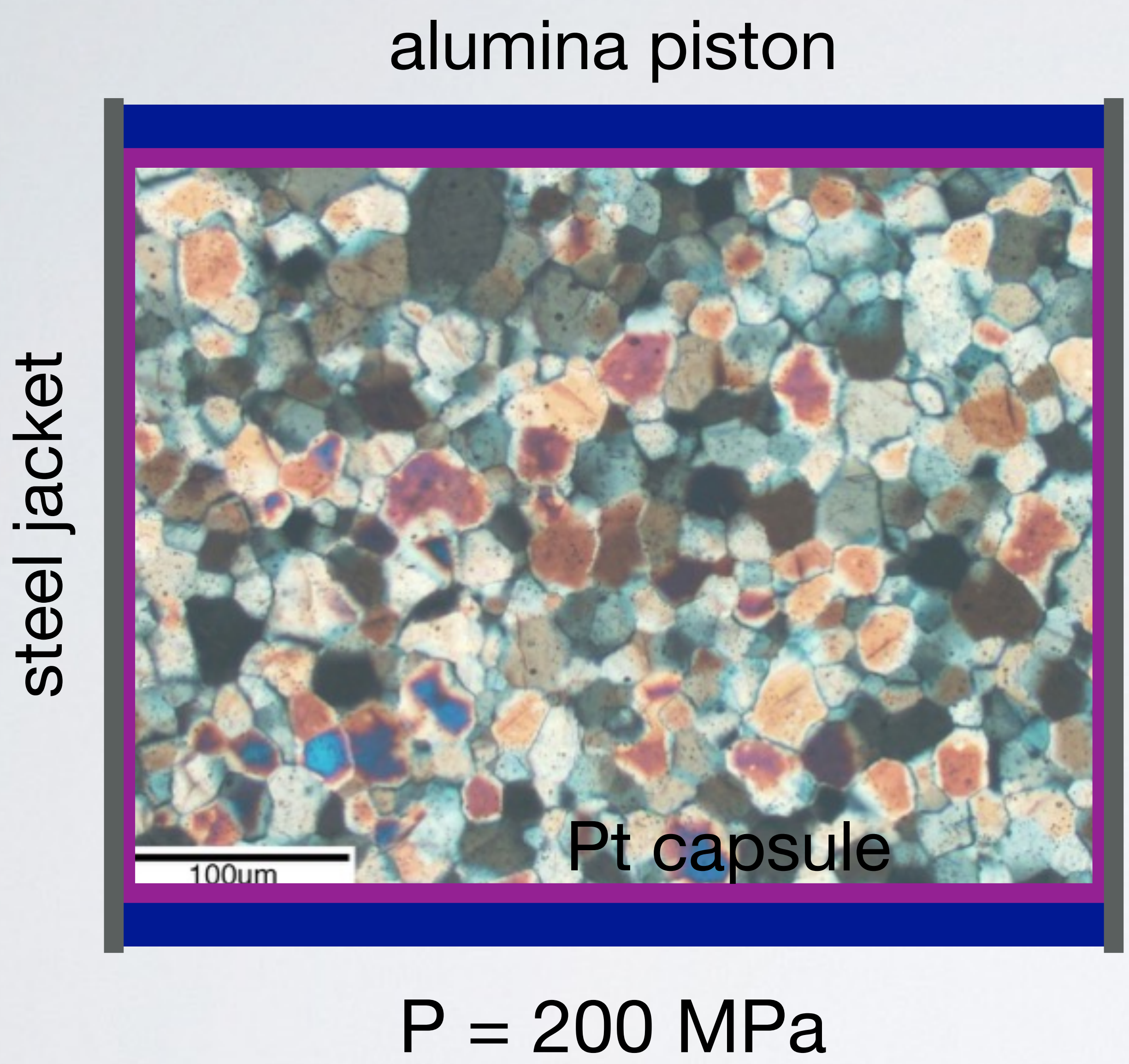
black: seismic models
red, green: experimental

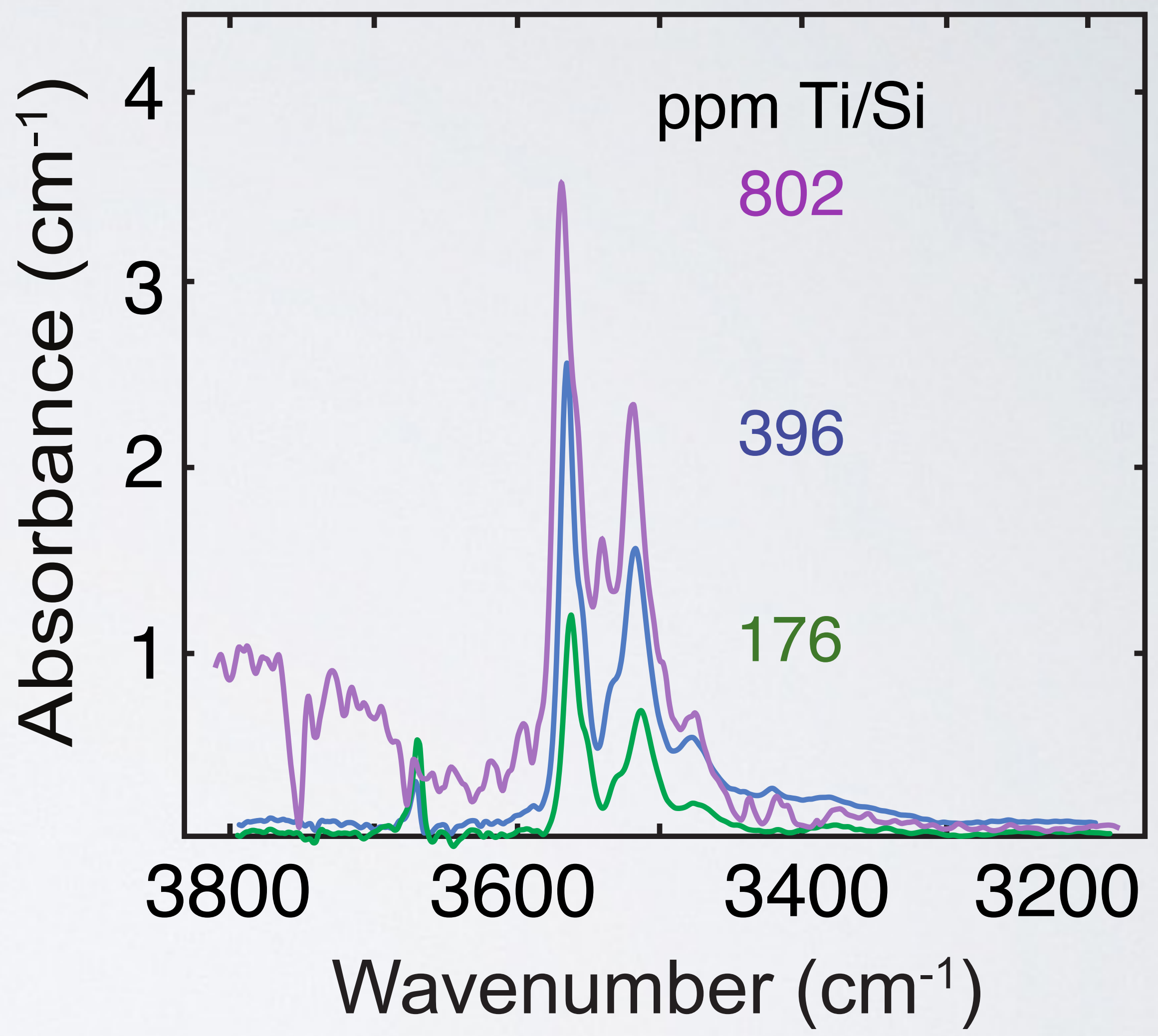
Jackson & Faul, 2010

younger ages need additional mechanisms to match velocity

NF: Nishimura & Forsyth, 1989, PA5: Gaherty et al., 1996

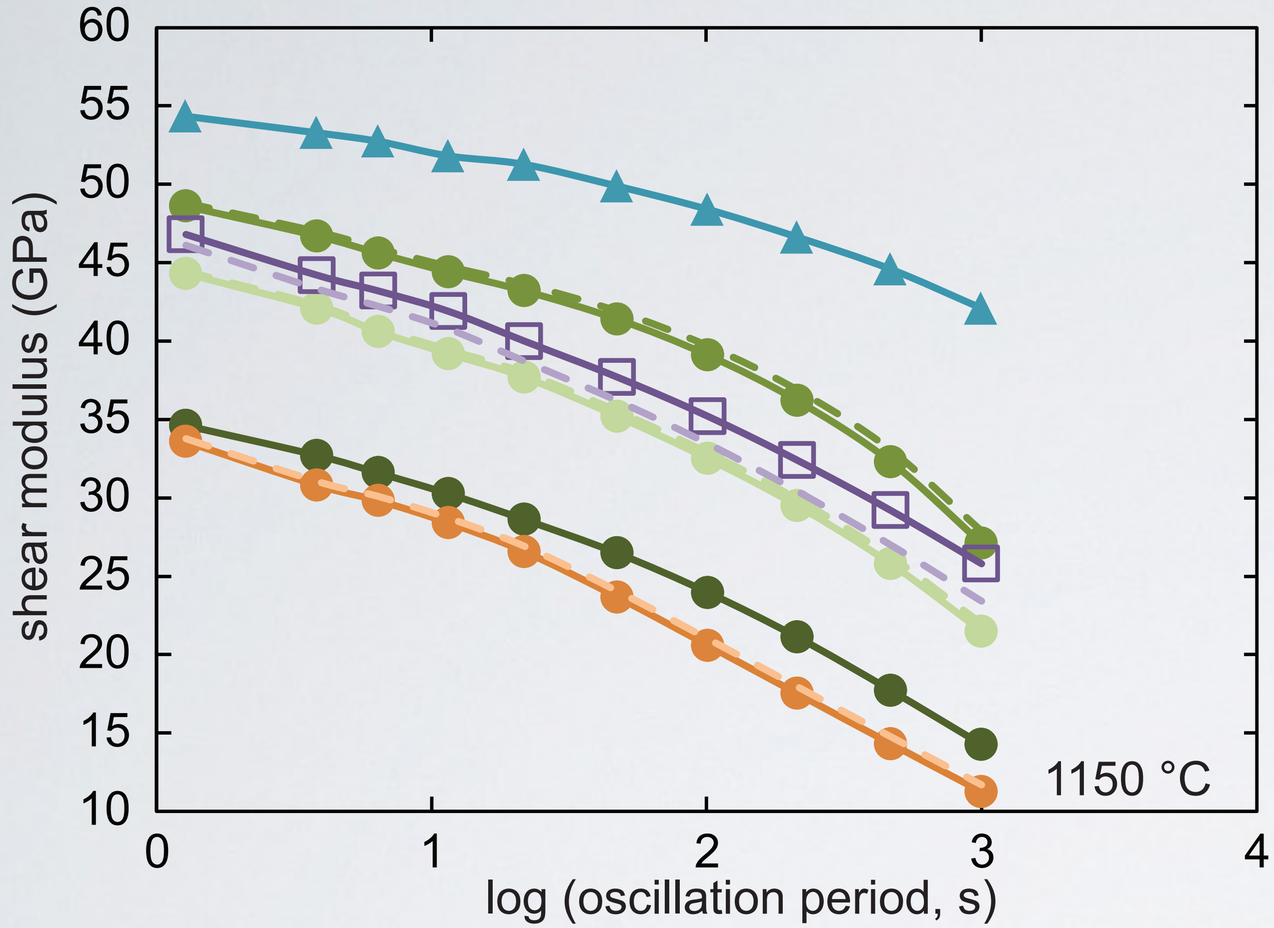
Samples encapsulated in FeNi or Pt metals, no water buffer
olivine doped with a range of Ti contents (0 - 0.04 wt. % TiO_2)

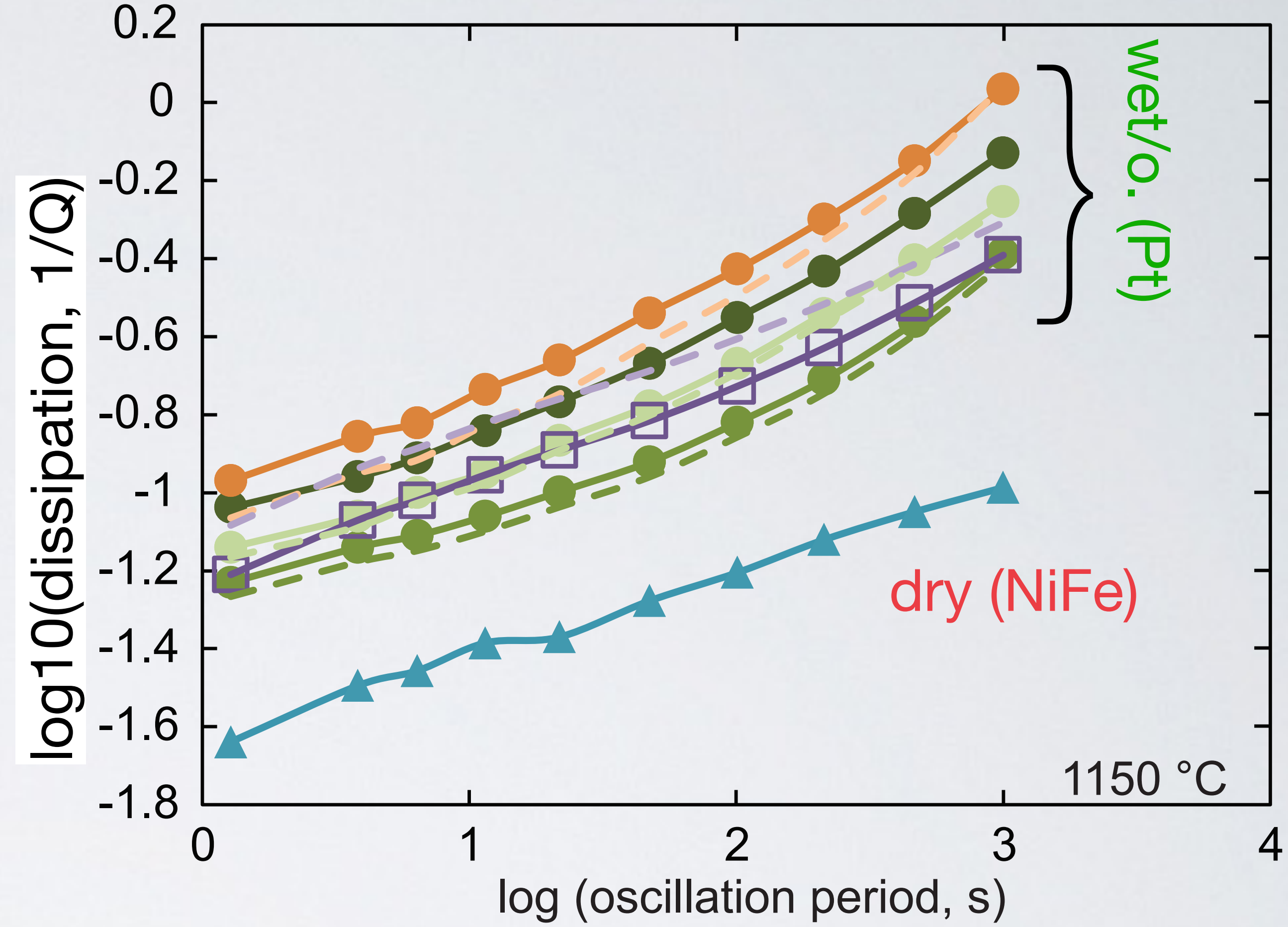




work in progress - Chris Cline -> AGU

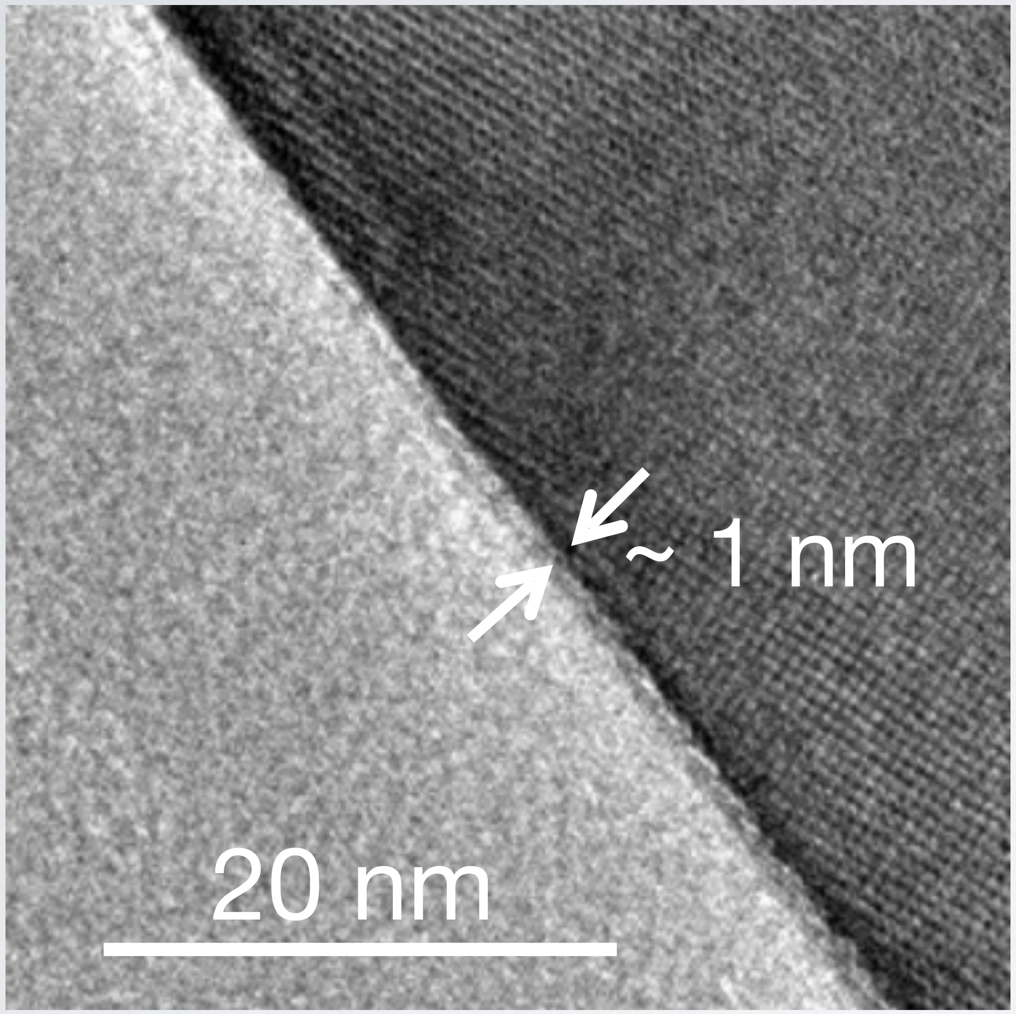
Results:

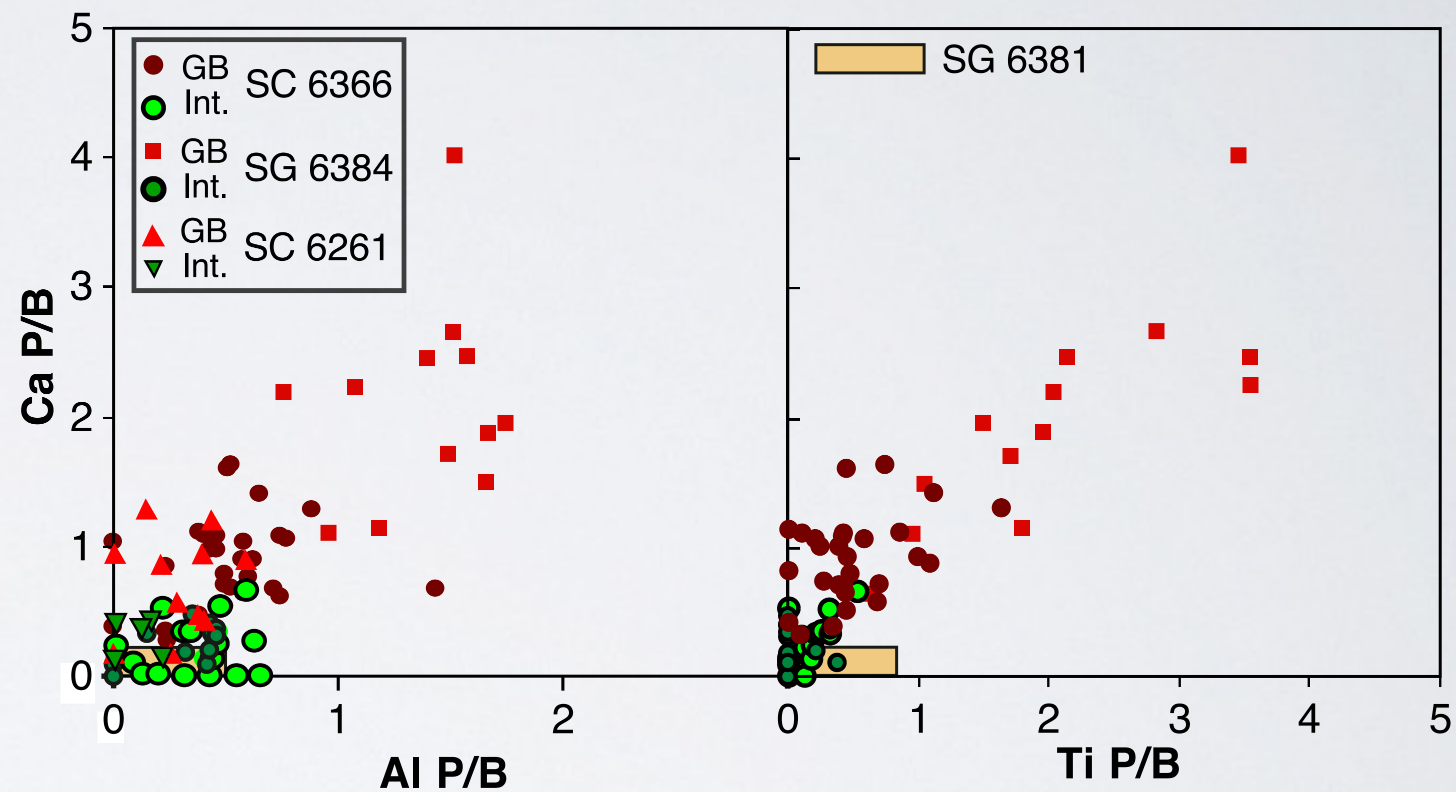




- frequency dependence the same for ‘wet’ and dry
- no systematic dependence on water content
- samples in Pt capsules have significantly lower modulus and higher attenuation

Grain boundaries enriched in incompatible elements - including Fe^{3+} and ‘water’

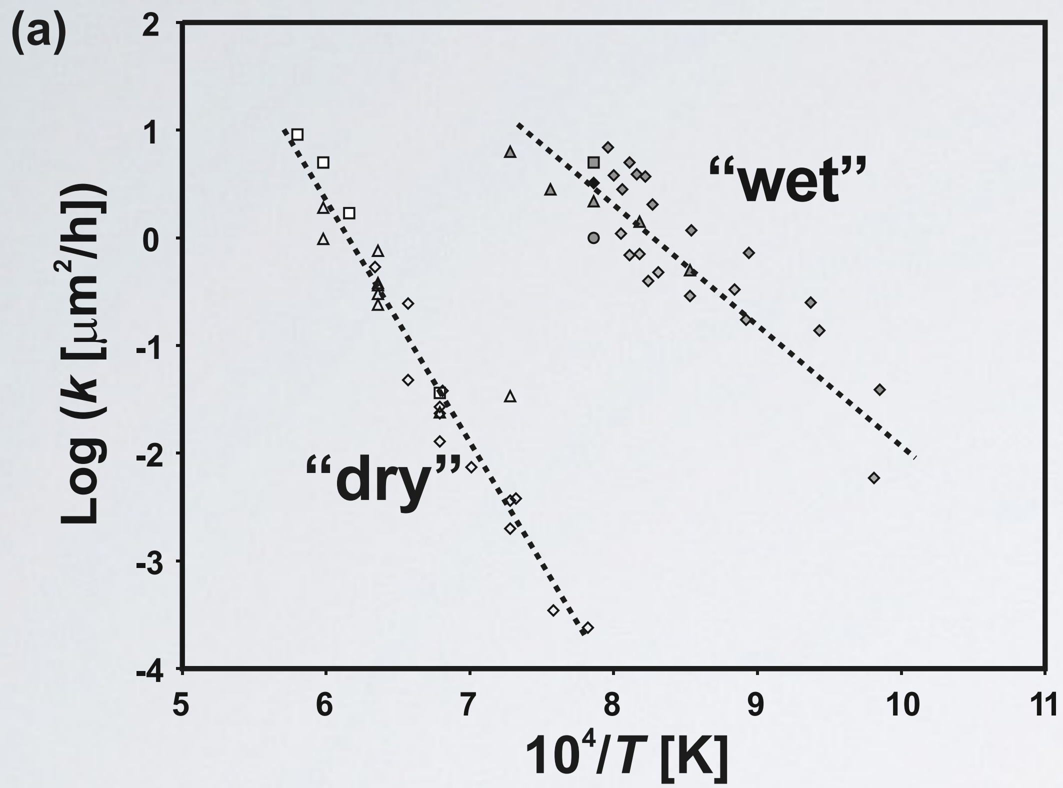




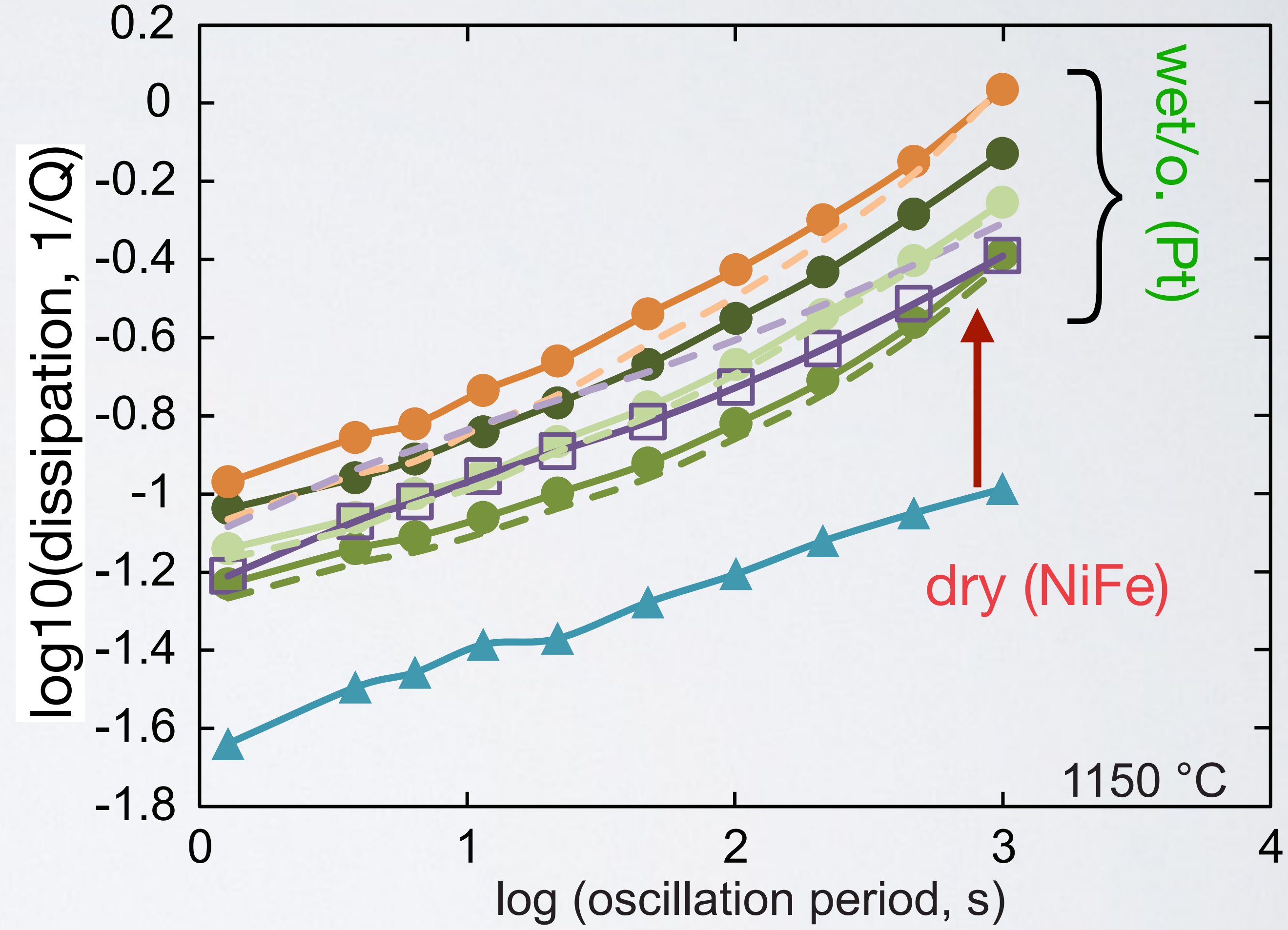
John Fitz Gerald, ANU

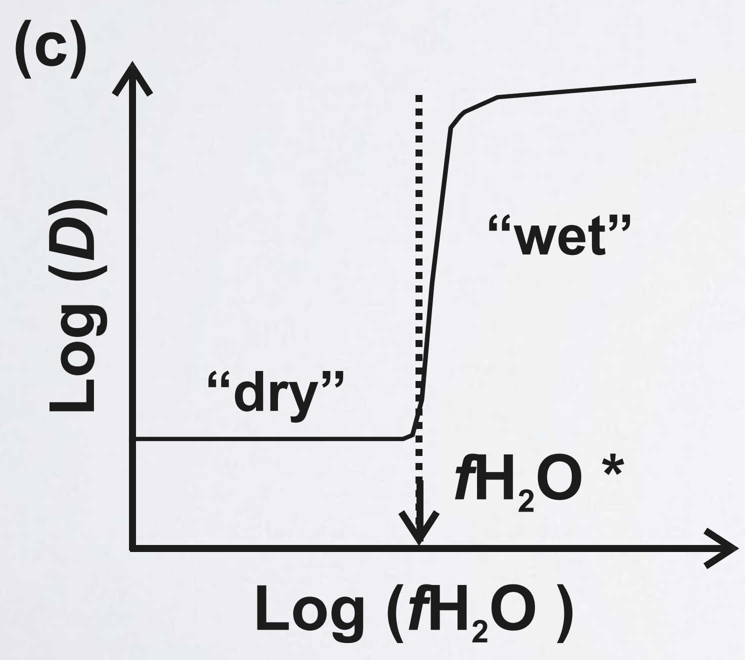
Katharina Marquardt, BGI (Marquardt et al., in prep)

Diffusion-controlled reaction rim growth of opx: 'binary' transition from wet to dry behaviour,



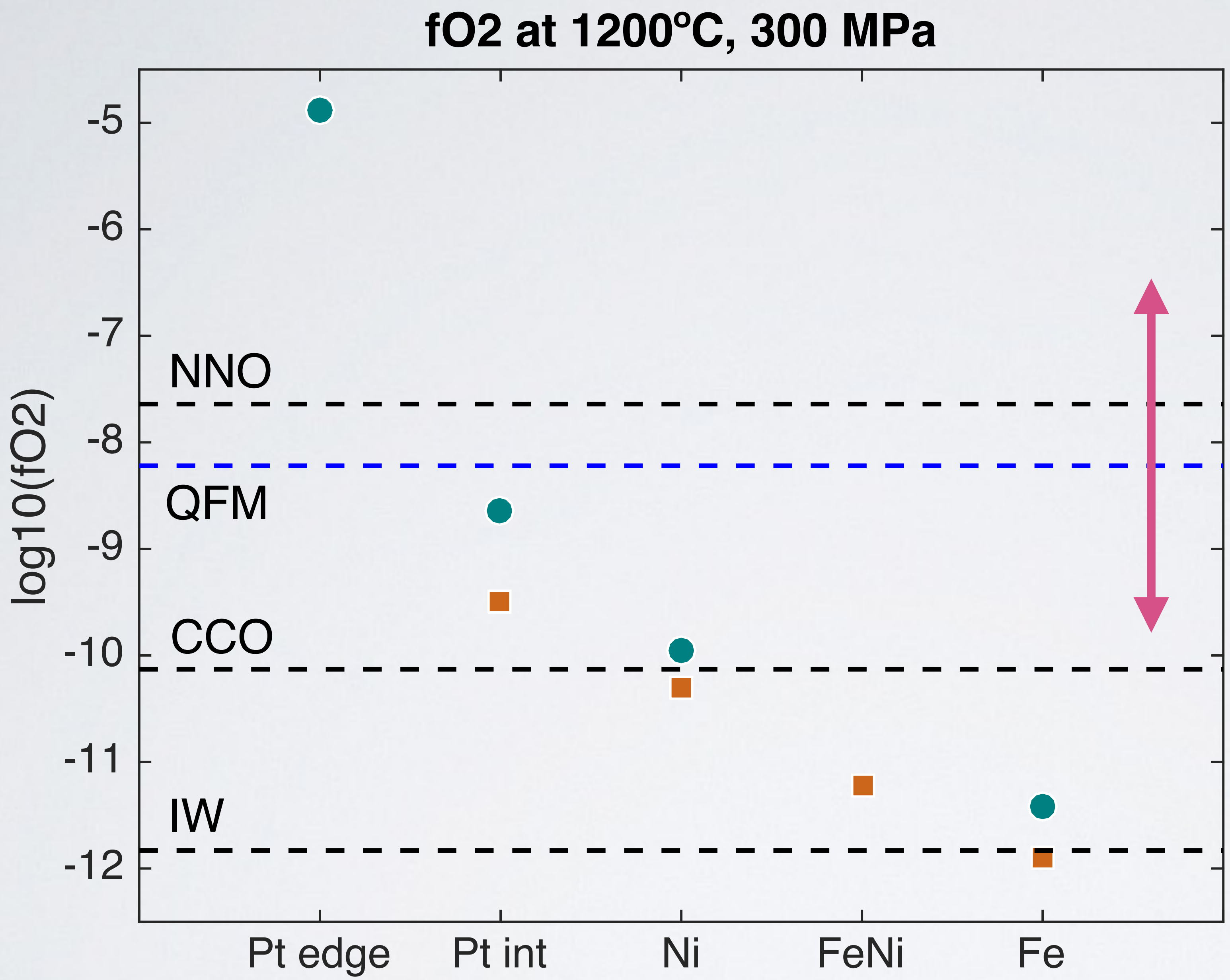
no sensitivity to water content





(Dohmen and Milke, 2010)

Oxygen fugacity



subduction zones

peridotite massifs

range of upper mantle fO_2 (Frost & McCammon, 2008)

Summary

- dislocation creep linearly enhanced by hydroxyl
- defect involved is extrinsic (Ti-clinohumite)
- Ti defect first to hydrate also at higher pressure

- seismic properties affected by ‘water’
- no relationship with water content
- mechanism is grain boundary sliding, enhanced even at very small bulk water contents at relatively oxidising conditions

- seismic properties may not directly translate to rheological properties (?)