Origin and distribution of water contents in continental and oceanic lithospheric mantle

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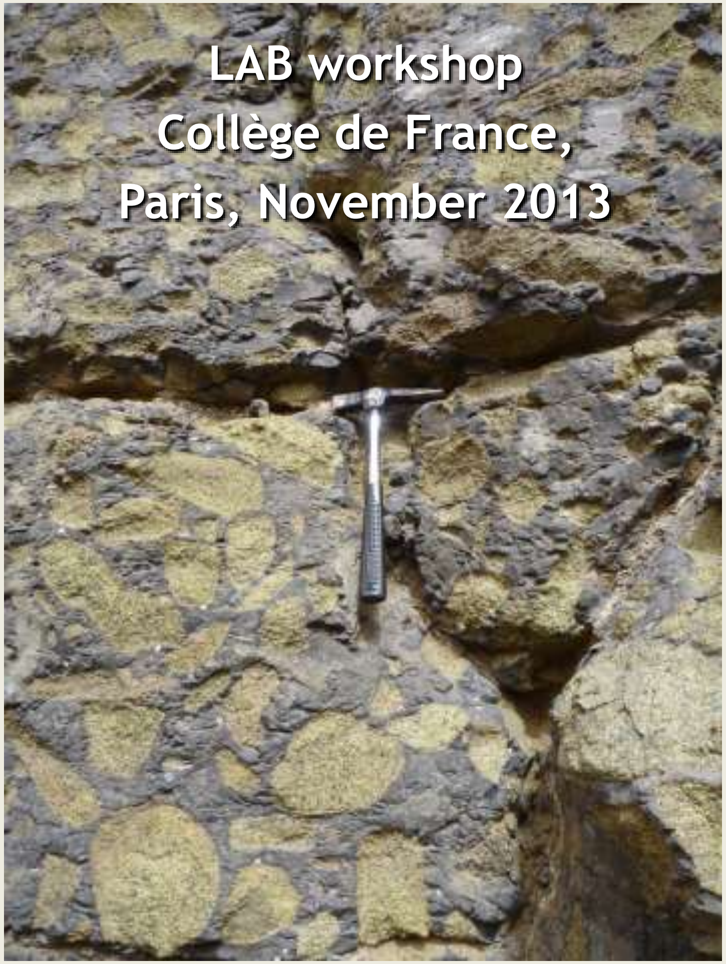

Mantle xenoliths in basalt, Jieshaba, China

Igor **Ashchepkov** (Novossibirsk, Russia),
David **Bell** (ASU, USA; NMMU, South Africa),
Michael **Bizimis** (USC, USA),
Alan **Brandon** (U Houston, USA),
Luc **Doucet** (ULB, Belgium),
Alexander **Golovin** (Novossibirsk, Russia),
Alesksei **Goncharov** (St Petersburg, Russia),
Eric **Hellebrand** (U Hawaii, USA),
Hejiu **Hui** (UND, USA),
Dmitri **Ionov** (U Montpellier, France),
Tom **Lapen** (U Houston, USA),
Marina **Lazarov** (U Hannover, Germany),
Cin-Ty **Lee** (Rice U, USA),
Zheng-Xue **Li** (oil industry, Houston, USA),
Roberta **Rudnick** (U Maryland, USA),
Jon **Snow** (U Houston, USA),
Alan **Woodland** (U Frankfurt, Germany)

Origin and distribution of water contents in continental and oceanic lithospheric mantle

Talk outline

- Importance of “Water” in the mantle
- Samples and techniques
- Water in the oceanic lithosphere
- Water in the cratonic lithosphere
- Global dataset comparison
- Conclusion

“Water” in the upper mantle

- Water in melts and fluids:
  H_2O, CH_4, H_2, OH^-: $f(P,T, fO_2, X_{melt})$
  Localized phases
- Water in hydrous minerals:
  Amphibole (pargasite), mica (phlogopite), apatite
  Minor phases
- **Water in nominally anhydrous minerals** (NAMS):
  Olivine, pyroxene, garnet, plagioclase
  H located in minerals defects, <1 to 1000 ppm H_2O
  Major phases
- Other volatiles:
  C (not in NAMS), F (same size & charge as OH^-), Cl

Why is "Water" important?

- Water lowers the solidus of mantle lithologies:

  facilitates partial melting, lower T

- Water and rheology:

  Presence of water in olivine makes it weaker*

  * maybe not: Fei et al. Nature 2013

  Melt circulation and eruption style

- Water and remote sensing of the deep Earth:

  Seismic properties: seismic wave attenuation & anisotropy

  Electrical conductivity

  Thermal conductivity

(Gaetani & Grove, 1998; Green, 1973; Hirose & Kawamoto, 1995; Chopra & Paterson, 1984; Dixon et al., 2004; Drury, 1991; Hirth & Kohlstedt, 1996; Hirth et al., 2000; Justice et al., 1982; Karato, 1993; 2010; Mackwell et al., 1985; Mei & Kohlstedt, 2000; Walker et al., 2007; Jung & Karato, 2001; Demouchy et al 2012; Karato, 2004; 2006; Jones, Evans, Muller, Fullea, Pommier 1990-2013; Lizzaralde et al 1995; Udata et al 2003; Hofmeister 2004)

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  Melt circulation and eruption style
- Water and remote sensing of the deep Earth:

  Seismic properties: seismic wave attenuation & anisotropy

  Electrical conductivity

  Heat conductivity

→ Mapping water contents in the upper mantle

→ Understand what controls the water contents

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Samples

- Mantle peridotite xenoliths:

  olivine, pyroxene,

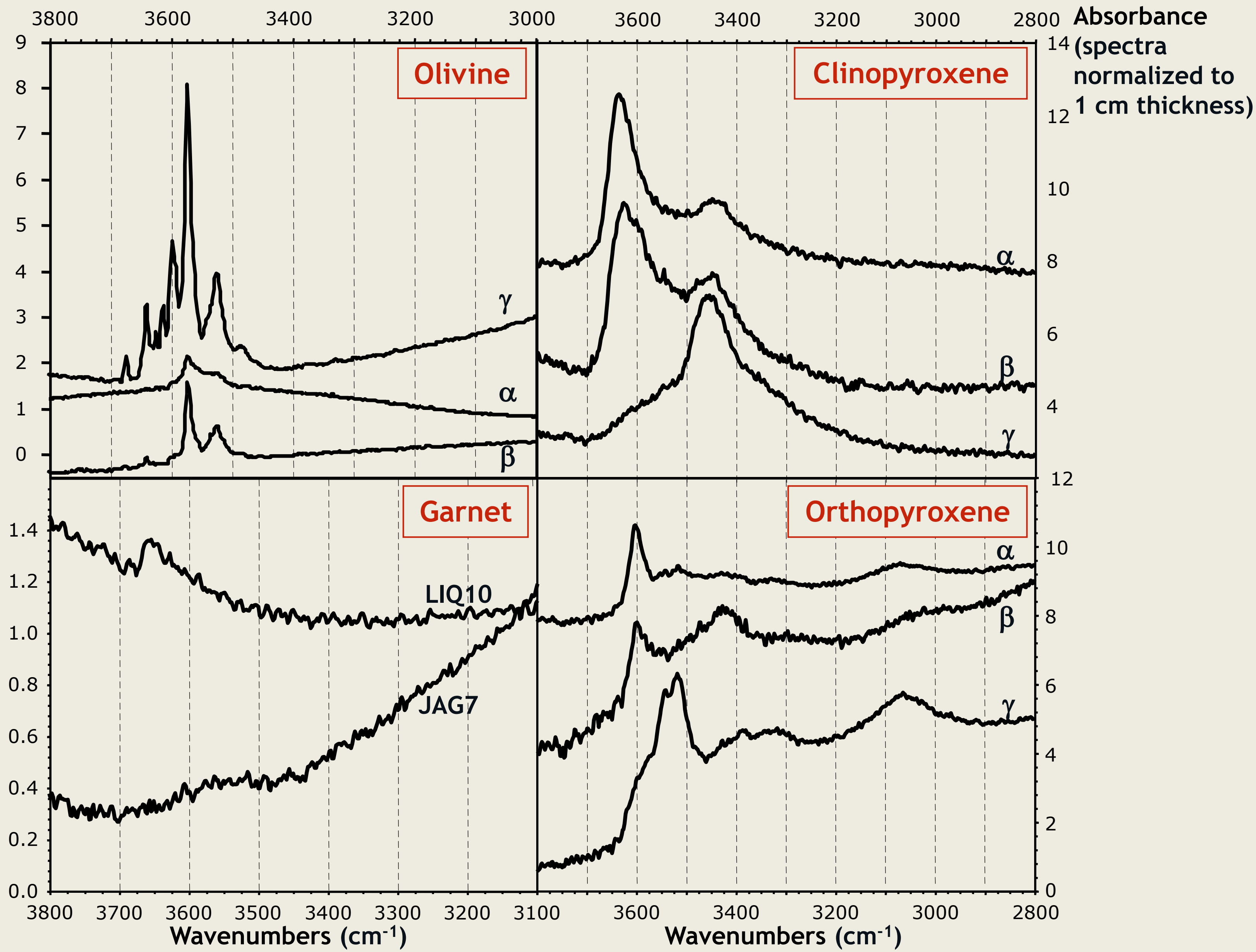
  garnet &/or spinel
- Chunks of mantle brought up by alkali magmas and kimberlites

Mantle xenoliths, Jieshaba, China

Mantle xenolith, Kimberley, South Africa

Fourier transform infrared spectrometry data (FTIR)

- O-H vibration region



H loss during xenolith ascent in host magma?

- H diffuses quickly through Ol & Px
  (e.g. Mackwell & Kohlstedt 1990; Ingrin et al 1995, 1999, Stalder & Skogby 2003)
- Px have homogeneous water contents
- Ol can record H loss

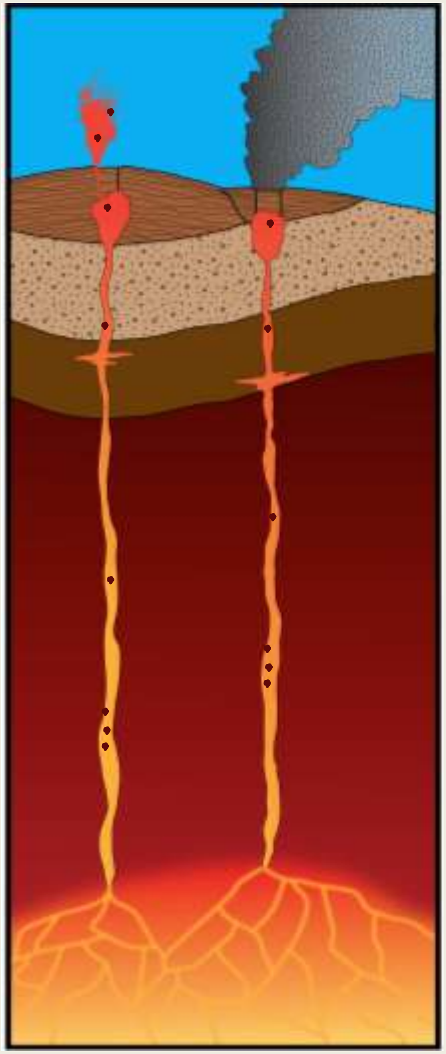
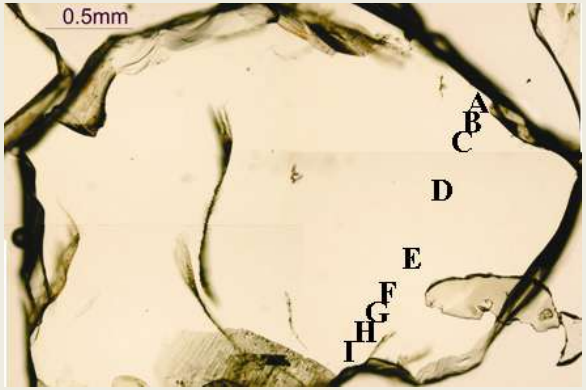
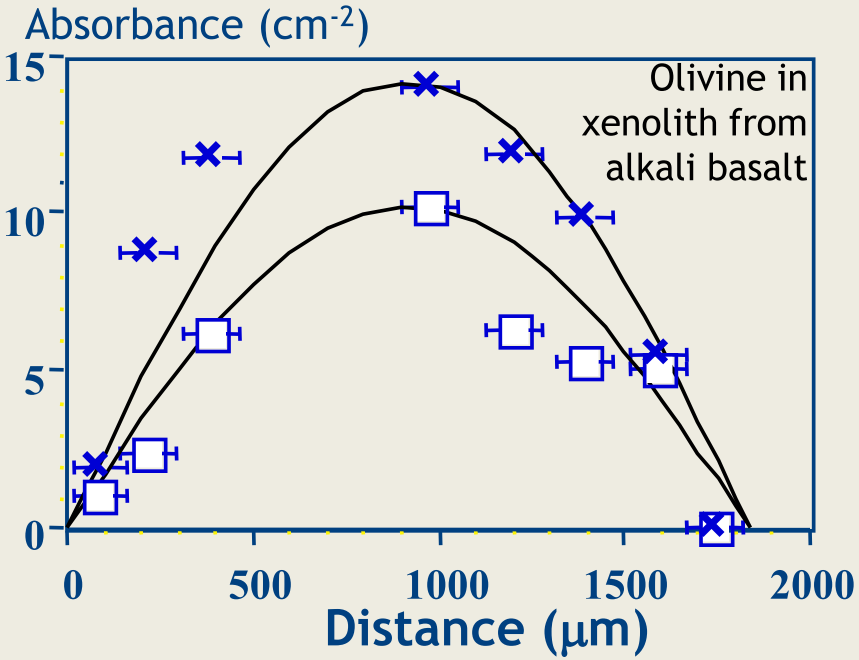


Figure stolen from AGU Chapman conference website (xenoliths added)

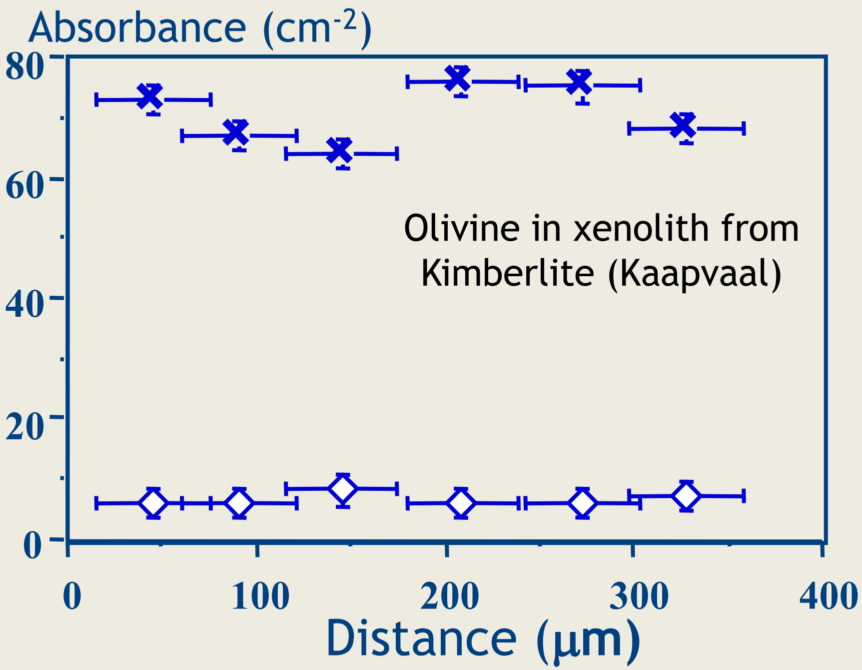


Olivine from Mexican mantle xenolith

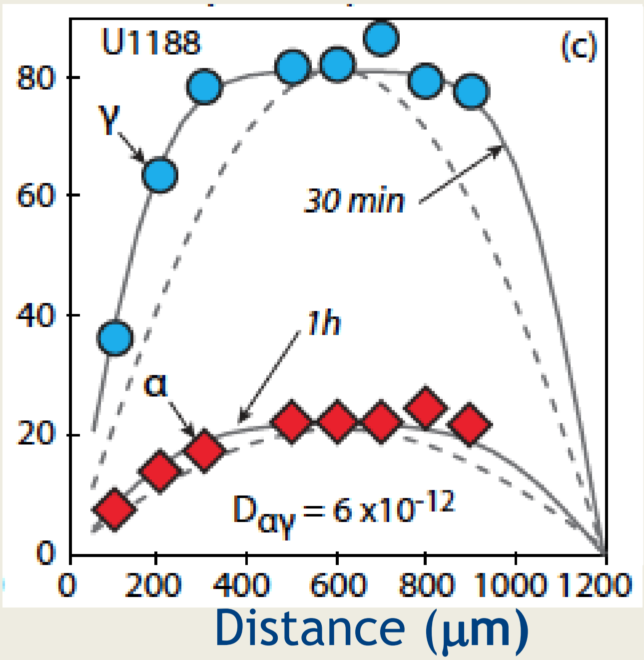


H loss during xenolith ascent in host magma?

- H diffuses quickly through Ol & Px at magmatic T
  (e.g. Mackwell & Kohlstedt 1990; Ingrin et al 1995, 1999, Stalder & Skogby 2003)
- But H not always lost because H diffusion is coupled with that of slower elements (Al in px) or H enters low P micro hydrous phases (olivine)
- Mantle values if:
  - Plateau diffusion profiles
  - Co-var with other elements (Al, Ti, REE…)



Olivine from Udachnaya mantle xenolith from kimberlite (Doucet et al 2013 submitted to GCA)



→ Data shown here are mantle [H_2O] values

Origin and distribution of water contents in continental and oceanic lithospheric mantle

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Water in the oceanic lithosphere

- **Oceanic basalt glass and melt inclusion analyses:**

👍 lots of data *(e.g., Dixon et al papers, Michael et al papers, Stolper et al papers, 1980'-2010, Saal et al 2002)*

👎 potential degassing

👎 recalculated source water content

- **Abyssal peridotite mineral analyses:**

👍 direct mantle analysis

👎 often hydrothermally altered

👎 data are rare

(Kane FZ Opx: Gose et al 2009,2011, Schmädicke et al. 2011;
Gakkel ridge: Peslier et al unpublished)

👎 loss of water during mantle upwelling & melting

→ not representative of MORB source


Salt Lake Crater xenoliths (photo M Bizimis)

- **Analysis of mantle xenoliths in oceanic island basalts:**

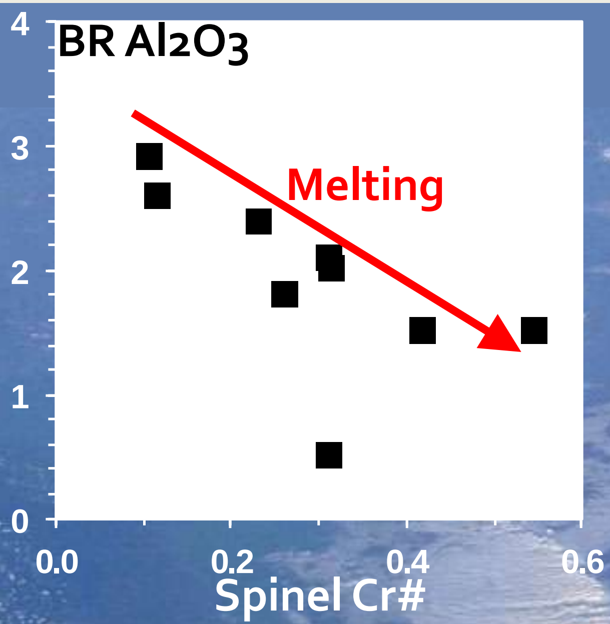
👍 direct mantle analysis

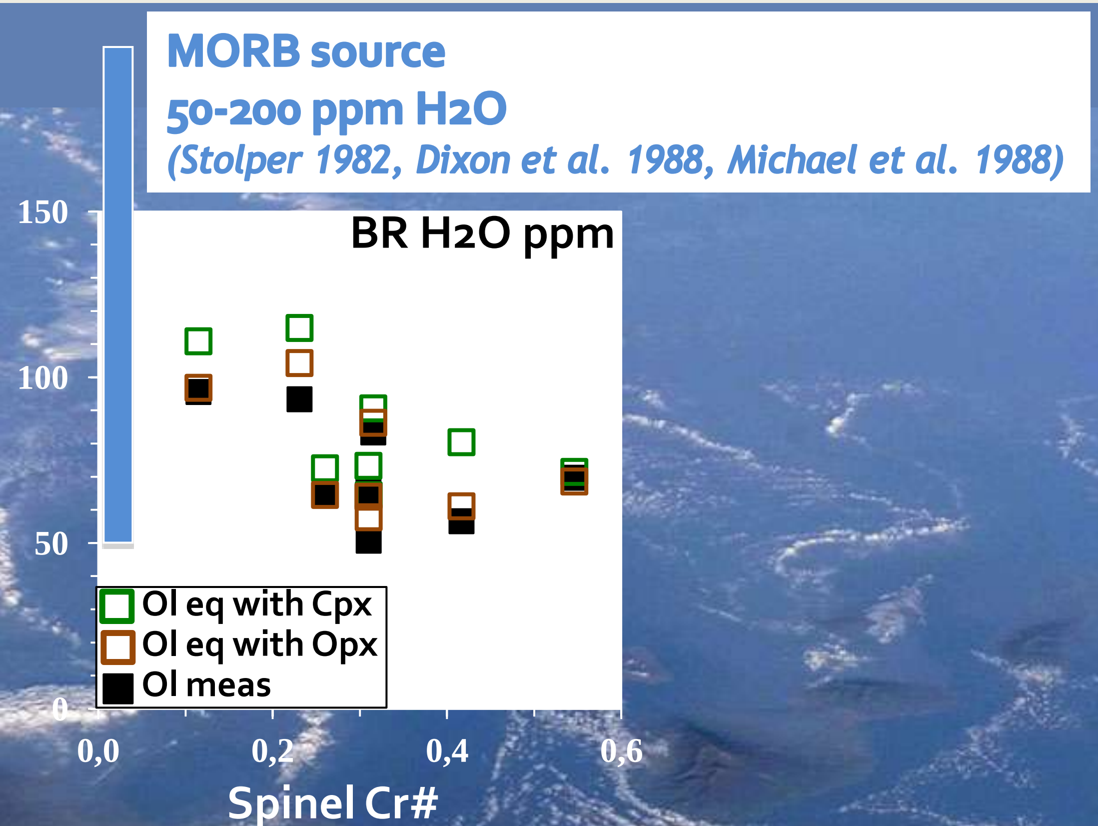
👎 potential H loss during host magma ascent (olivine)

👎 rare

→ Analysis of peridotite xenoliths from Hawaii

Water in the oceanic lithosphere **Hawaii**



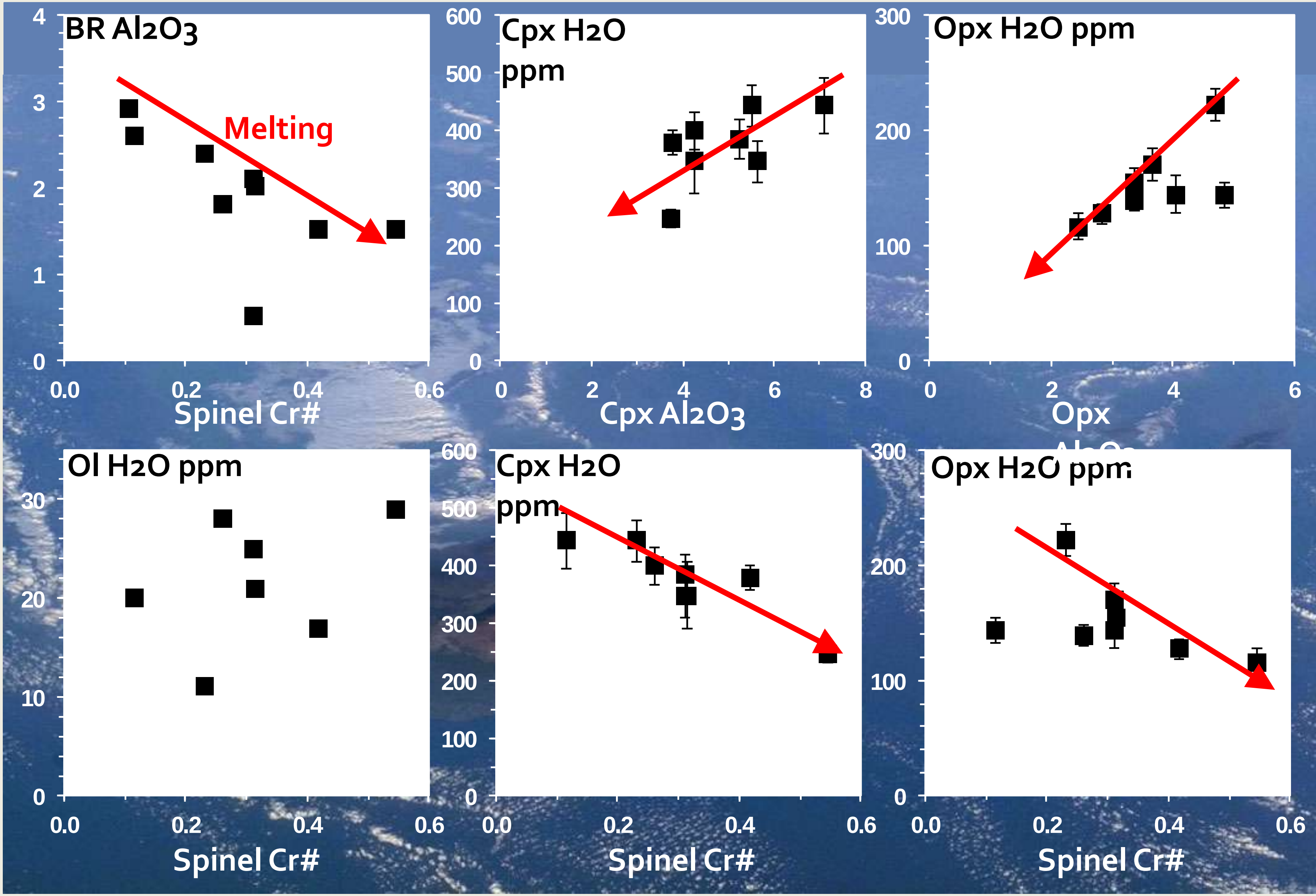


- **H is an incompatible element: goes into the melt during partial melting.**

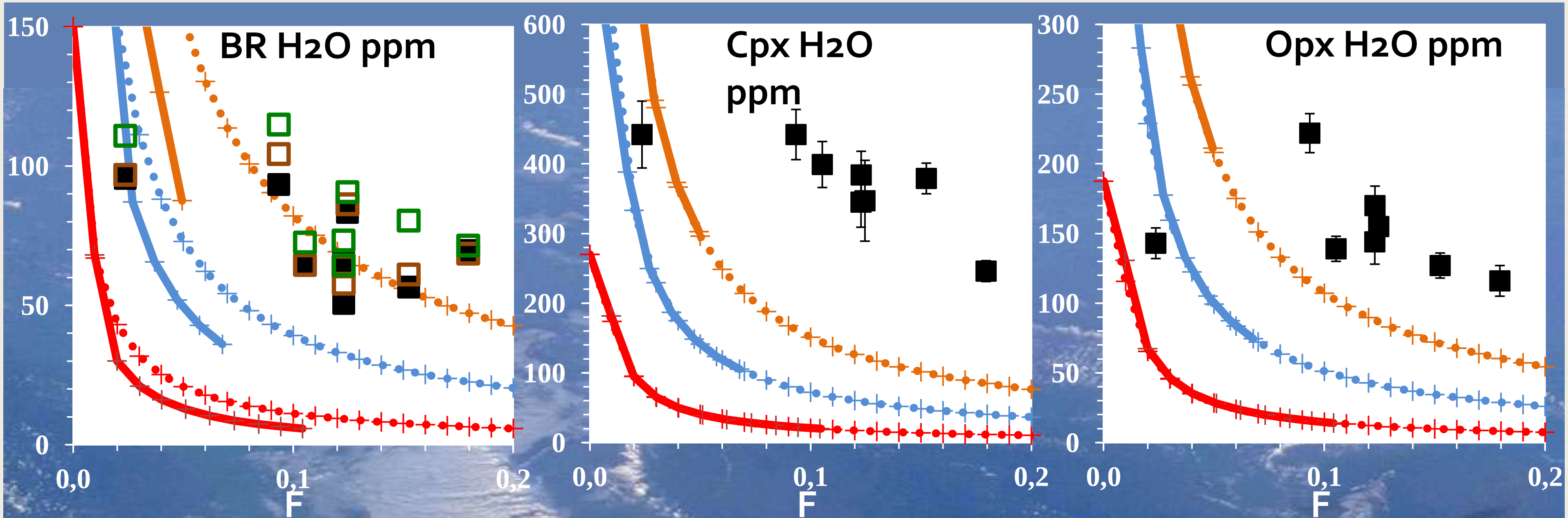
↑ degree of fusion, ↓ water in peridotite

Peslier & Bizimis, unpublished

Water in the oceanic lithosphere Hawaii



Water in the oceanic lithosphere **Hawaii**



Melting modeling

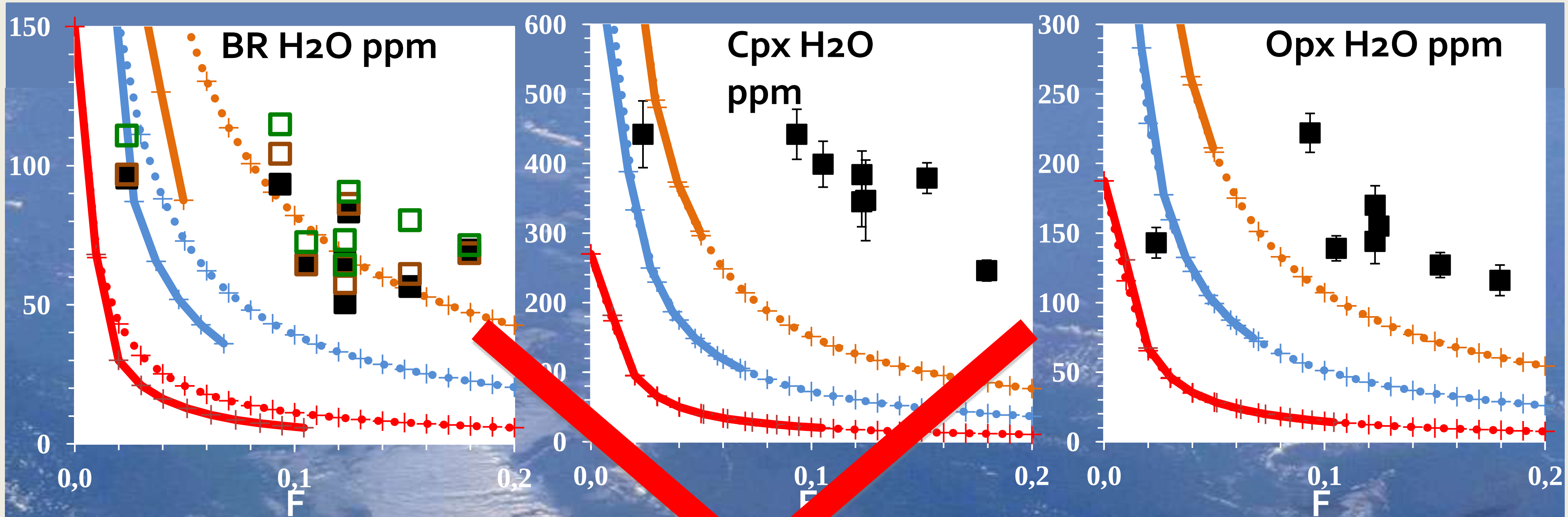
- Source = DM (150 ppm H_2O)
- Source = Hawaiian volcanics source (525 ppm H_2O)
- Source = PM (1100 ppm H_2O)

Simple batch melting (dotted line)

Near fractional melting (X & P from MELTS simulations) (solid line)

(Modeling: Shaw, 1979; Norman 1998; Ghiorso et Sack 1995, 2002; Asimow et al. 2001, 2004; D_H: Tenner et al. 2009, O'Leary et al. 2010; source [H2O]: Dixon et al. 1988, 2001; Palme & O'Neill 2004)

Water in the oceanic lithosphere **Hawaii**



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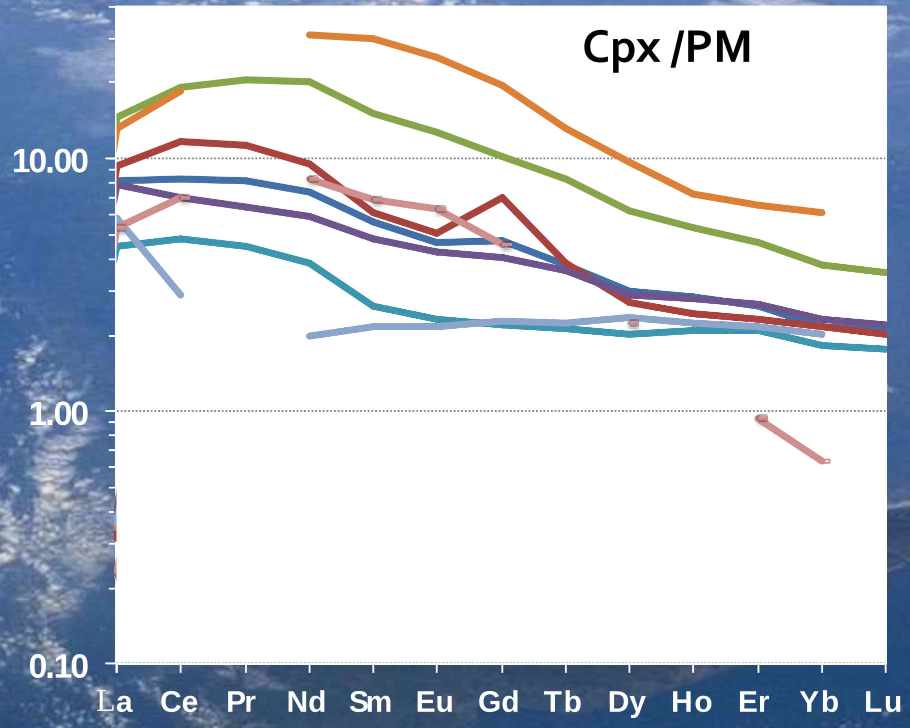
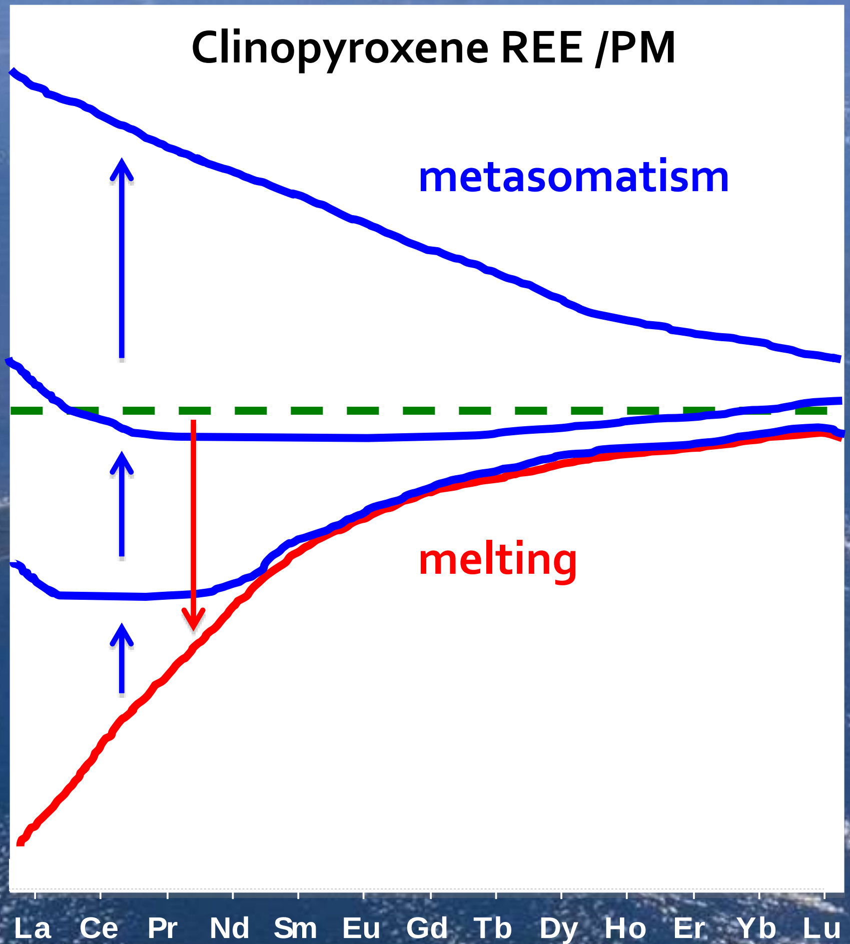
Water in the oceanic lithosphere **Hawaii**

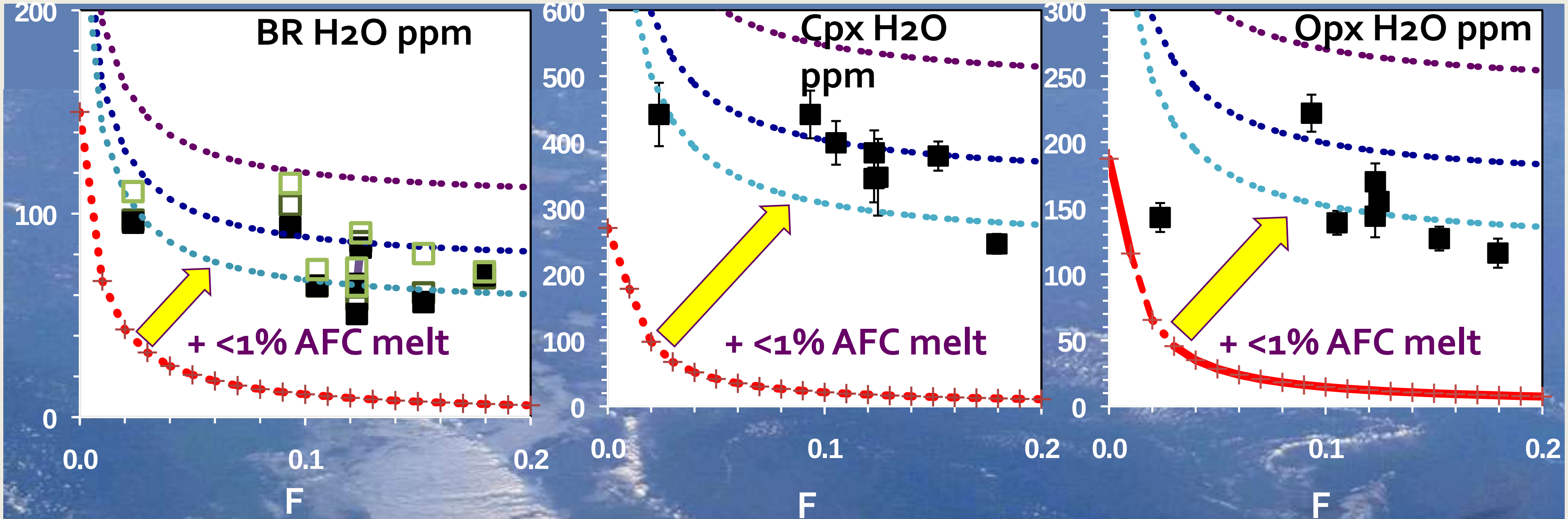
- **Salt Lake Crater peridotites contain evidence for peridotite-melt interaction (melts = parent melts of Honolulu volcanics)**





(Sen et al., 1993, Bizimis et al. 2003, 2007)

Water in the oceanic lithosphere **Hawaii**

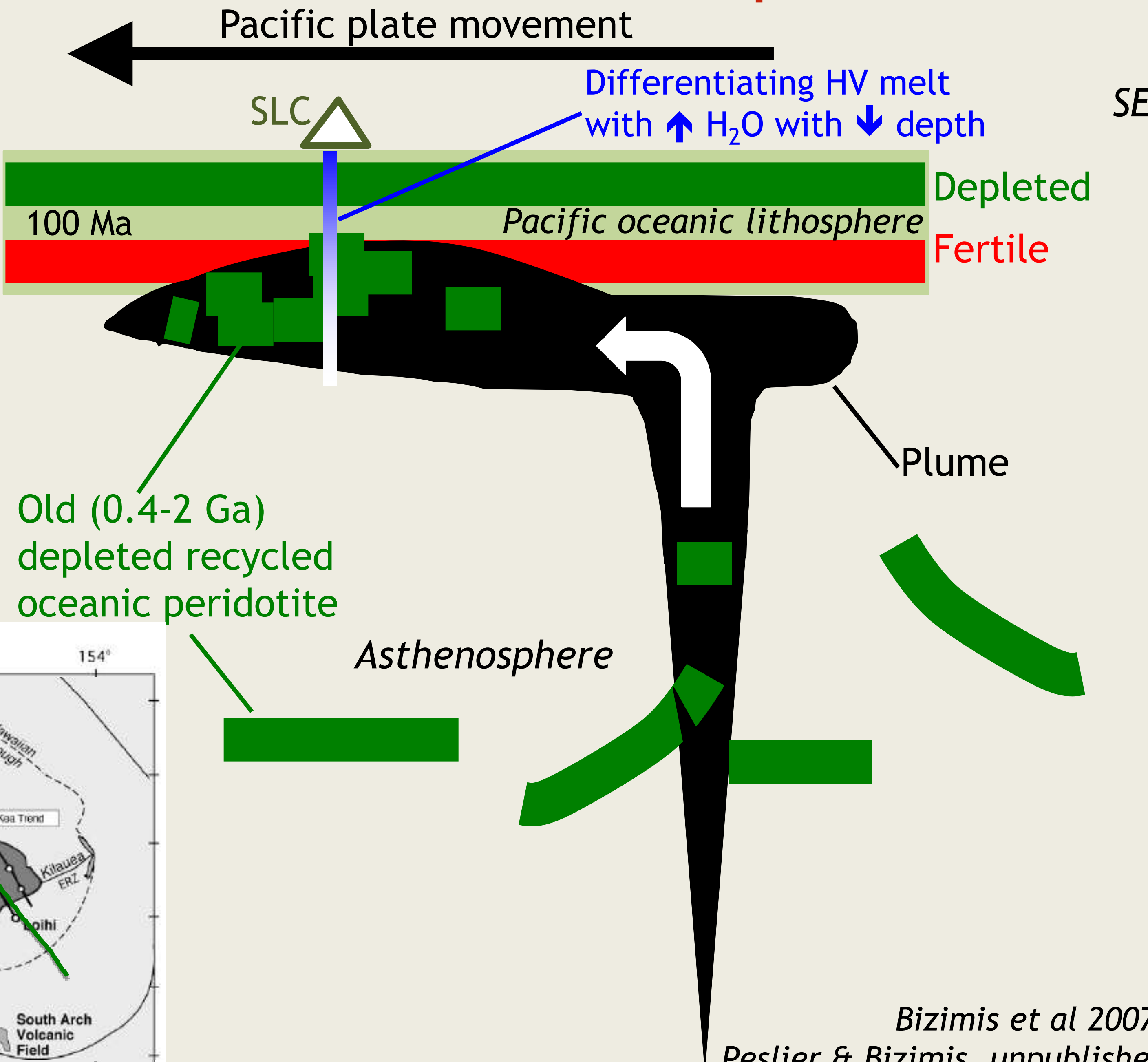


Mantle melt interaction modeling

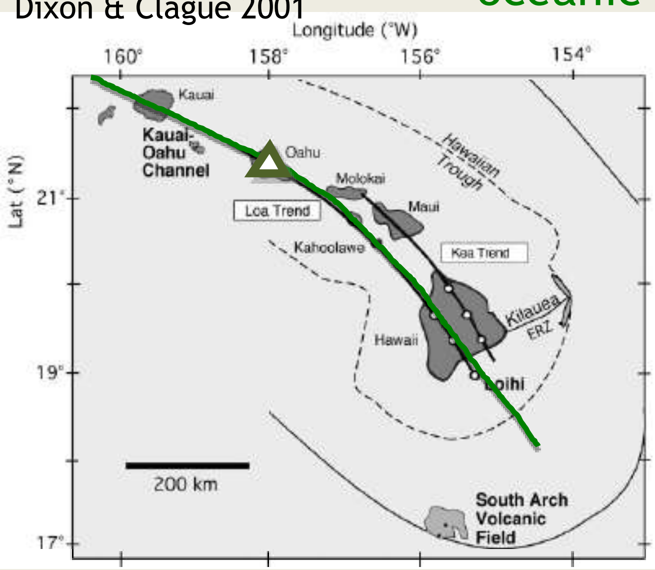
- source = DM (150 ppm H_2O), simple batch melting
- 1) AFC: HV melt (0.51-1.95 wt% H_2O) assimilates DM peridotite
  2) 1% AFC melt metasomatizes DM peridotite

(Modeling: Shaw, 1979; Norman 1998; DePaolo 1981; D_H: Tenner et al. 2009, O'Leary et al. 2010; source [H2O]: Dixon et al. 1988, 2001)

Water in the oceanic lithosphere **Hawaii**



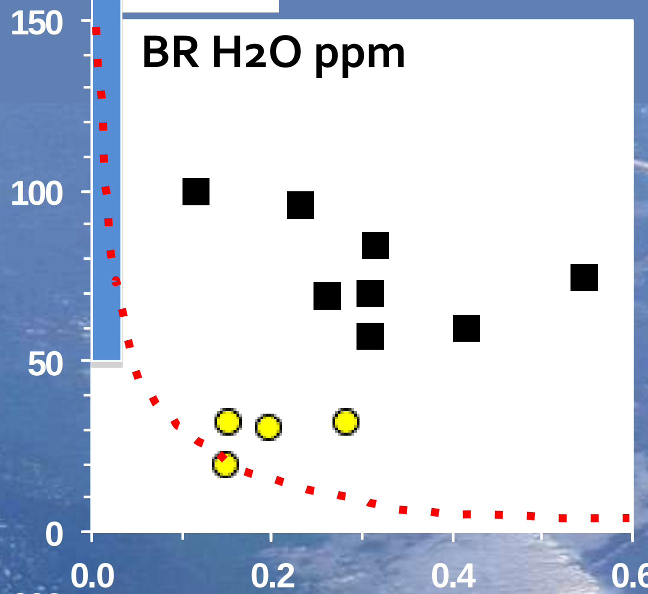
Map modified from Dixon & Clague 2001



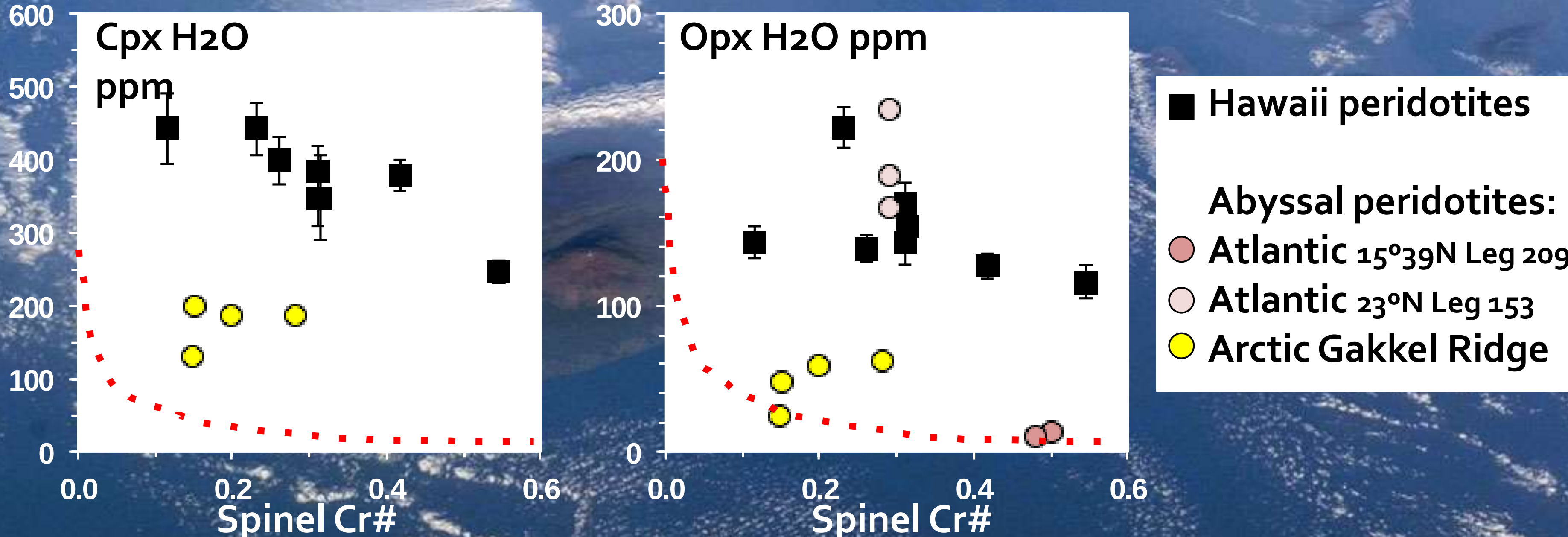
Bizimis et al 2007,
Peslier & Bizimis, unpublished

MORB source

Water in the oceanic lithosphere



- Not enough data!
- Oceanic mantle is heterogeneously hydrated
- Spinel peridotites: Hawaii SLC 2-4 GPa
  Abys Perid <2 GPa
- Hawaii [H_2O] controlled by mantle-melt interaction. Partial melting trends still in px.
- Melting may explain some abys perid [H_2O]



(Gose et al., 2009, Schmädicke et al., 2011, Peslier & Bizimis, Peslier et al., unpublished)

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Water in the continental lithosphere: cratons

- Cratons have deep keels (>200 km depth)
- Crust and mantle lithosphere are old (>3 Ga)

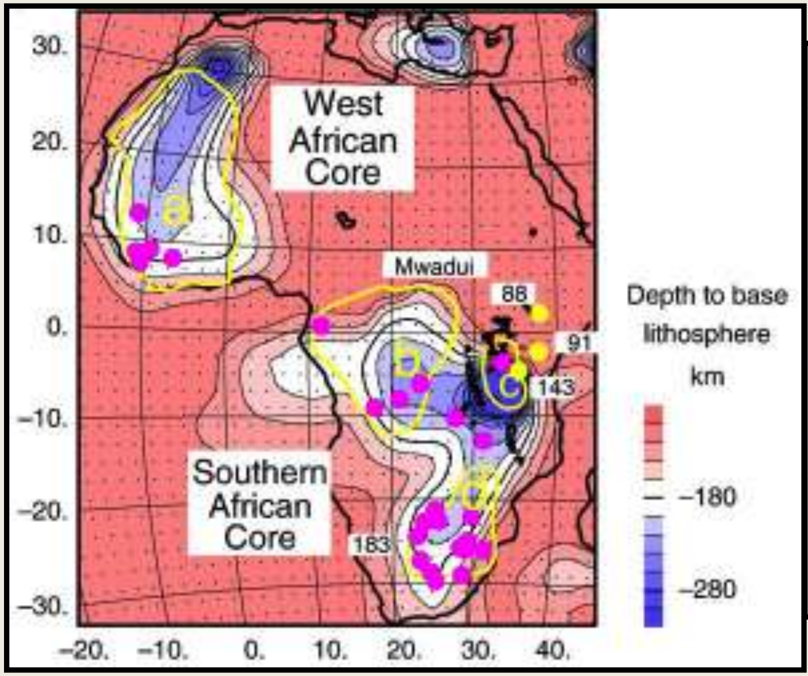


Fig. From Priestley & McKenzie 2006, depths from shear waves velocities

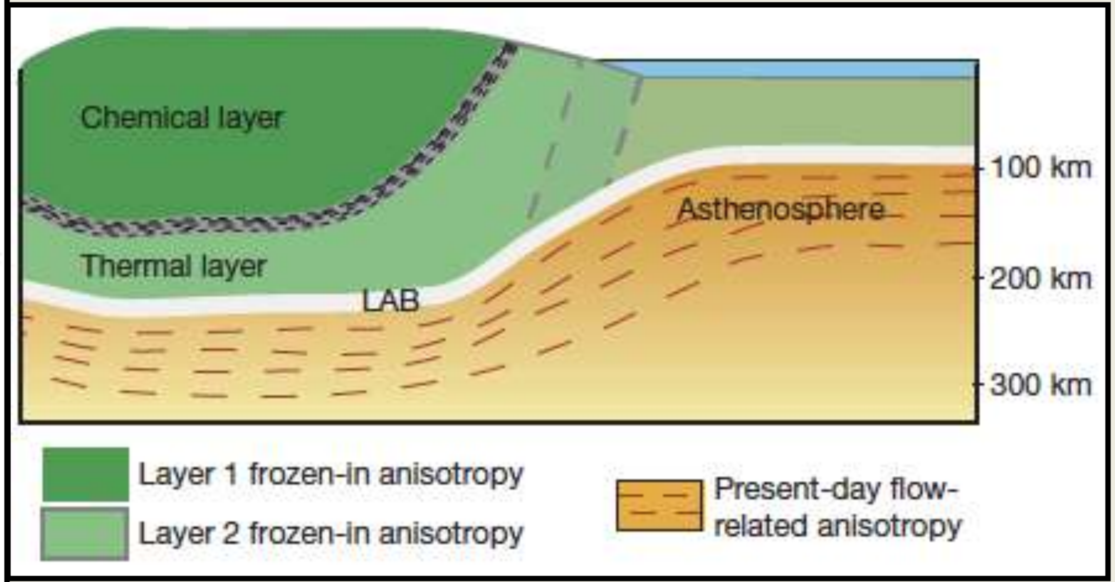


Fig. from Yuan & Romanowicz 2010, interpretation of azimuthal anisotropy

References: e.g. Jordan 78, Li & Burke 06, Larson et al 06, Eaton et al 08, Michaut et al 07, Priestley et al, Priestley & McKenzie 06, Muller et al 09, Yuan & Romanowicz 10, Richardson et al 84-93; Walker et al 89

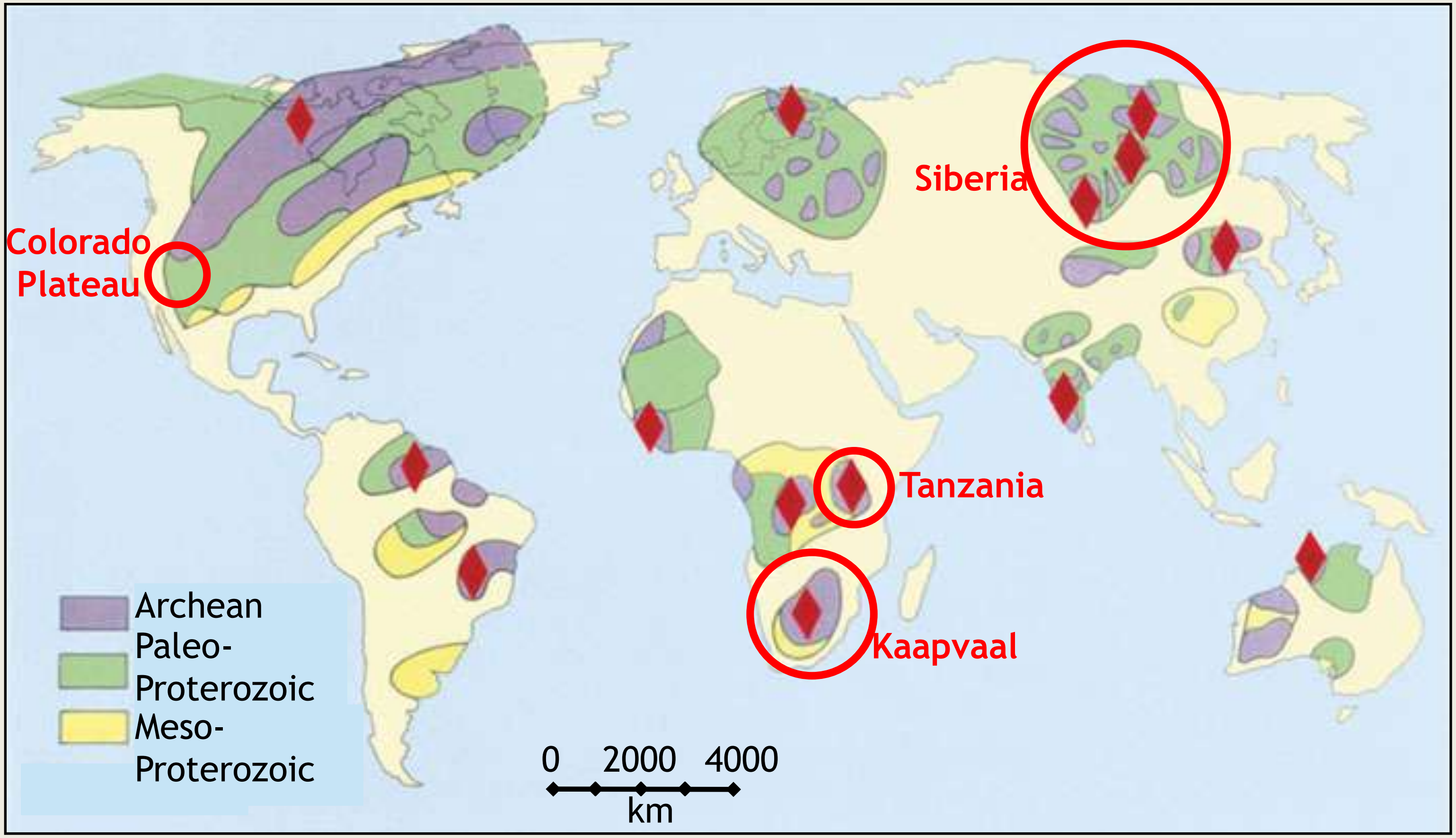
Water in the continental lithosphere: cratons

Why do craton keels resist delamination by asthenospheric convection over billions of years?

- Low density ✔
  → Buoyant
- Low T ✔
  → Strong
- Low water content ?
  → Strong

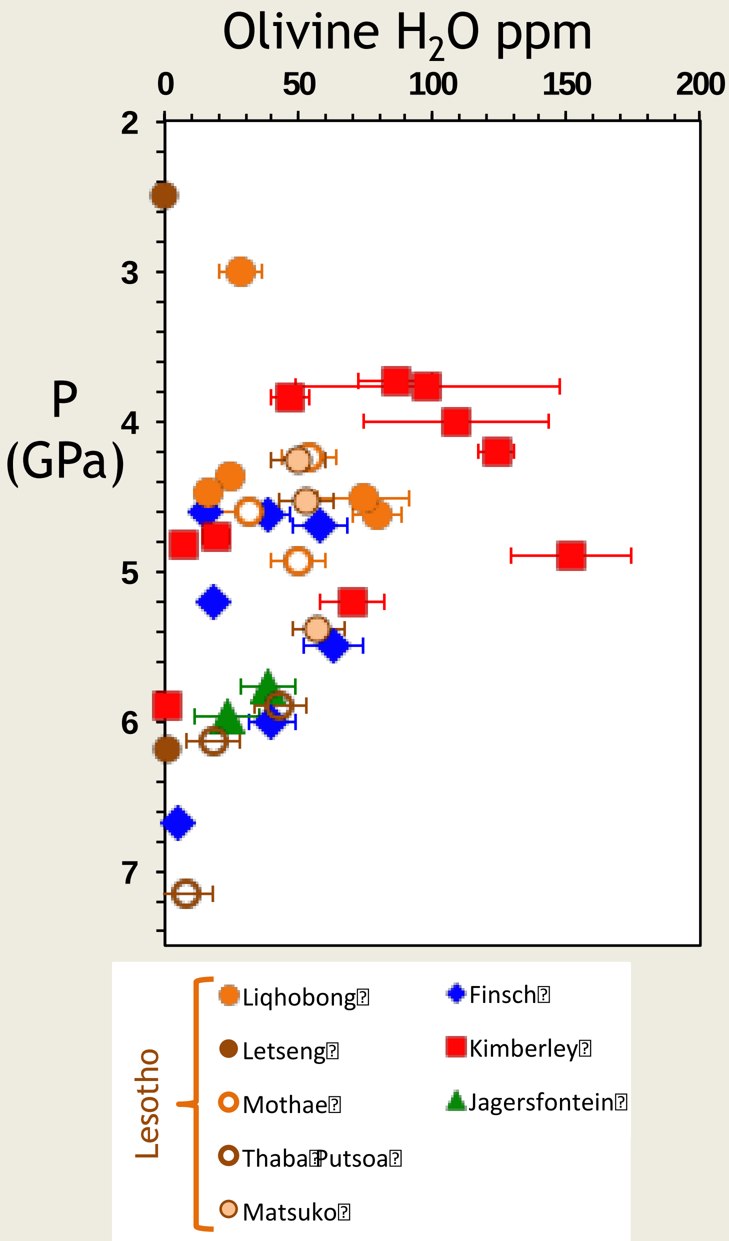
e.g. Jordan 1978, Poudjom-Djomani et al 2001, James et al 2004, Lenardic et al 1997, 1999, 2000, Shapiro et al 1999, Sleep 2005, Hirth et al 2000, Karato 2010

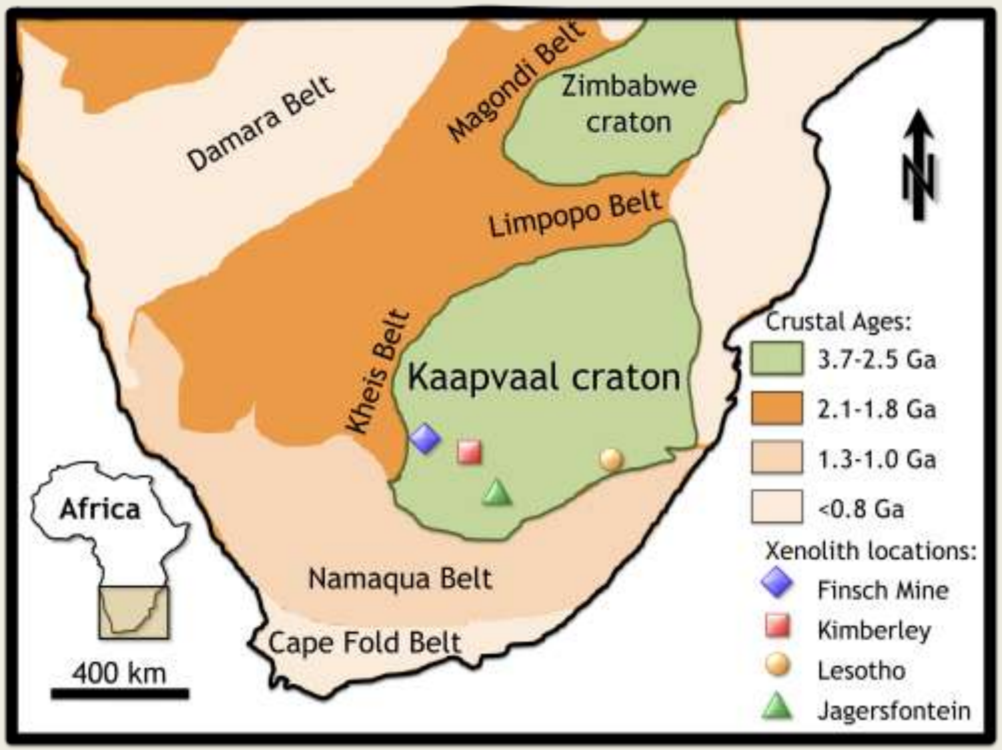
Water in the continental lithosphere: cratons



Map stolen then modified from http://www.conferencenet.org/conference/iccfd.htm

Water in the continental lithosphere: cratons





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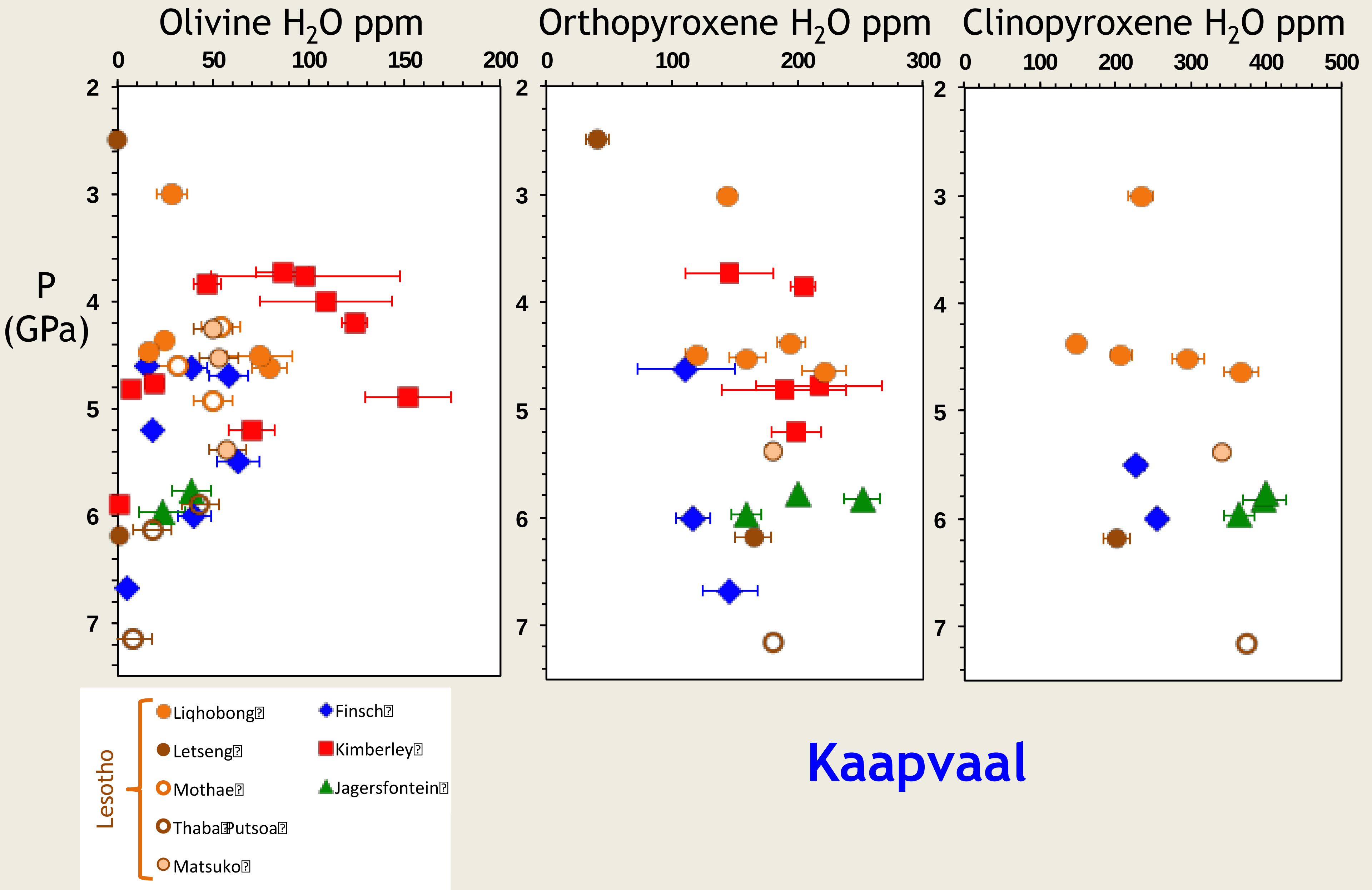
Peslier et al 2010, 2012; Kurozawa et al 1997; Grant et al 2007; Baptiste et al 2012

Water in the continental lithosphere: cratons



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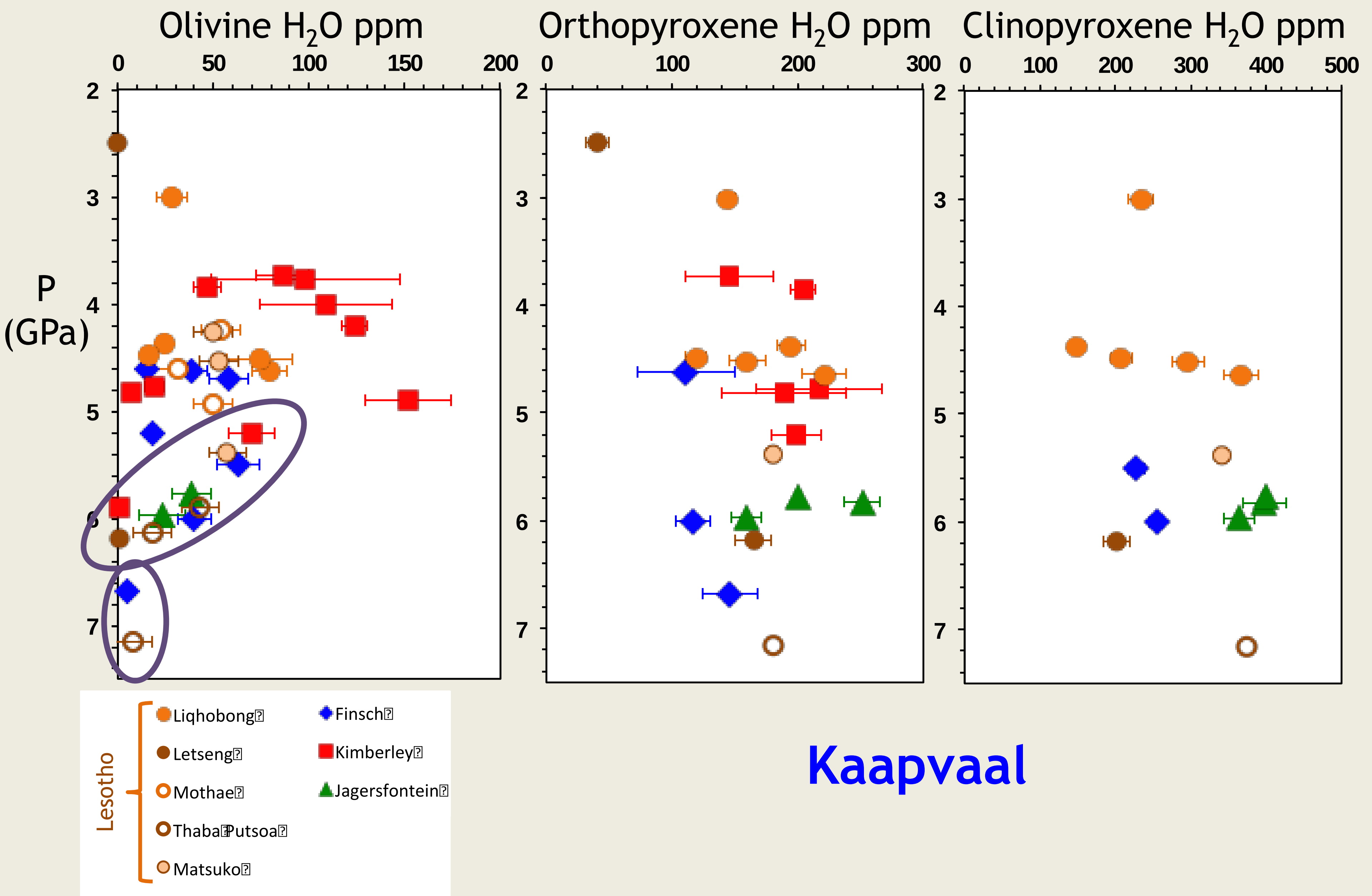
Water in the continental lithosphere: cratons



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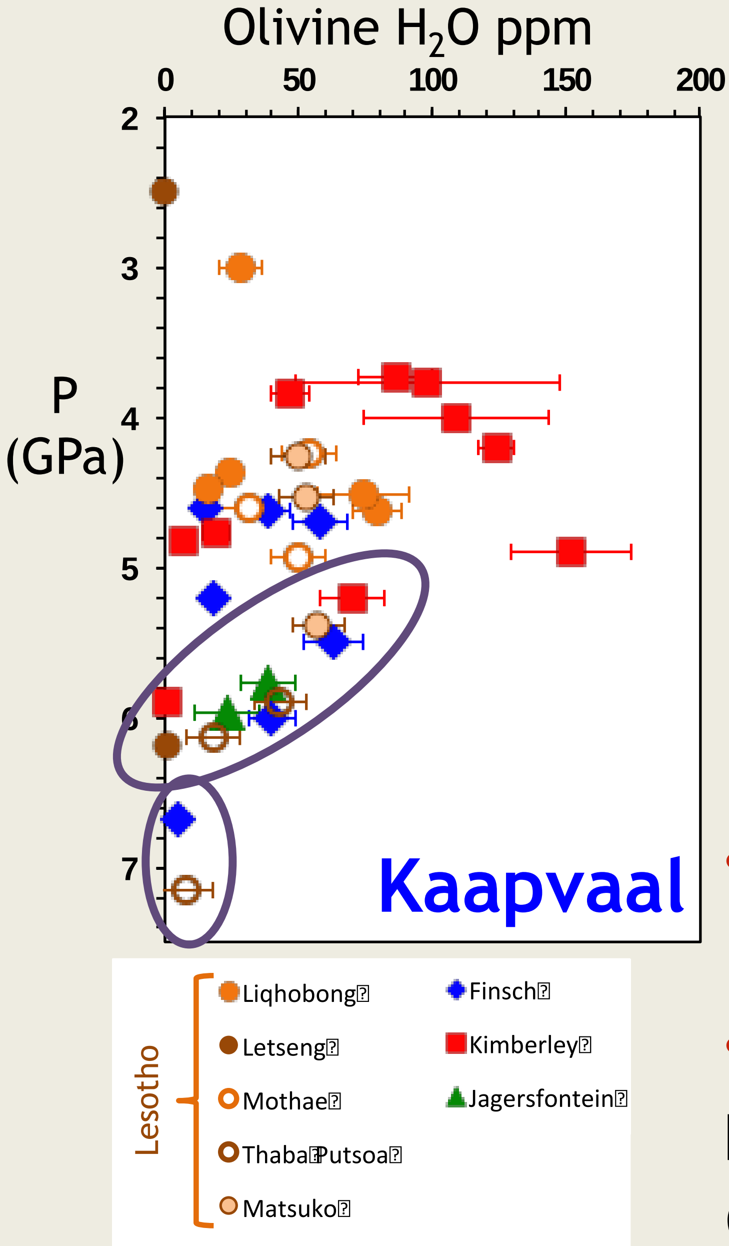
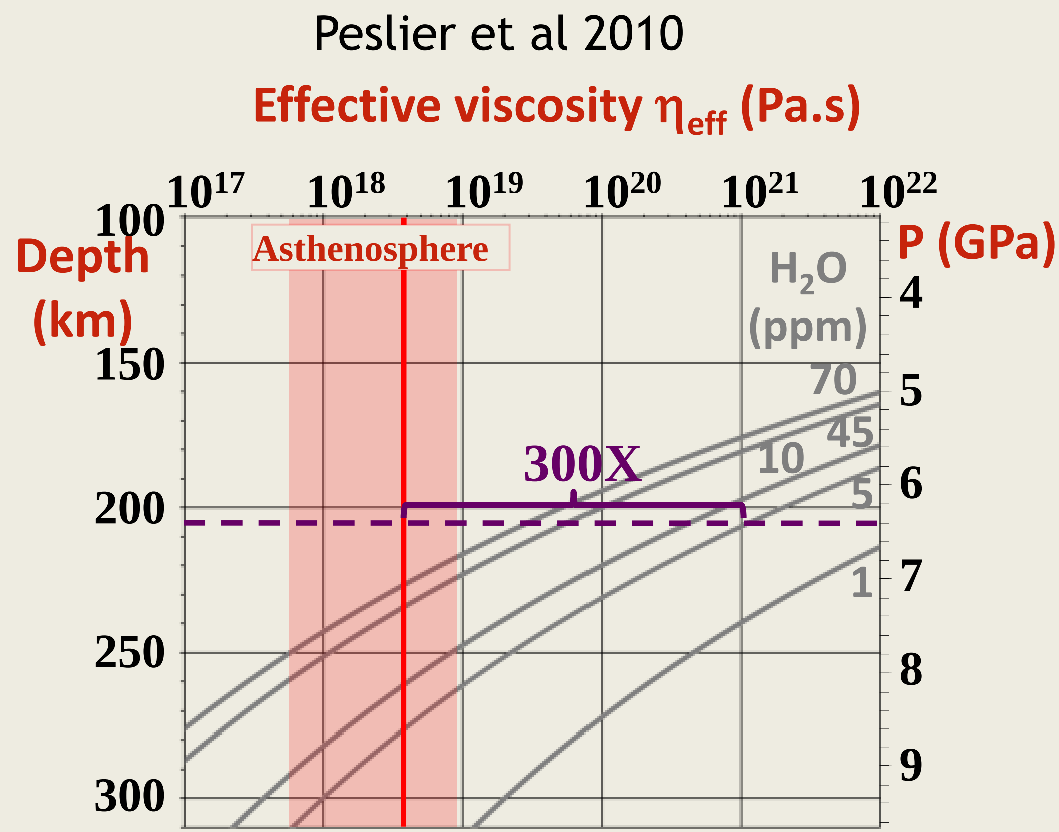
Water in the continental lithosphere: cratons

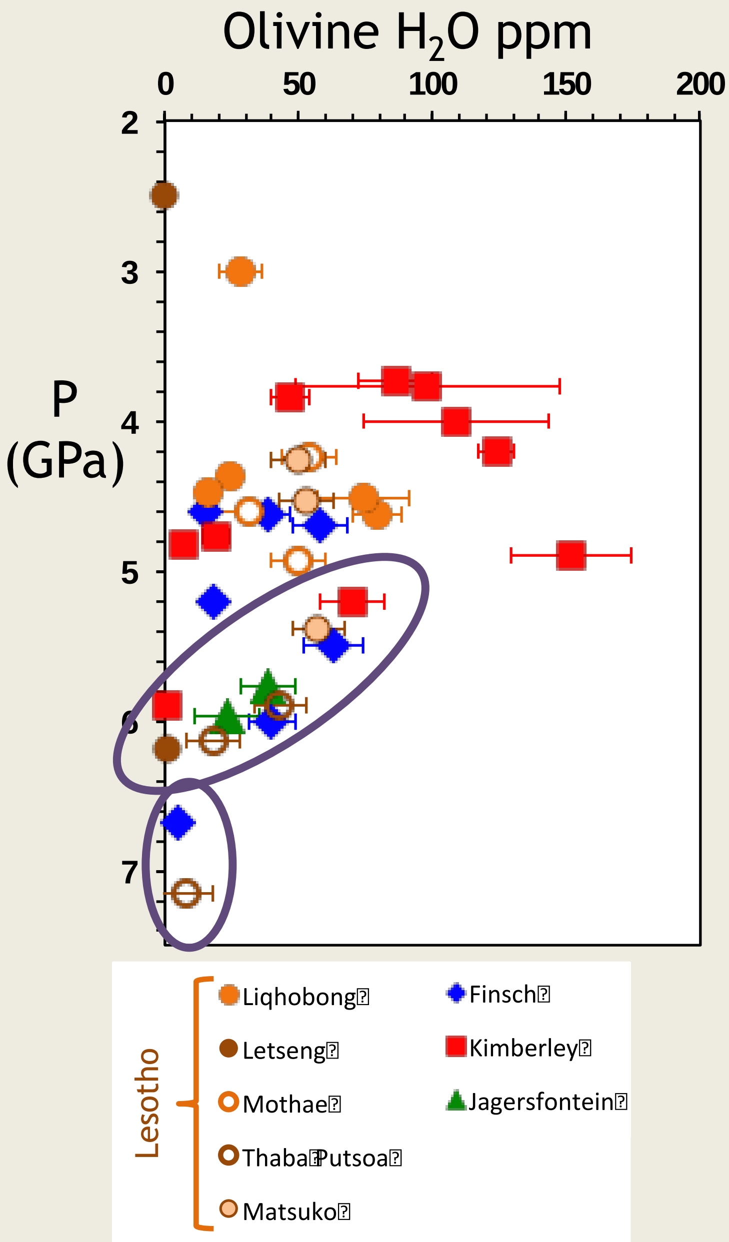




- Viscosity ratio between LAB and asthenosphere: 20 to 3000
- Viscosity ratio necessary for LAB to resist asthenosphere erosion: 10

(Lenardic et al 99-03, Sleep 03, O'Neill et al 08)

Water in the continental lithosphere: cratons



Peslier et al 2010

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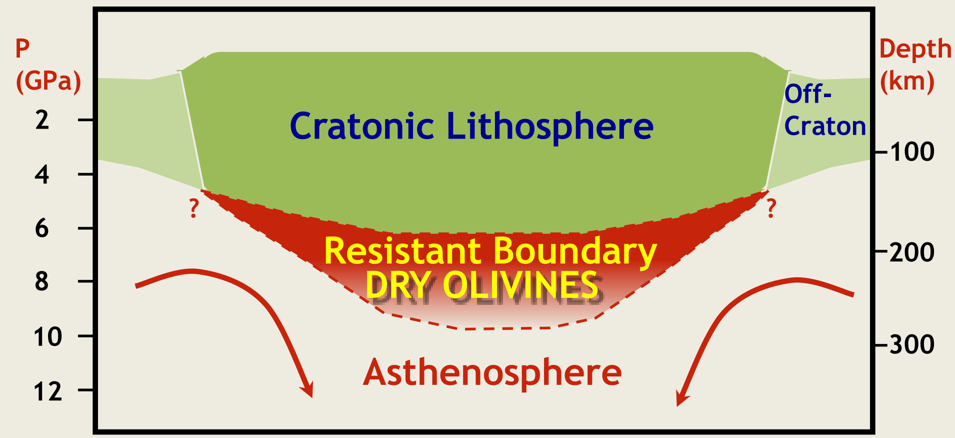

Water in the continental lithosphere: cratons

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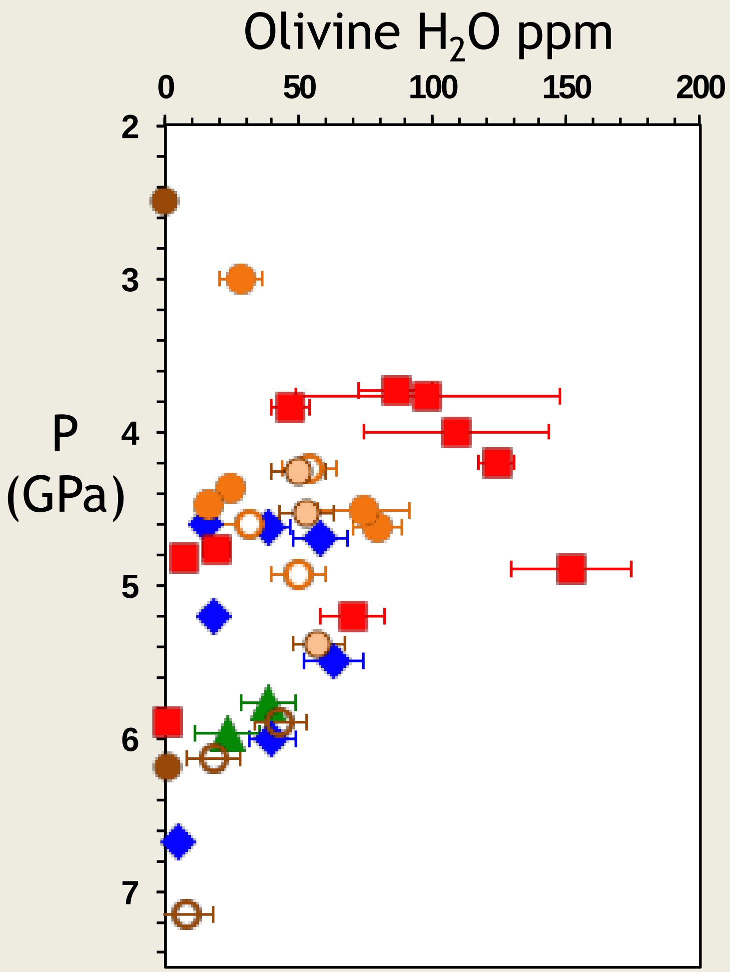

Other cratons?

Water in the continental lithosphere: cratons

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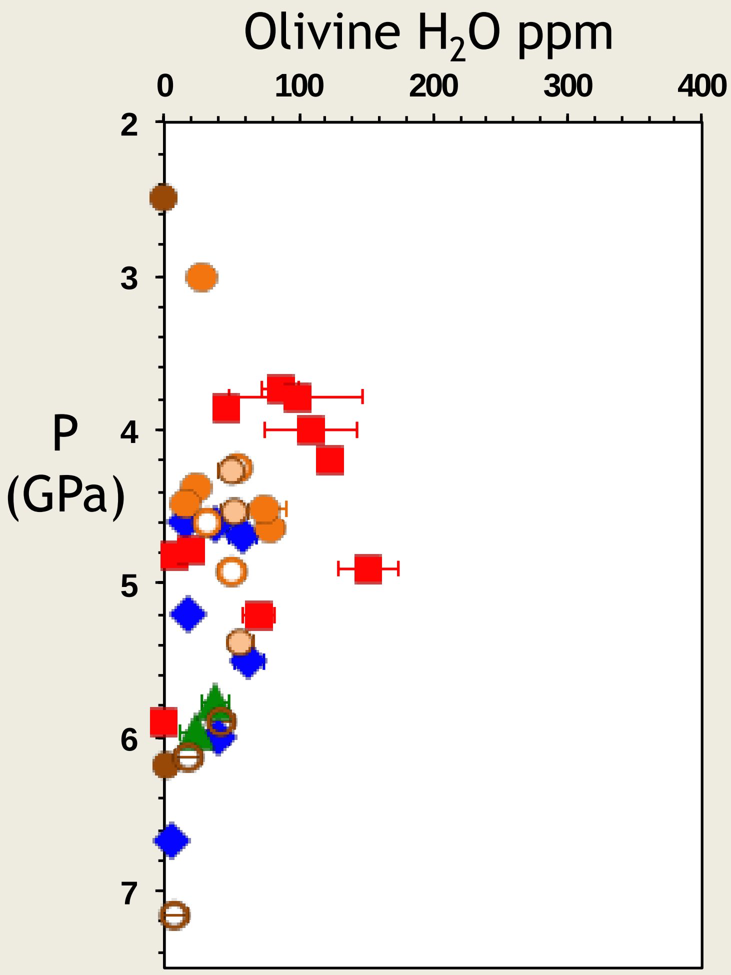
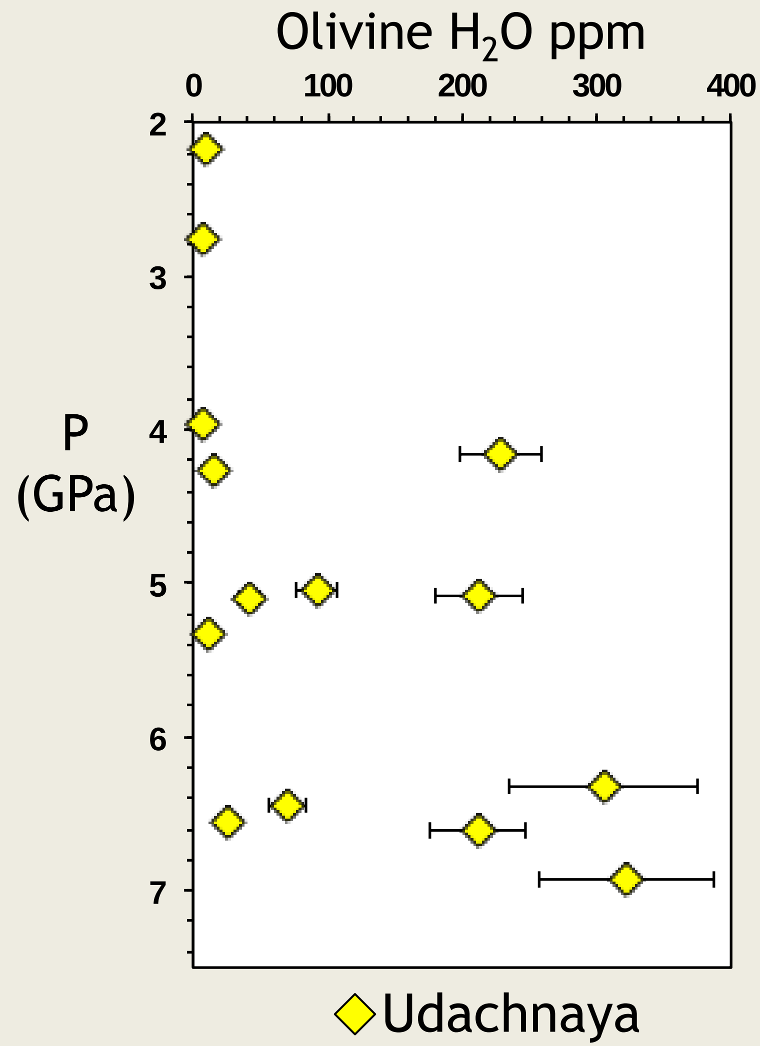


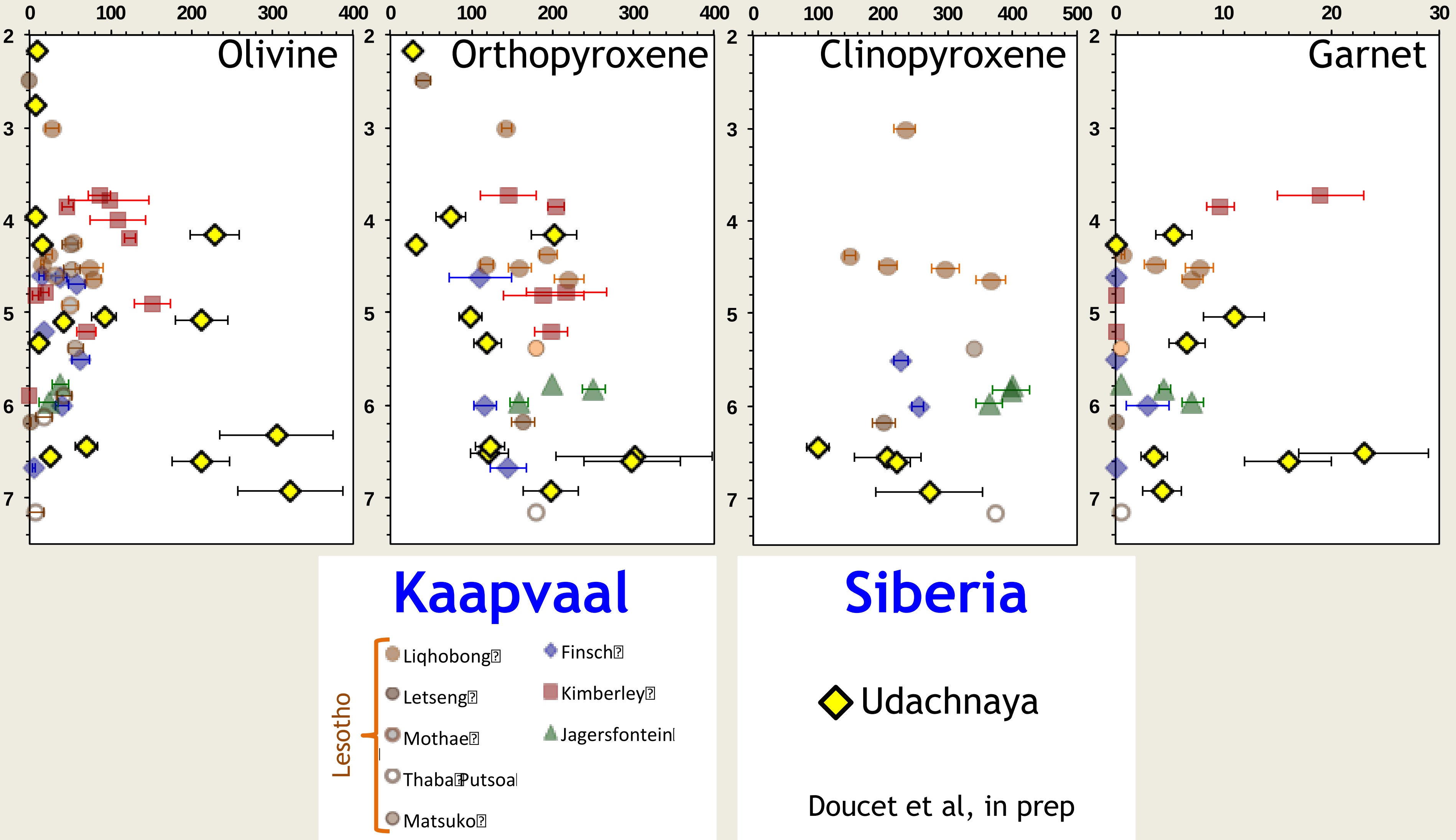
Siberia



Doucet et al, in prep

Water in the continental lithosphere: cratons

H_2O (ppm) vs P (GPa)



Water in the continental lithosphere: cratons

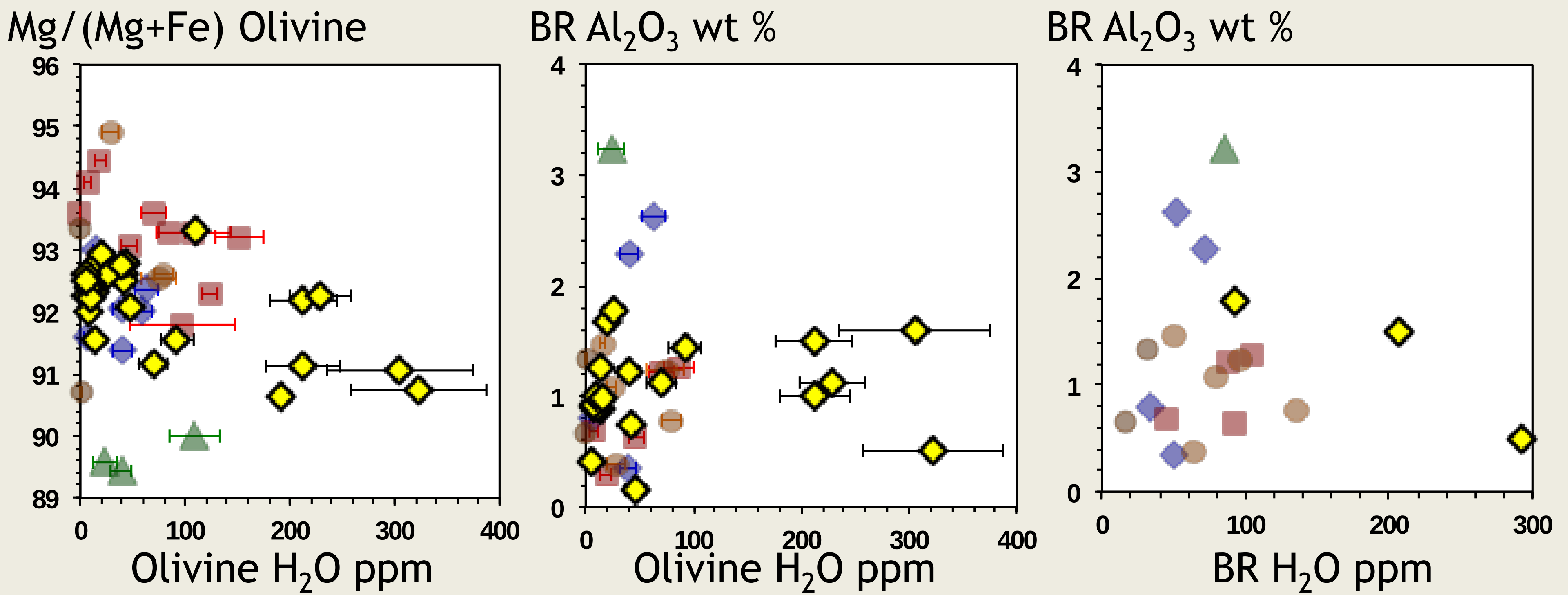
What controls [H_2O]?

- Partial melting?

- Metasomatism/refertilization?

Water in the continental lithosphere: cratons

Partial melting?



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Lesotho: Liqhobong, Letseng, Mothae, Thaba Putsoa, Matsuko

Finsch

Kimberley

Jagersfontein

Siberia

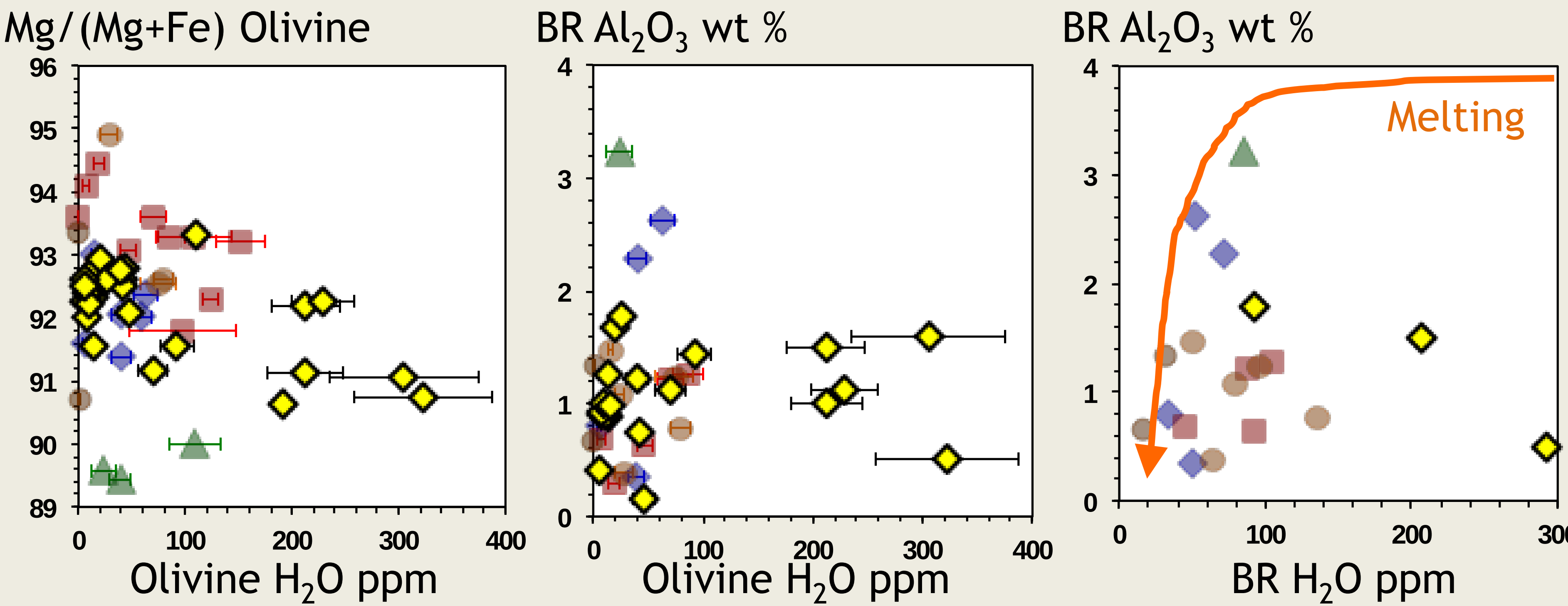
Udachnaya

Doucet et al, in prep

Matsyuk & Langer 2004

Water in the continental lithosphere: cratons

Partial melting?



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Lesotho:
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- Thaba Putsoa
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- Finsch
- Kimberley
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Siberia

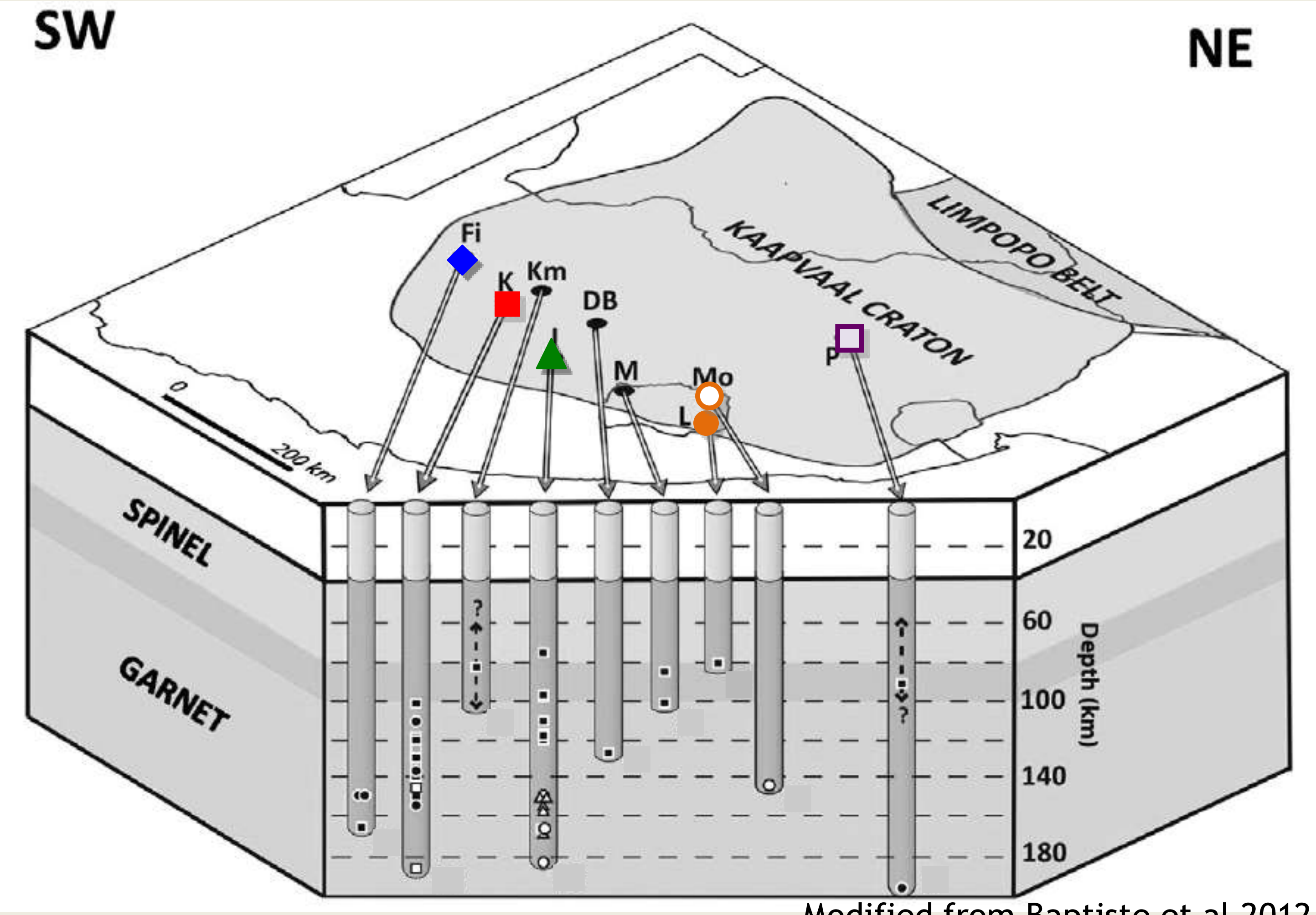
Udachnaya

Doucet et al, in prep
Matsyuk & Langer 2004

- No correlation with indices of melting
- Too high water contents

Water in the continental lithosphere: cratons

Metasomatism/refertilization?



Modified from Baptiste et al 2012

- Each kimberlite pipe samples a region of the mantle with a unique metasomatic history (can be multiple events)

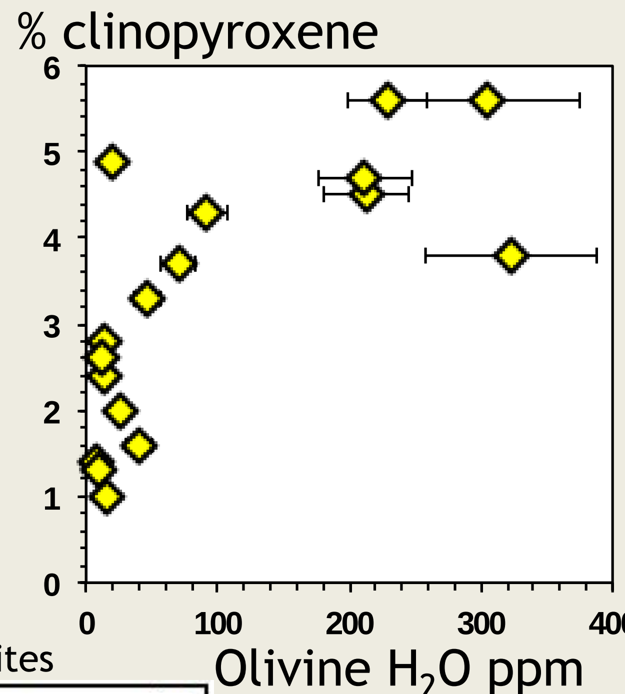
Water in the continental lithosphere: cratons

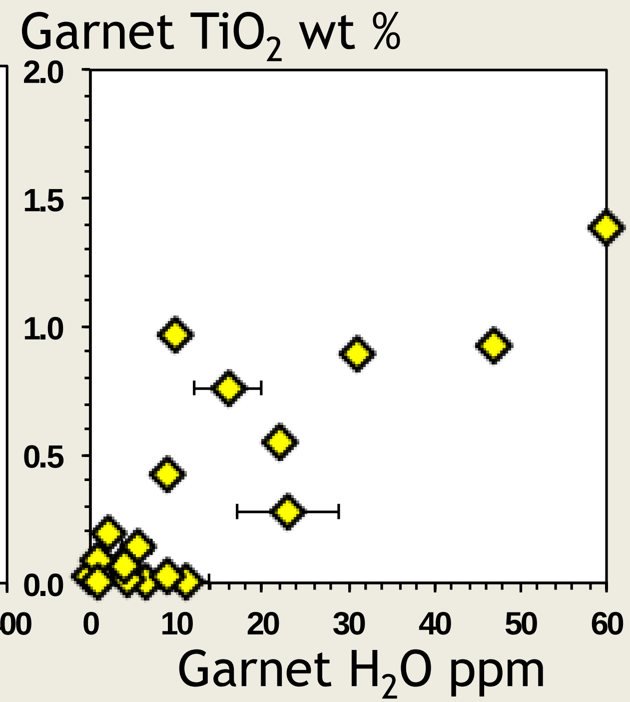
Metasomatism/refertilization?

Siberia

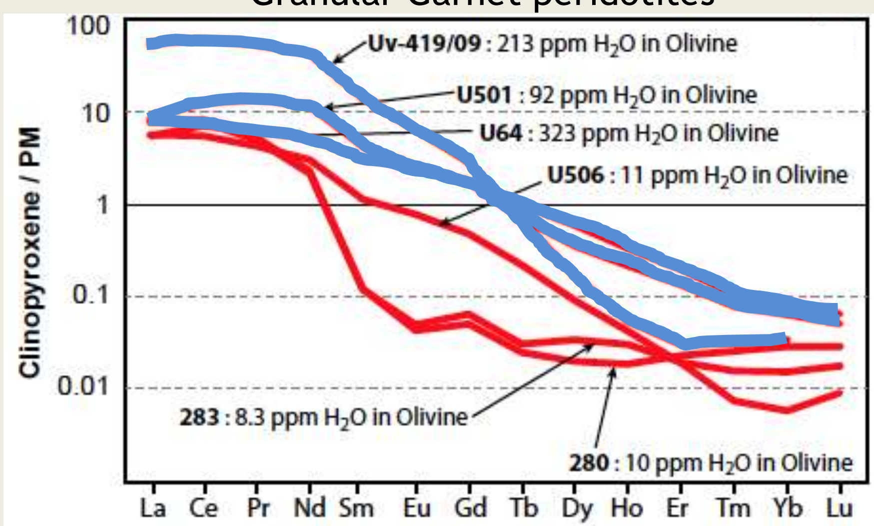
◆ Udachnaya

Doucet et al, in prep
Matsyuk & Langer 2004
Matsyuk et al 1998



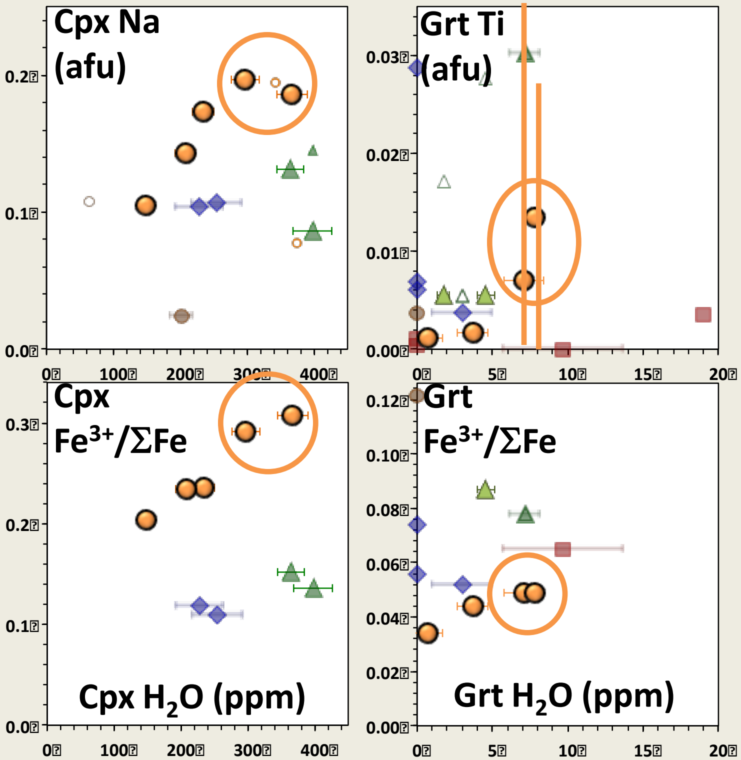


Granular Garnet peridotites



- Correlation with metasomatic indices
- Water addition

Water in the continental lithosphere: cratons

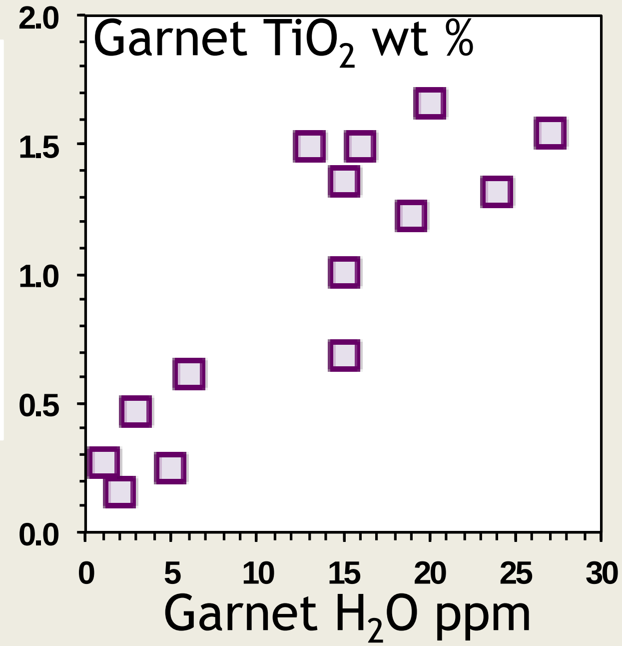


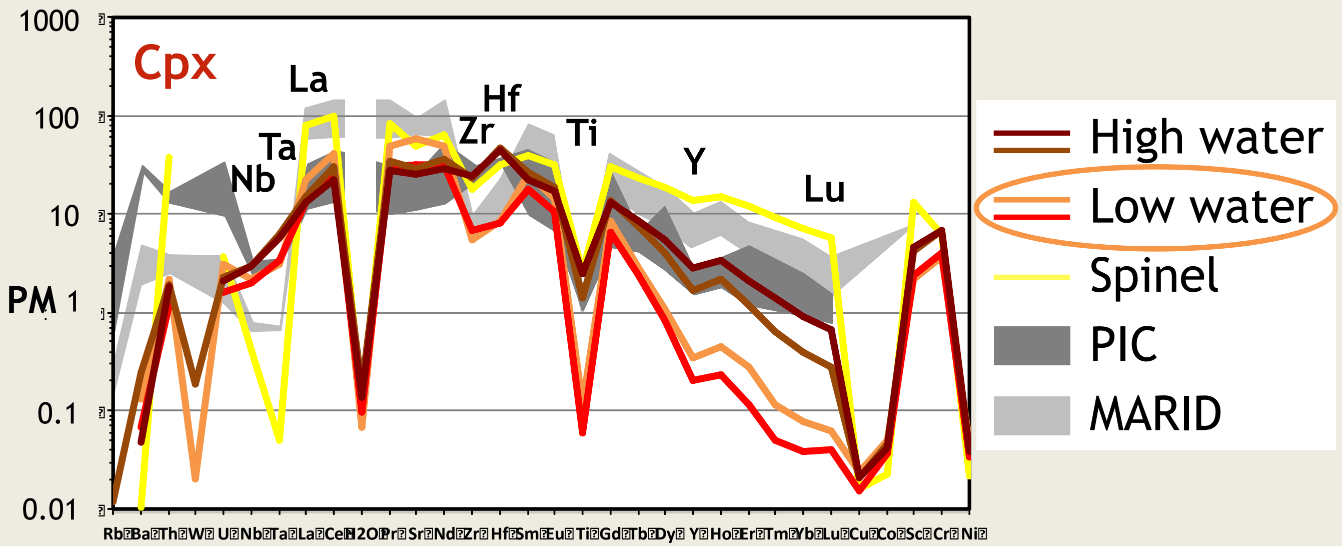
Metasomatism?

Kaapvaal

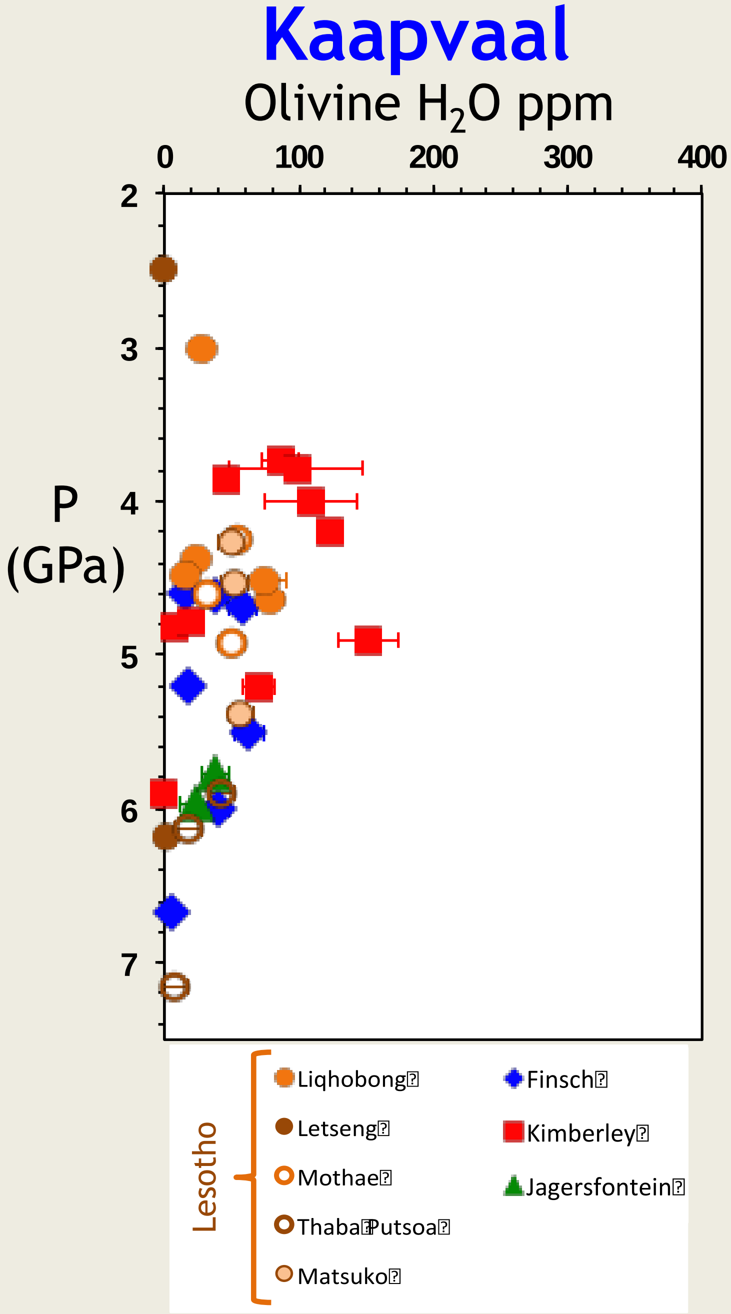
Liqhobong
Peslier et al 2012

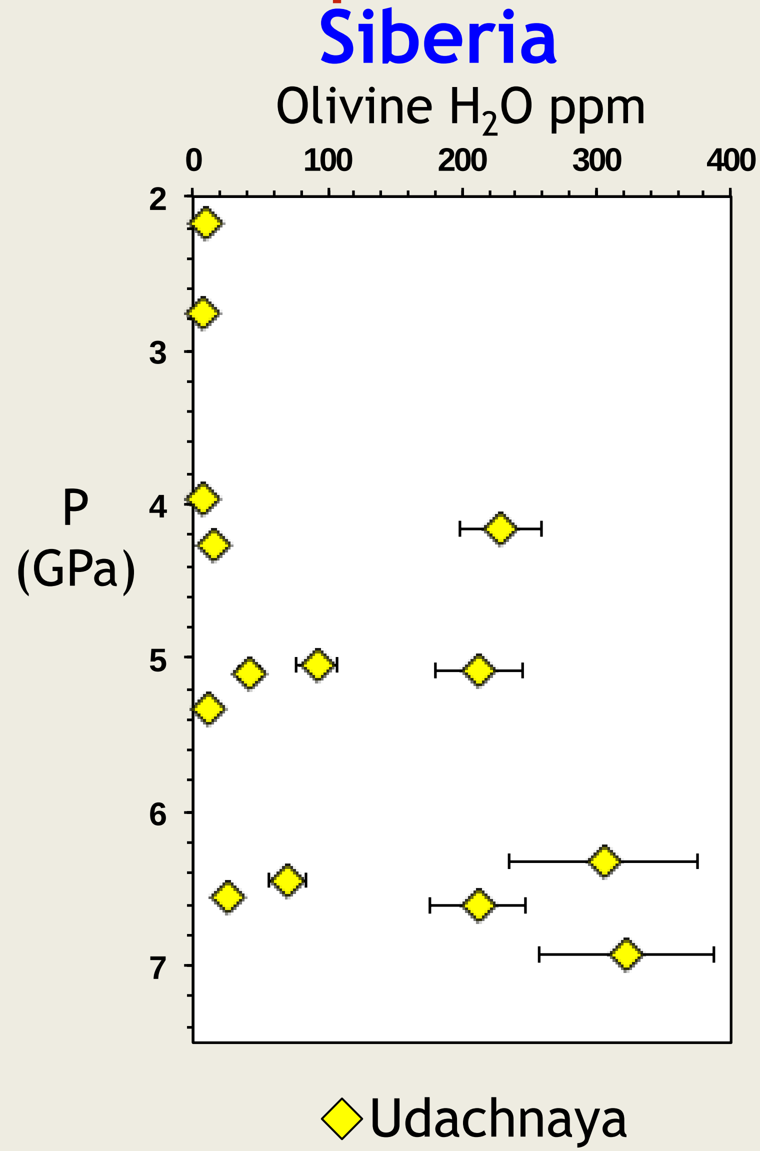
Premier
Bell et al 1992





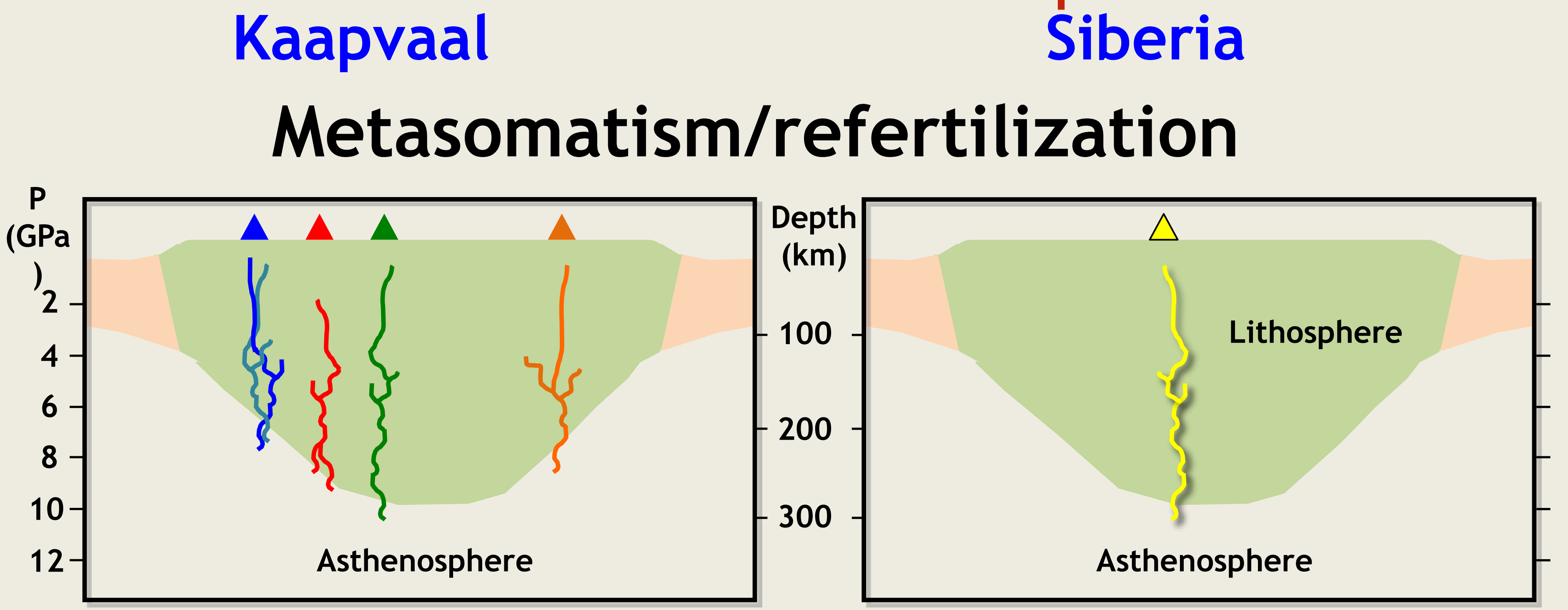
Water in the continental lithosphere: cratons





Doucet et al, in prep

Water in the continental lithosphere: cratons

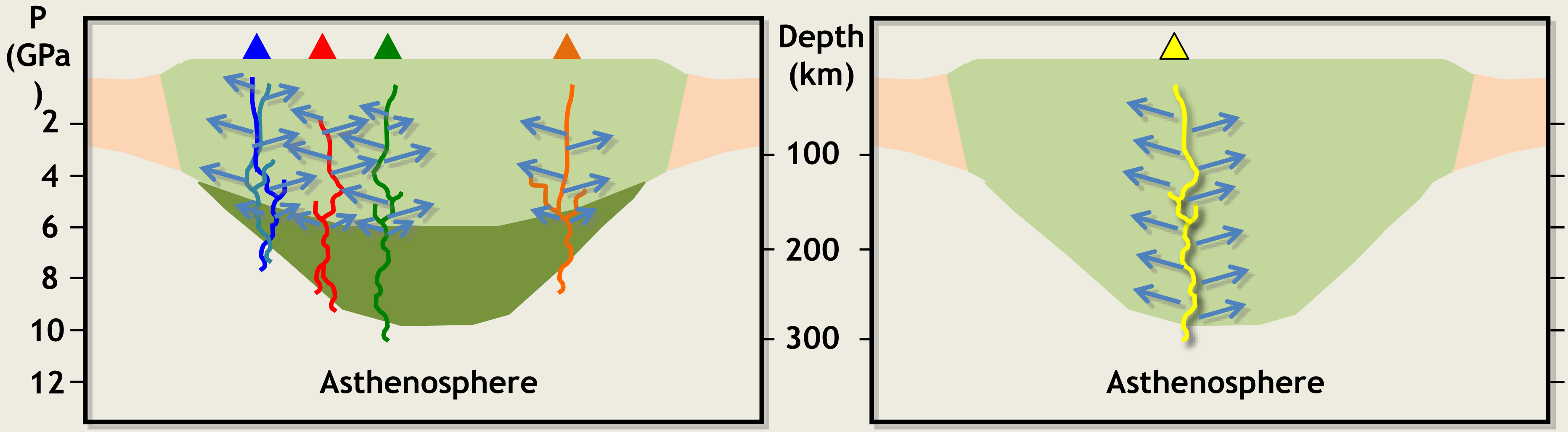


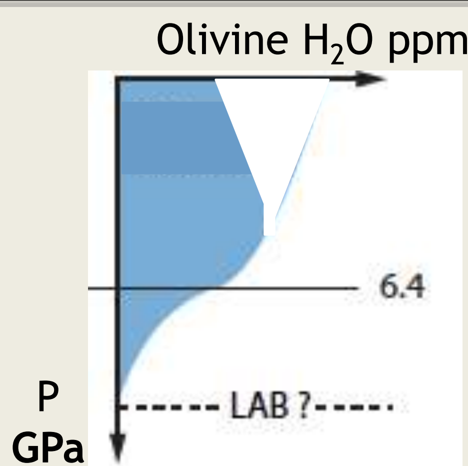
- Water brought in by melts/fluids along veins/conduits/shear zones

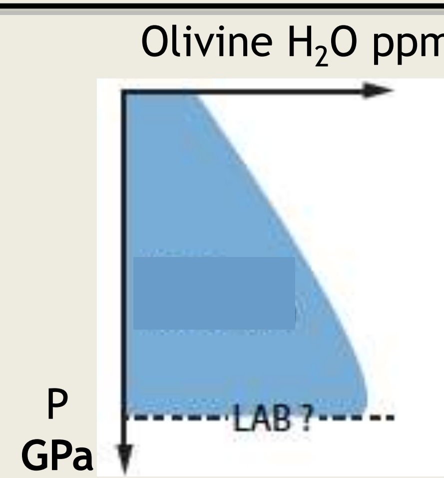
Water in the continental lithosphere: cratons

Kaapvaal | Siberia

Metasomatism/refertilization







- Water brought in by melts/fluids along veins/conduits/shear zones

Water in the continental lithosphere: cratons

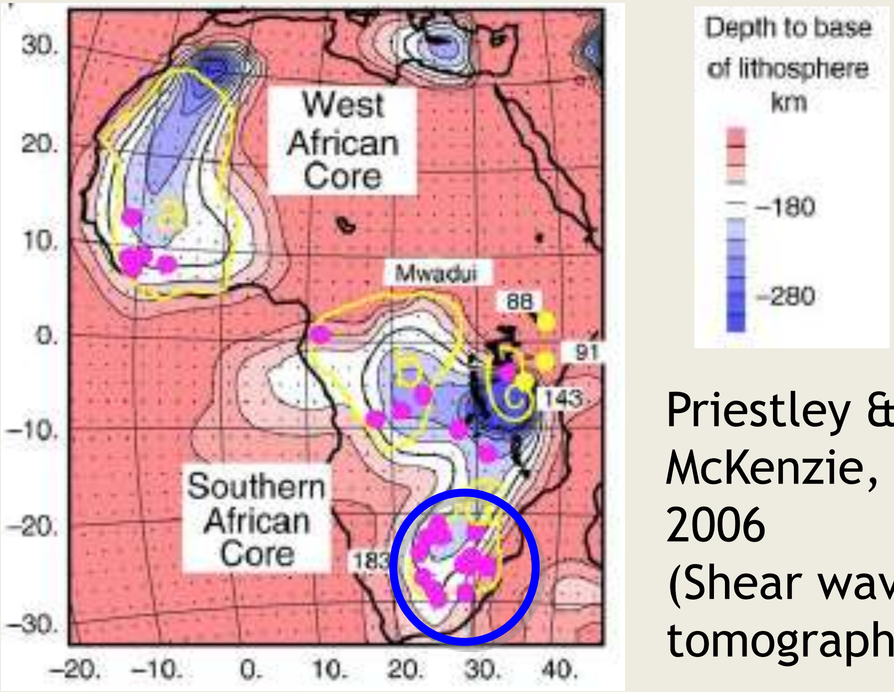
Similarities

Kaapvaal

- Oldest crust & mantle rocks: > 3 Ga
- Kimberlites: 80-90 Ma, Finsch 119 Ma
- Metasomatism:

  - some Si enrichments, kimberlite parent melts, hydrous silicic melts/fluids (Phlog), ultramafic melts/fluids

  - Archean to Mesozoic
- Depth LAB:



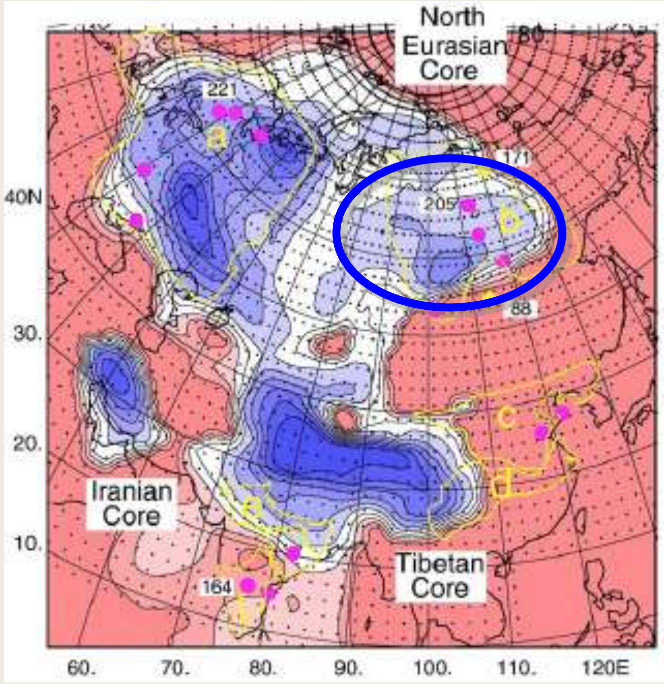
Priestley & McKenzie, 2006 (Shear wave tomography)

Siberia

- Oldest crust & mantle rocks: > 3 Ga
- Udachnaya kimberlite: 360 Ma
- Metasomatism:

  - some Si enrichments, kimberlite parent melts

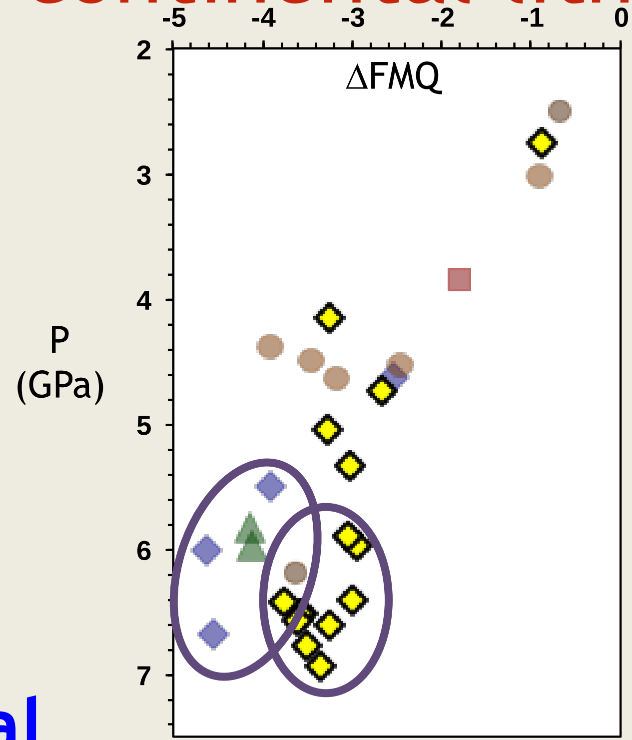
  - Age?
- Depth LAB:



Water in the continental lithosphere: cratons

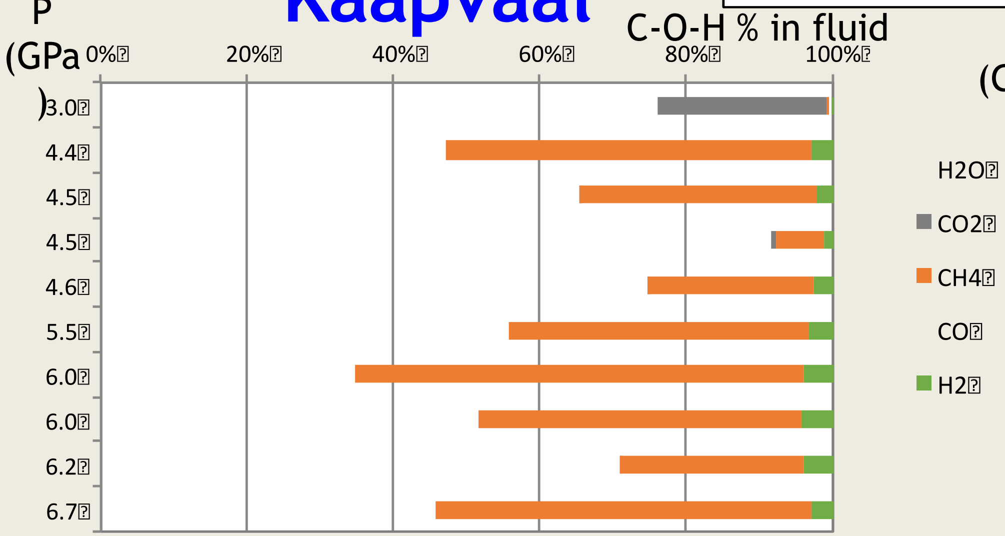
Differences

- Oxygen fugacity

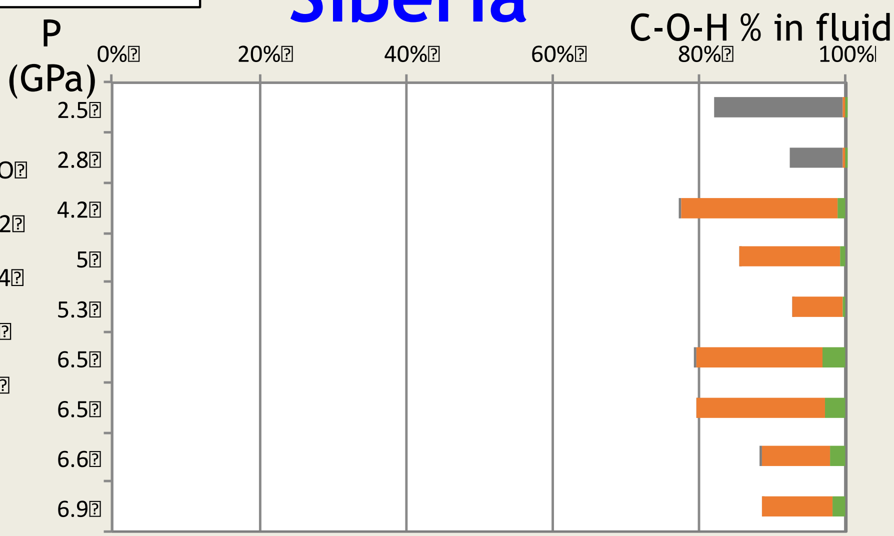


From Mössbauer data from Woodland & Koch 2003, Lazarov et al 2009, Gondcharov et al 2012
(using Gudmundsson & Wood 1995, *not* Stagno et al 2013)

Kaapvaal



Siberia

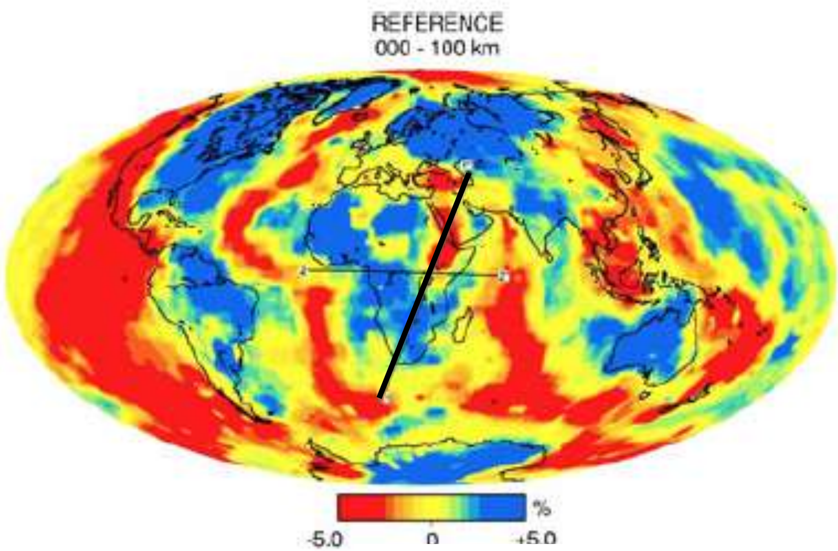


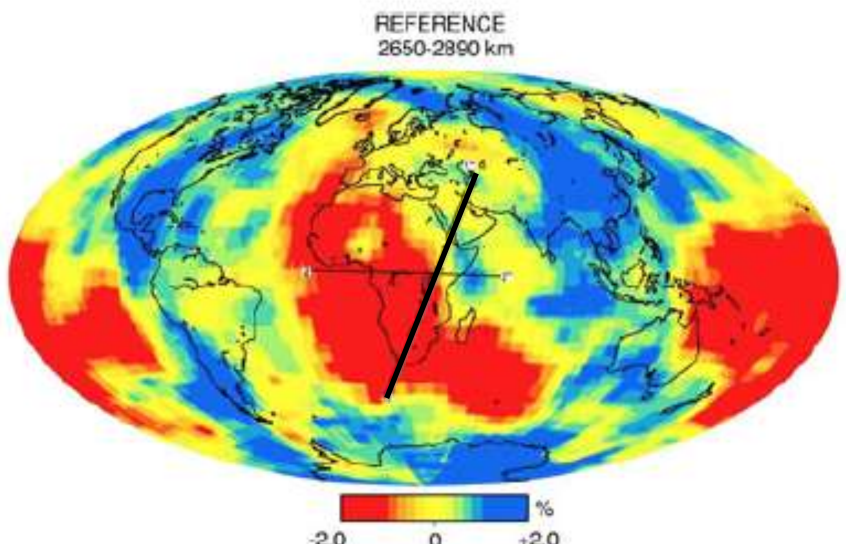
Doucet et al, in prep

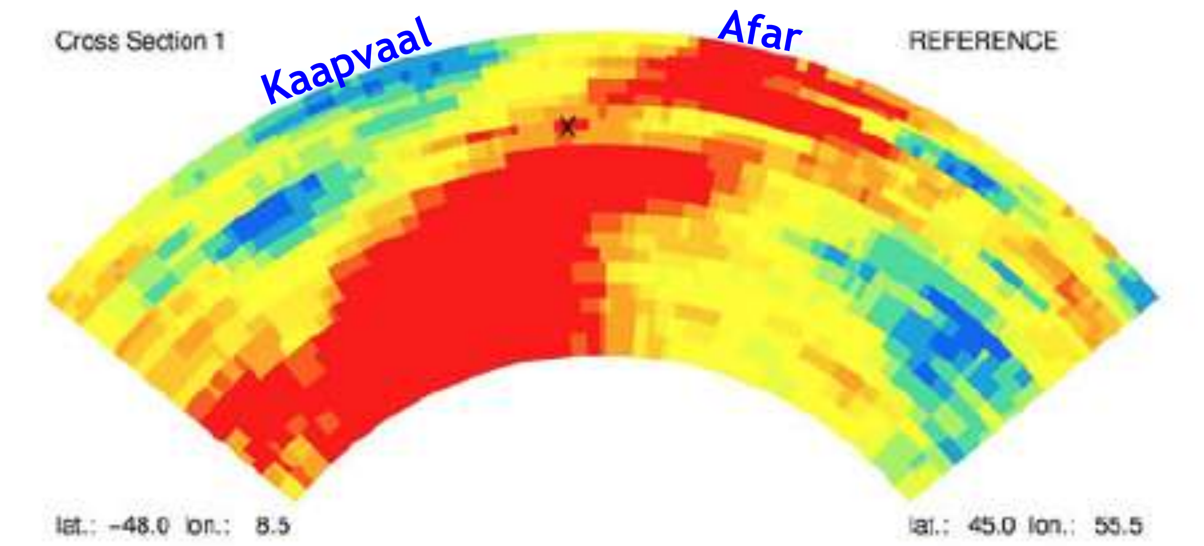
Water in the continental lithosphere: cratons

Differences

Large slow shear velocity provinces (LLSVP)







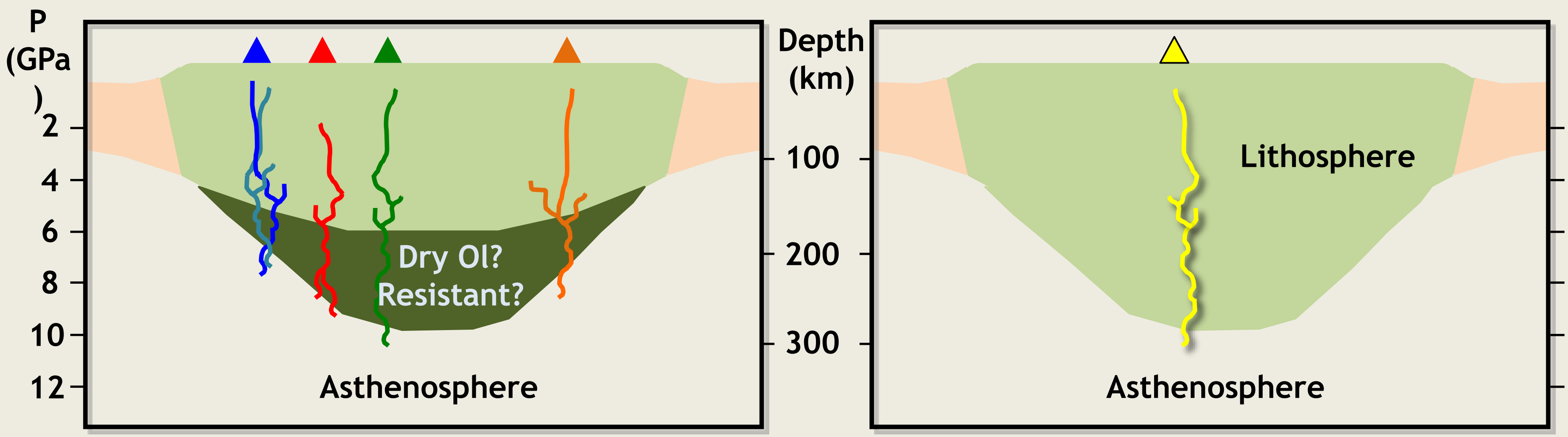
Ritsema et al 1999

Brandt 2012

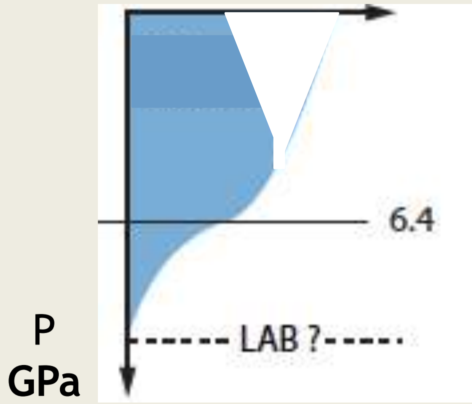
Water in the continental lithosphere: cratons

Kaapvaal / Siberia

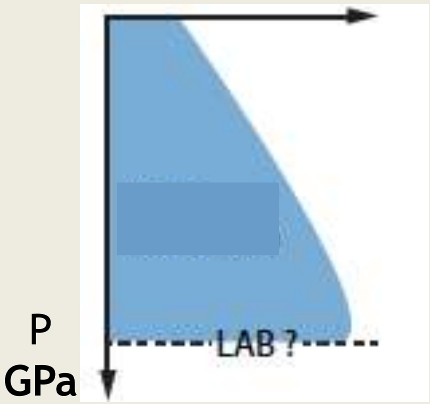
Water distribution and rheology



Olivine H_2O ppm

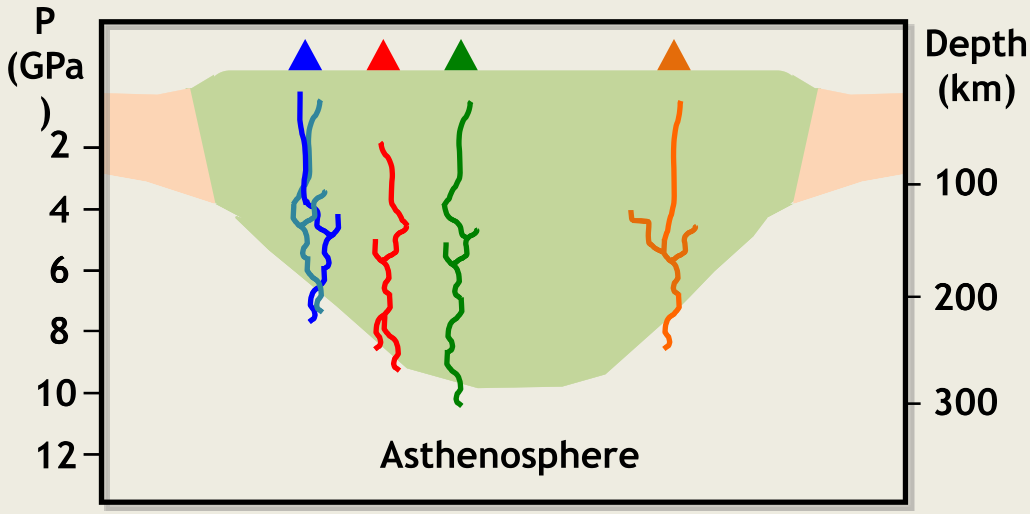


Olivine H_2O ppm



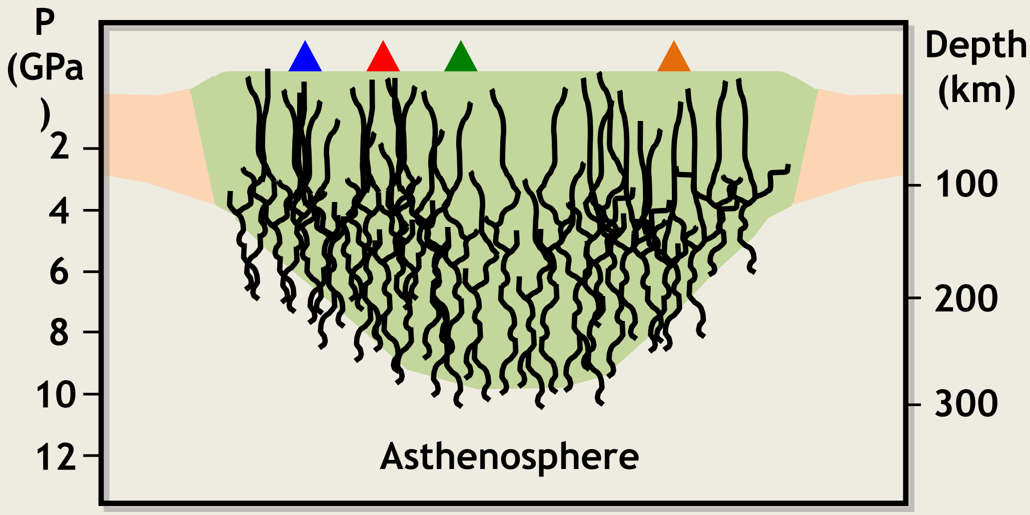
Water in the continental lithosphere: cratons

Water distribution and rheology



Scenario 1:

- Xenoliths not representative of whole mantle lithosphere
- Over-representation of metasomatized water-rich perid near melt/fluid channels
- Overall mantle lithos dry
- Water has a role in cratonic root long term longevity



Scenario 2:

- Xenoliths representative of whole mantle lithosphere
- Water has no role in cratonic root long term longevity
- Fei et al. (Nature 2013) may be right, no large effect of water on olivine rheology

Water in the continental lithosphere: cratons

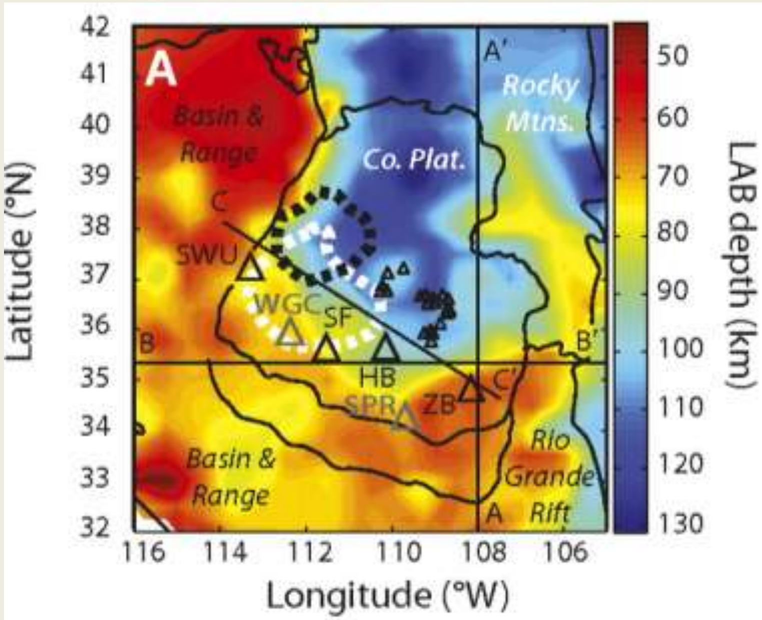
Water and cratonic root erosion

- Could cratonic root erosion be caused by water addition?

Water in the continental lithosphere: cratons

Water and cratonic root erosion

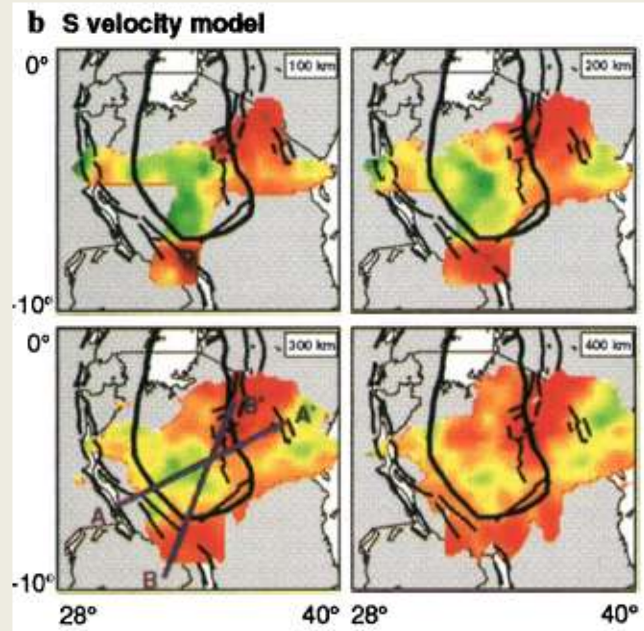
Colorado Plateau

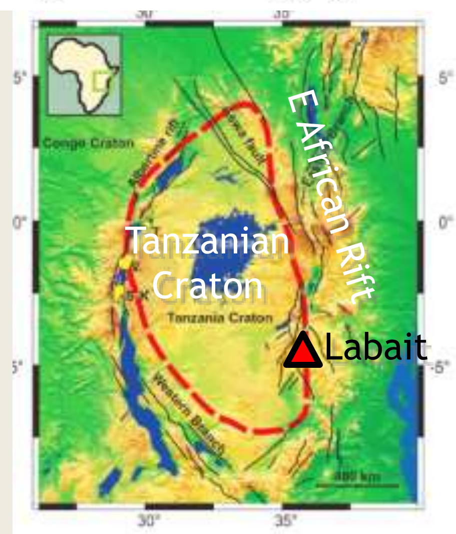


From Reid et al 2012 after Levander et al 2011

Max extent Farallon subduction plate after Bird 1984

Tanzanian craton



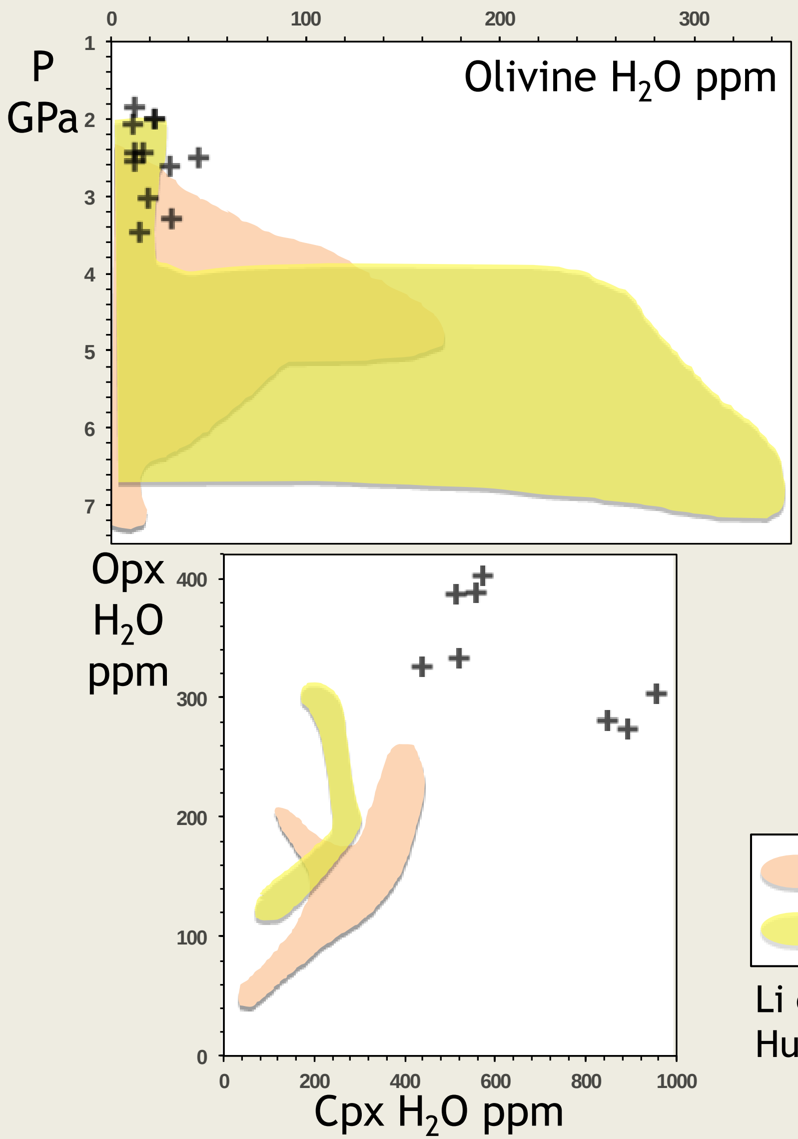


From Ritsema et al 1998 and Wölbern et al 2012

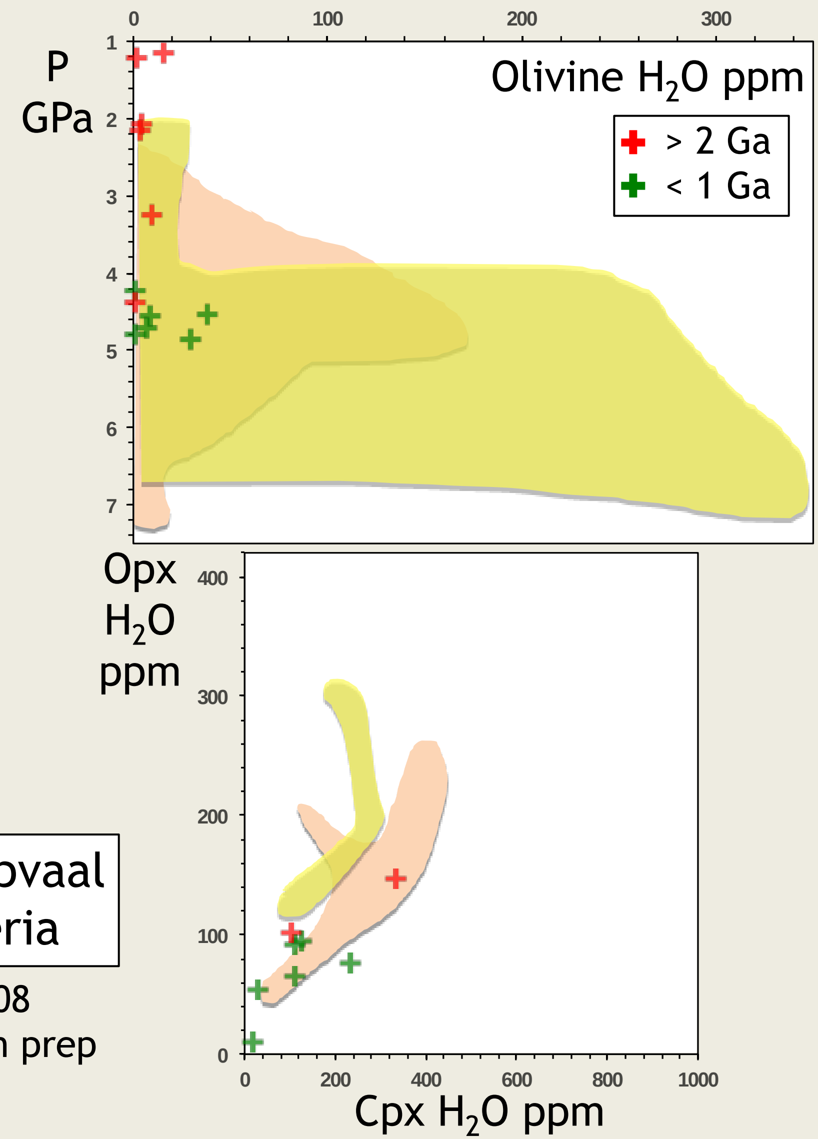
Water in the continental lithosphere: cratons

Water and cratonic root erosion

Colorado Plateau



Tanzanian craton



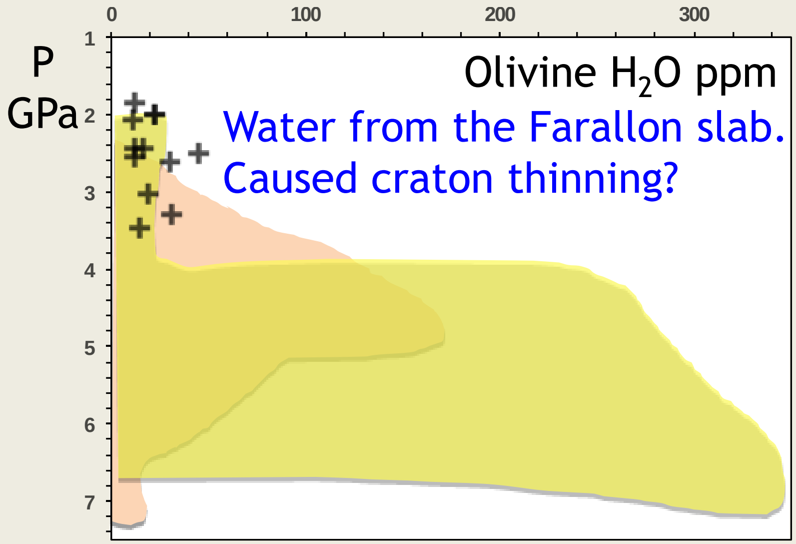
Kaapvaal
Siberia

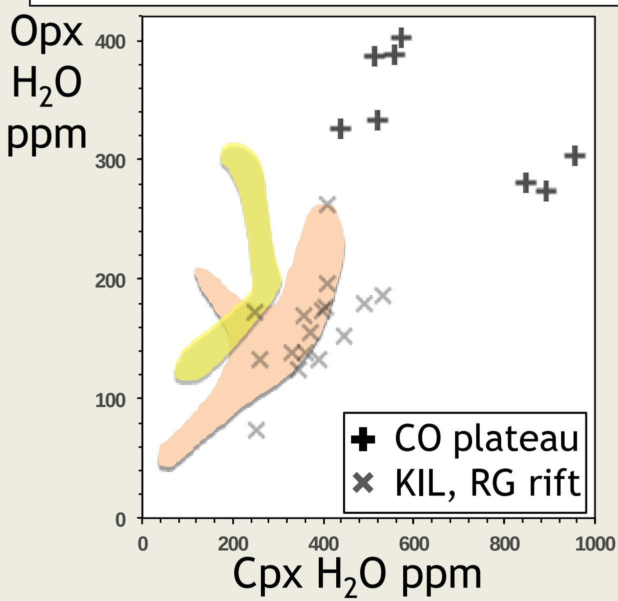
Li et al 2008
Hui et al in prep

Water in the continental lithosphere: cratons

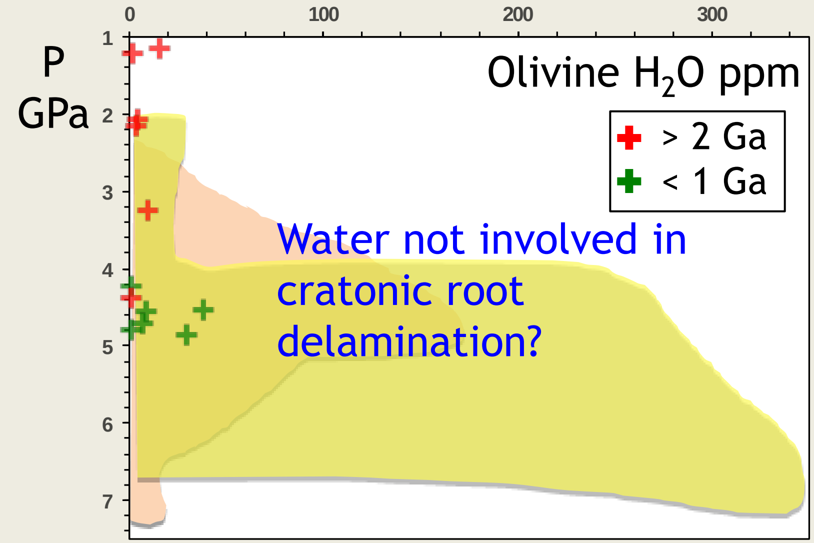
Water and cratonic root erosion

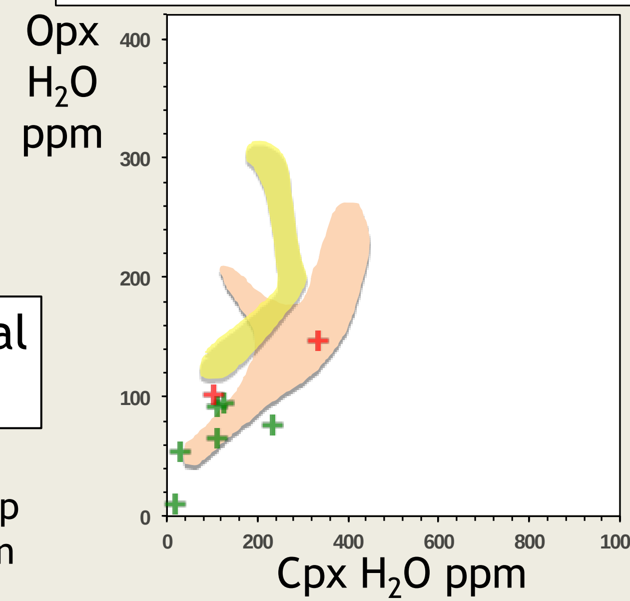
Colorado Plateau





Tanzanian craton





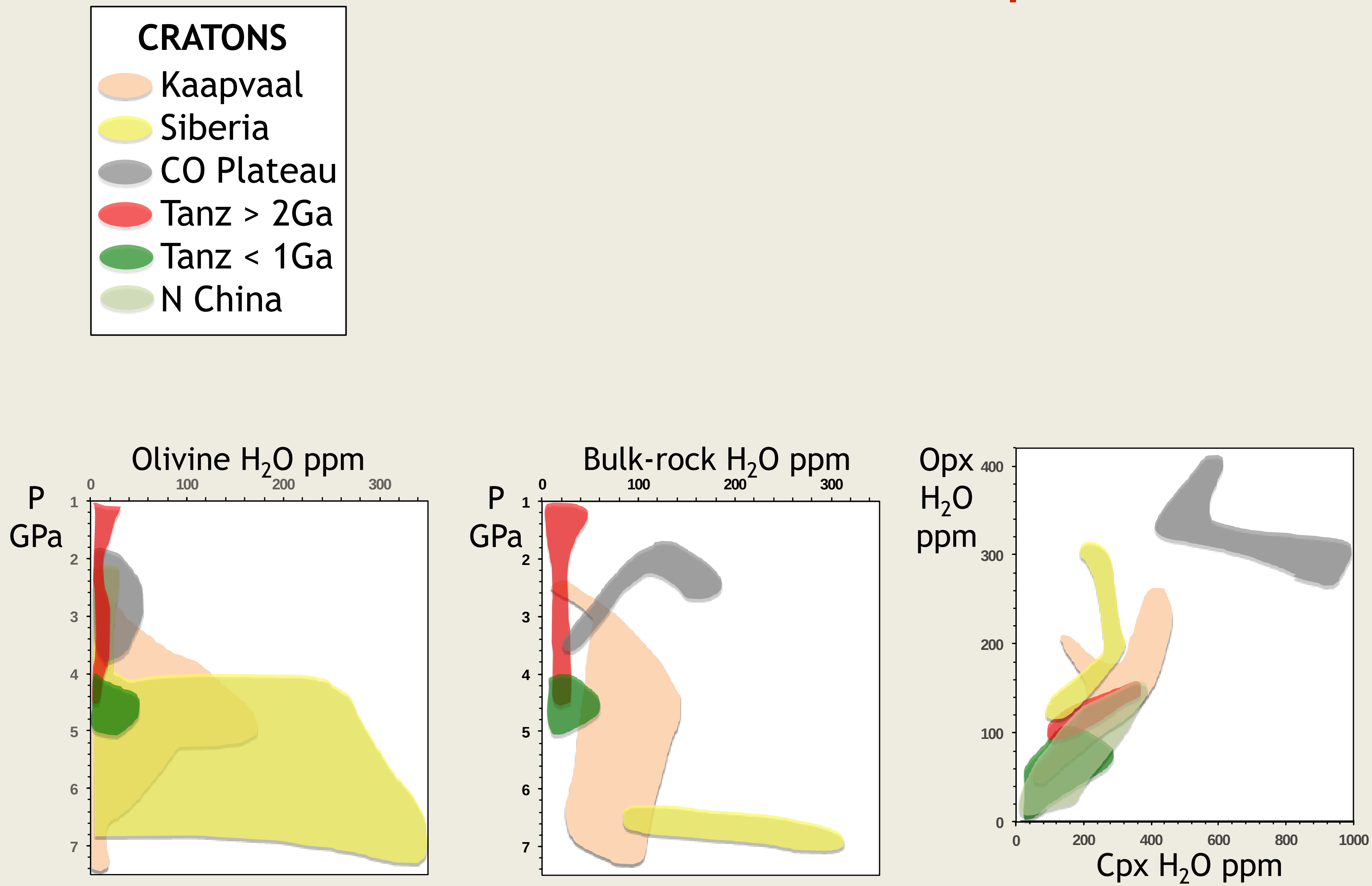
Li et al 2008
Hui et al in prep
Schaffer et al in prep

Origin and distribution of water contents in continental and oceanic lithospheric mantle

Talk outline

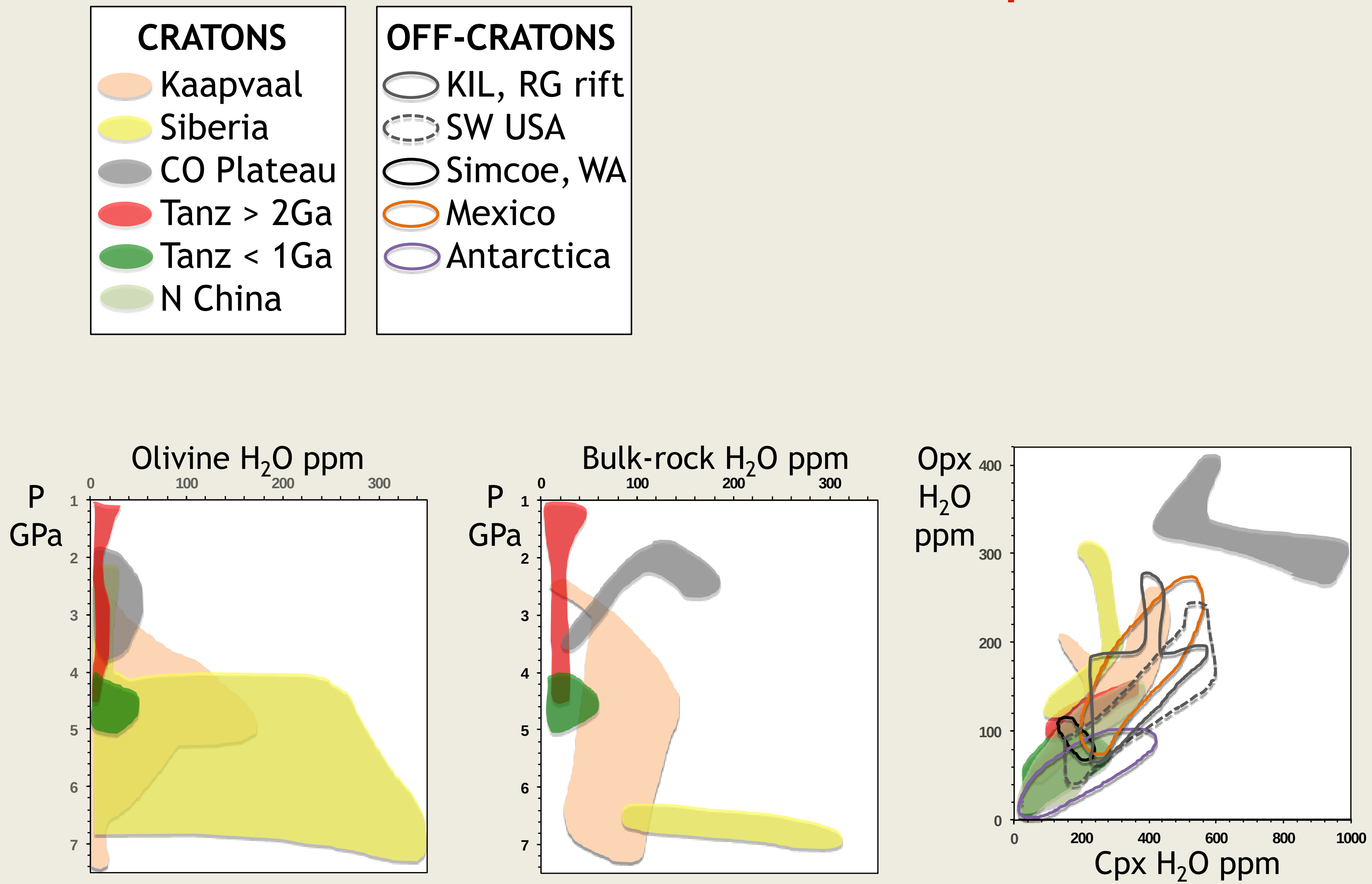
- Importance of “Water” in the mantle
- Samples and techniques
- Water in the oceanic lithosphere
- Water in the cratonic lithosphere
- Global dataset comparison
- Conclusion

Water in the mantle lithosphere



Peslier et al 2010, 2012; Kurozawa et al 1997; Grant et al 2007; Li et al 2008; Baptiste et al 2012; Xia group 2004-2013; Doucet et al in prep; Hui et al in prep

Water in the mantle lithosphere



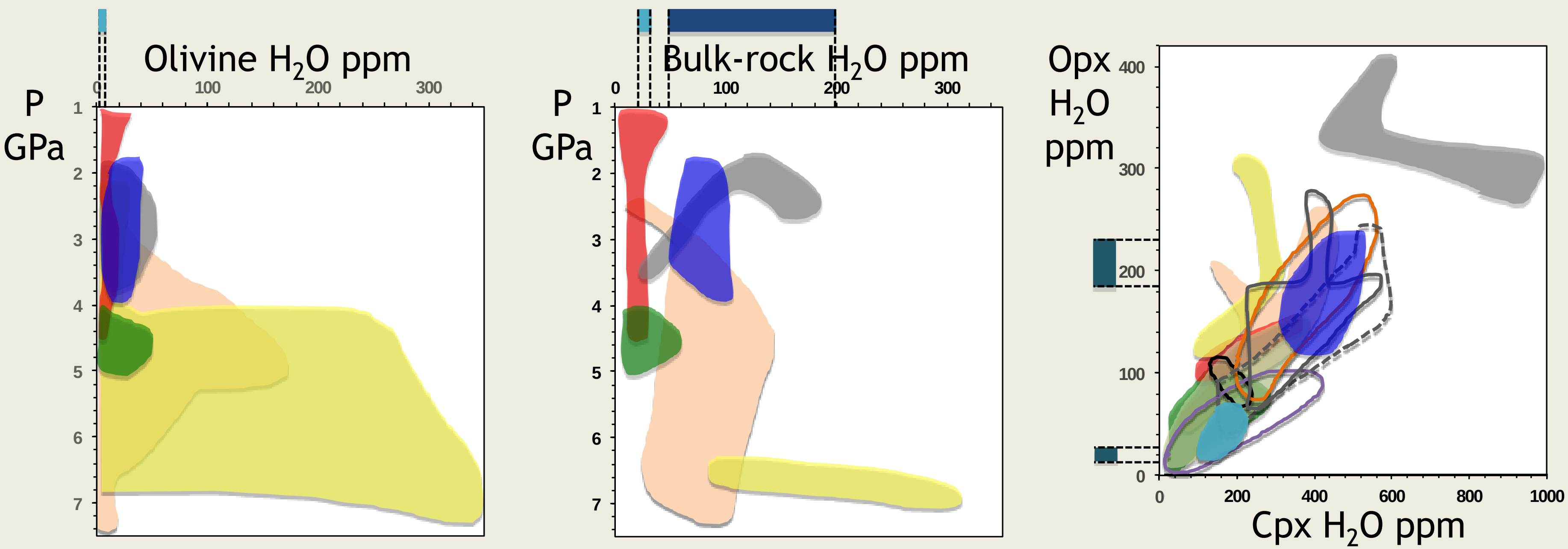
Peslier et al 2002-2012; Kurozawa et al 1997; Grant et al 2007; Li et al 2008; Bonadiman et al 2009; Baptiste et al 2012; Xia group 2004-2013; Doucet et al in prep; Hui et al in prep

Water in the mantle lithosphere

CRATONS
- Kaapvaal
- Siberia
- CO Plateau
- Tanz > 2Ga
- Tanz < 1Ga
- N China

OFF-CRATON
- KIL, RG rift
- SW USA
- Simcoe, WA
- Mexico
- Antarctica

OCEANIC
- SLC Hawaii
- Gakkel R
- Atlantic
- MORB source



Peslier et al 2002-2013; Kurozawa et al 1997; Grant et al 2007; Li et al 2008; Bonadiman et al 2009; Gose et al 2009; Schmädicke et al 2011; Baptiste et al 2012; Xia group 2004-2013; Doucet et al in prep; Hui et al in prep

Origin and distribution of water contents in continental and oceanic lithospheric mantle

Talk outline

- Importance of “Water” in the mantle
- Samples and techniques
- Water in the oceanic lithosphere
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- Conclusion

Conclusions

- Water in the oceanic mantle lithosphere
  - Not enough data
  - Heterogeneous [H_2O]
  - Abyssal peridotites:
    - some [H_2O] controlled by melting?
    - some [H_2O] from metasomatism?
  - Hawaii: [H_2O] result from mantle-melt interaction
- Water in the cratonic lithosphere
  - [H_2O] controlled by metasomatism/refertilization, fO_2
  - Kaapvaal: dry Ol at > 6 GPa
  - Siberia: dry and wet Ol at > 6 GPa
- [H_2O] similar in continental and oceanic mantle: 10-150 ppm H_2O
  - Wet (>150): Siberian craton (cause?), CO plateau (Farallon slab?)
  - Dry (<40): some abyssal perid, Tanzanian craton near E African rift
- Data challenge the role of water in the stabilization and destruction of cratons (rheology of olivine)

Thank you for your time!

Water in the upper mantle at Fall AGU

- Siberian craton: Luc Doucet

  T23A-2563 *Poster* Tuesday pm

- Hawaii pyroxenites: Michael Bizimis

  V32A-03 *Talk* Wednesday at 10:50 am

- Rio Grande rift: Lillian Schaffer

  V33A-2724 *Poster* Wednesday pm