INTERNATIONAL SPACE SCIENCE INSTITUTE

Earth total water content

Anne Peslier

Jacobs, NASA-JSC, Houston TX, USA

NASA

ARES ASTROMATERIALS RESEARCH & EXPLORATION SCIENCE

JACOBS

Science Department

Earth total water content

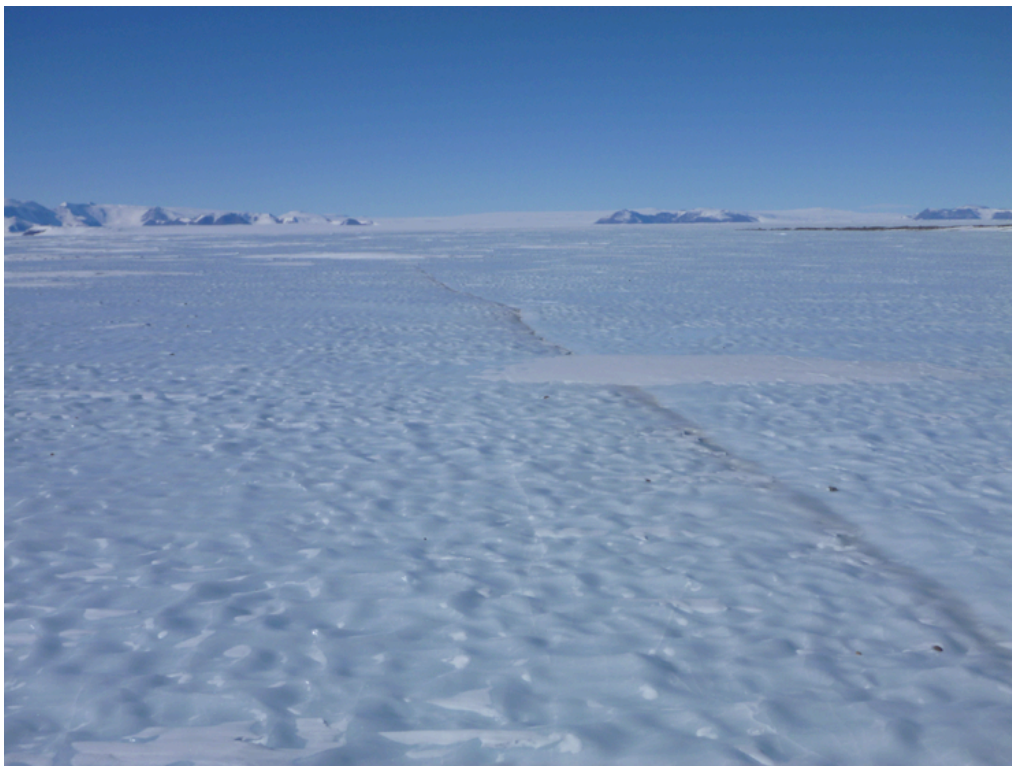
Anne Peslier

Jacobs, NASA-JSC, Houston TX, USA

David **Bell** (ASU, USA; NMMU, South Africa),
Michael **Bizimis** (USC, USA),
Alan **Brandon** (U Houston, USA),
Luc **Doucet** (ULB, Belgium),
McKensie **Gelber** (U Houston, USA),
Alesksei **Goncharov** (St Petersburg, Russia),
Eric **Hellebrand** (U Hawaii, USA),
Hejiu **Hui** (Nanjing U, USA),
Dmitri **Ionov** (U Montpellier, France),
Marina **Lazarov** (U Hannover, Germany),
Cin-Ty **Lee** (Rice U, USA),
Zheng-Xue **Li** (oil industry, Houston, USA),
Mark **Matney** (NASA-JSC, Houston, USA),
Roberta **Rudnick** (U Maryland, USA),
Lillian **Schaffer** (U Houston, USA),
Jon **Snow** (U Houston, USA),
Larry **Taylor** (U Tennessee)
Alan **Woodland** (U Frankfurt, Germany)

Earth total water content

- ✧ (Water in the exosphere)
- ✧ Water in the crust
- ✧ **Water in the mantle**
- ✧ Water in the core



Glacier in the Miller range, Antarctica

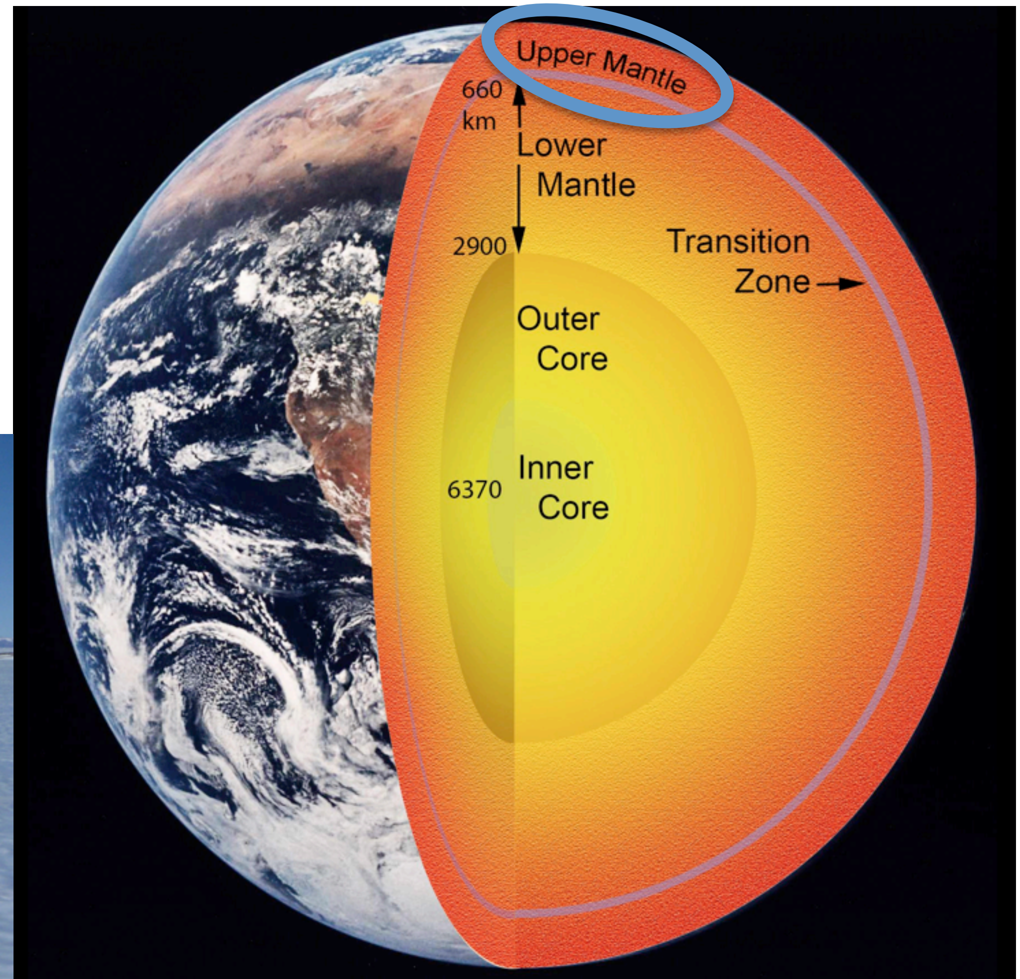


Image Credit: Japan Times

Earth total water content

- ✧ **Type of data**
- ✧ Water in the mantle
  - ✧ Definition
  - ✧ Importance
  - ✧ Distribution & controls
    - ✧ H diffusion
    - ✧ Water in the continental mantle lithosphere
    - ✧ Water in the lithosphere
    - ✧ Water in the oceanic lithosphere
- ✧ The big picture
  - ✧ Water in the Earth layers
  - ✧ Fluxes
- ✧ Comparison with other differentiated planetary bodies

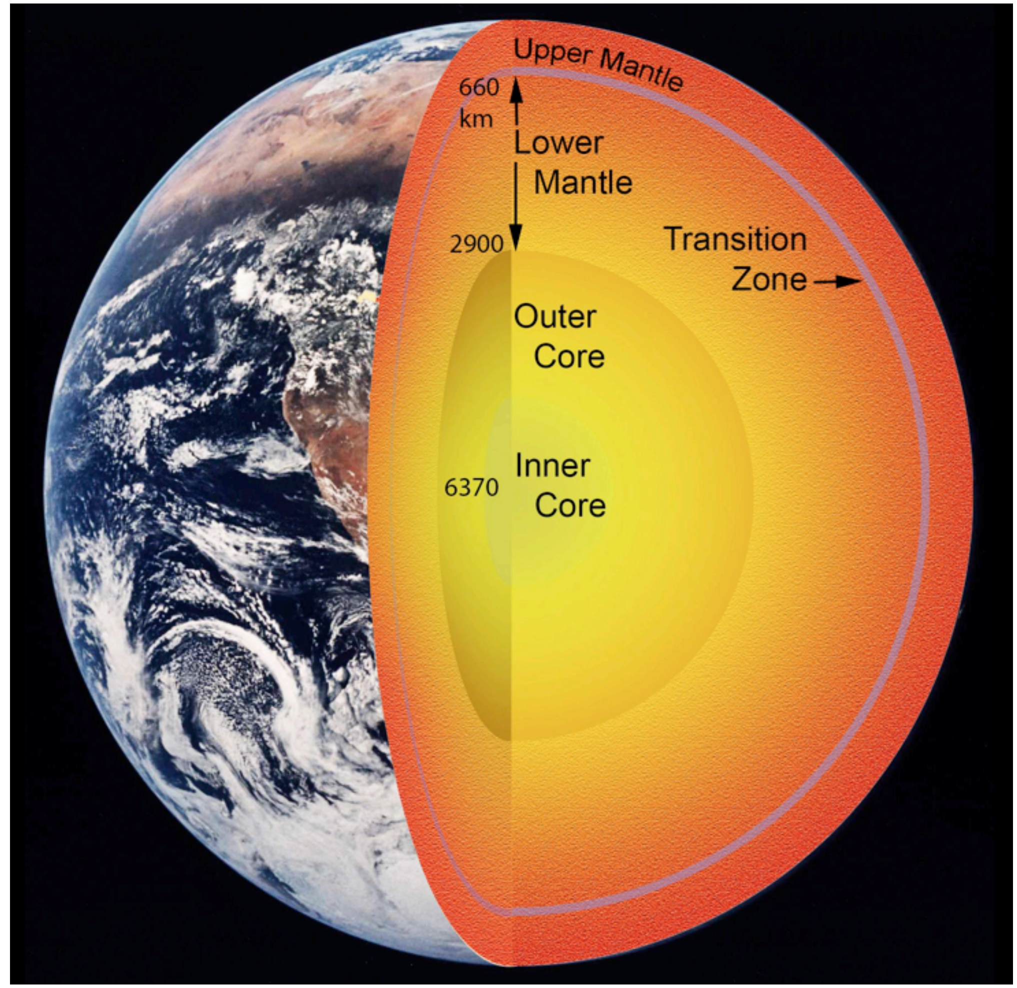
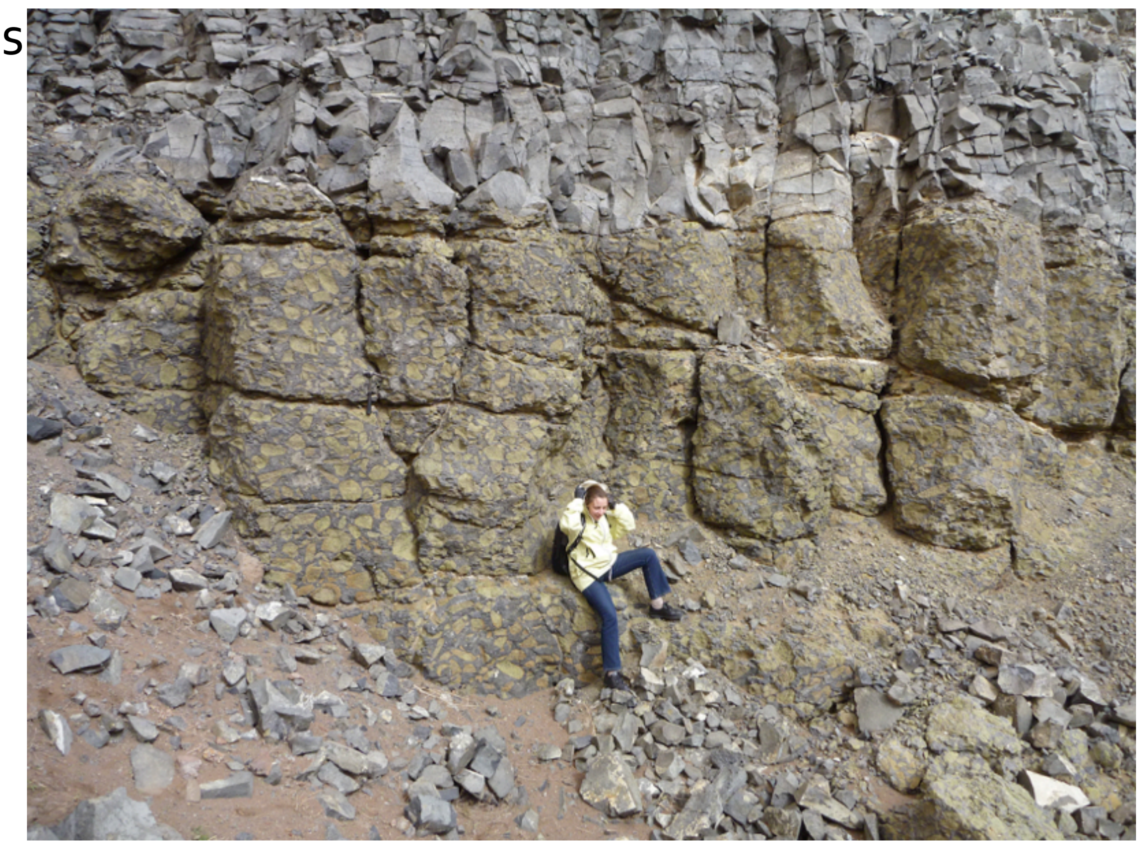


Image Credit: Japan Times

Type of data for water in the deep Earth

- **Crust**
  - Direct samples: crustal rocks
- **Mantle lithosphere**
  - Direct samples: Peridotites, pyroxenites samples
- **Asthenosphere**
  - Direct samples: Rare deep diamond inclusions
  - Indirect samples: Oceanic basalts (undegassed glasses, melt inclusions)
  - HP Experiments
  - First principle calculations
- **Core**
  - H solubility in Fe-Ni metal
  - Accretion models



Mantle xenoliths in basaltic flow, Jieshaba, China

Earth total water content

- Type of data
- **Water in the mantle**
  - **Definition**
  - Importance
  - Distribution & controls
    - H diffusion
    - Water in the continental mantle lithosphere
    - Water in the lithosphere
    - Water in the oceanic lithosphere
- The big picture
  - Water in the Earth layers
  - Fluxes
- Comparison with other differentiated planetary bodies

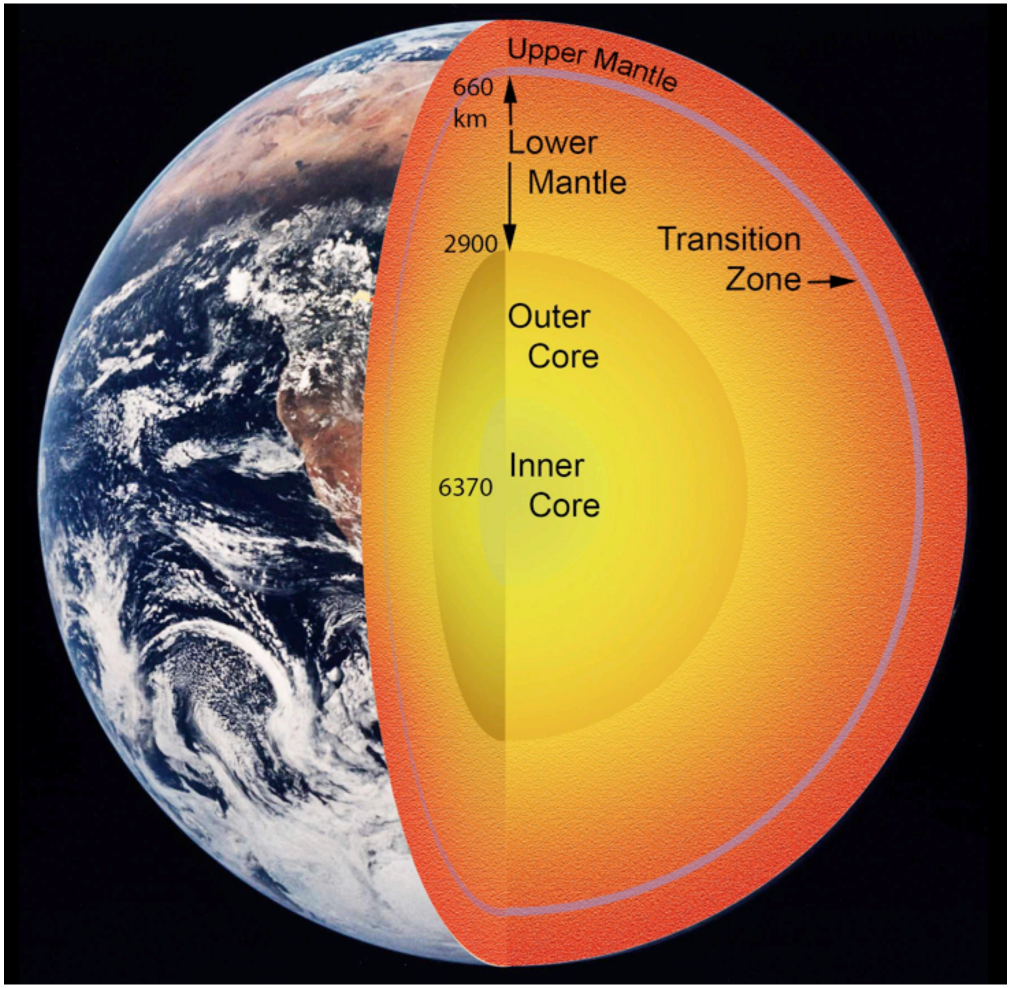


Image Credit: Japan Times

Disclaimer about “water” in the mantle

- **“Water” in anhydrous minerals = Hydrogen**

Ol, Px, Gr, Fd,
Ring, Wads, Perov

H

O structural

Apatite, Amph, Mica,
Phase B, D, H and Egg

OH

Minor phases

Melt, Glass,
Fluid, Gas, (Fd)

OH H_2O
CH_4 H_2

- **Calculated in ppm wt H_2O (<1-1000’)**

Disclaimer about "water" in the mantle

- **"Water" in anhydrous minerals = Hydrogen**

Ol, Px, Gr, Fd,
Ring, Wads, Perov

H

O structural

Apatite, Amph, Mica,
Phase B, D, H and Egg

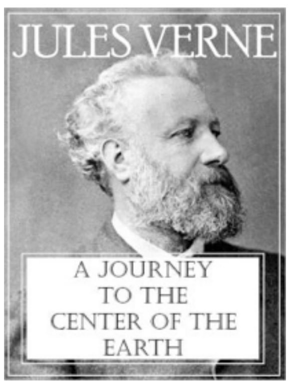
OH

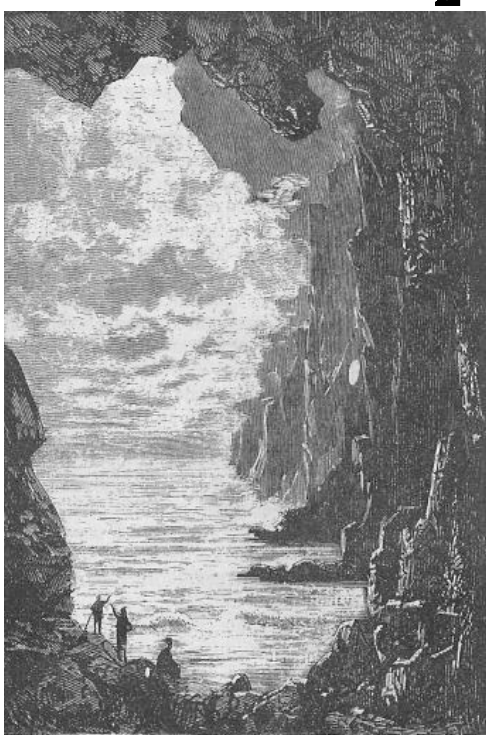
Minor phases

Melt, Glass,
Fluid, Gas, (Fd)

OH H_2O
CH_4 H_2

- **Calculated in ppm wt H_2O (<1-1000')**





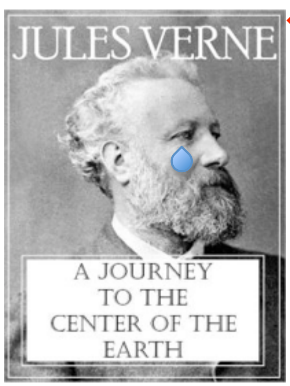
Equivalent of several Earth's oceans in the mantle

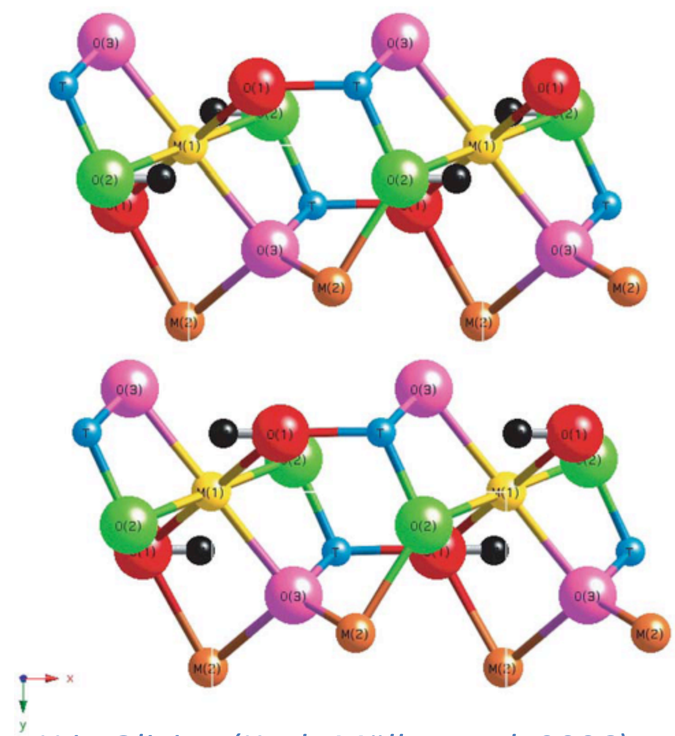
Disclaimer about "water" in the mantle

- "Water" in anhydrous minerals = Hydrogen

Ol, Px, Gr, Fd, Ring, Wads, Perov	Apatite, Amph, Mica, Phase B, D, H and Egg	Melt, Glass, Fluid, Gas, (Fd)
H	**OH**	**OH H_2O CH_4 H_2**
O structural	Minor phases	

- Calculated in ppm wt H_2O (<1-1000')





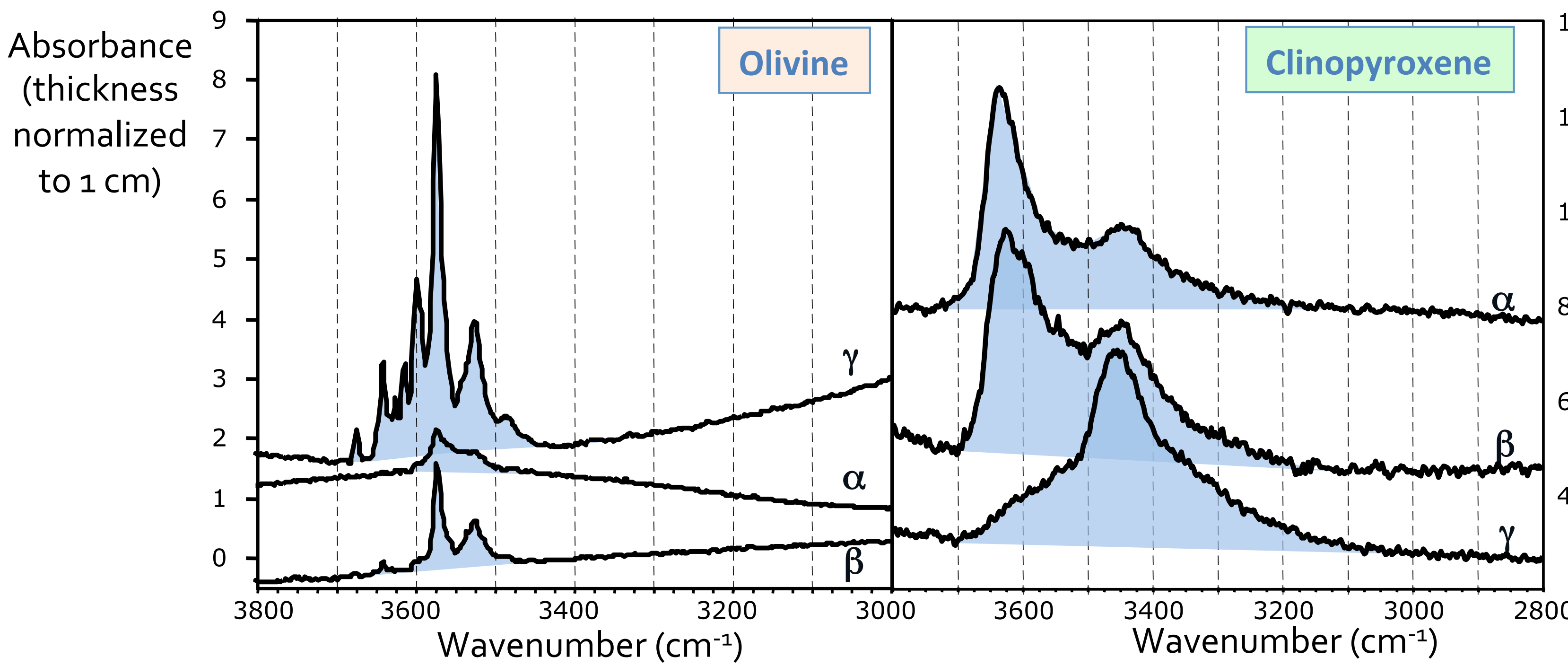
H in Olivine (Koch-Müller et al. 2006)

Techniques

- **FTIR** → **H_2O content**
  → **speciation**
  → **location H mineral defects**
- **SIMS** → **H_2O content**
  → **H isotopes**
  → **Cl, F**

Detection limits
FTIR <0.5 ppm H_2O
SIMS ≤ 2 ppm H_2O

FTIR spectra in the O-H region



Earth total water content

- Type of data
- Water in the mantle
  - Definition
  - **Importance**
  - Distribution & controls
    - H diffusion
    - Water in the continental mantle lithosphere
    - Water in the lithosphere
    - Water in the oceanic lithosphere
- The big picture
  - Water in the Earth layers
  - Fluxes
- Comparison with other differentiated planetary bodies

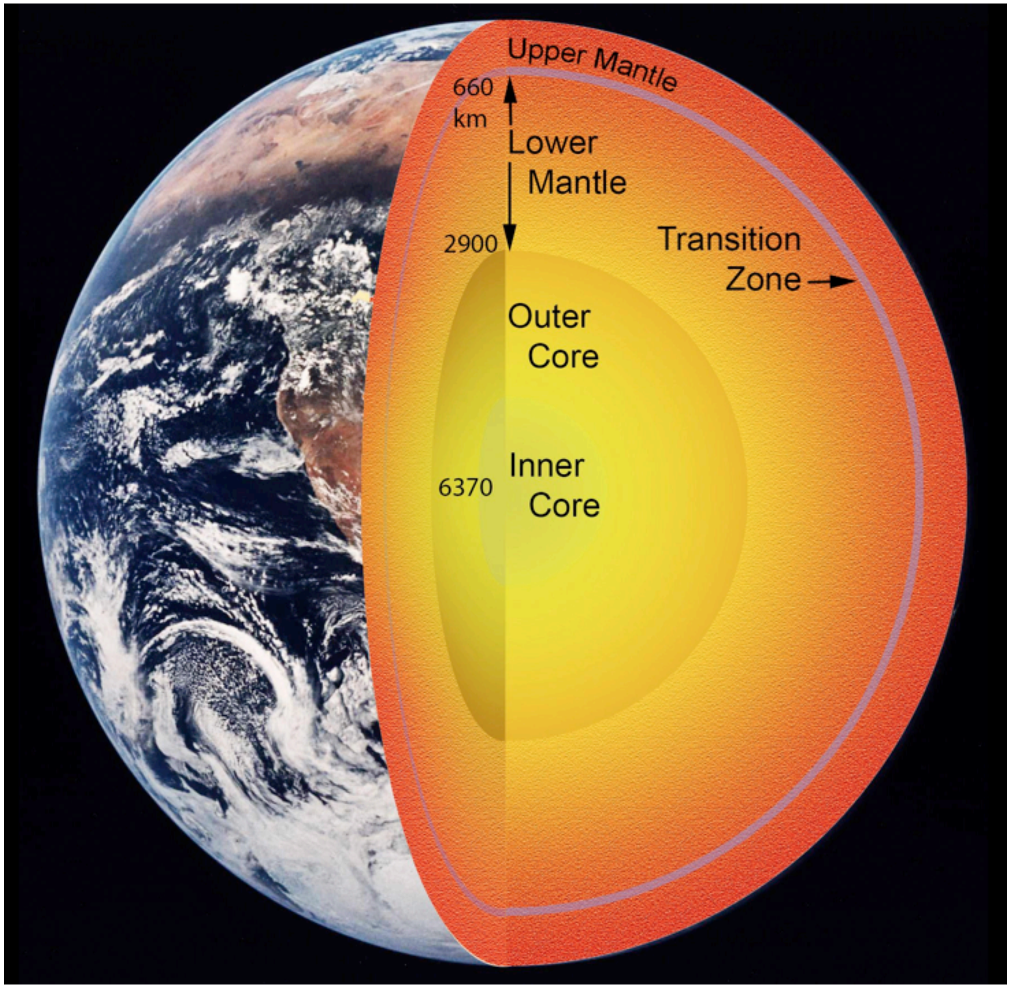


Image Credit: Japan Times

Why is water important?

- ✧ **Water lowers the solidus of mantle lithologies:**
  - Facilitates partial melting, lower T
- ✧ **Influence on magmatism**
  - Magma composition
  - Magma transfer and eruption style
    - ➔ origin of oceans & atmosphere
- ✧ **Water and rheology:**
  - Presence of water in olivine makes it weaker
    - ➔ crucial for plate tectonics
  - Melt circulation and eruption style
- ✧ **Water and remote sensing of the deep Earth:**
  - Seismic properties: seismic wave attenuation & anisotropy
  - Electrical conductivity
  - Thermal conductivity

Image Credit: J. Head Brown U., Stromboli

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; 2004; 2006; 2010; Mackwell et al., 1985; Mei & Kohlstedt, 2000; Walker et al., 2007; Jung & Karato, 2001; Demouchy et al 2012; Jones, Evans, Muller, Fullea, Pommier 1990-2015; Lizzaralde et al 1995; Sarafian et al. 2015; Udata et al 2003; Hofmeister 2004

Earth total water content

- Type of data
- Water in the mantle
  - Definition
  - Importance
  - **Distribution & controls**
    - **H diffusion**
    - Water in the continental mantle lithosphere
    - Water in the lithosphere
    - Water in the oceanic lithosphere
- The big picture
  - Water in the Earth layers
  - Fluxes
- Comparison with other differentiated planetary bodies

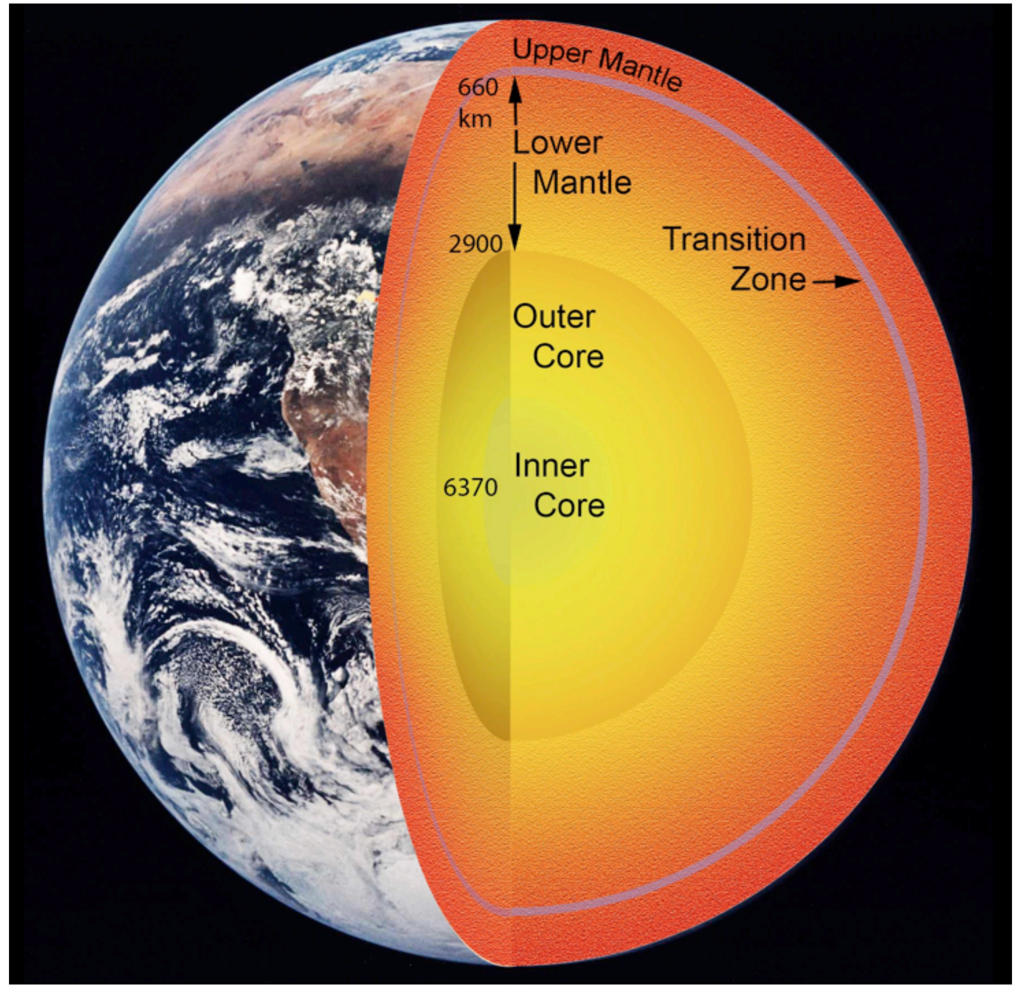


Image Credit: Japan Times

H loss during xenolith ascent in host magma?

- ✧ H diffuses quickly through Ol & Px
  (e.g. Mackwell & Kohlstedt 1990; Ingrin et al 1995-2006, Stalder & Skogby 2003)
- ✧ Px have homogeneous water contents
- ✧ Ol can record H loss

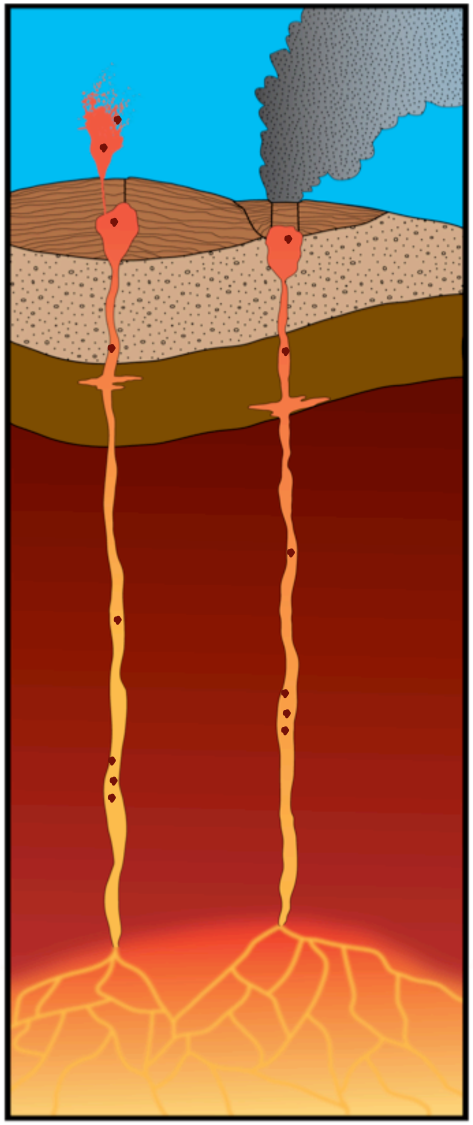
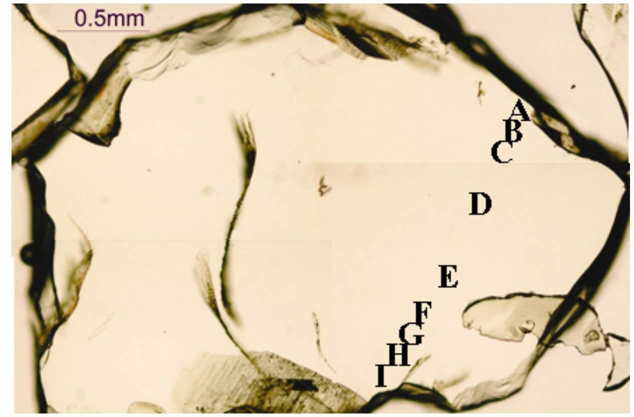
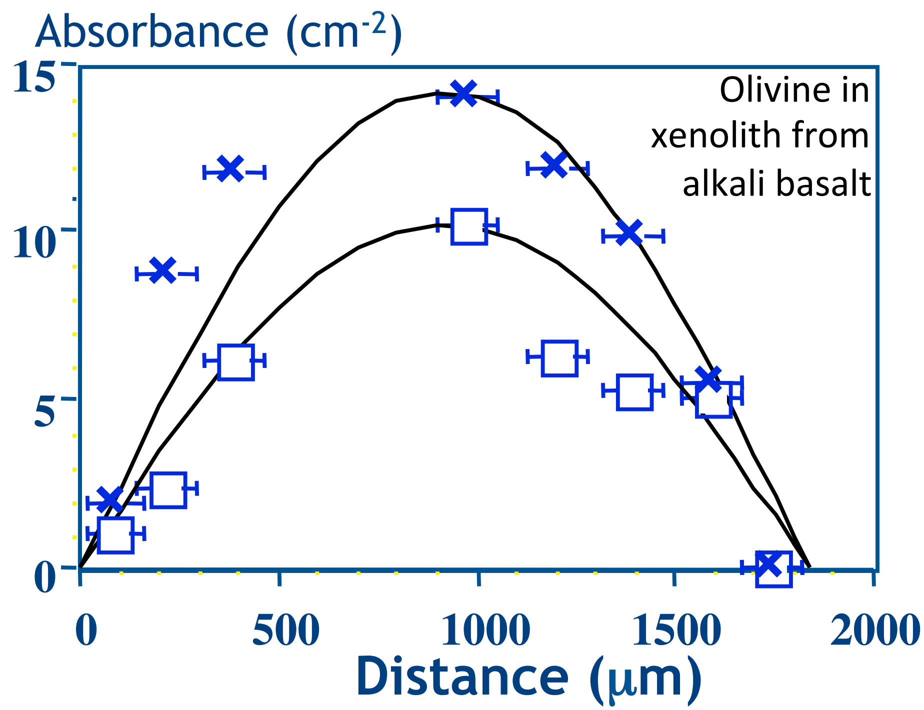


Figure stolen from AGU Chapman conference website (xenoliths added)



Olivine from Mexican mantle xenolith



H loss during xenolith ascent in host magma?

- H diffuses quickly through Ol & Px at magmatic temperatures

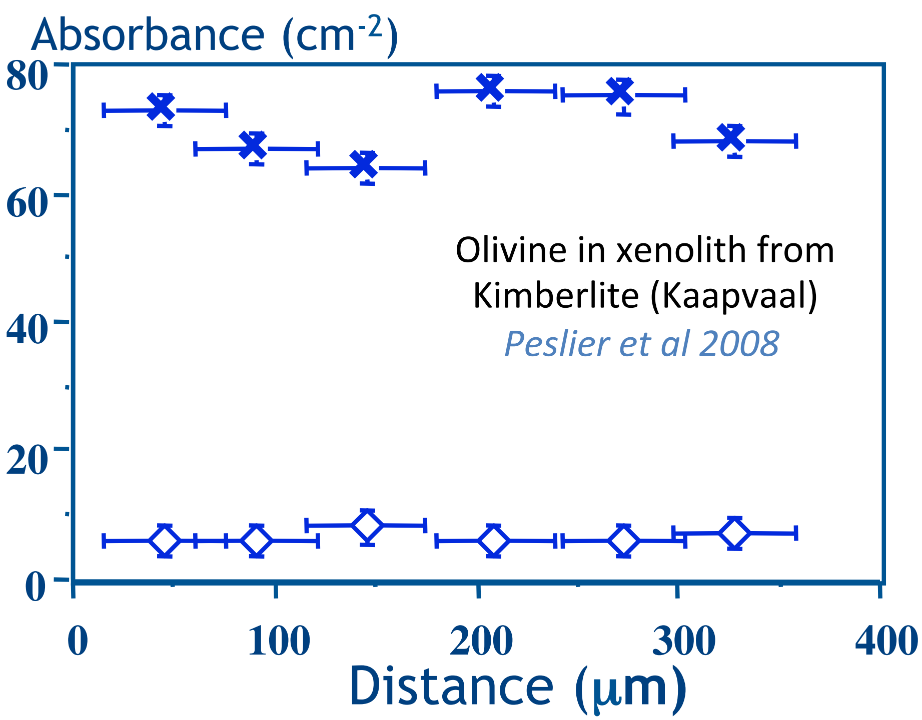
  (e.g. Mackwell & Kohlstedt 1990; Ingrin et al 1995, 1999, Stalder & Skogby 2003)

- But H not always lost because H diffusion is coupled with that of slower elements
  (e.g. Berry et al 2007, Novella et al 2015, Skogby, Stalder, Sundval 1989-2009)

- Check:

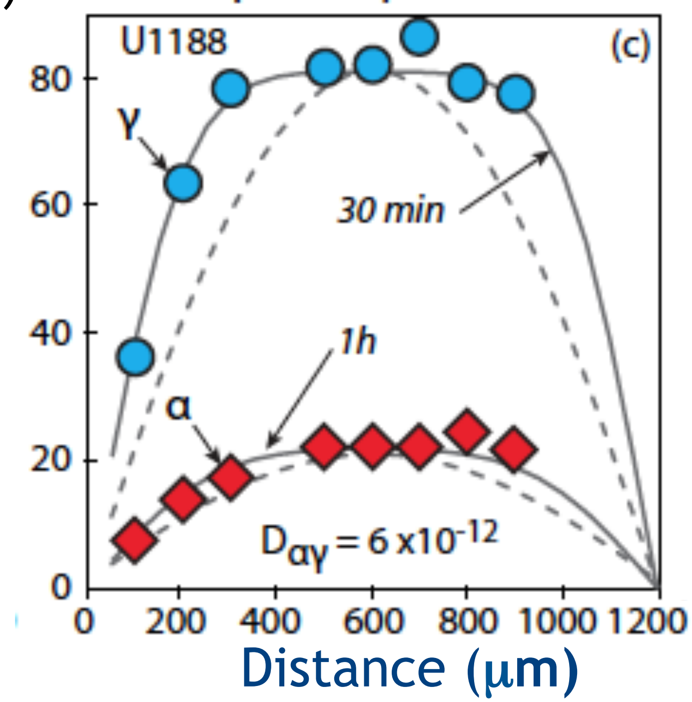
  With diffusion modeling

  If co-var with other elements (Al, Ti, REE…)



Olivine from Udachnaya mantle xenolith from kimberlite

(Doucet et al 2014)



→ Data shown here are mantle [H_2O] values

Earth total water content

- ✧ Type of data
- ✧ Water in the mantle
  - ✧ Definition
  - ✧ Importance
  - ✧ Distribution & controls
    - ✧ H diffusion
    - ✧ **Water in the continental mantle lithosphere**
    - ✧ Water in the lithosphere
    - ✧ Water in the oceanic lithosphere
- ✧ The big picture
  - ✧ Water in the Earth layers
  - ✧ Fluxes
- ✧ Comparison with other differentiated planetary bodies

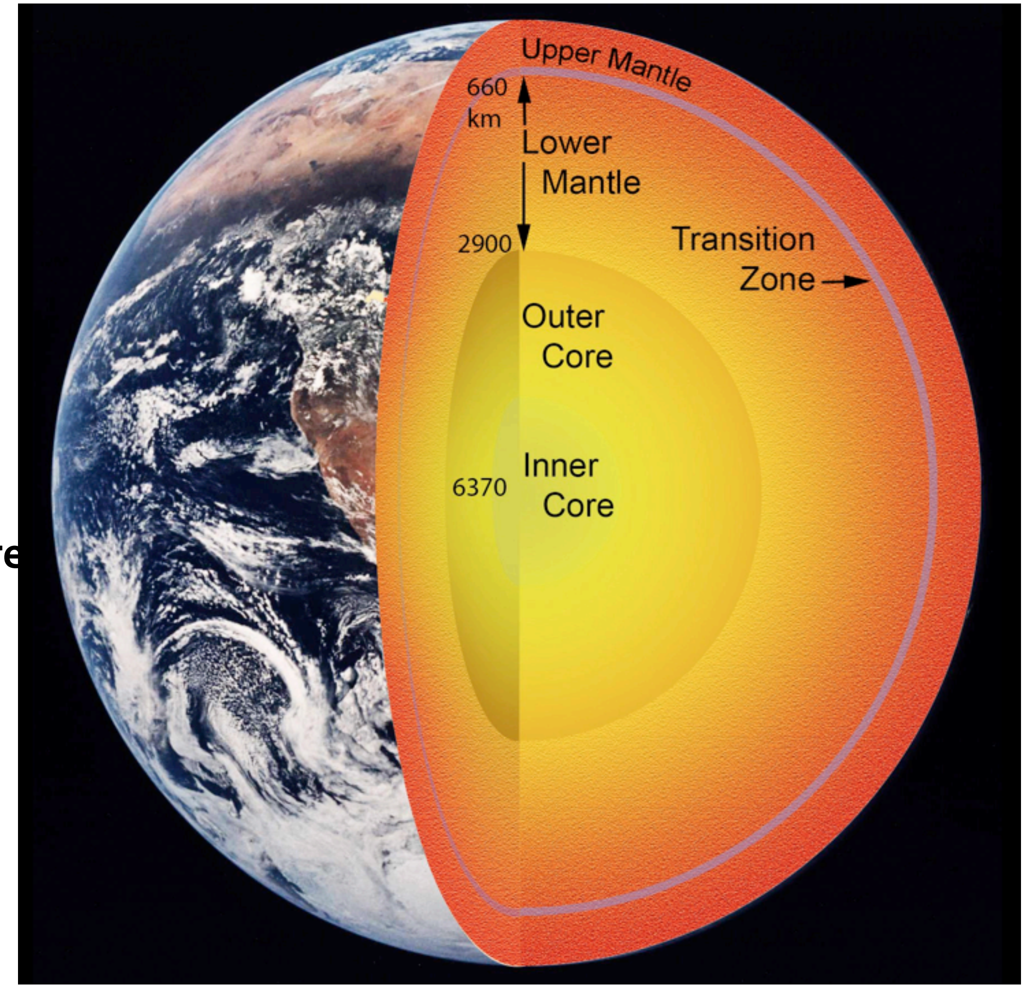
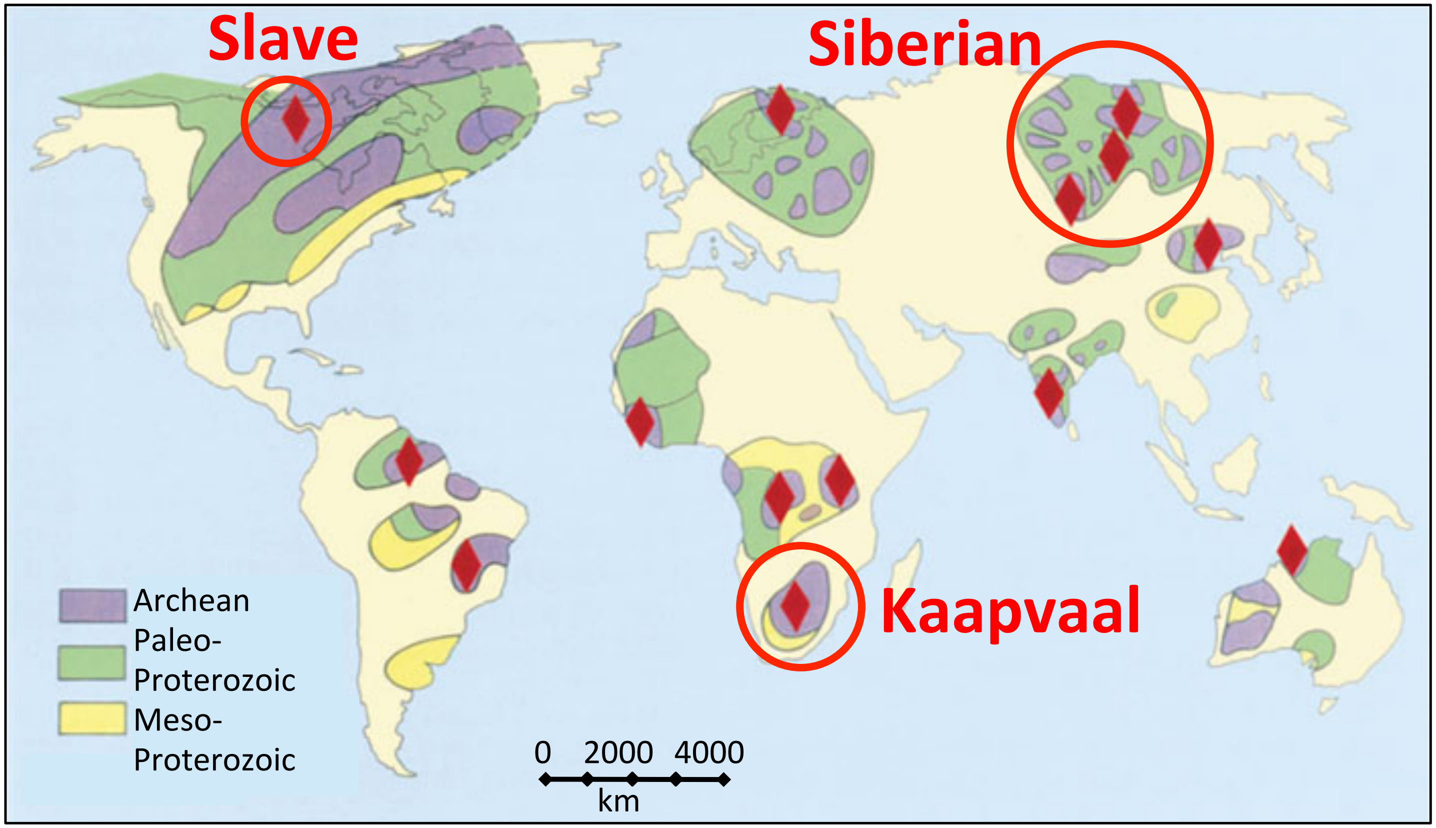
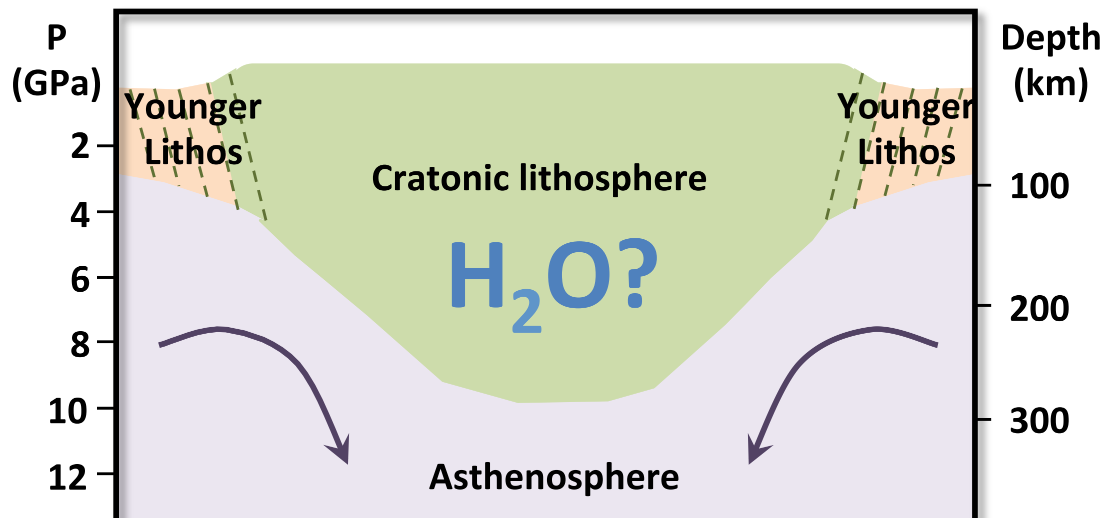


Image Credit: Japan Times

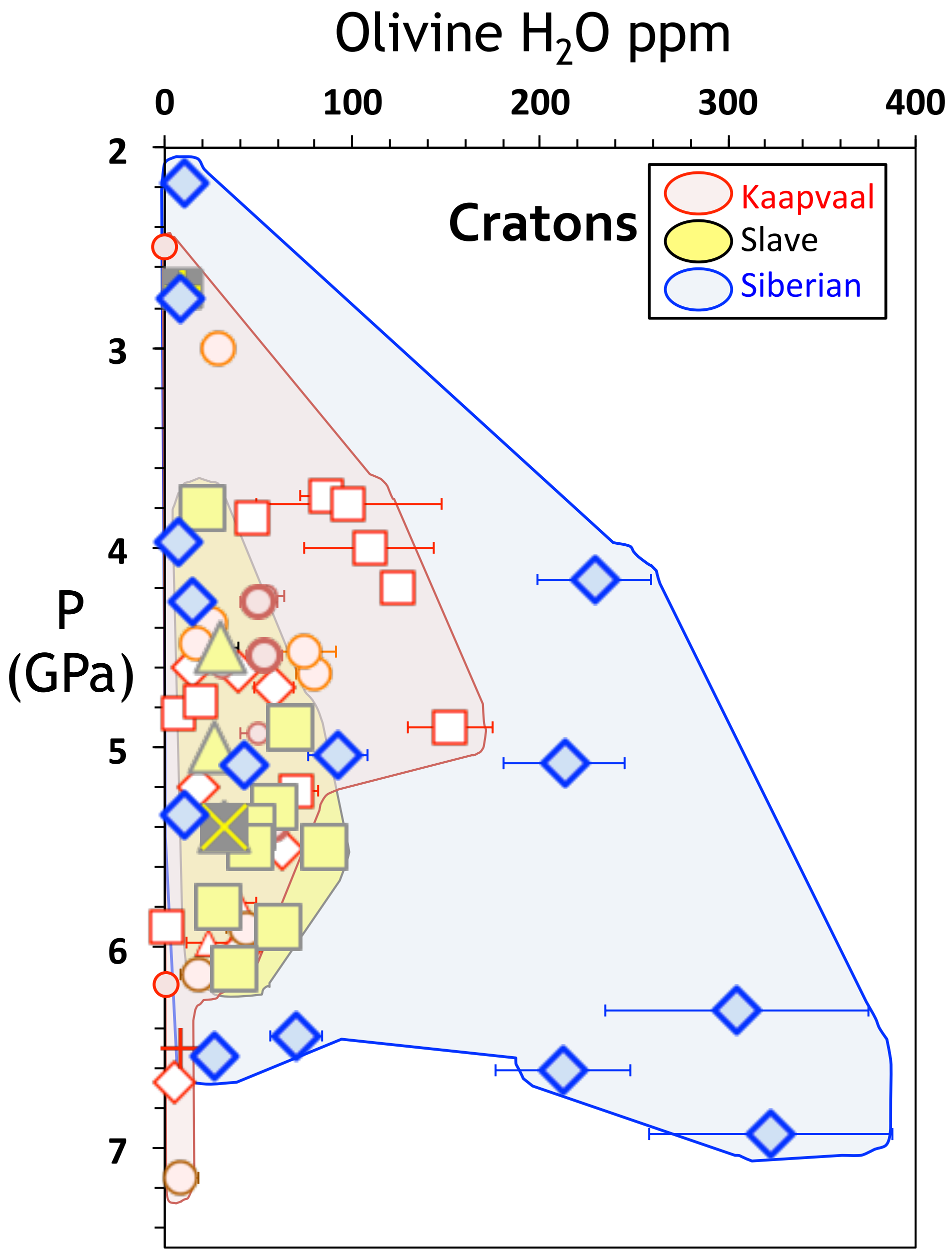
Water in the continental lithosphere

- Cratons



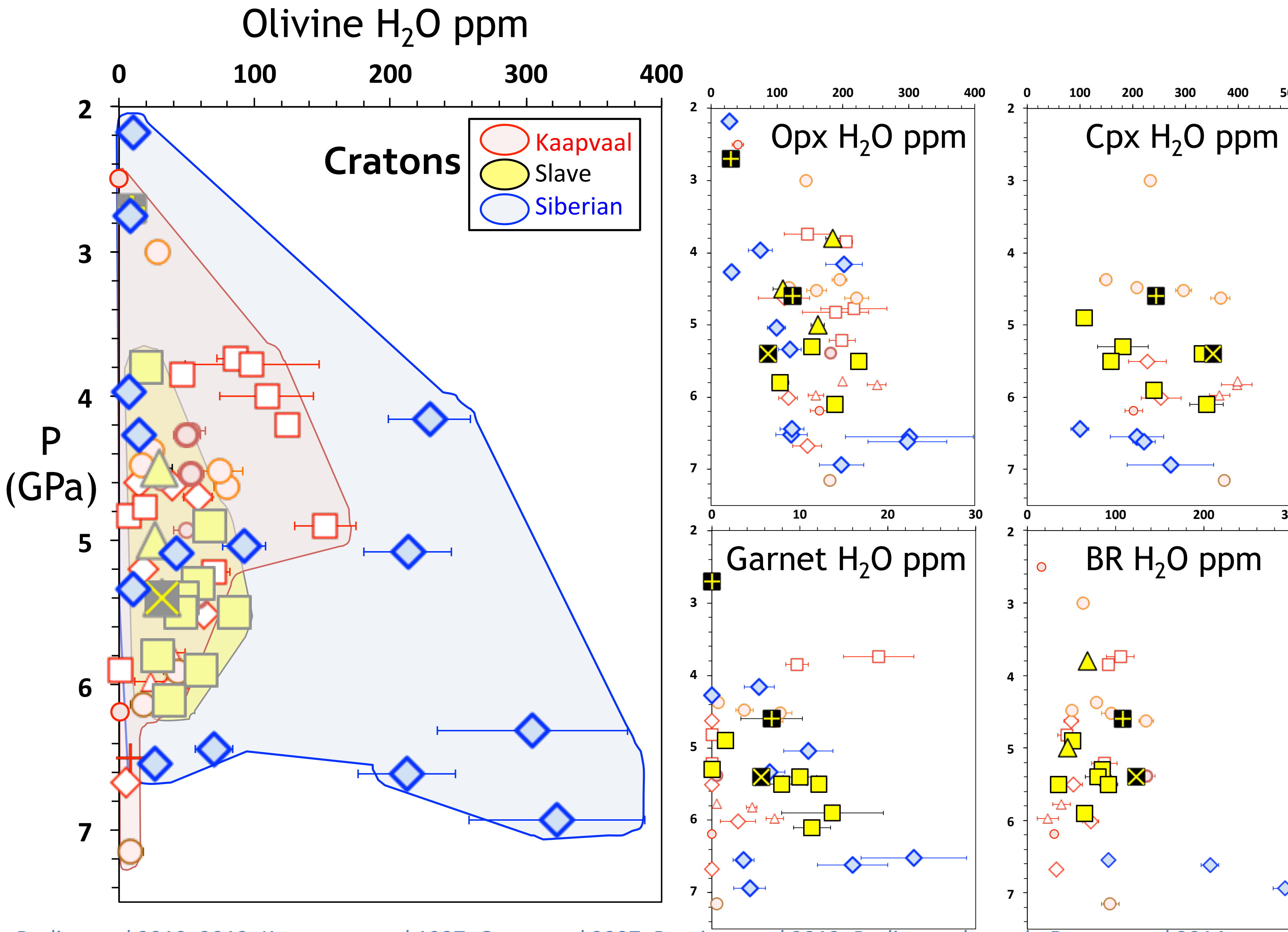


Water in the continental lithosphere



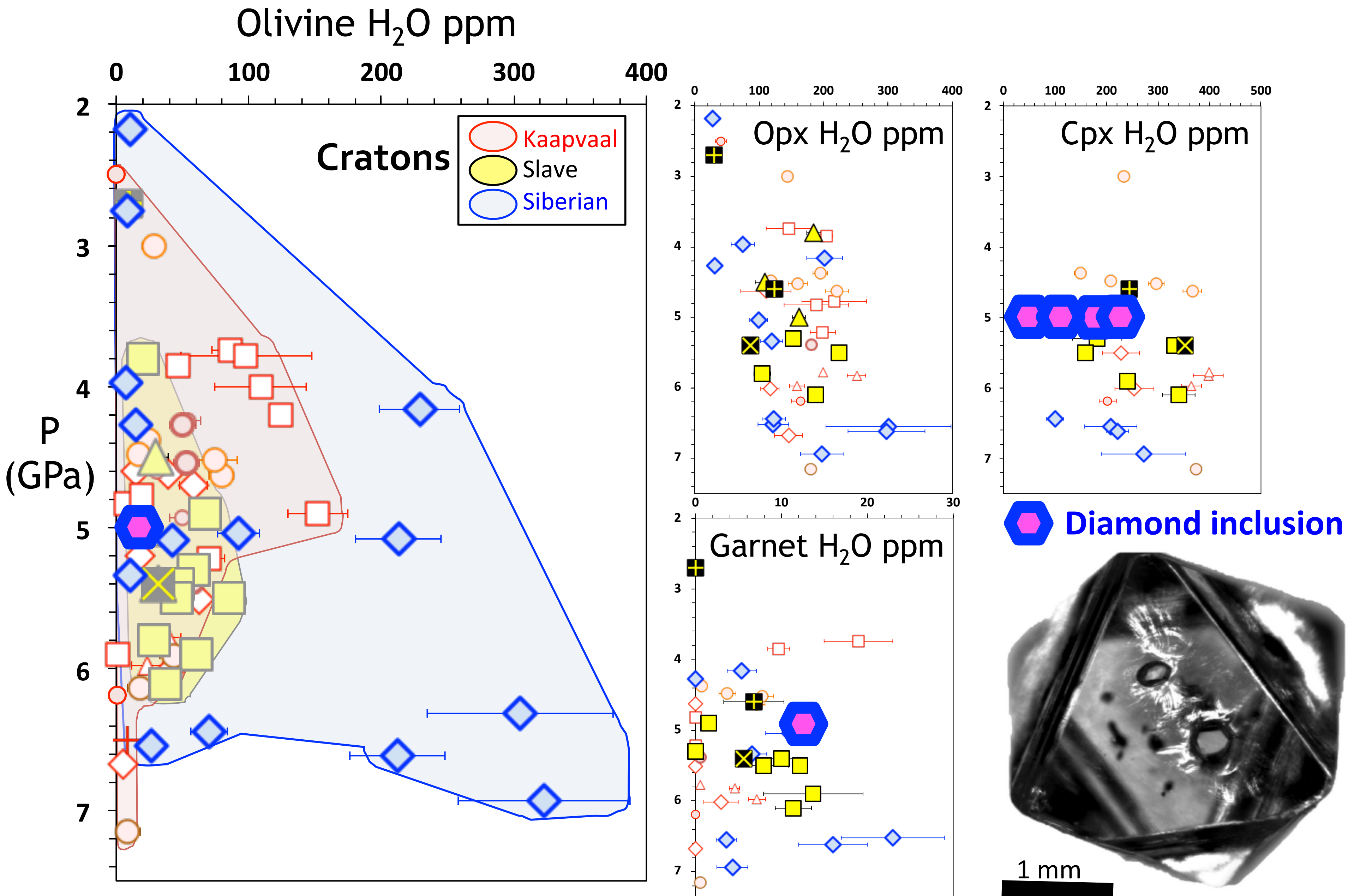
Peslier et al 2010, 2012; Kurozawa et al 1997; Grant et al 2007; Baptiste et al 2012; Peslier et al unpub; Doucet et al 2014

Water in the continental lithosphere



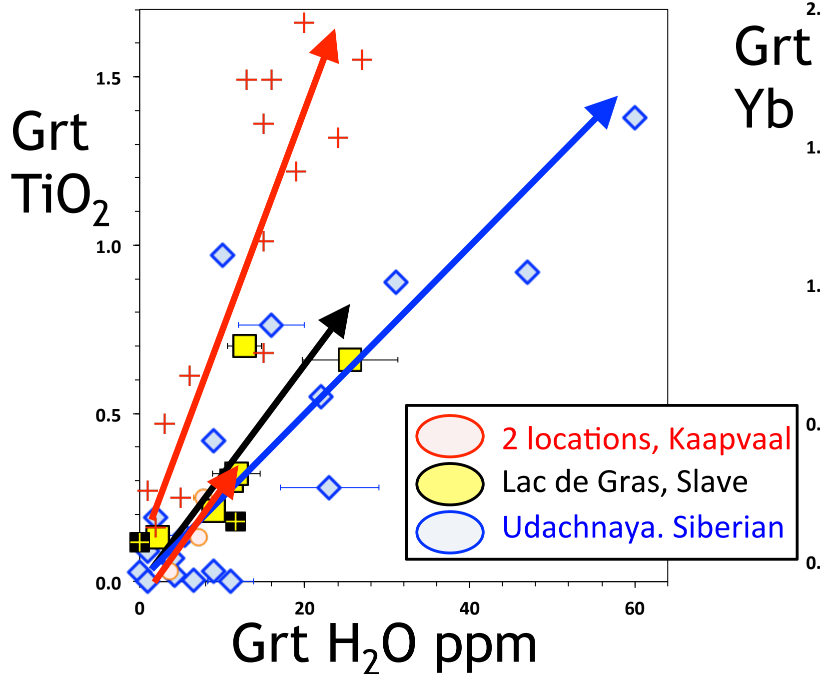
Peslier et al 2010, 2012; Kurozawa et al 1997; Grant et al 2007; Baptiste et al 2012; Peslier et al unpub; Doucet et al 2014

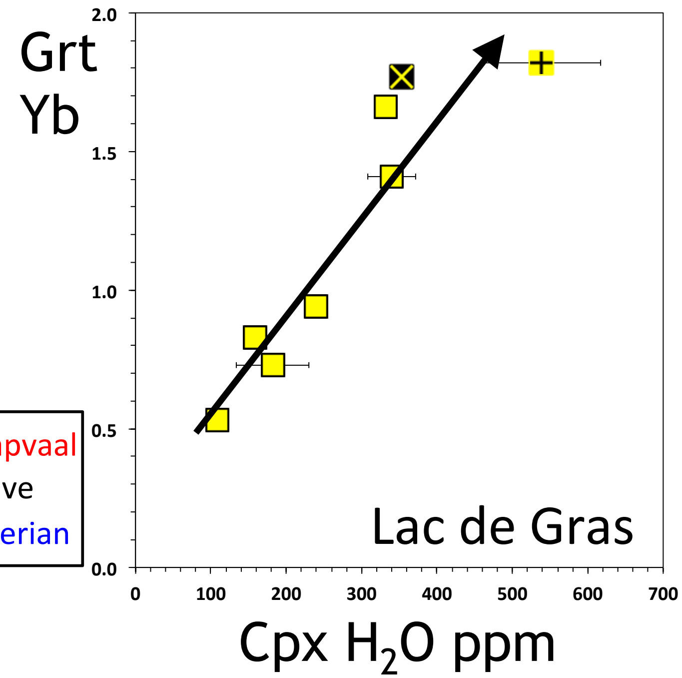
Water in the continental lithosphere

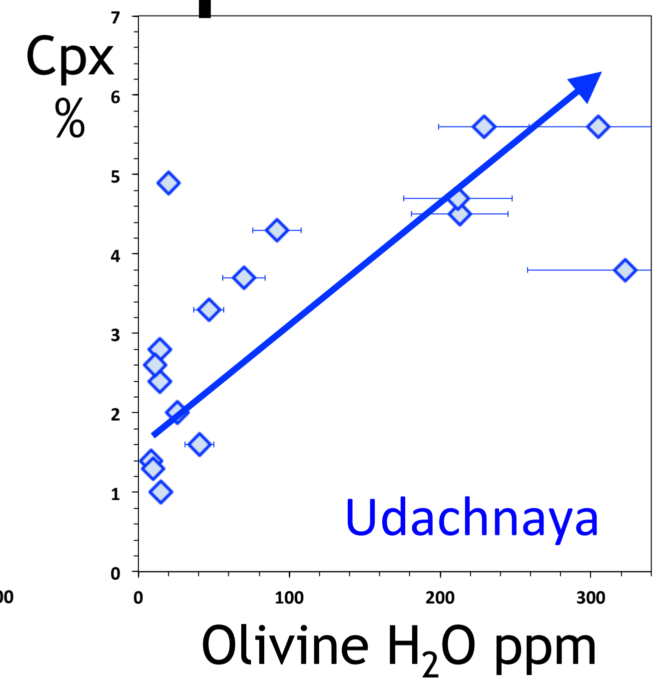


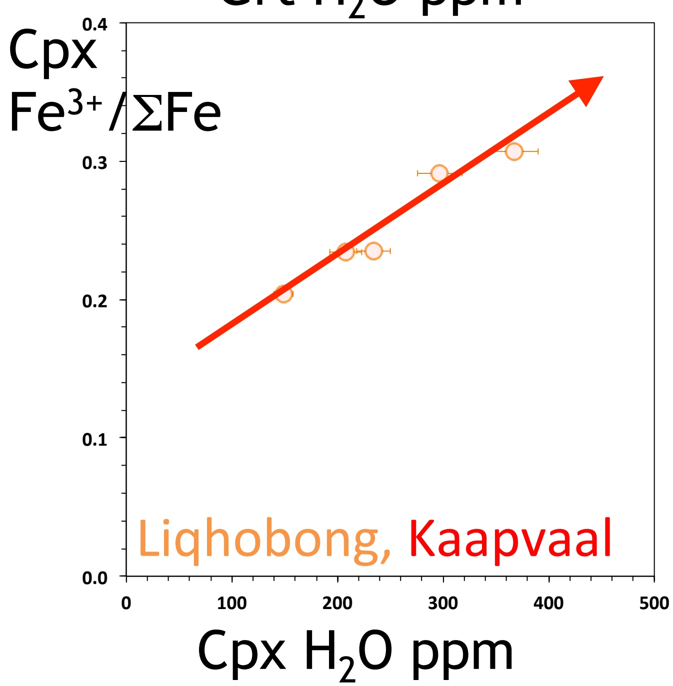
Peslier et al 2010, 2012; Kurozawa et al 1997; Grant et al 2007; Baptiste et al 2012; Peslier et al unpub; Doucet et al 2014, Novella et al 2015, Taylor et al 2016

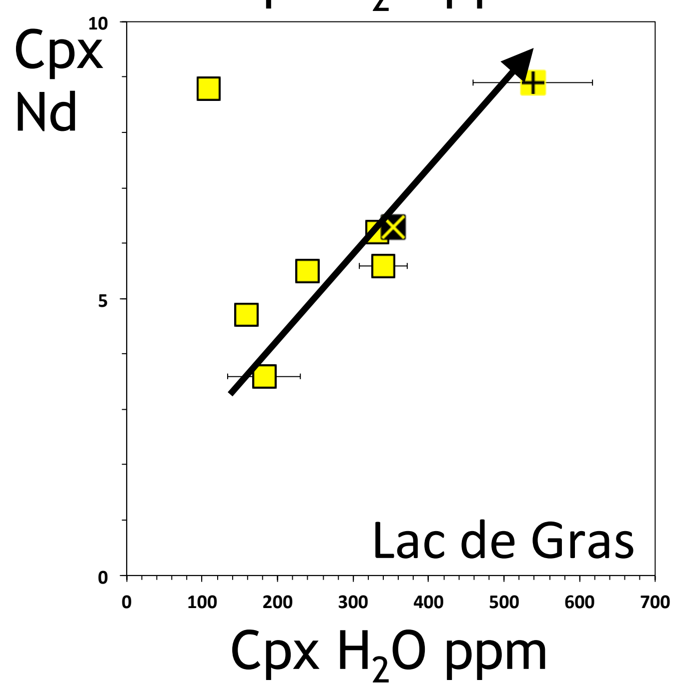
Water in the continental lithosphere







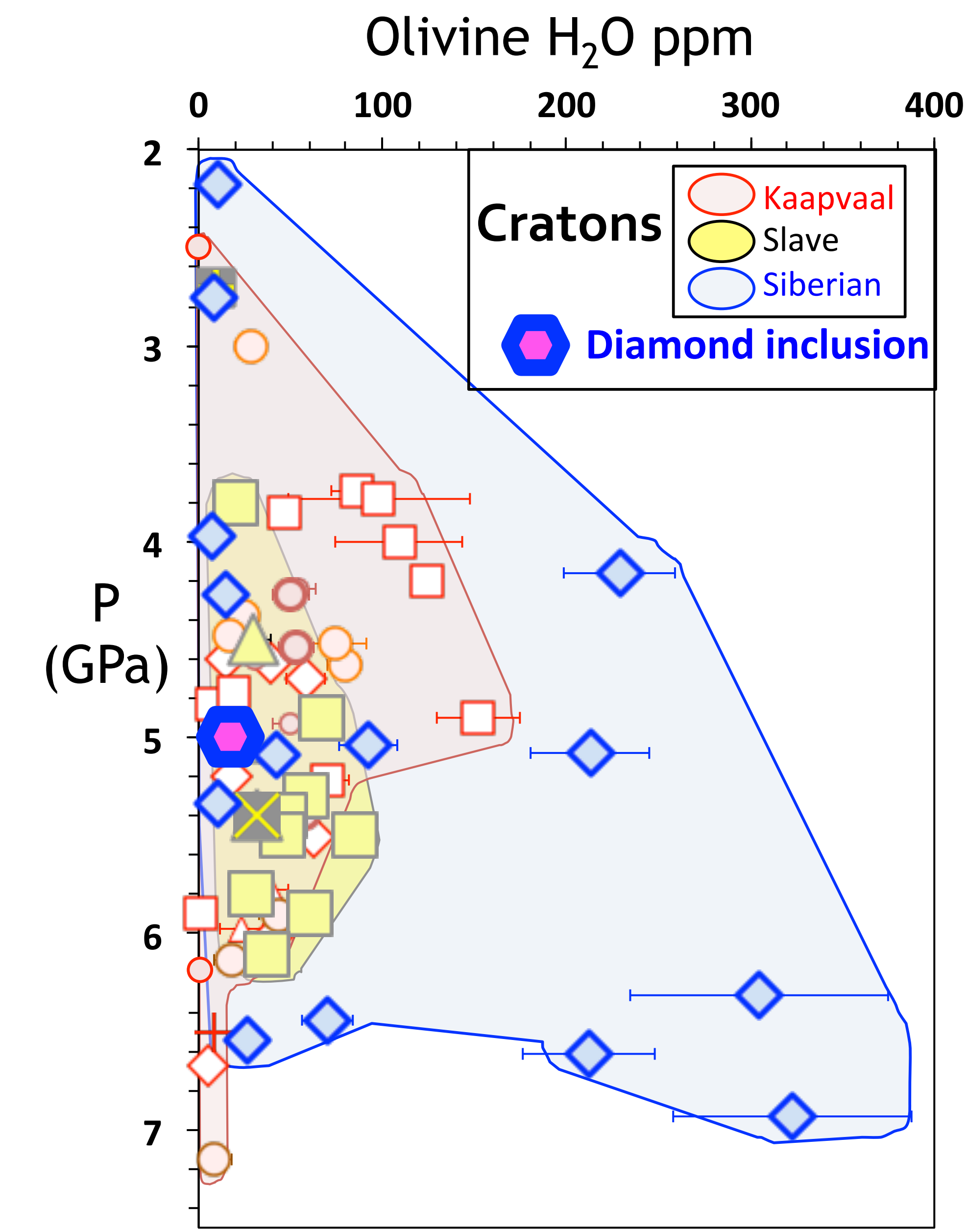




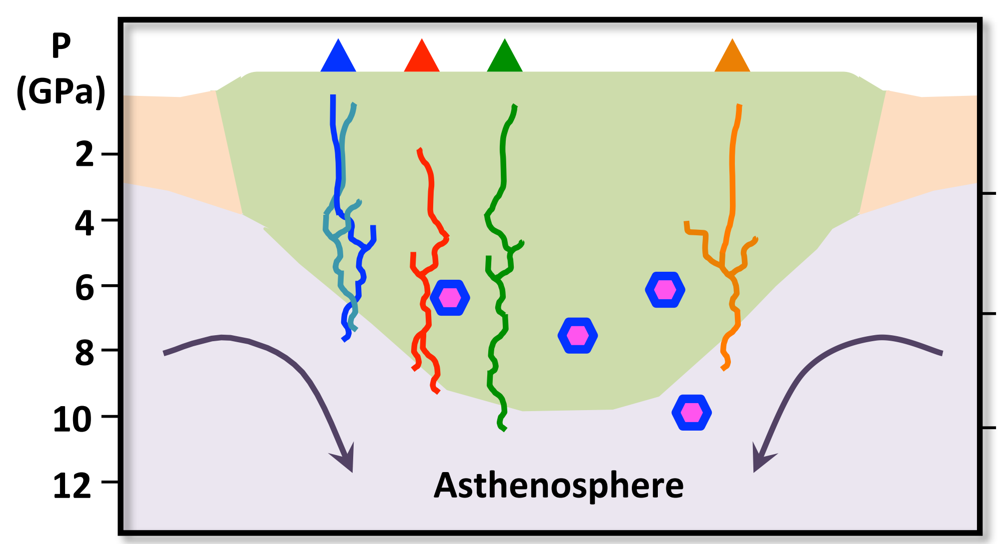
Water brought in via metasomatism/ refertilization by melts/fluids

Bell et al., 1992; Peslier et al 2012; Doucet et al 2014; Peslier et al unpublished

Water in the continental lithosphere



Xenoliths NOT representative of whole mantle lithosphere



- **Over-representation of metasomatized water-rich peridotite near melt/fluid channels**
- **Overall mantle lithos dry (preserved in diamond mineral inclusions)**
- **Water has a role in cratonic root long term longevity**

Peslier et al 2010, 2012; Kurozawa et al 1997; Grant et al 2007; Baptiste et al 2012; Peslier et al unpub; Doucet et al 2014, Novella et al 2015, Taylor et al 2016

Earth total water content

- ✧ Type of data
- ✧ Water in the mantle
  - ✧ Definition
  - ✧ Importance
  - ✧ Distribution & controls
    - ✧ H diffusion
    - ✧ Water in the continental mantle lithosphere
    - ✧ **Water in the lithosphere**
    - ✧ Water in the oceanic lithosphere
- ✧ The big picture
  - ✧ Water in the Earth layers
  - ✧ Fluxes
- ✧ Comparison with other differentiated planetary bodies

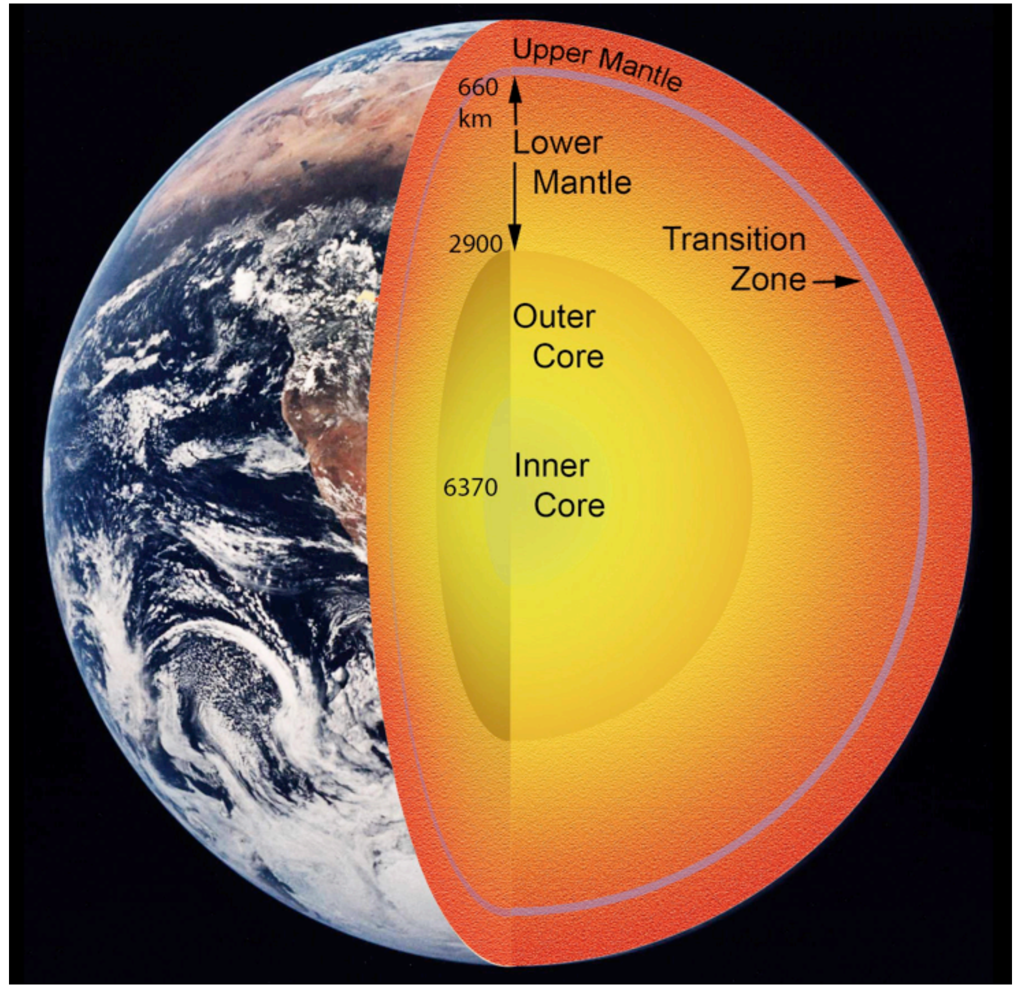
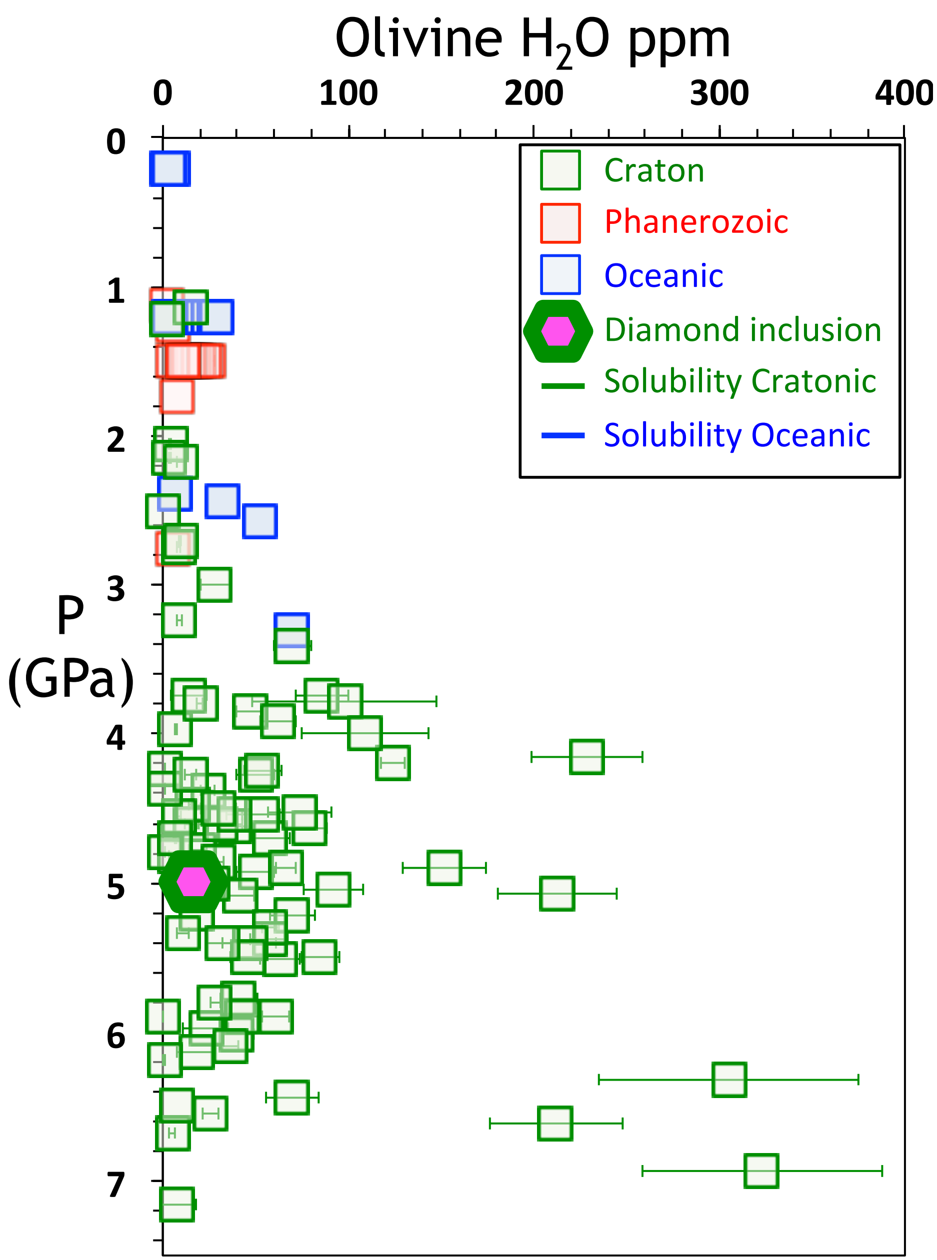


Image Credit: Japan Times

Water in the lithosphere



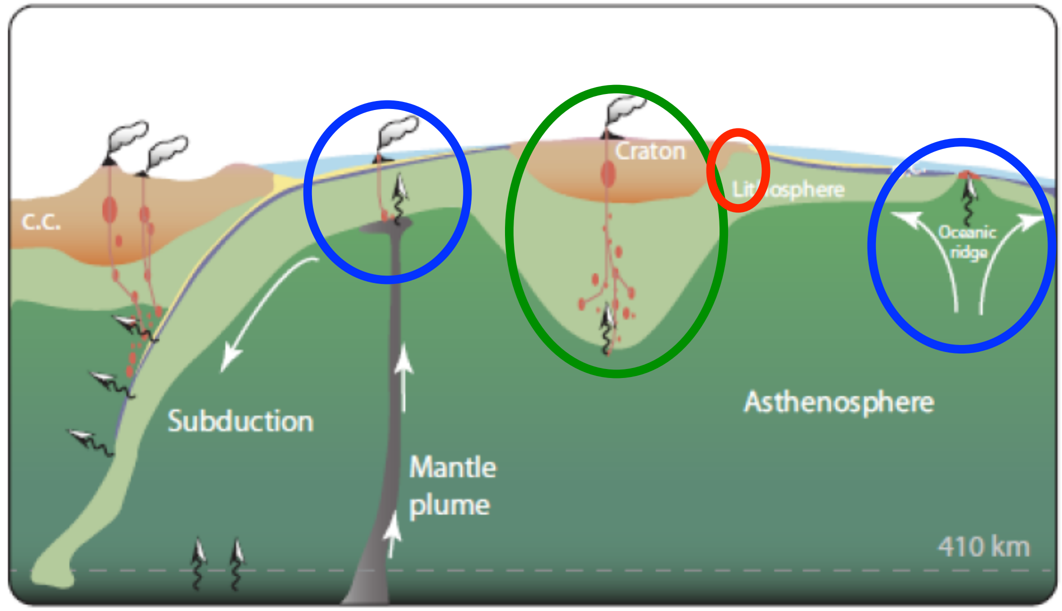
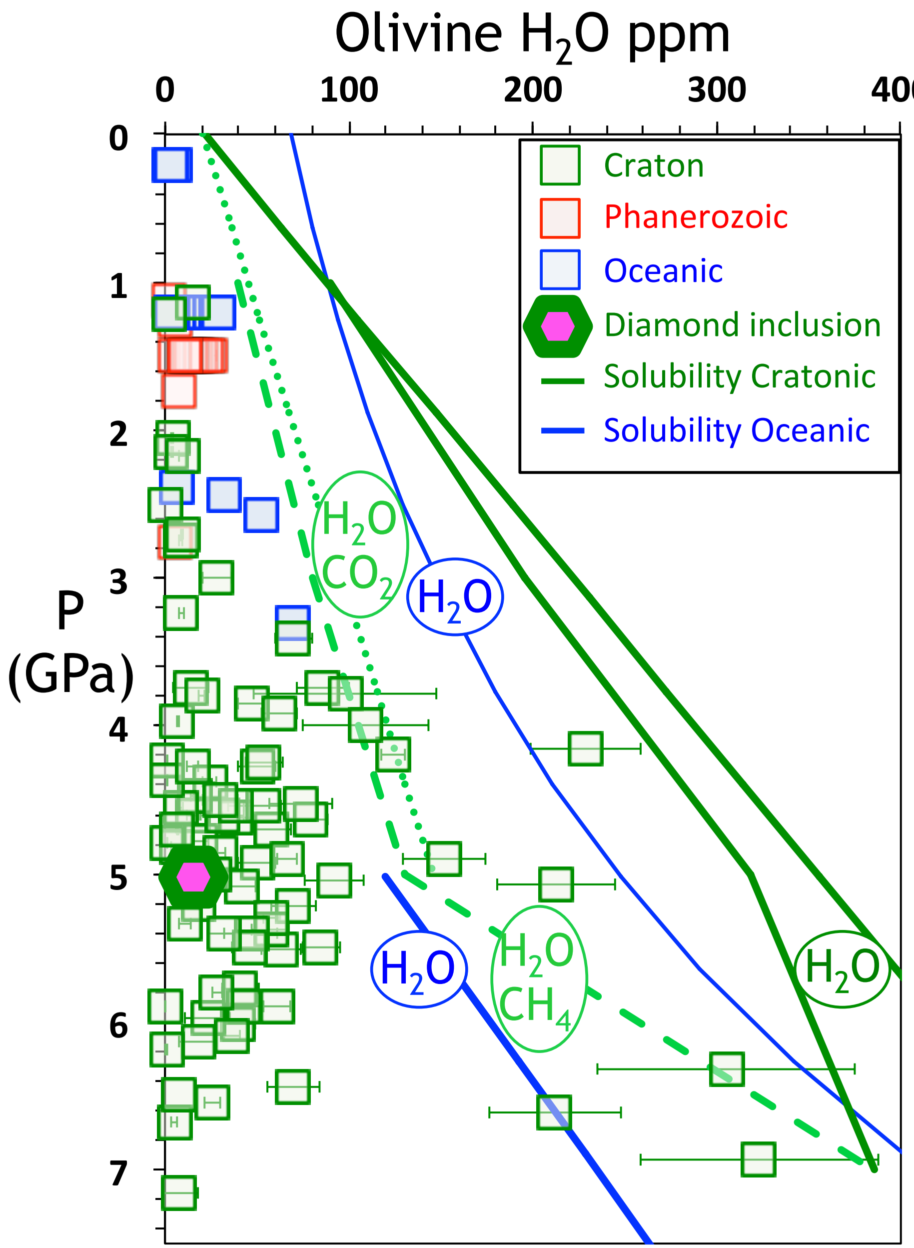


Image Credit: Demouchy & Bolfan-Casanova 2016

- **Off-craton olivine: most have lost H during xeno ascent**

Peslier et al 2010- 2015-Unpub; Kurozawa et al 1997; Grant et al 2007; Baptiste et al 2012; Doucet et al 2014, Novella et al 2015, Taylor et al 2016; Warren & Hauri 2014

Water in the lithosphere



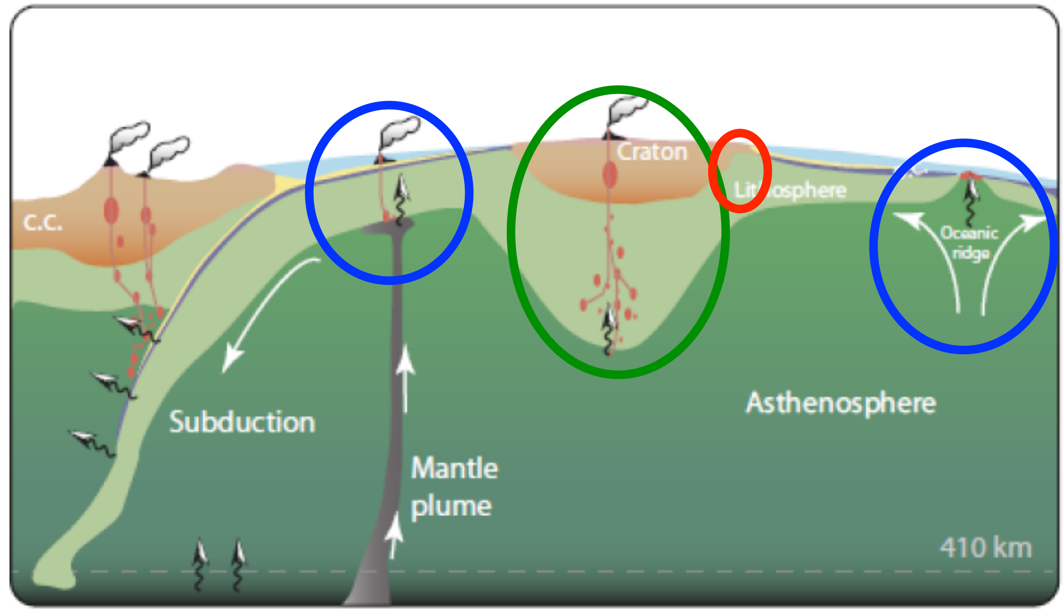
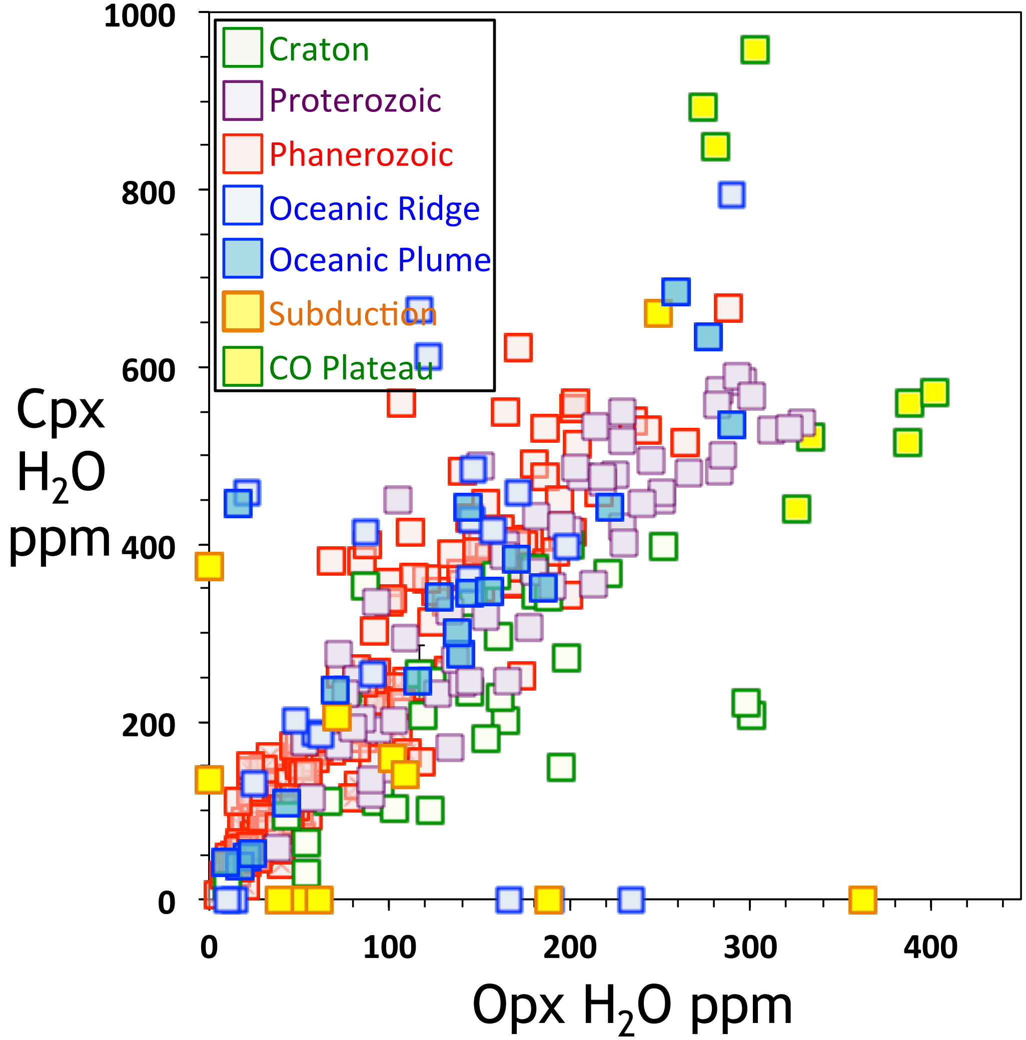


Image Credit: Demouchy & Bolfan-Casanova 2016

- **Off-craton olivine: most have lost H during xeno ascent**
- **Max [H2O] in olivine limited by solubility?**
- **Max [H2O] in olivine depends on local melt/fluid water activity**
- **Mantle lithosphere is unsaturated in water**

Peslier et al 2010- 2015-Unpub; Kurozawa et al 1997; Grant et al 2007; Baptiste et al 2012; Doucet et al 2014, Novella et al 2015, Taylor et al 2016; Warren & Hauri 2014; Férot & Bolfan-Casanova 2012, Tenner, Ardia et al 2012; Yang et al 2014-15; Demouchy & Bolfan-Casanoca 2016

Water in the lithosphere



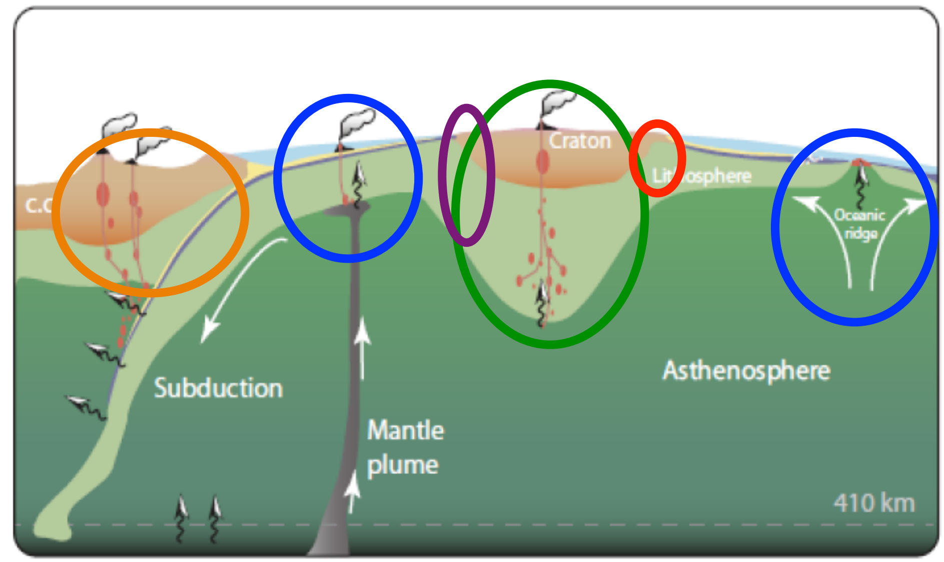
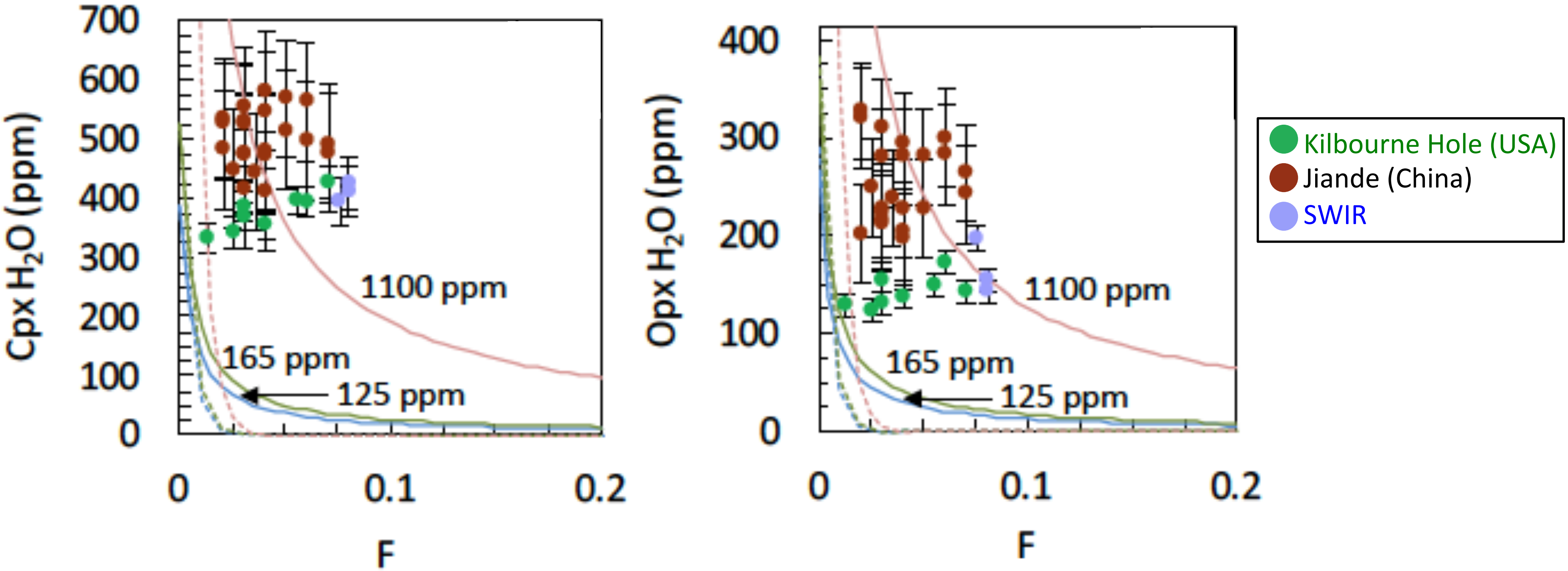


Image Credit: Demouchy & Bolfan-Casanova 2016

- **Similar [H_2O] for all tectonic settings**
- **Subduction peridotite not more wet (except CO Plateau)**

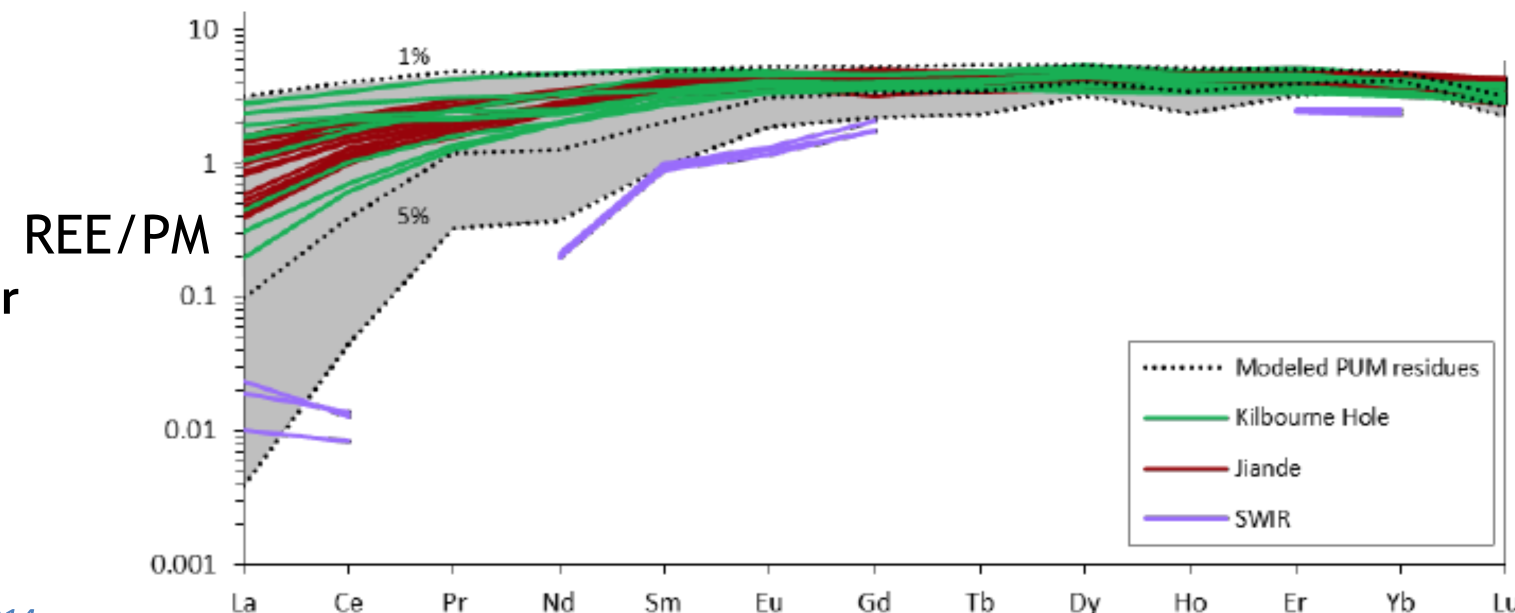
Skogby & Co 2006-2015; Peslier & Co 2002- 2015-Unpub; Demouchy & Co 2006-2016; Xia & Co 2004-2015 ; Stalder et al 2005; Schmädicke-Göse 2009-2015; Warren & Hauri 2014

Water in the lithosphere



✧ **Least metasomatized peridotites**

✧ **Too high [H2O] for a degree of melting F**



Shaffer et al in preparation;
Hao et al 2014;Warren & Hauri 2014

Earth total water content

- Type of data
- Water in the mantle
  - Definition
  - Importance
  - Distribution & controls
    - H diffusion
    - Water in the continental mantle lithosphere
    - Water in the lithosphere
    - **Water in the oceanic lithosphere**
- The big picture
  - Water in the Earth layers
  - Fluxes
- Comparison with other differentiated planetary bodies

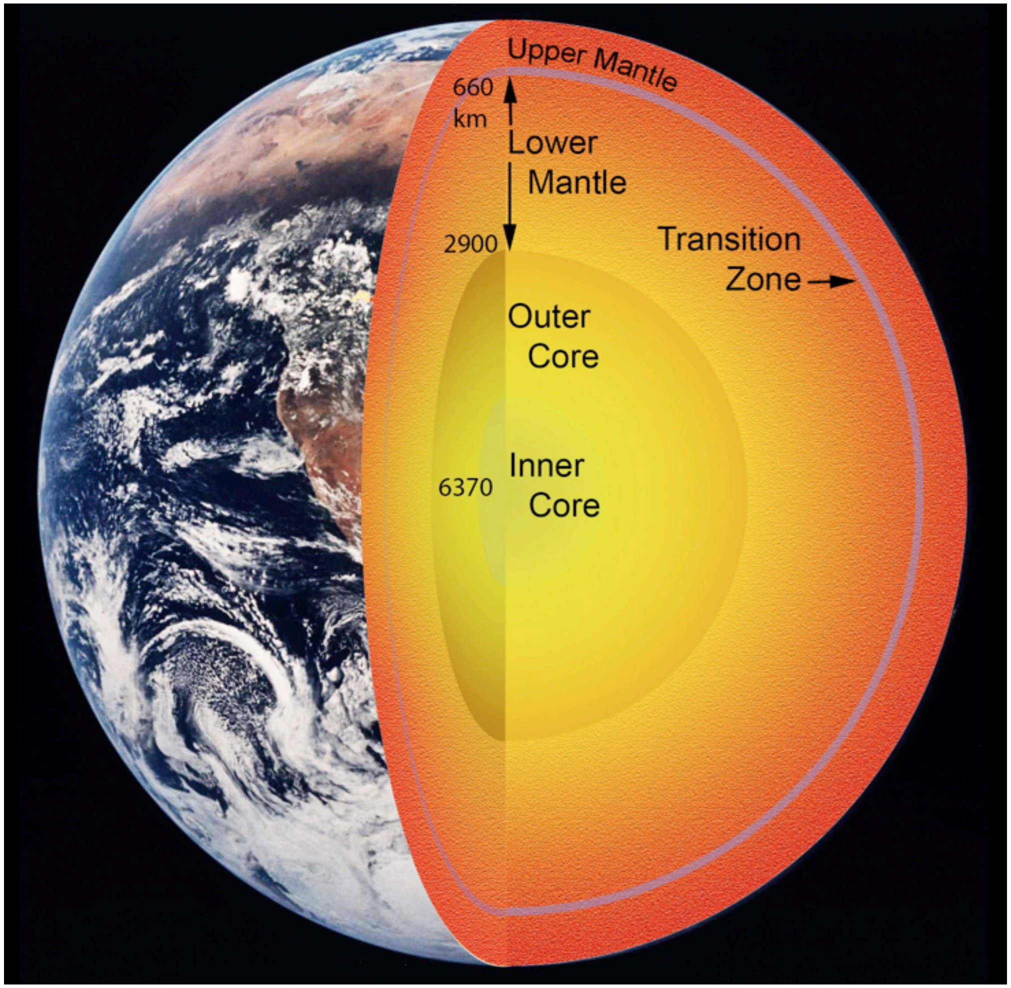
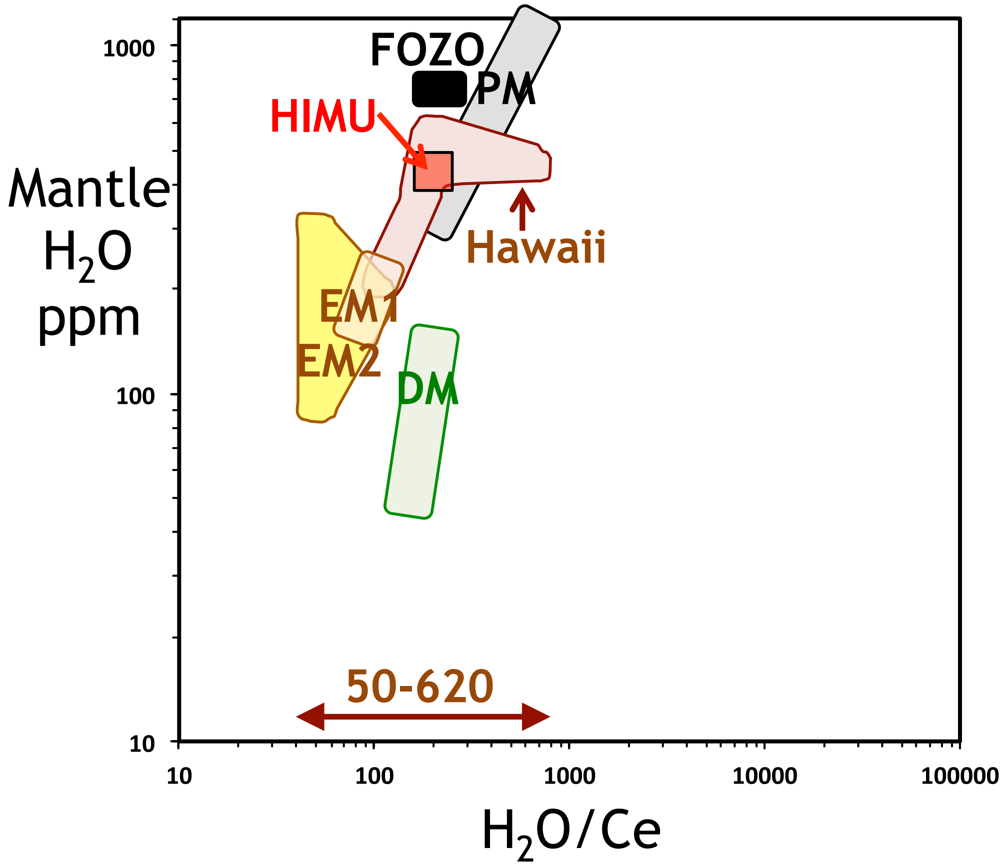


Image Credit: Japan Times

Water in the oceanic mantle



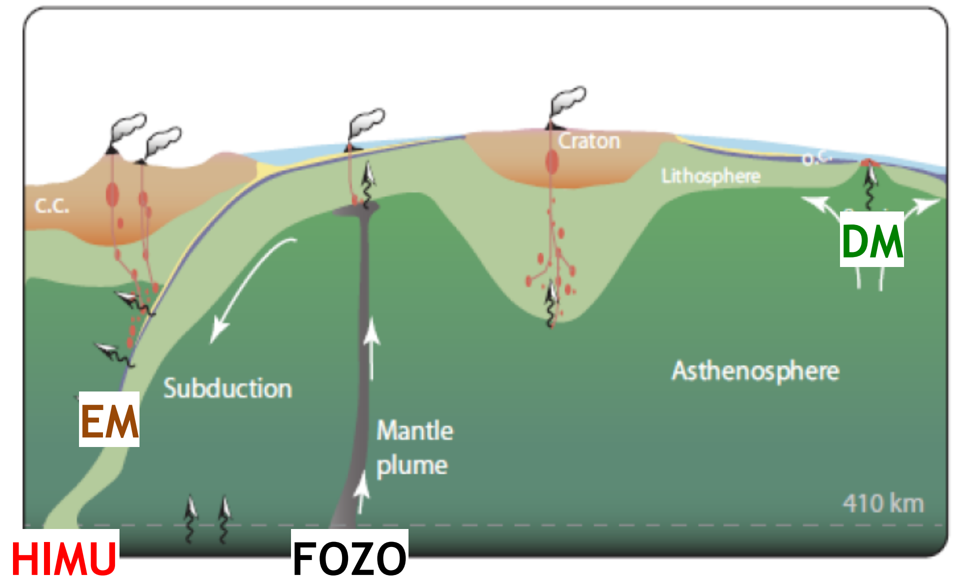
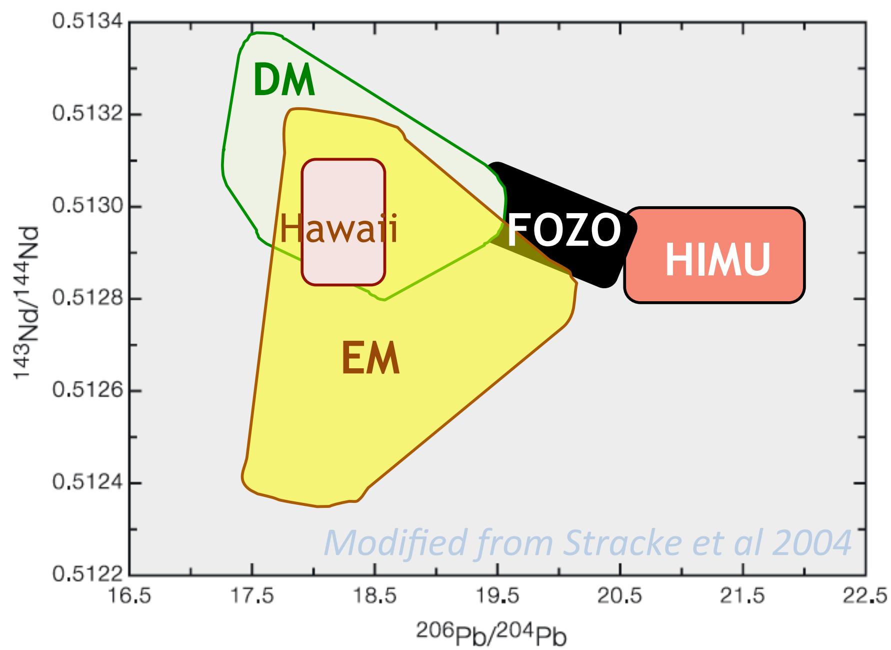


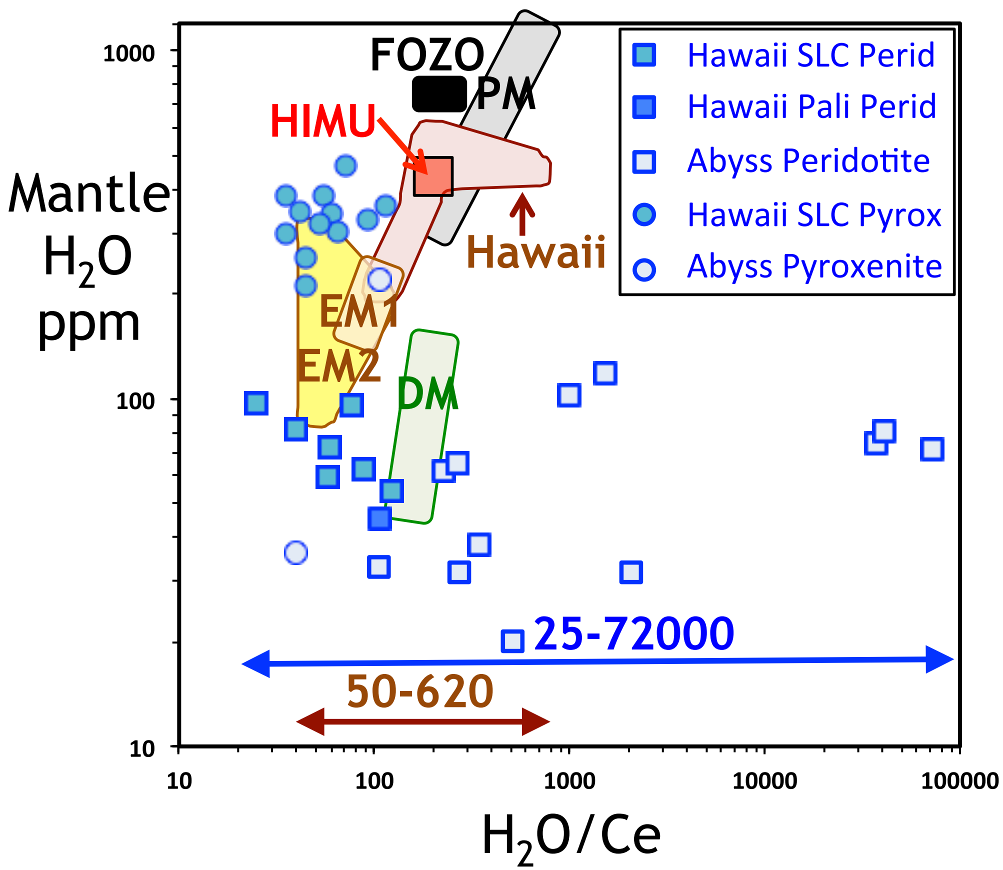
Image Credit: Demouchy & Bolfan-Casanova 2016



- **Water in melt inclusions & undegassed glasses**
- **Oceanic island basalts (OIB) have more water than MORB**
- **Oceanic basalts: water & Ce similarly incompatible**

McDonough & Sun 1995; Palme & O'Neill 2007; Dixon et al 2001-08; Salters & Stracke 2004; Cabral et al. 2014; Workman et al. 2004-06; Kendrick et al. 2014-15; Jackson et al. 2007, 2015; Métrich et al. 2014; Seaman et al. 2004

Water in the oceanic mantle



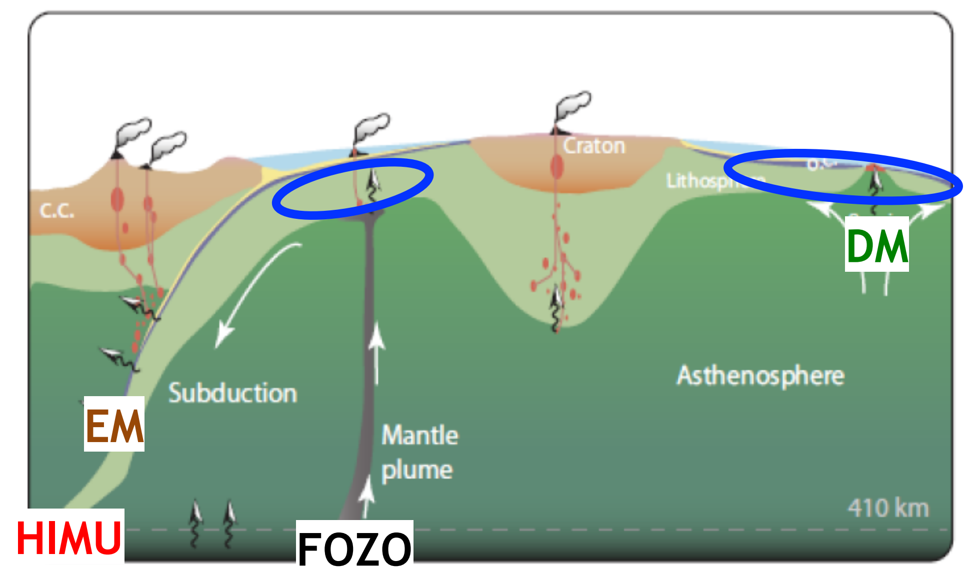
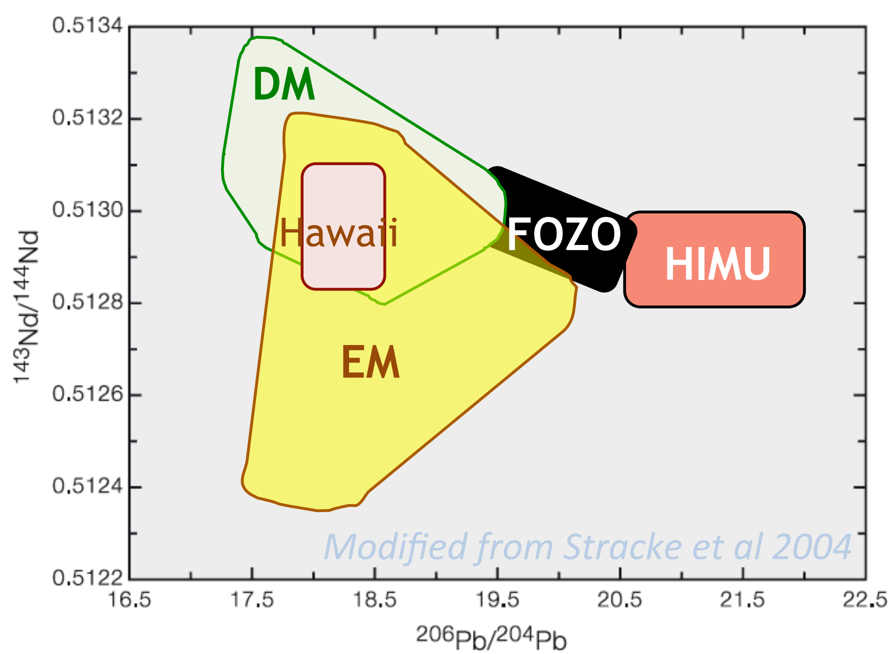


Image Credit: Demouchy & Bolfan-Casanova 2016

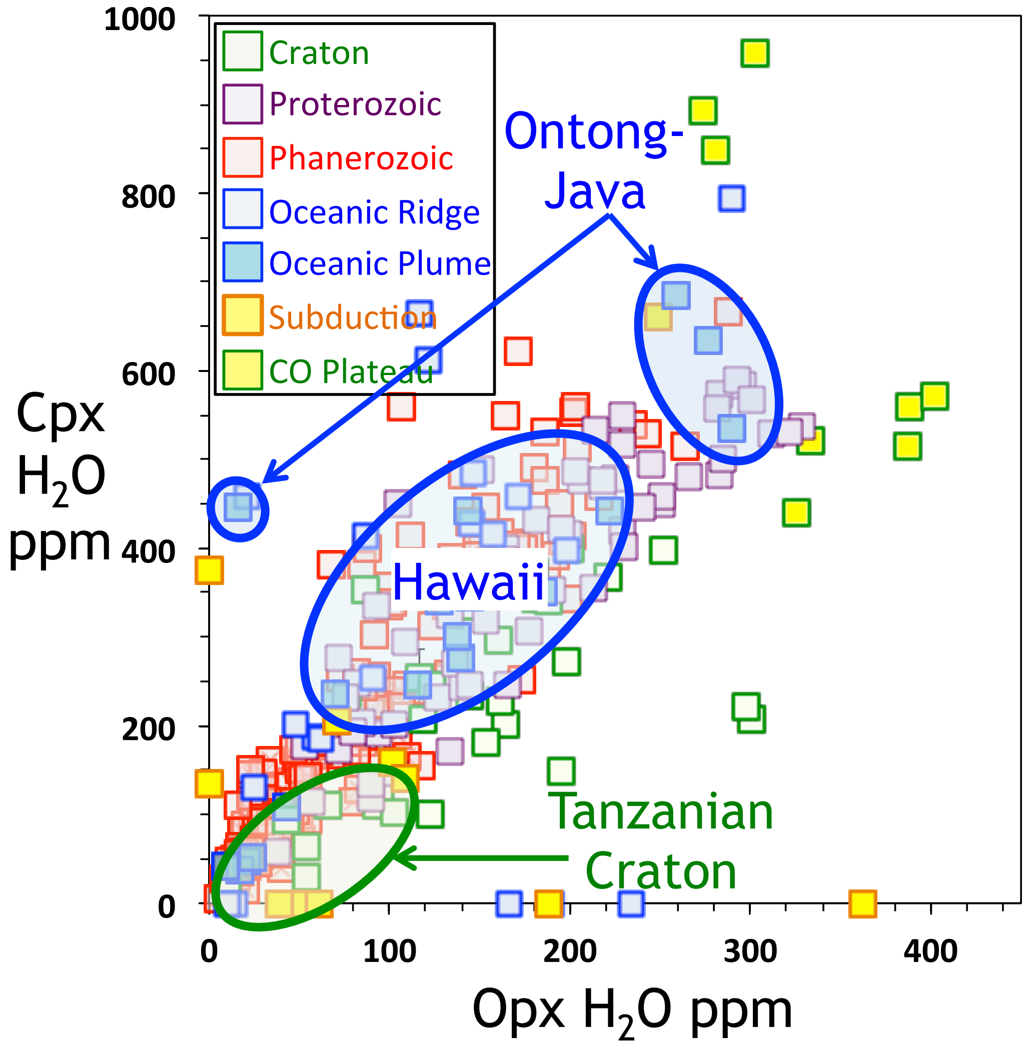


- **Oceanic basalts: water & Ce similarly incompatible**
- **Oceanic peridotites: water & Ce decoupled**

➔ **Large scale re-equilibration of water?**
➔ **Partition coefficient problem?**

McDonough & Sun 1995; Palme & O'Neill 2007; Dixon et al 2001-08; Salters & Stracke 2004; Cabral et al. 2014; Workman et al. 2004-06; Kendrick et al. 2014-15; Wallace 20024; Jackson et al. 2007, 2015; Métrich et al. 2014; Seaman et al. 2004; Peslier & Bizimis, 2015; Bizimis & Peslier 2015; Warren & Hauri, 2014; Peslier et al unpublished

Plume-lithosphere interaction



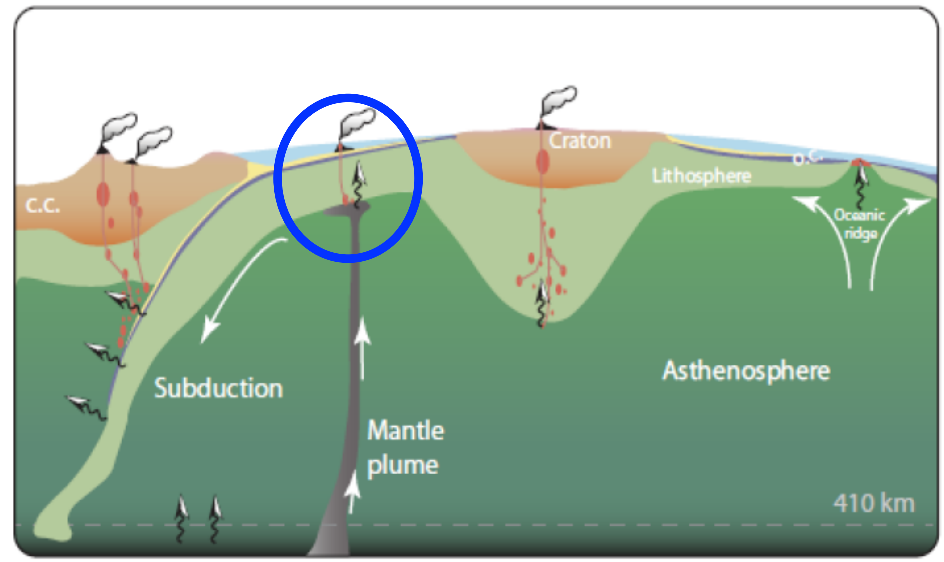


Image Credit: Demouchy & Bolfan-Casanova 2016

- **Similar [H_2O] for all tectonic settings**
- **Subduction peridotite not more wet (except CO Plateau)**
- **Plume interaction (Hawaii, Ontong-Java, Tanz craton) lithosphere not more wet**

Skogby & Co 2006-2015; Peslier & Co 2002- 2015-Unpub; Demouchy & Co 2006-2016; Xia & Co 2004-2015 ; Stalder et al 2005; Schmädicke-Göse 2009-2015; Warren & Hauri 2014; Peslier & Bizimis 2015; Bizimis & Peslier 2015; Hui et al 2015

Earth total water content

- Type of data
- Water in the mantle
  - Definition
  - Importance
  - Distribution & controls
    - H diffusion
    - Water in the continental mantle lithosphere
    - Water in the lithosphere
    - Water in the oceanic lithosphere
- **The big picture**
  - **Water in the Earth layers**
  - Fluxes
- Comparison with other differentiated planetary bodies

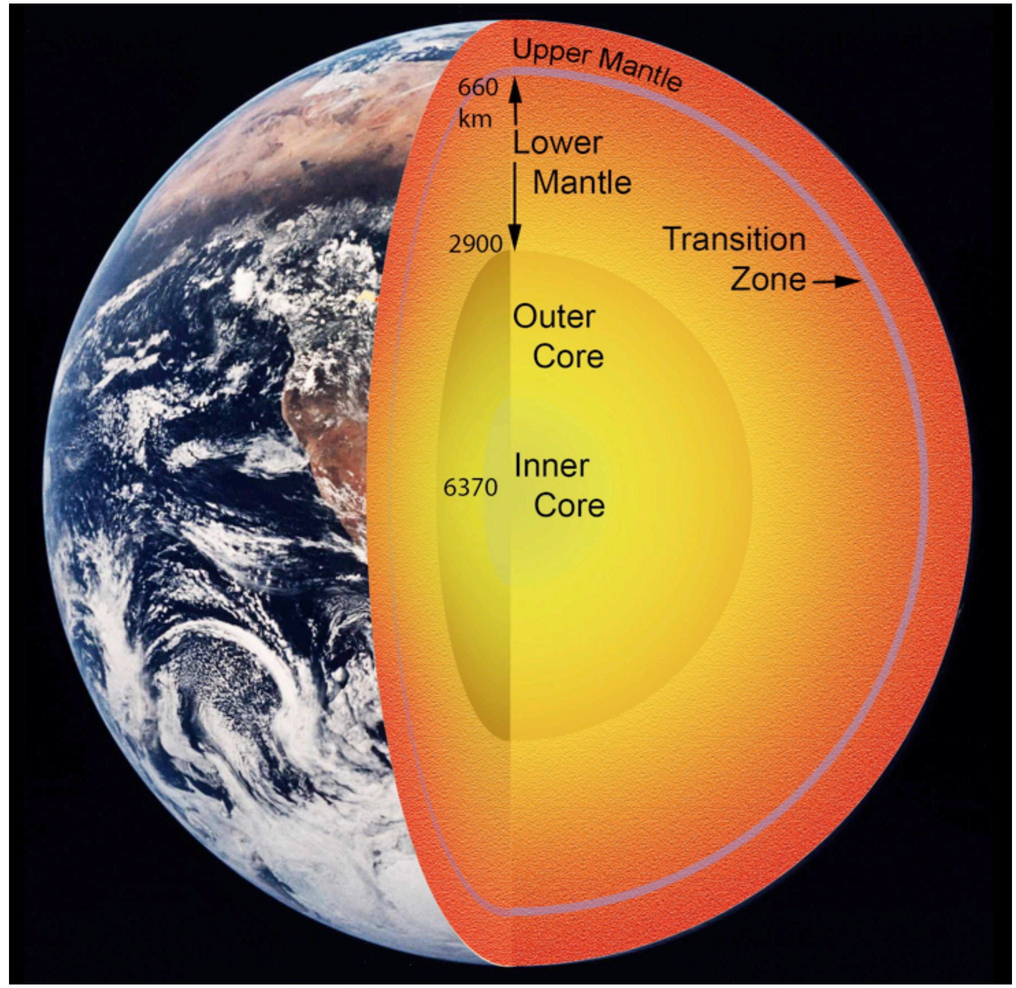


Image Credit: Japan Times

How much water in the Earth?

INTERNATIONAL GEOLOGY REVIEW
http://dx.doi.org/10.1080/00206814.2015.1056758
Taylor & Francis
Taylor & Francis Group

REVIEW ARTICLE

Diamonds and water in the deep Earth: a new scenario

Fabrizio Nestola[a] and Joseph R. Smyth[b]

[a]Dipartimento di Geoscienze, Università di Padova, I-35131 Padova, Italy; [b]Department of Geological Science, University of Colorado, Boulder CO 80309, USA

ABSTRACT
Earth is a water planet, but how much water exists on and in the Earth? Is the water limited to the Earth's surface and limited depths of our planet (molecular water of the hydrosphere), or do deep reservoirs of hydrogen and oxygen really exist as proposed in recent works but not yet proven? Due to the importance of H_2O for life and geological processes on the Earth, these questions are among the most significant in all of the Earth sciences. Water must be present in the deep Earth as plate tectonics could not work without water as a major driving force that lowers both viscosity and density of the solid mineral phases of the interior and controls the onset of melting. On subduction, water is returned to the hydrosphere first by dewatering of hydrous phases and second by melting and arc magmatism in and above the subducting slab. The mantle is composed of oxygen minerals, and the extent to which hydrogen is dissolved in them constitutes the true reservoir of the planet's water. Are 'deep water and diamonds' intimately related as indicated in the title of the present article? What is the connection between these two important terrestrial materials? The necessity to review this issue arises from the recent discovery of a strongly hydrous ringwoodite in a Brazilian diamond. As ringwoodite constitutes 60% or more of the lower part of the transition zone, between 525 and 660 km depth, this could correspond to a huge amount of water in this region, comparable or greater in mass to all of Earth's hydrosphere. If the water found in this ringwoodite is representative of the water concentrations of the transition zone, then estimates of Earth's total water reservoir are in need of major revision. This work is an attempt at such a revision.

ARTICLE HISTORY
Received 5 April 2015
Accepted 27 May 2015

KEYWORDS
diamond; water; Earth; reservoir; mantle

spe500-13 2nd pgs page 431

The Geological Society of America
Special Paper 500
2013

THE GEOLOGICAL SOCIETY OF AMERICA® 1888 125 Years 2013
CELEBRATING ADVANCES IN GEOSCIENCE

Whole Earth geohydrologic cycle, from the clouds to the core: The distribution of water in the dynamic Earth system

Robert J. Bodnar*
Tristan Azbej*
Stephen P. Becker*
Claudia Cannatelli*
András Fall*
Matthew J. Severs*
Fluids Research Laboratory, Department of Geosciences, Virginia Tech, Blacksburg, Virginia 24061, USA

Icarus 248 (2015) 89–108

Contents lists available at ScienceDirect
Icarus
journal homepage: www.elsevier.com/locate/icarus
ELSEVIER
ICARUS

Accretion and differentiation of the terrestrial planets with implications for the compositions of early-formed Solar System bodies and accretion of water

CrossMark

D.C. Rubie [a,*], S.A. Jacobson [a,b], A. Morbidelli [b], D.P. O'Brien [c], E.D. Young [d], J. de Vries [a], F. Nimmo [e], H. Palme [f], D.J. Frost [a]

[a] *Bayerisches Geoinstitut, University of Bayreuth, D-95490 Bayreuth, Germany*
[b] *Laboratoire Lagrange, Universite' de Nice - Sophia Antipolis, Observatoire de la Cote d'Azur, CNRS, 06304 Nice, France*
[c] *Planetary Science Institute, 1700 E. Ft. Lowell, Suite 106, Tucson, AZ 85719, USA*
[d] *Dept. of Earth, Planetary, and Space Sciences, UCLA, Los Angeles, CA 90095, USA*
[e] *Dept. of Earth & Planetary Sciences, UC Santa Cruz, CA 95064, USA*
[f] *Forschungsinstitut und Naturmuseum Senckenberg, 60325 Frankfurt am Main, Germany*

Chemical Geology 418 (2015) 6–15

Contents lists available at ScienceDirect
Chemical Geology
journal homepage: www.elsevier.com/locate/chemgeo
ELSEVIER
CHEMICAL GEOLOGY

Hydrous minerals and the storage of water in the deep mantle

CrossMark

Eiji Ohtani *

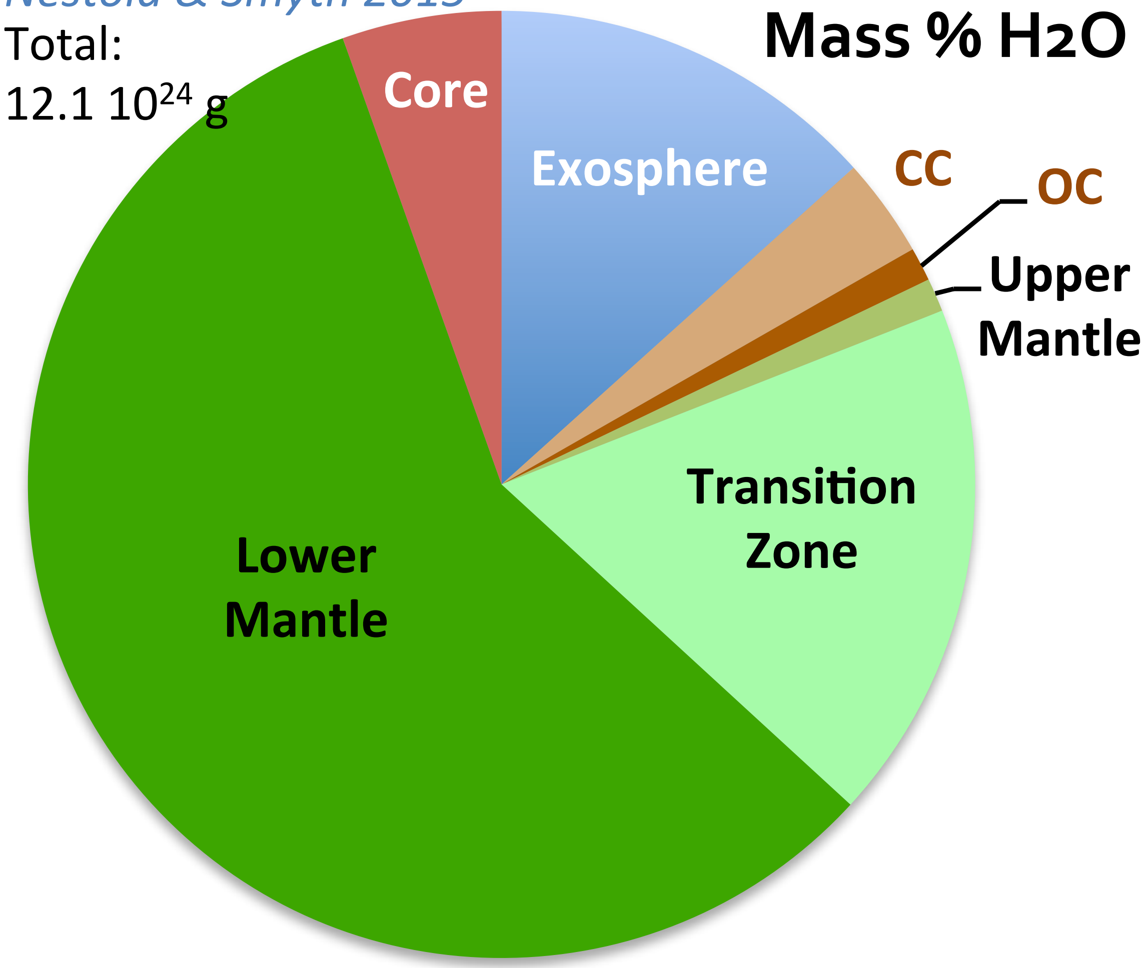
Department of Earth Science, Graduate School of Science, Tohoku University, Sendai, 980-8578, Japan
V.S. Sobolev Institute of Geology and Mineralogy, Siberian Branch, Russian Academy of Sciences, Novosibirsk, 630090, Russia

How much water in the Earth?

Nestola & Smyth 2015

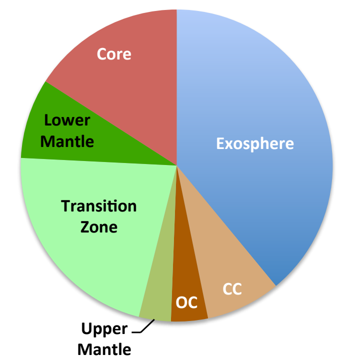
Total:
12.1 10^{24} g

Mass % H_2O



Bodnar et al 2013

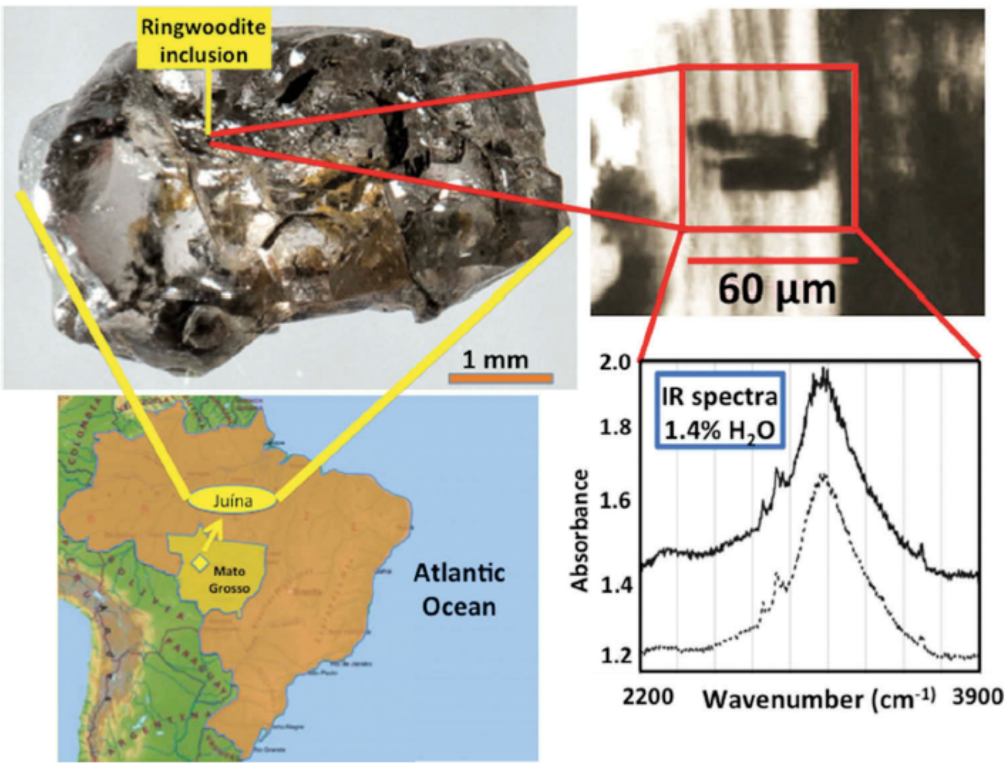
Total: 3.61 10^{24} g



How much water in the Earth?

✧ **Transition zone**: probably wet

- High [H_2O] in ringwoodite, wadsleyite and majorite from exp *(Inoue, Smyth, Ohtani, Demouchy, Bolfan-Casanova)*
- Phase Egg ($AlSiO_3(OH)$) & hydrous ringwoodite as diamond inclusions *(Wirth et al 2007; Pearson et al 2014)*
- Consistent with electrical conductivity & seismic tomography *(Karato 2001, Yoshino 2010, Koyama et al 2006)*



✧ Slab stagnation (Okino et al 1989, van der Hilst et al 1991-93, Fukao et al 1992, 2009)

✧ TZ water filter (Bercovici & Karato 2003)

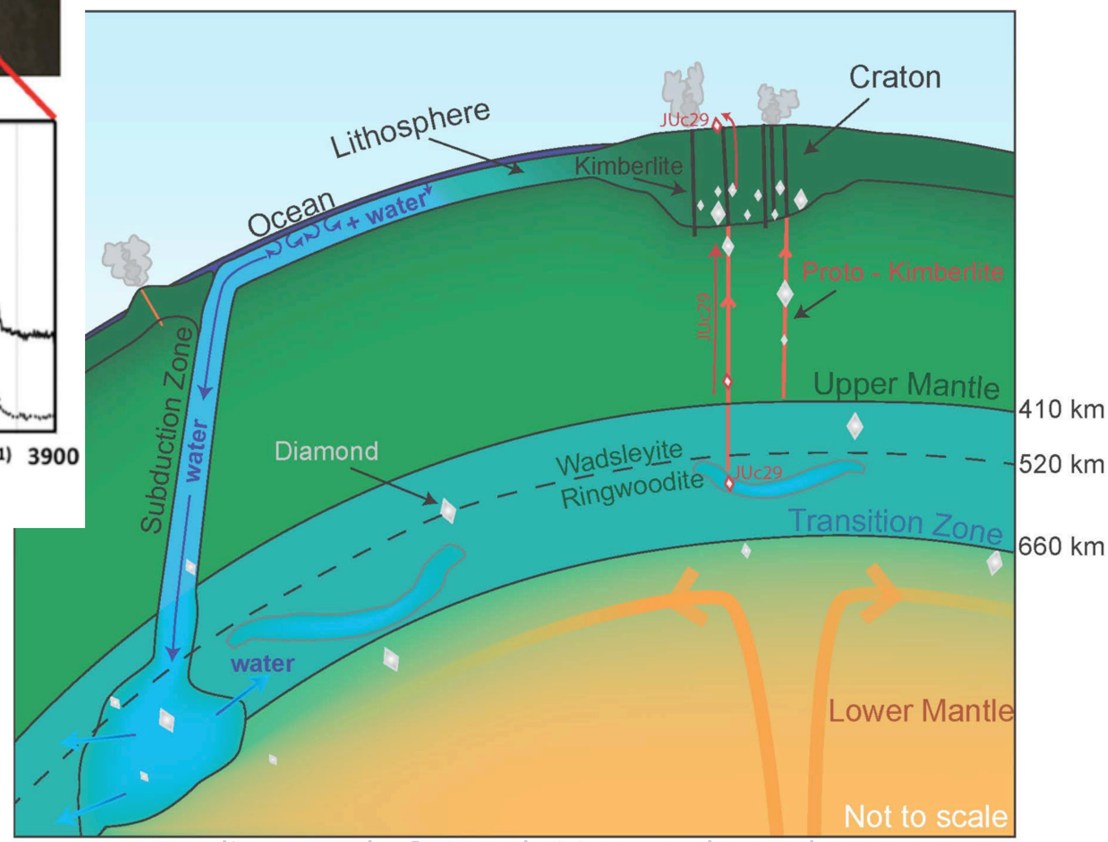


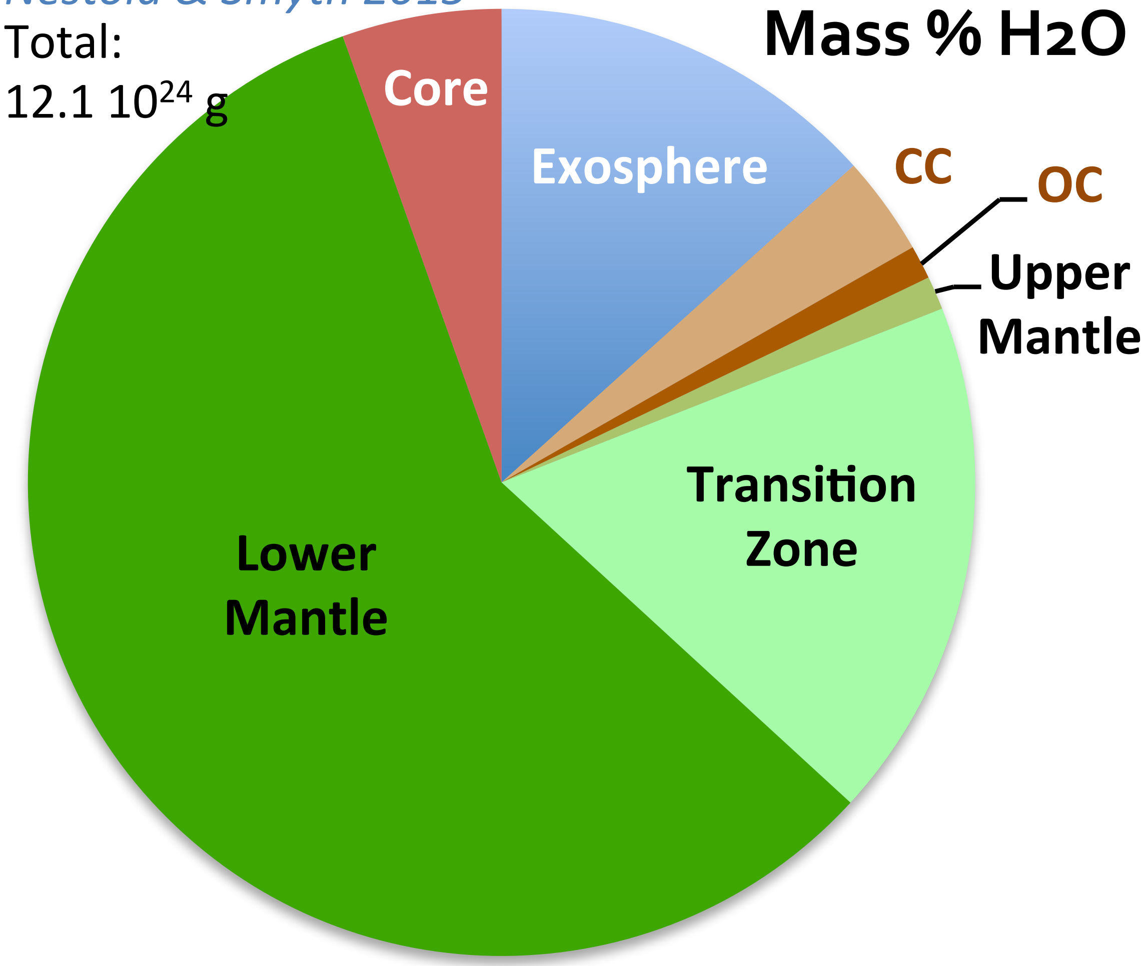
Image Credit: Nestola & Smyth 2015, Kathy Maher

How much water in the Earth?

Nestola & Smyth 2015

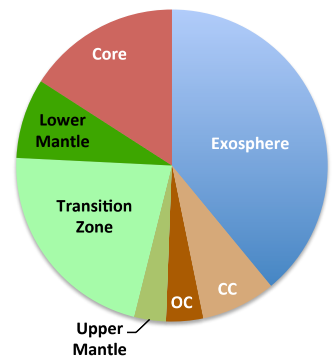
Total:
12.1 10^{24} g

Mass % H_2O



Bodnar et al 2013

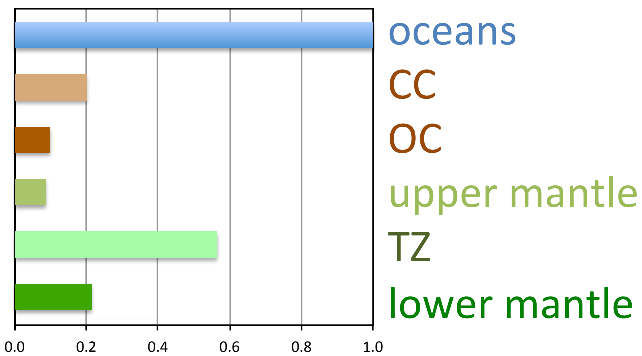
Total: 3.61 10^{24} g



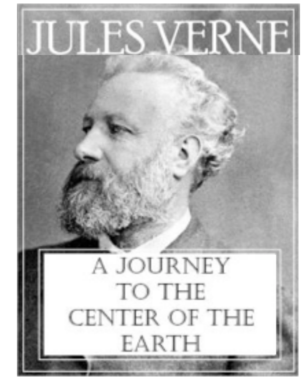
- ✧ TZ: - uncertainty on [H_2O] of ringwoodite, wadsleyite and majorite
  - Phase Egg & hydrous ringwoodite as diamond inclusions *(Wirth et al 07, Pearson et al 14)*
- ✧ Lower mantle: - uncertainty on [H_2O] of bridgmanite *(Meade, Bolfan-Casanova, Litasov, Murakami...)*
- ✧ Back to problem of storage capacity (exp) vs actual water content
- ✧ Uncertainty on amount of hydrous phases (B, Egg, D, H, δ-AlOOH) *(Ohtani, Ghosh, Walter)*

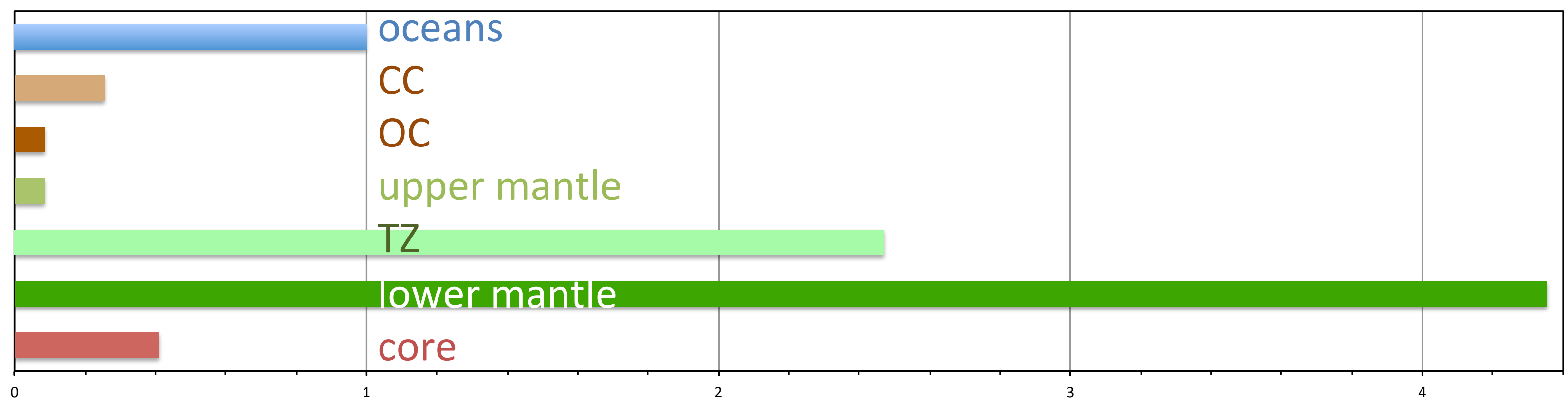
How much water in the Earth?

X mass oceans

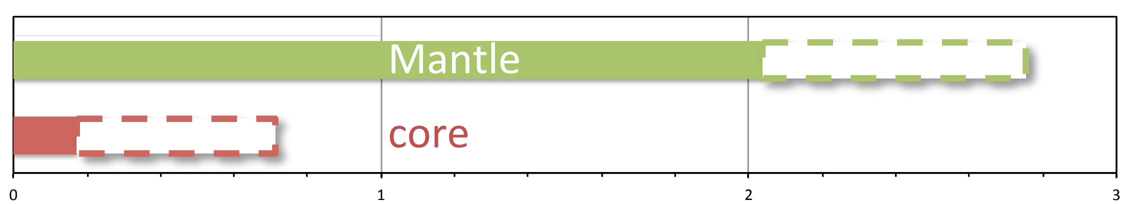


Bodnar et al 2013





Nestola & Smyth 2015



Rubie et al 2015

From accretion models

Earth total water content

- ✧ Type of data
- ✧ Water in the mantle
  - ✧ Definition
  - ✧ Importance
  - ✧ Distribution & controls
    - ✧ H diffusion
    - ✧ Water in the continental mantle lithosphere
    - ✧ Water in the lithosphere
    - ✧ Water in the oceanic lithosphere
- ✧ The big picture
  - ✧ Water in the Earth layers
  - ✧ **Fluxes**
- ✧ Comparison with other differentiated planetary bodies

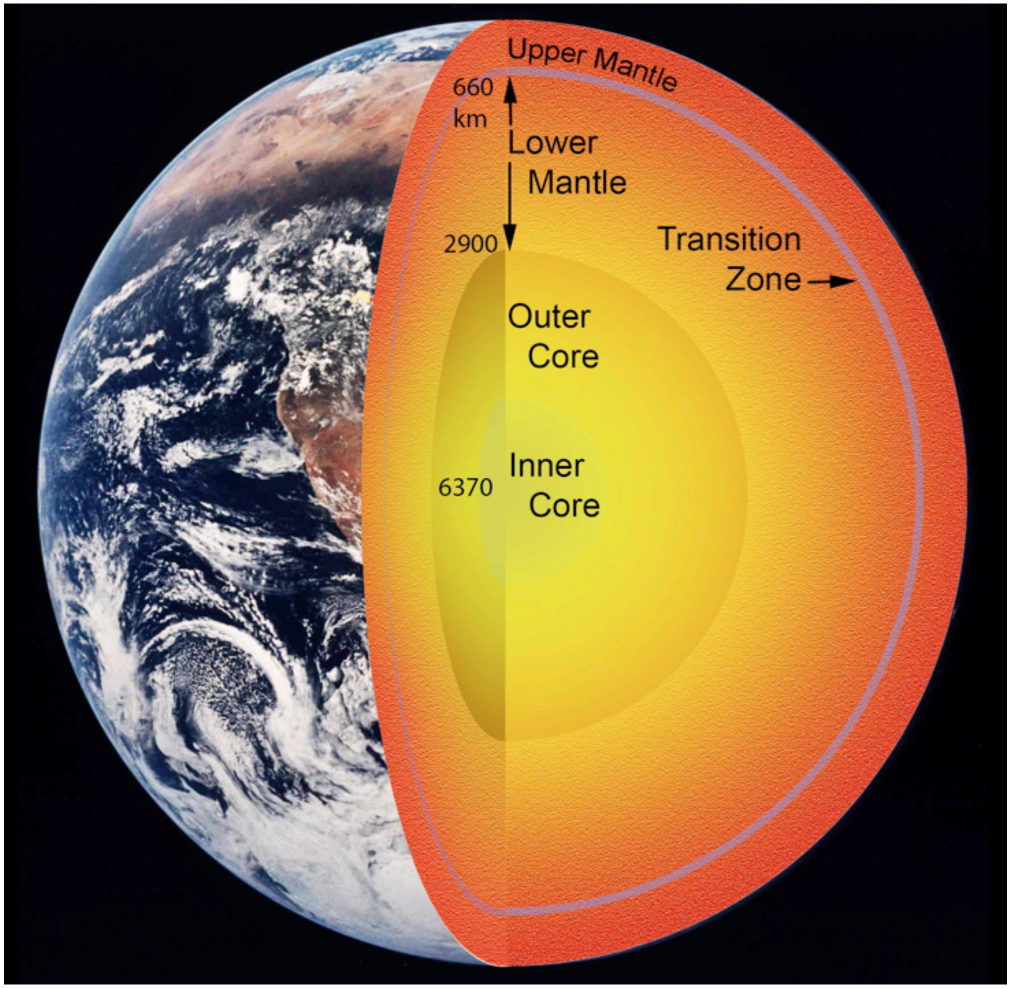


Image Credit: Japan Times

Water deep cycle in the Earth

Fluxes in 10^{11} kg/year

Oceans: 1.4×10^{21} kg
10^{11} kg = 7 ppb oceans

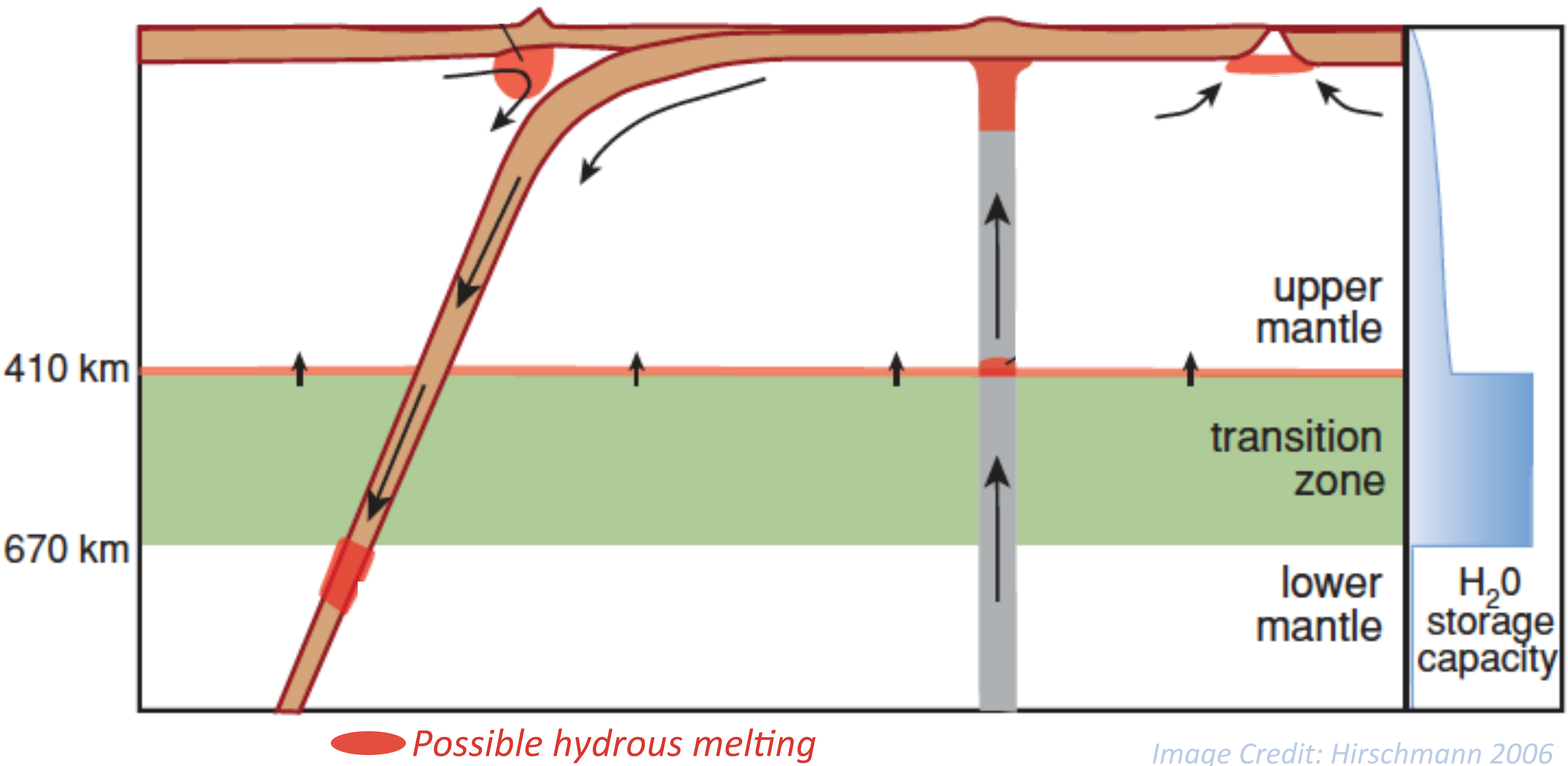
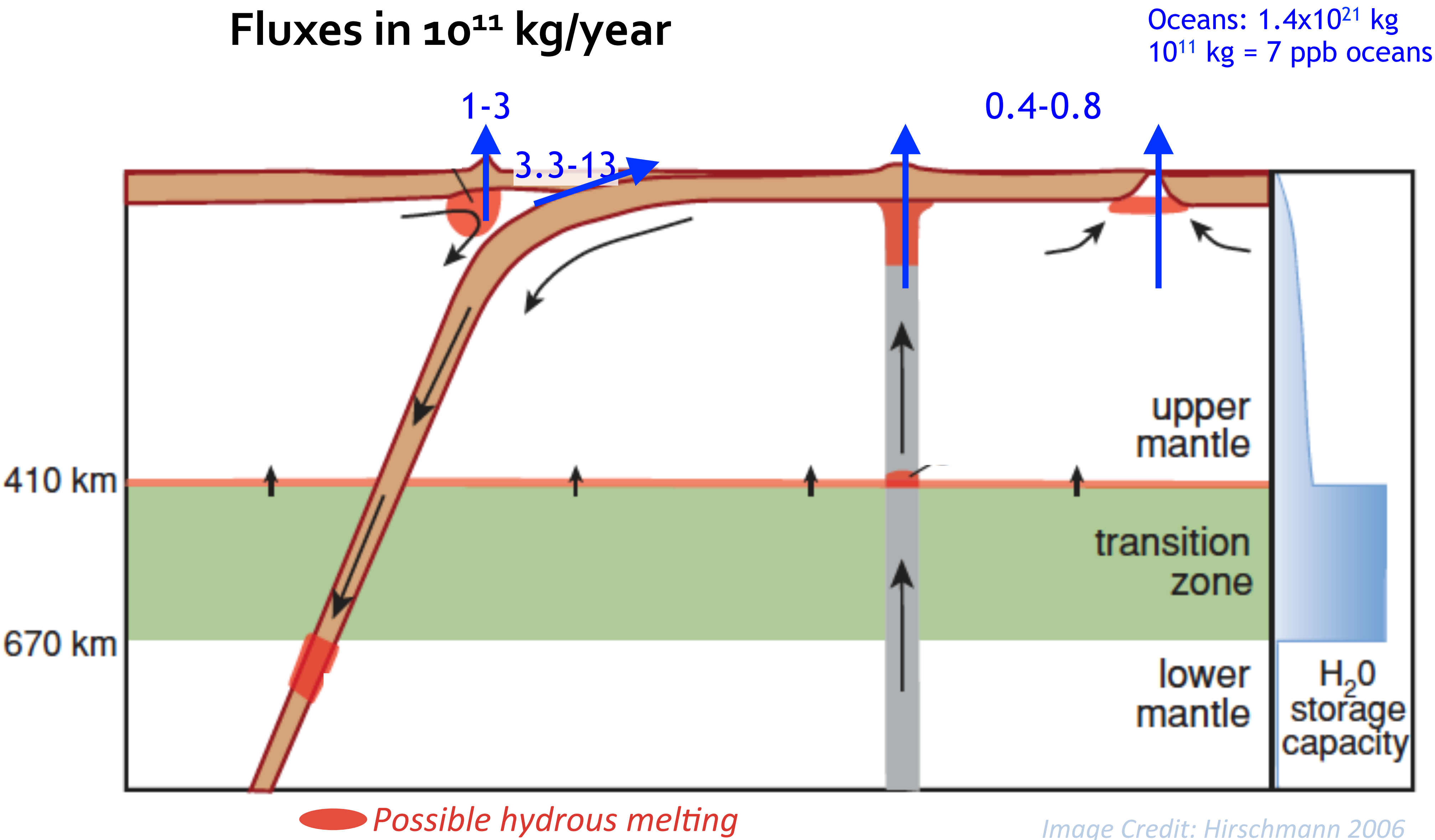


Image Credit: Hirschmann 2006

Peacock 1990; Wallmann 2001; Hilton et al 2002; Jarrad 2003; Bercovici & Karato 2003; Wallace 2005; Rüpke et al 2006; van Keken et al 2011; Parai & Mukhopadhyay 2012; Bodnar et al 2013

Water deep cycle in the Earth

Fluxes in 10^{11} kg/year



Peacock 1990; Wallmann 2001; Hilton et al 2002; Jarrad 2003; Bercovici & Karato 2003; Wallace 2005; Rüpke et al 2006; van Keken et al 2011; Parai & Mukhopadhyay 2012; Bodnar et al 2013

Water deep cycle in the Earth

Fluxes in 10^{11} kg/year

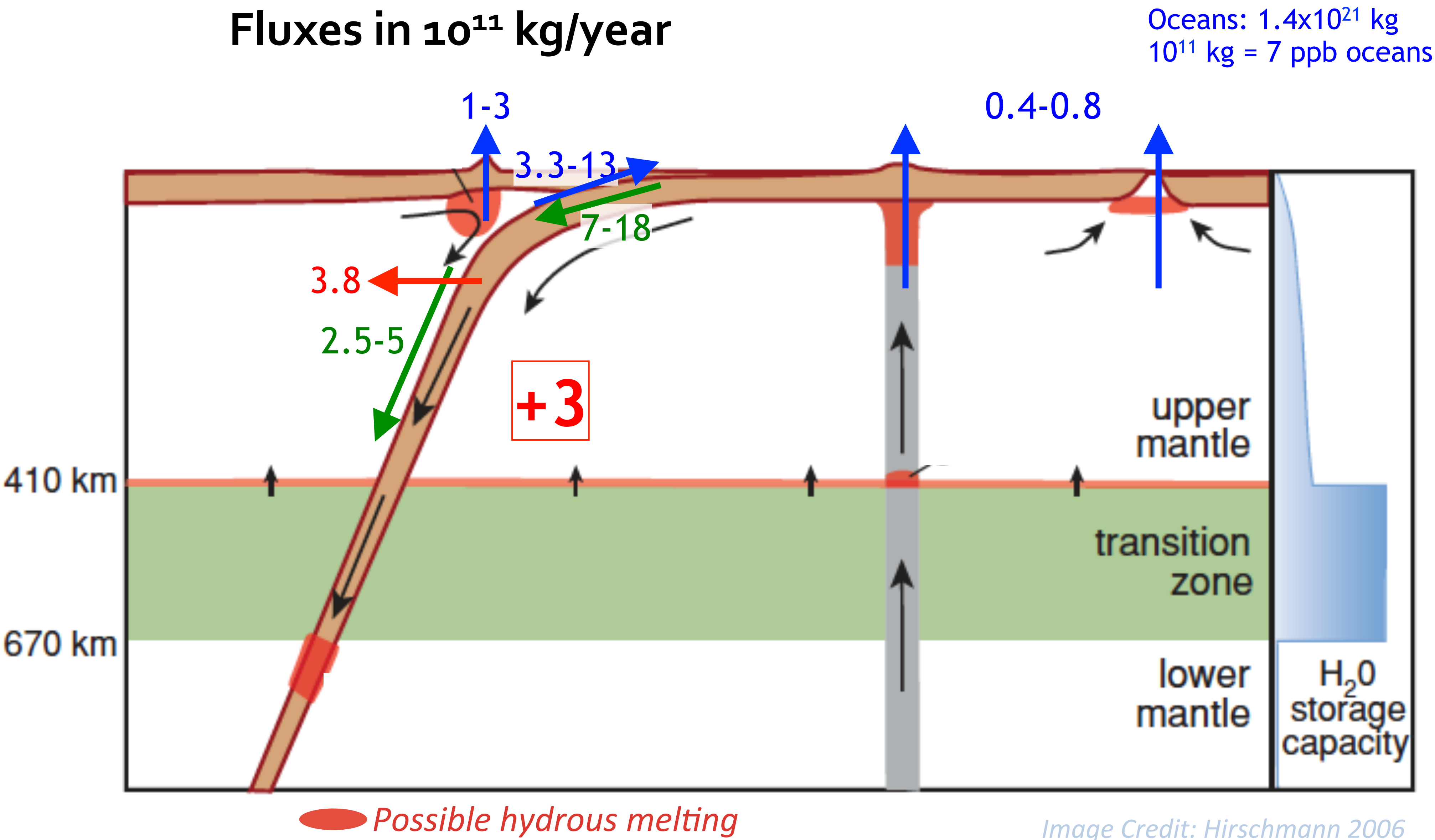
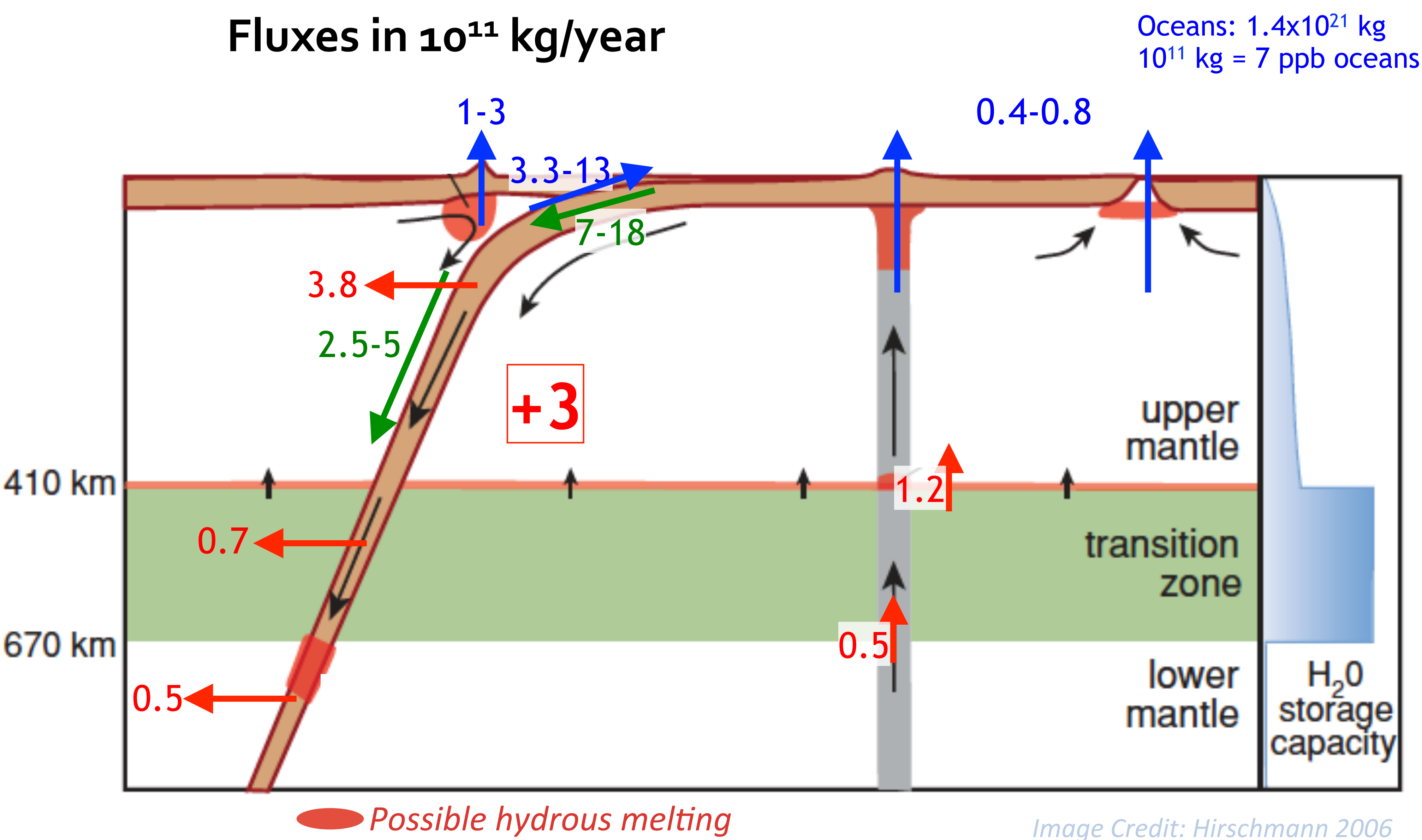


Image Credit: Hirschmann 2006

Peacock 1990; Wallmann 2001; Hilton et al 2002; Jarrad 2003; Bercovici & Karato 2003; Wallace 2005; Rüpke et al 2006; van Keken et al 2011; Parai & Mukhopadhyay 2012; Bodnar et al 2013

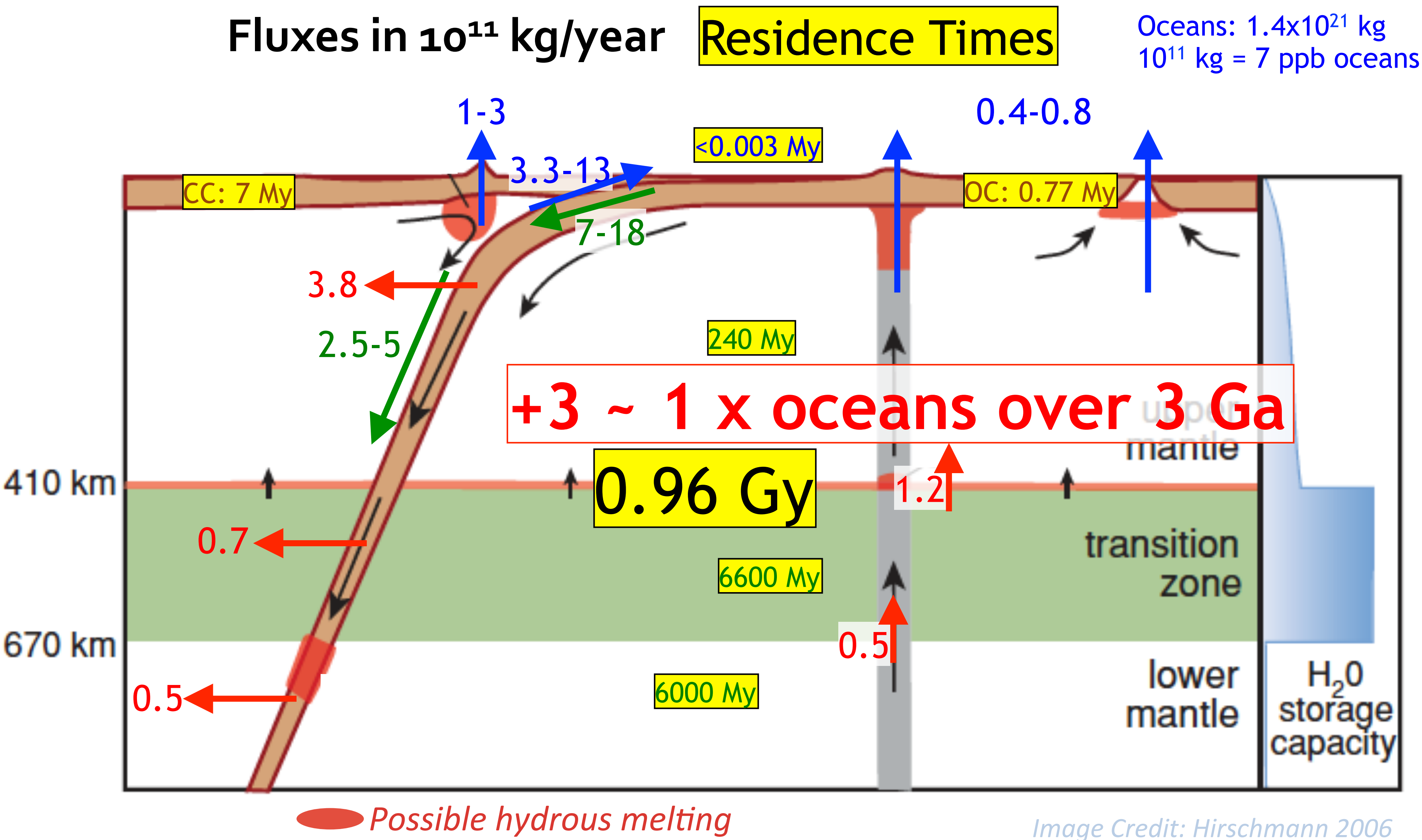
Water deep cycle in the Earth

Fluxes in 10^{11} kg/year



Peacock 1990; Wallmann 2001; Hilton et al 2002; Jarrad 2003; Bercovici & Karato 2003; Wallace 2005; Rüpke et al 2006; van Keken et al 2011; Parai & Mukhopadhyay 2012; Bodnar et al 2013

Water deep cycle in the Earth



Peacock 1990; Wallmann 2001; Hilton et al 2002; Jarrad 2003; Bercovici & Karato 2003; Wallace 2005; Rüpke et al 2006; van Keken et al 2011; Parai & Mukhopadhyay 2012; Bodnar et al 2013

Earth total water content

- Type of data
- Water in the mantle
  - Definition
  - Importance
  - Distribution & controls
    - H diffusion
    - Water in the continental mantle lithosphere
    - Water in the lithosphere
    - Water in the oceanic lithosphere
- The big picture
  - Water in the Earth layers
  - Fluxes
- **Comparison with other differentiated planetary bodies**

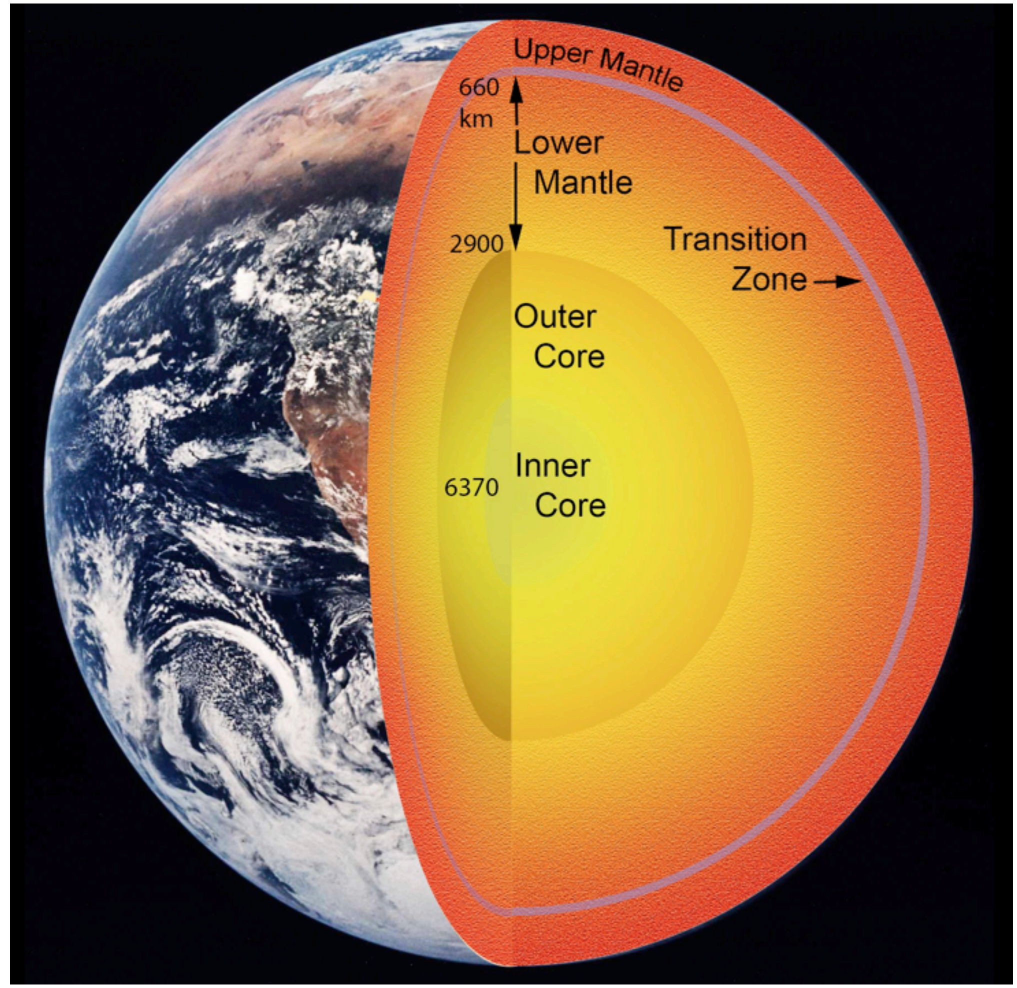
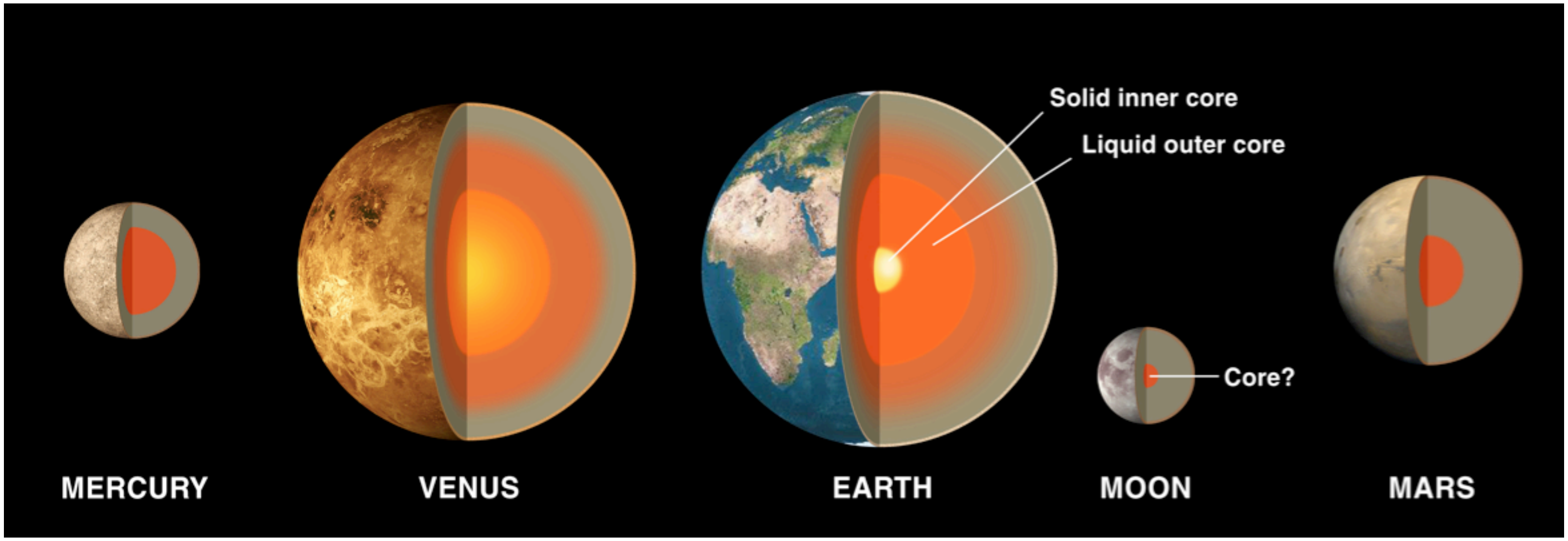
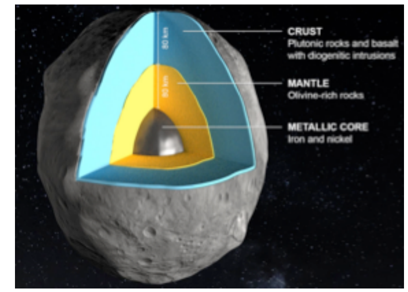


Image Credit: Japan Times

Water in the inner solar system



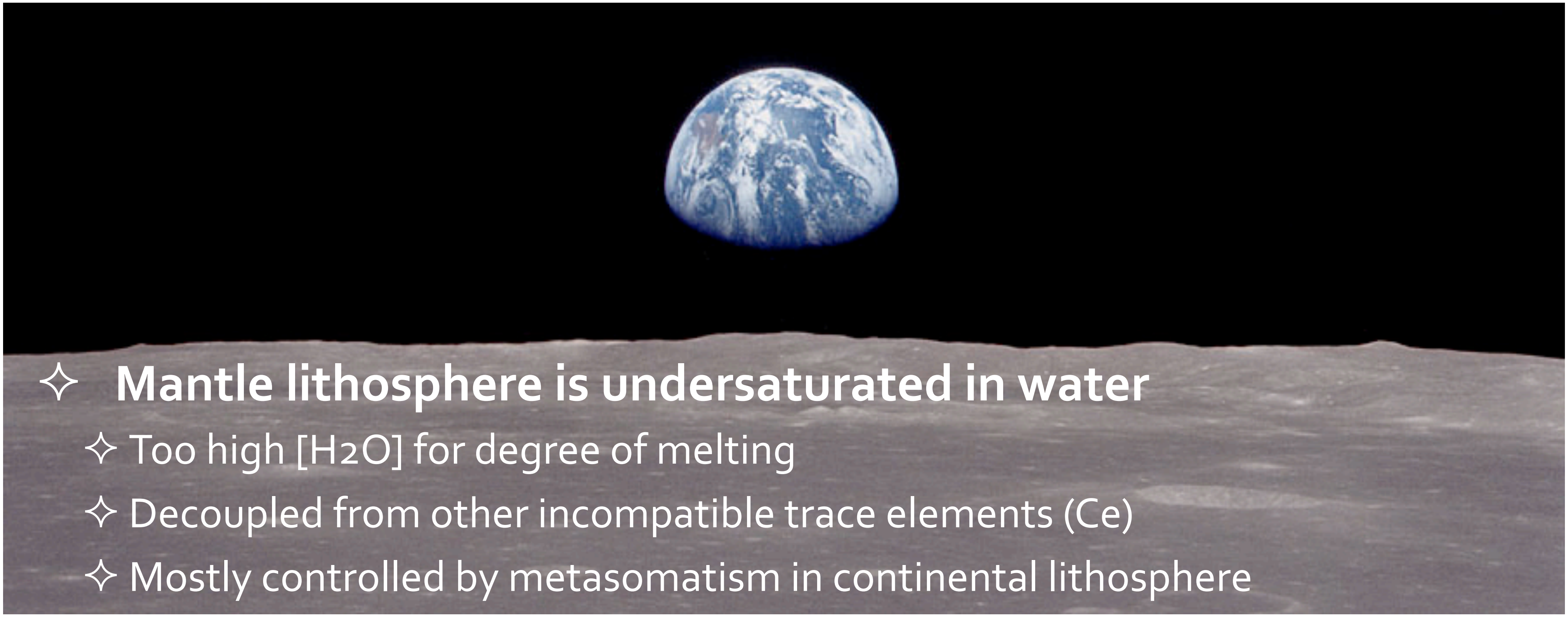


VESTA

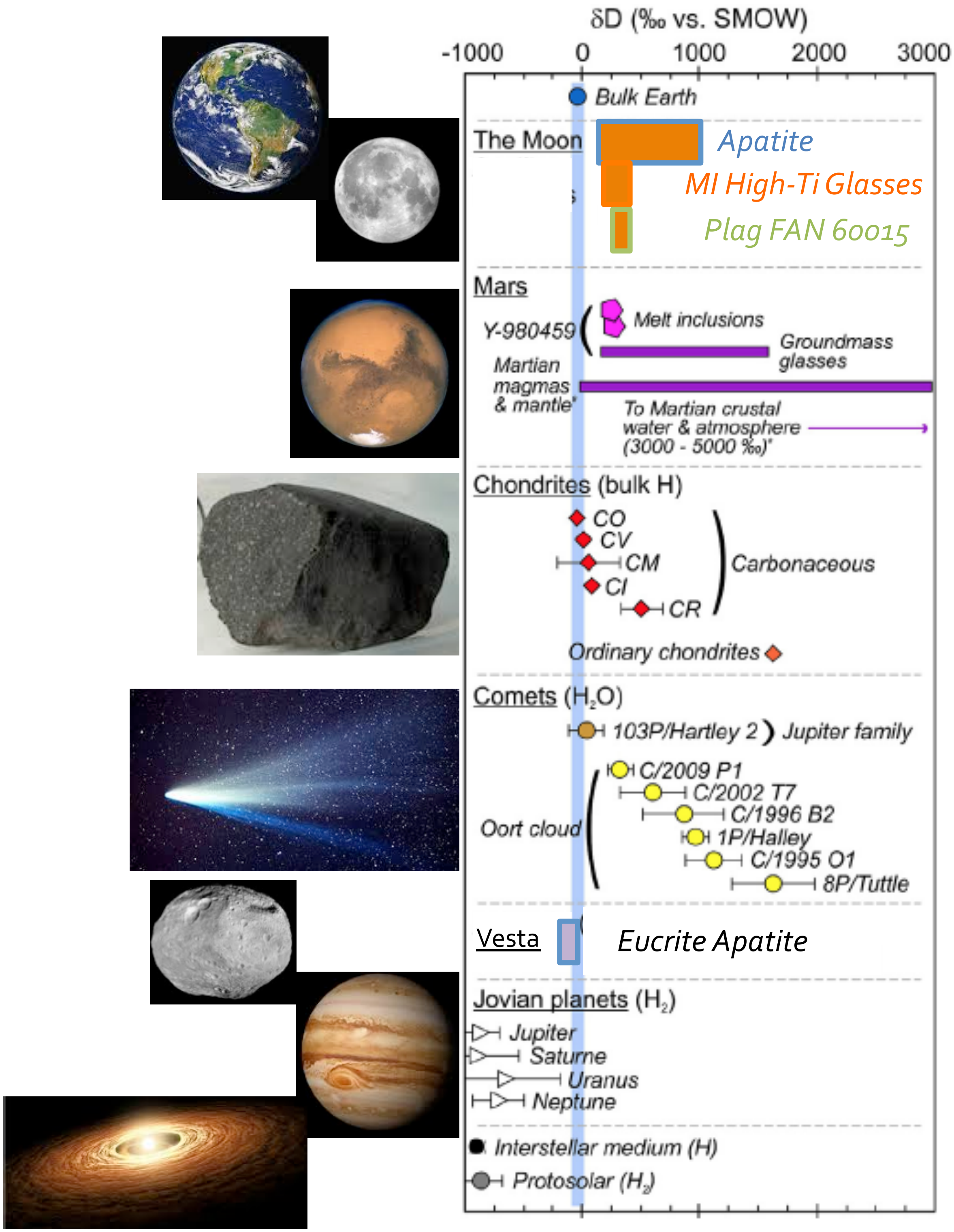
	Mercury	Venus	Earth	Moon	Mars	Vesta
Upper mantle ppm H_2O from samples	?	?	**150-350**	**5-100** **160**(LMO)	**130-230**(Ch) **15-47**(Sh)	**>0?**
Mantle water from accretion models (**Mantle H_2O**-*Core H*)	**?**	**961**-*35*	**948**-*33*	**?**	**0-4769**-*4*	**?**
Origin	?	?	**CC**	**CC**	**CC**	**CC**

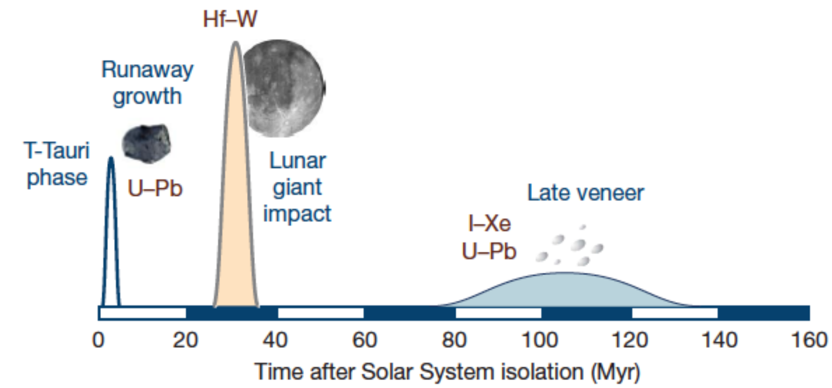
Albarède 2013; Marty 2012; Hauri et al. 2011; McCubbin et al. 2010; Usui et al. 2012; Sarafian et al. 2013-2014; Hui et al 2013; Peslier et al. 2015 ; Rubie 2015

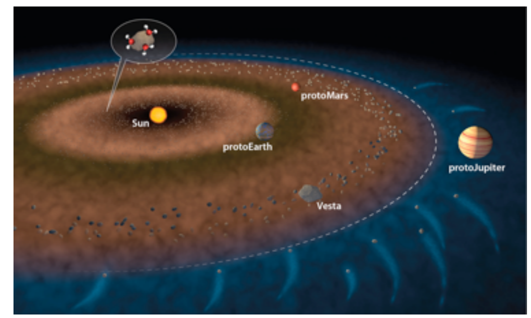
Conclusions



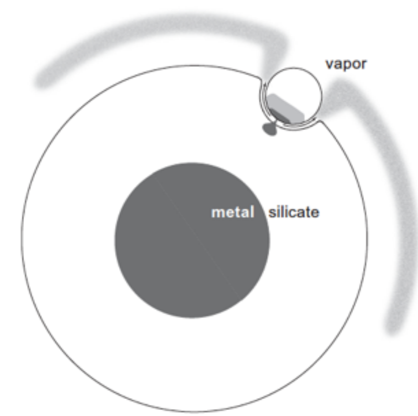
- ✧ **Mantle lithosphere is undersaturated in water**
  - ✧ Too high [H_2O] for degree of melting
  - ✧ Decoupled from other incompatible trace elements (Ce)
  - ✧ Mostly controlled by metasomatism in continental lithosphere
  - ✧ All tectonic settings have similar [H_2O]
- ✧ **The transition zone is rich in water**
- ✧ **Water content of lower mantle and core?**
- ✧ **Water deep cycle**
  - ✧ ~ 1 mass ocean re-added to mantle over 3 Ga
  - ✧ Residence time of water in Earth: ~ 1 Ga







or/and



Tartèse et al. 2013; Greenwood et al. 2011, Saal et al., 2013; Albarède et al., 2009, 2013; Sarafian et al., 2013-2014; Hui et al., 2015

Water deep cycle in the Earth

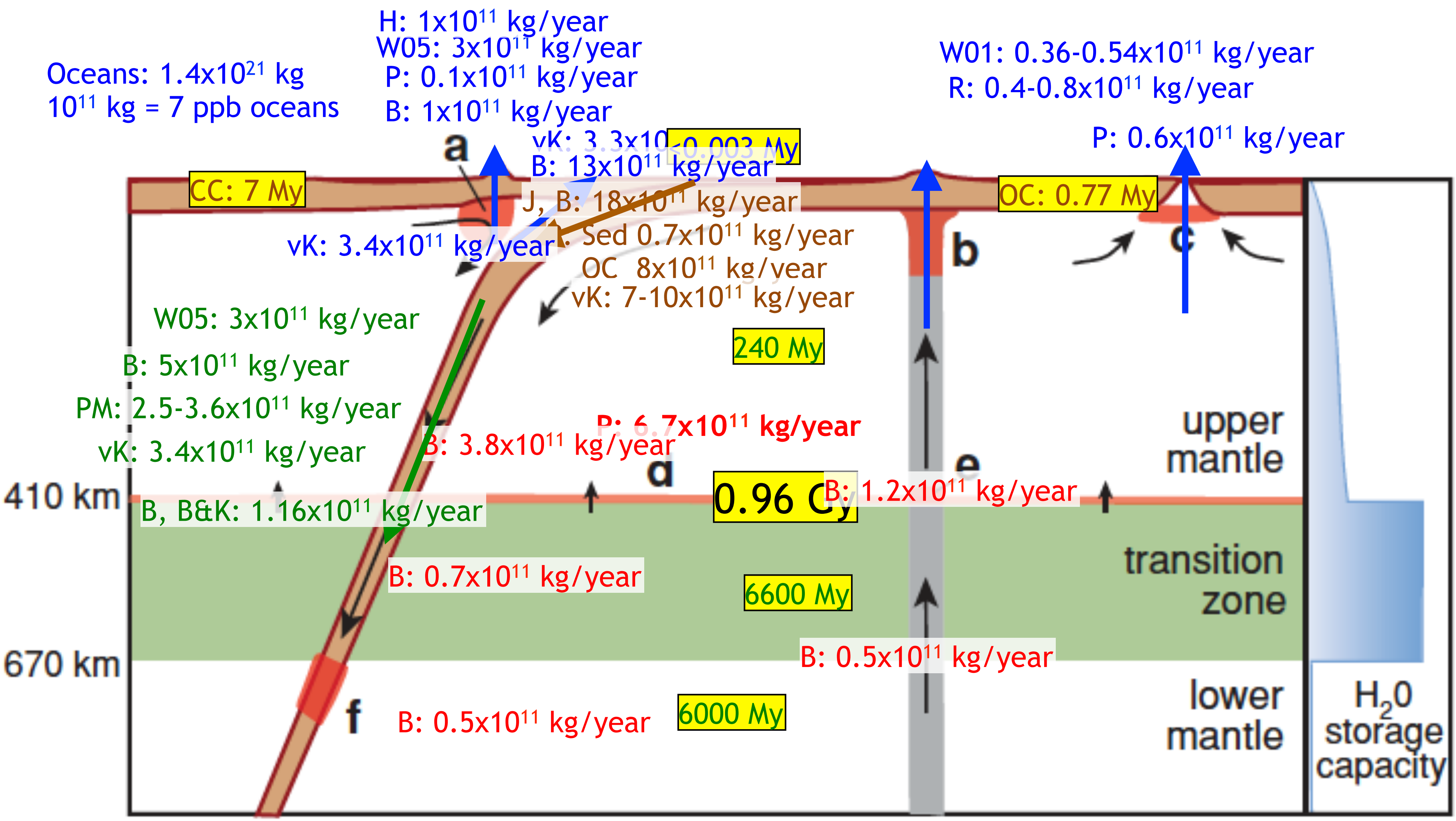
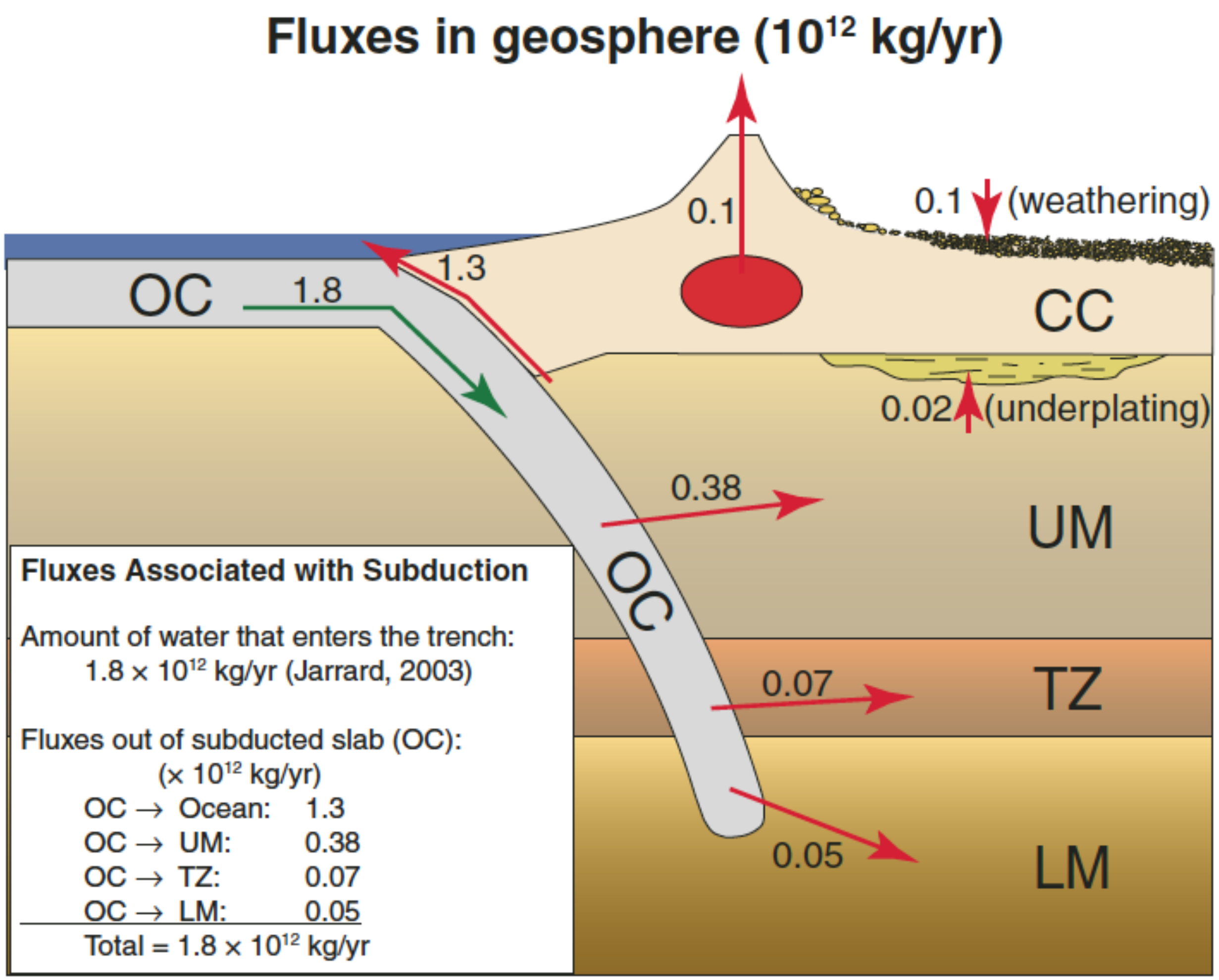
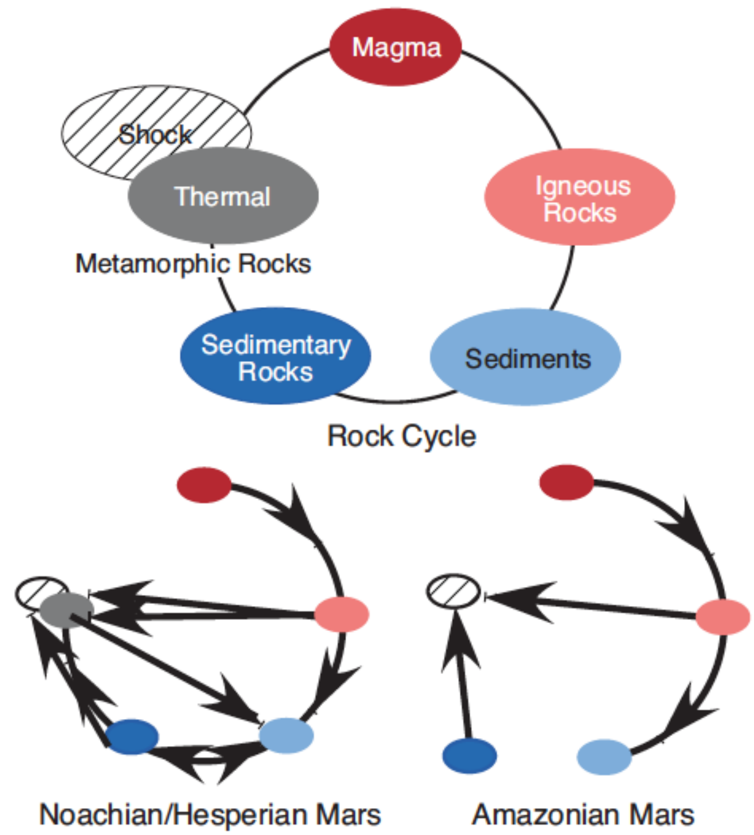


Image Credit: Hirschmann 2006

Peacock 1990, Wallmann 2001; Hilton et al 2002; Jarrad 2003; Bercovici & Karato 2003; Wallace 2005, Rüpke et al 2006, van Keken et al 2011, Bodnar et al 2013; Parai & Mukhopadhyay 2012



Bodnar et al 2013



McSween 2015

Parai & Mukhopadhyay 2012