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SPring-8

Hydrous Phases in TZ and Top of Lower Mantle

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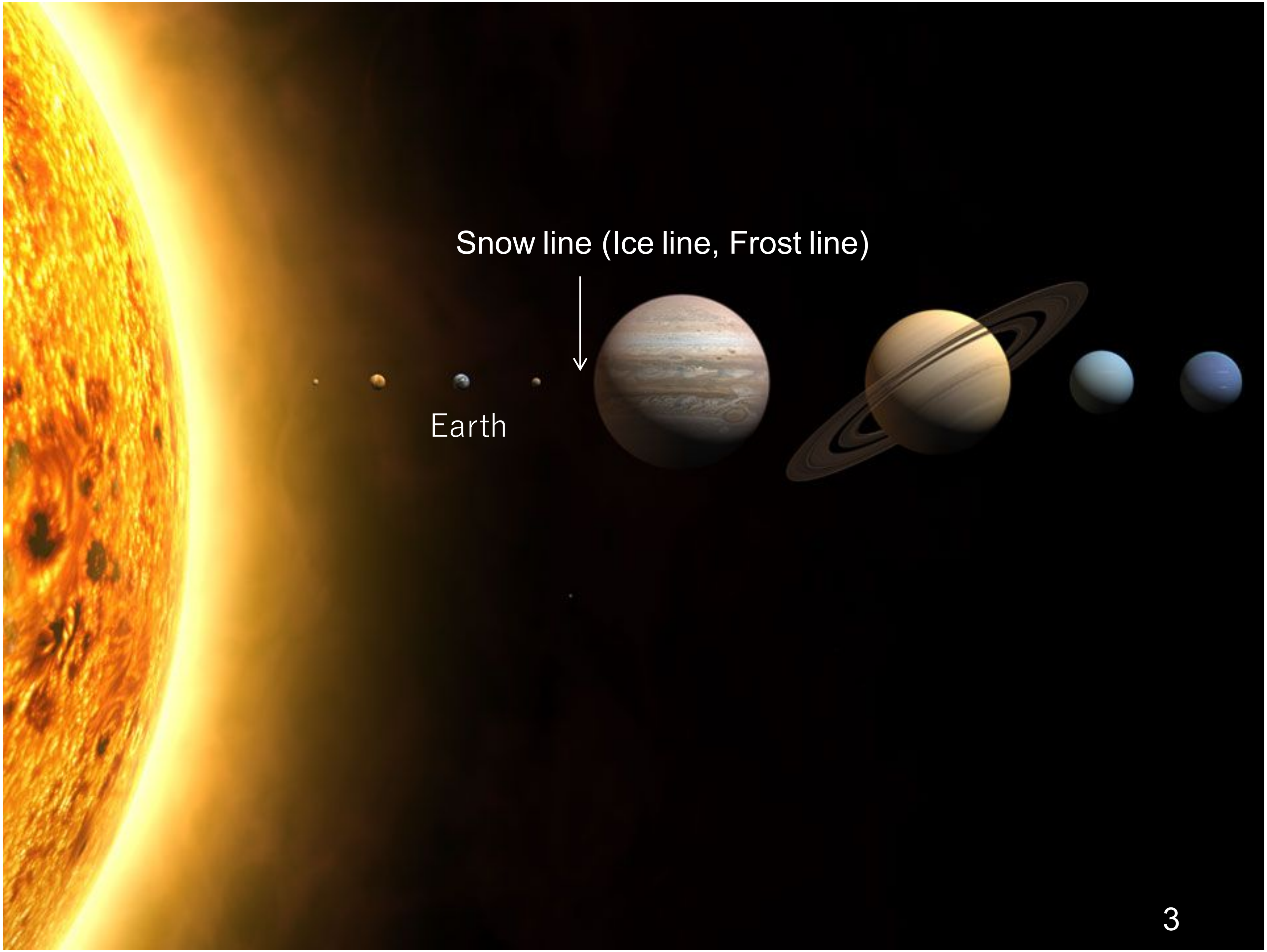
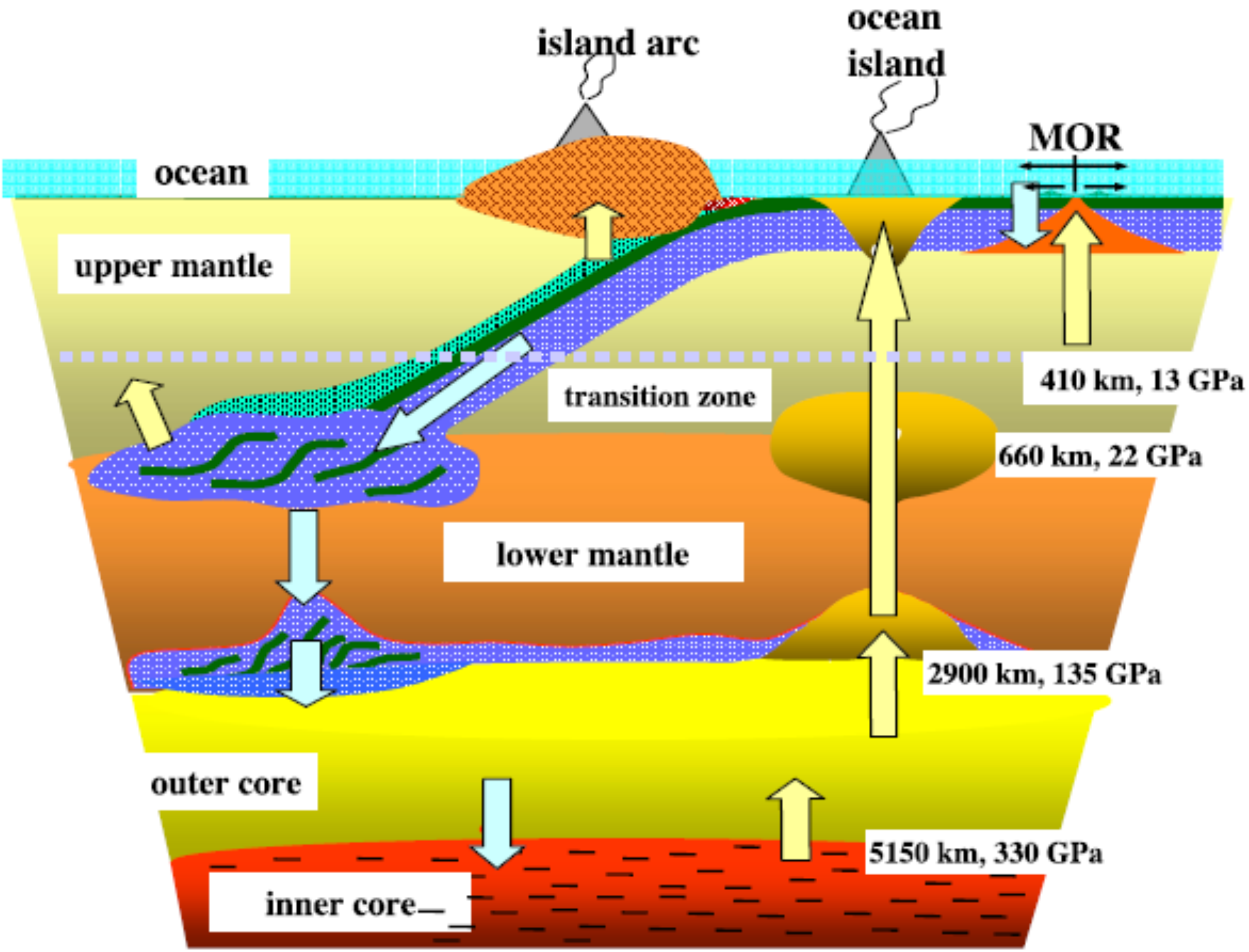
Contents:

1. Dehydration in TZ and Top of the Lower mantle, and deep seismicity.
2. Metastable olivine wedge and water in the slabs: Effect of water in $\alpha-\beta$ transformation and deep seismicity.
3. Hydrogen transport into the lower mantle


Snow line (Ice line, Frost line)
Earth

Deep Volatile Cycle in global Earth



Ohtani (Elements, 2005)

Tomographic images of the suduction zones in the circum Pacific region.

King (2007)

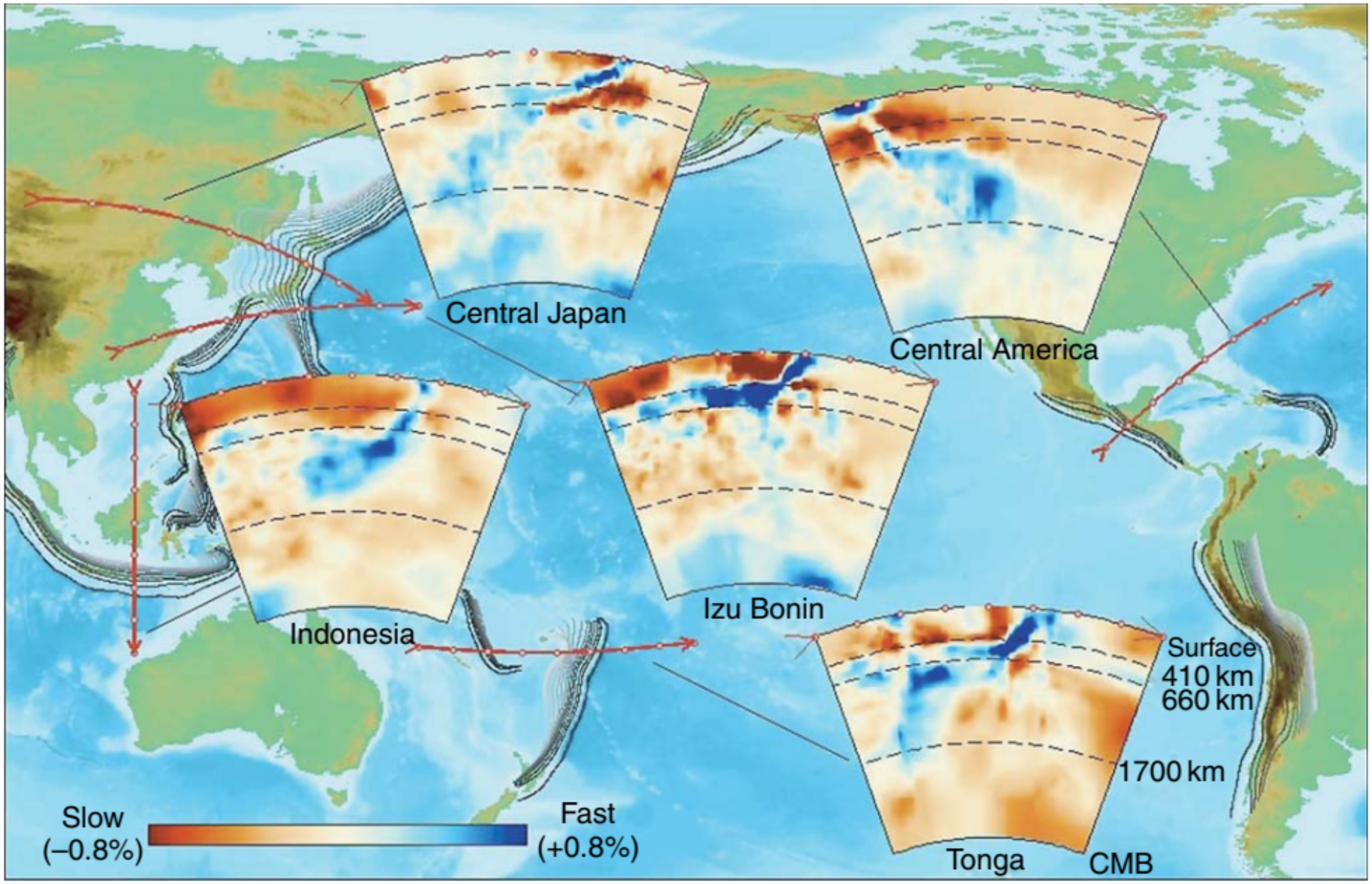


Figure 4 Summary of seismic tomography P-wave cross-sections through Pacific subduction zones. Reproduced from Albarède F and van der Hilst RD (2002) *Zoned mantle convection. Philosophical Transactions of the Royal Society of London A* 360: 2569–2592, with permission from Royal Society.

Tomography of the subducting Pacific slab and the 2015 Bonin deepest earthquake (Mw 7.9)

Zhao et al. (2017)

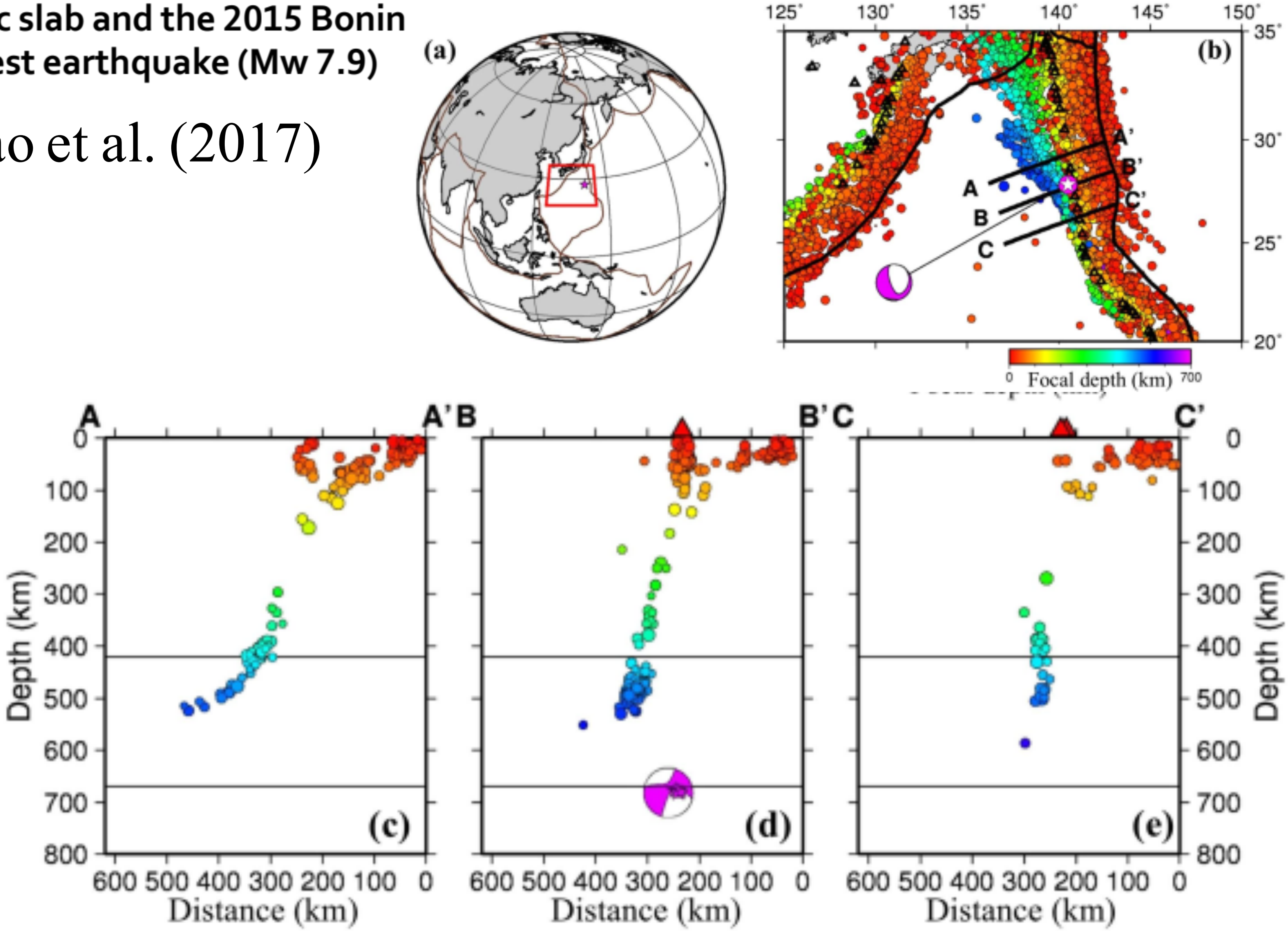


Figure 1. Seismicity of the study region. (a) The red star shows the epicenter of the 30 May 2015 Bonin deep earthquake (Mw 7.9). The red box shows the target area of the present study. The brown lines denote plate

King (2007)

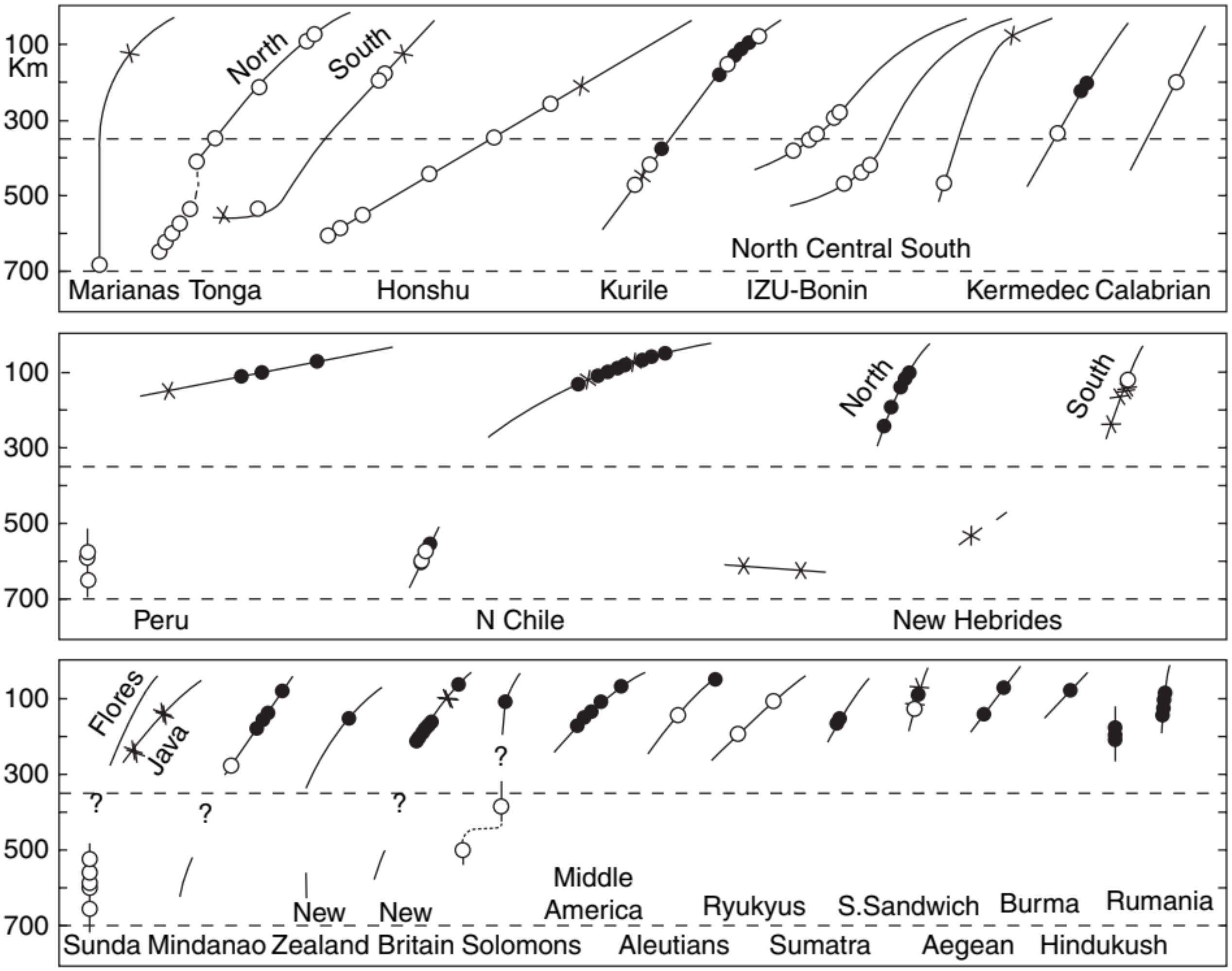
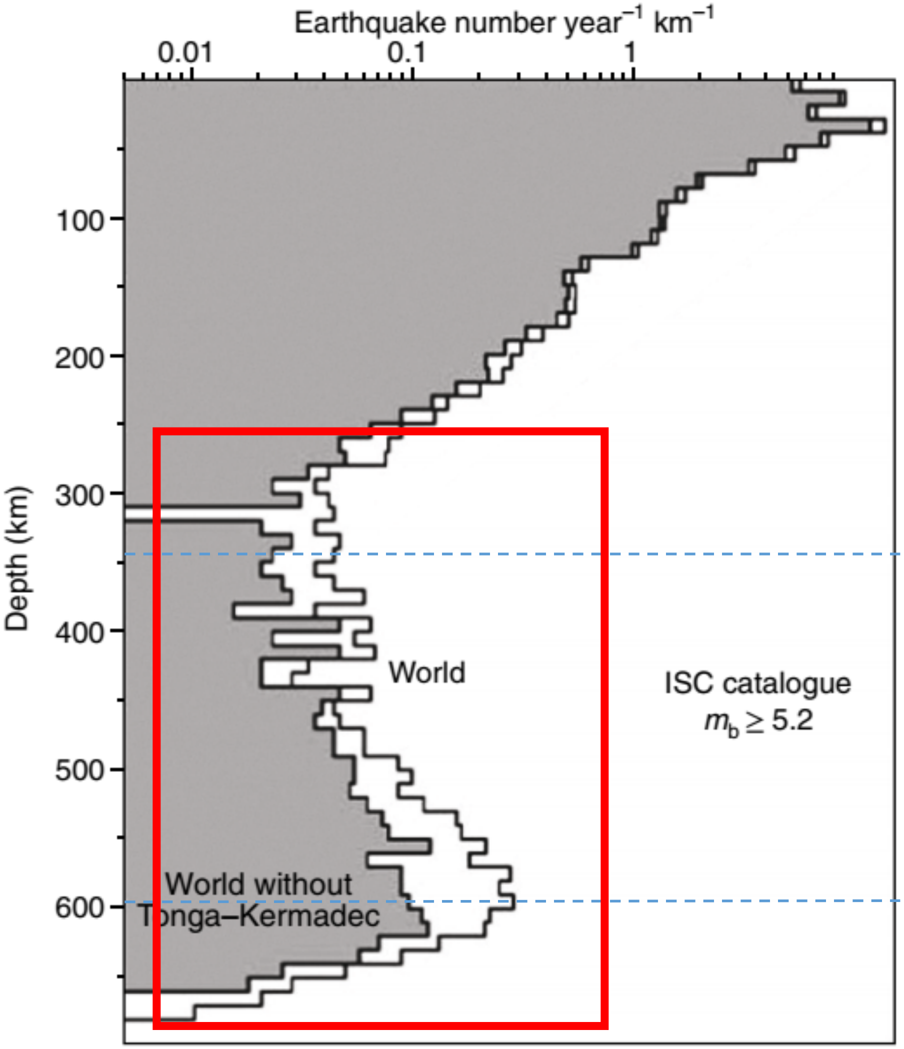


Figure 2 A global summary of down-dip compressive stresses calculated from focal mechanisms. The open circle is for down-dip compressive or *P* axis roughly parallel to the slab dip and the filled circles are down-dip *T* or tensional axis parallel to slab dip. The line represents the dip and length of the seismicity in the subduction zone. Reproduced from Isacks B and Molnar P (1971) Distribution of stresses in the descending lithosphere from a global survey of focal-mechanism solutions of mantle earthquakes. *Reviews of Geophysics and Space Physics* 9: 103–174. With permission from American Geophysical Union.

Deep Earthquakes are remarkable characteristics of slabs



Mechanism

Metastable phase transitions: Metastable olivine wedge (dry?)

Dehydration of hydrous phases, and fluid formation (wet?)

Other mechanisms: e.g., Existence of magnesite ($MgCO_3$) and/or carbonate liquid (other volatiles?)

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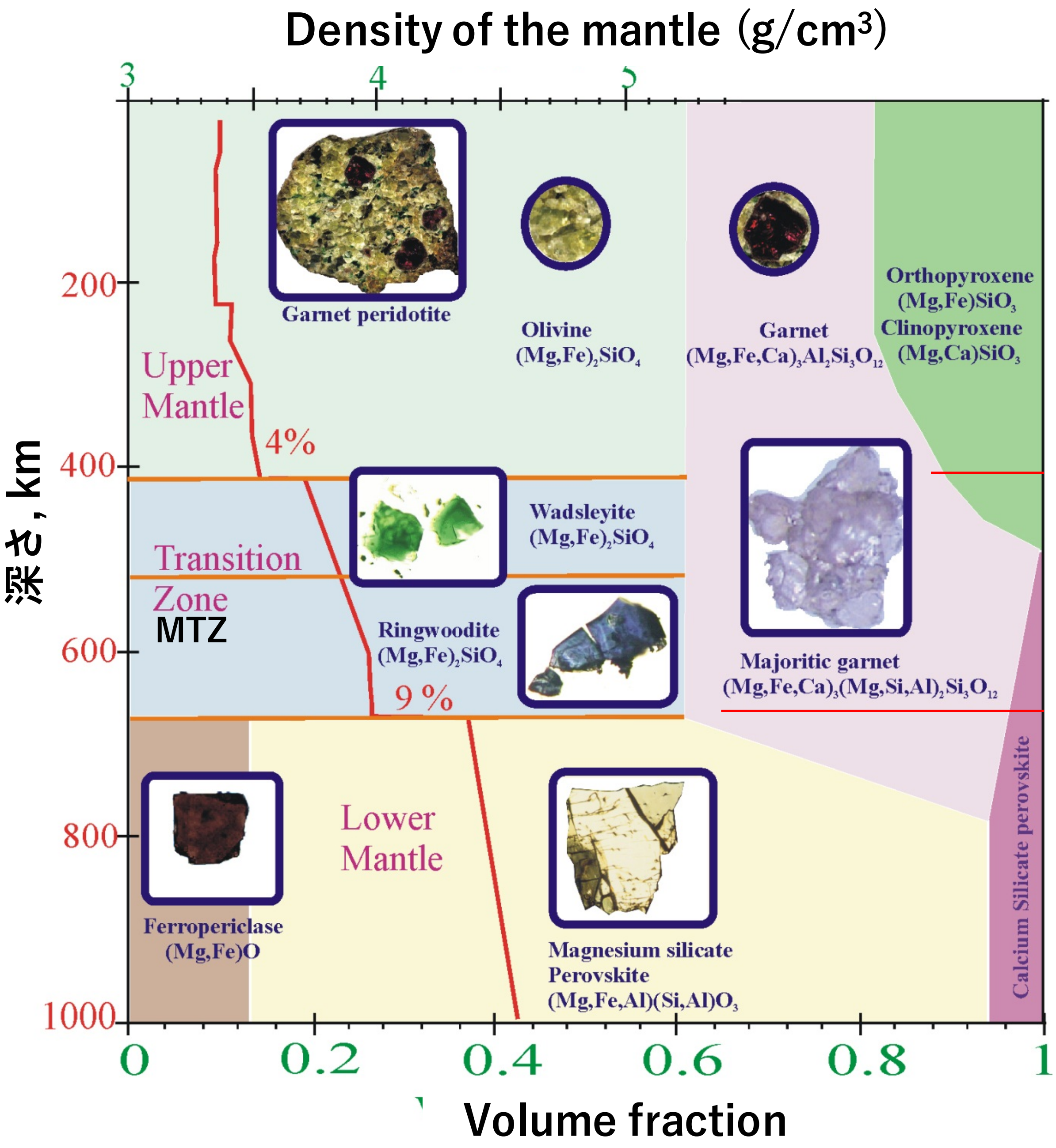
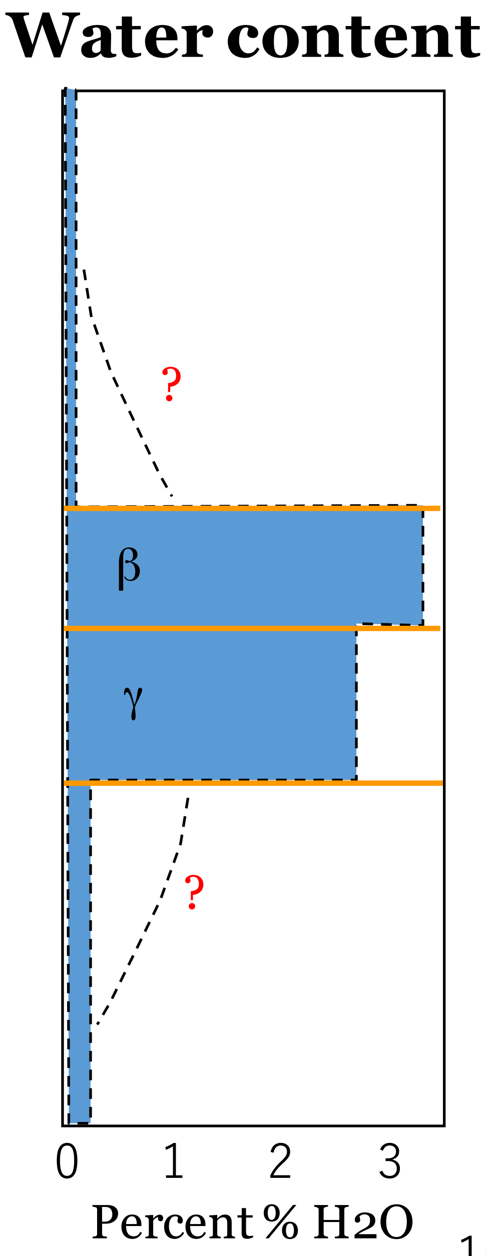
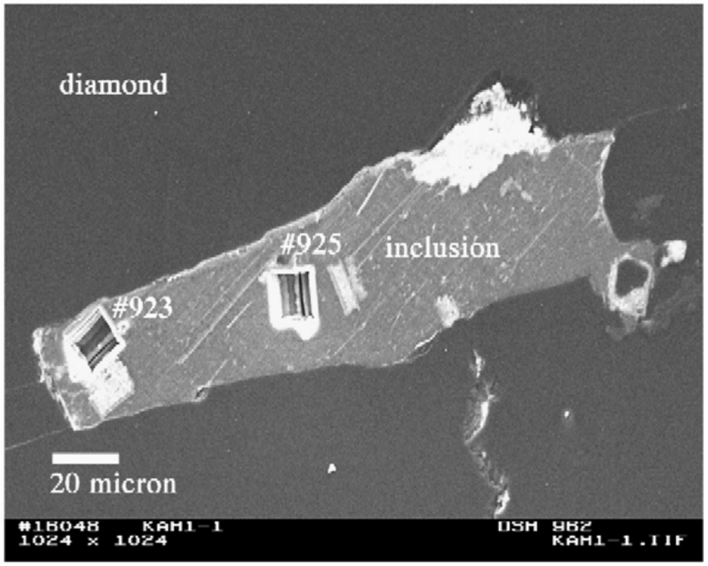
Water exists in NAMs（Nominaly Anhydrous Mminerals





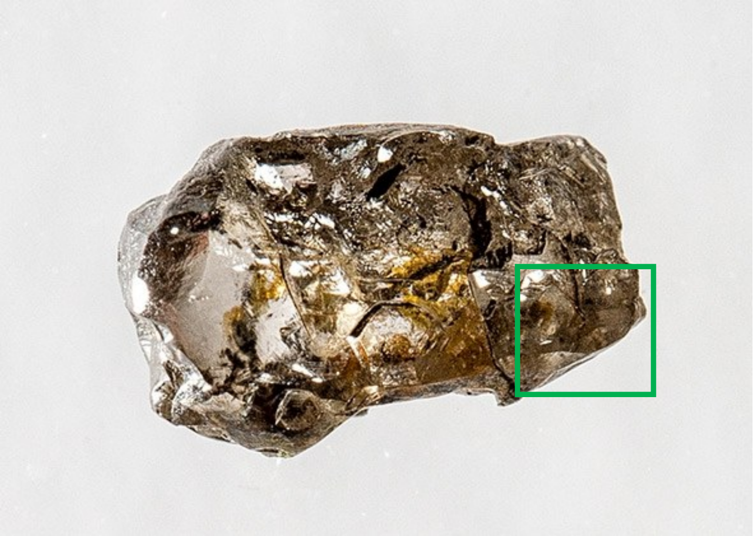
Transition zone: Some regions are wet.

Three hydrous minerals were reported as inclusions in kimberlitic diamond from Juina, Brazil



High pressure hydrous phases: **Phase Egg $AlSiO_3OH$** and **δ-AlOOH** (Wirth et al., 2007; Kaminsky, 2017)

Hydrous ringwoodite Mg_2SiO_4 (with~1wt.% water) inclusion in diamond JUc29 (Pearson et al., 2014)

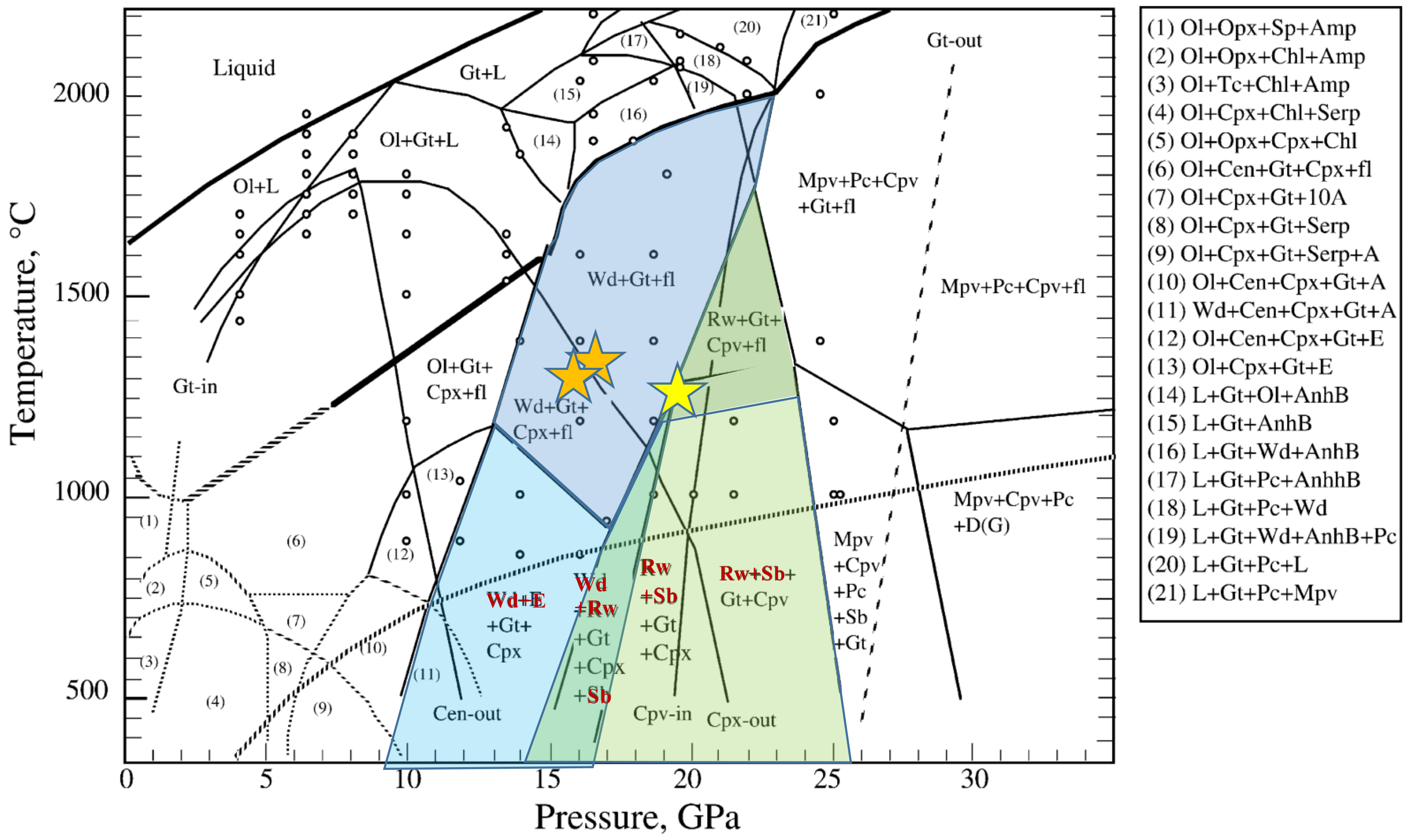


Candidates of the hydrogen carriers in the mantle transition zone

Phase A: $Mg_7Si_4O_8(OH)_6$
Wadsleyite Mg_2SiO_4
Ringwoodite Mg_2SiO_4
Phase E: $Mg_{2.3}Si_{1.25}H_{2.4}O_6$
Phase D: $Mg_{1.14}Si_{1.73}H_{2.81}O_6$
Superhydrous phase B: $Mg_{10}Si_3O_{14}(OH)_2$
EGG: $AlSiO_3OH$

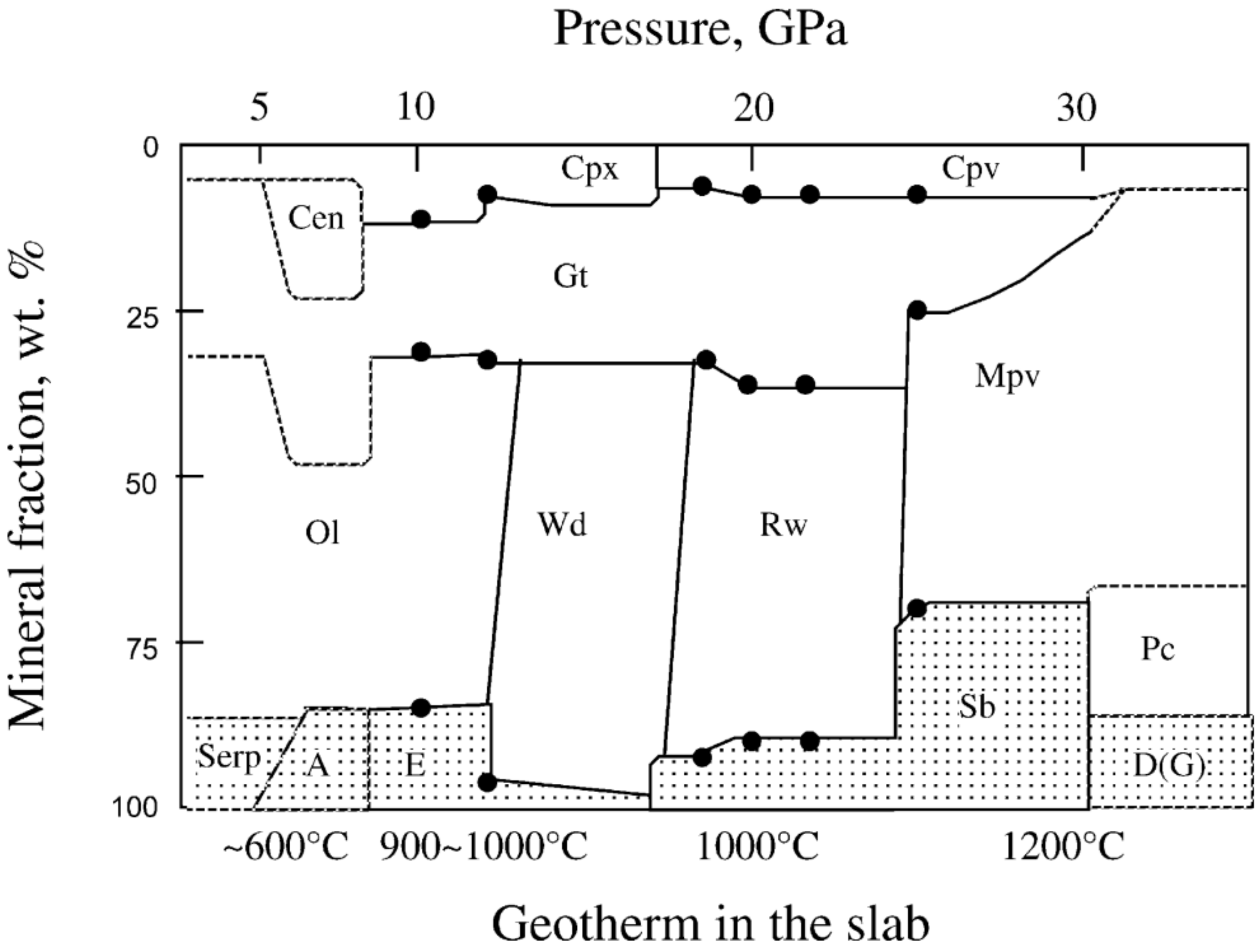
Partitioning of Hydrogen between Ol/Wd/Rg and hydrous phases

E. Ohtani et al. / Physics of the Earth and Planetary Interiors 143–144 (2004) 255–269



Hydrous phases coexist with Wd and Rg along the cold geotherm. High water contents in Wd and Rg were determined at higher temperature after dehydration of hydrous phases.

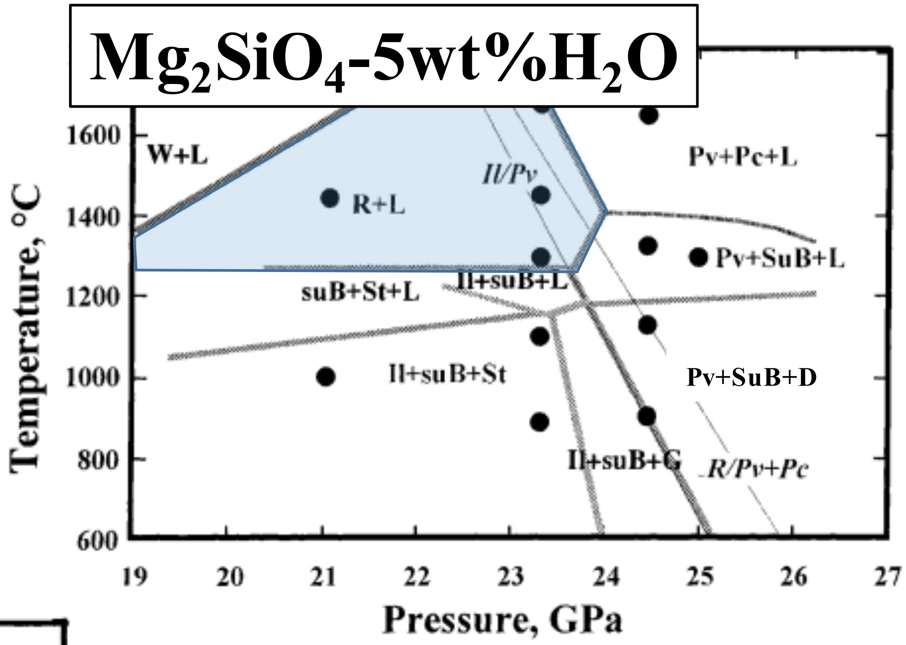
E. Ohtani et al. / Physics of the Earth and Planetary Interiors 143–144 (2004) 255–269



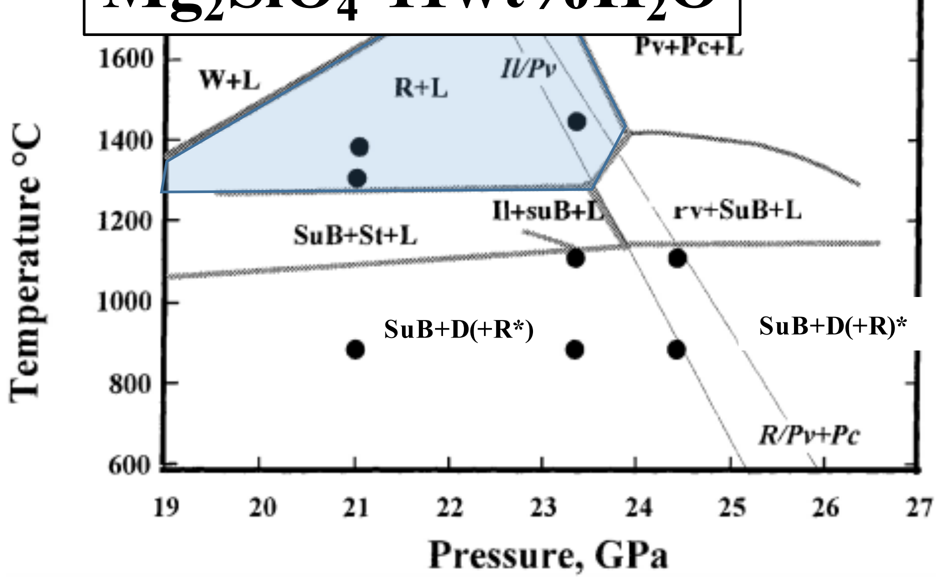
Ohtani et al. (2001)

Wadslyite and Ringwoodite are NOT stable under water saturated and low temperature conditions (T<1000 °C)

Mg_2SiO_4-5wt%H_2O



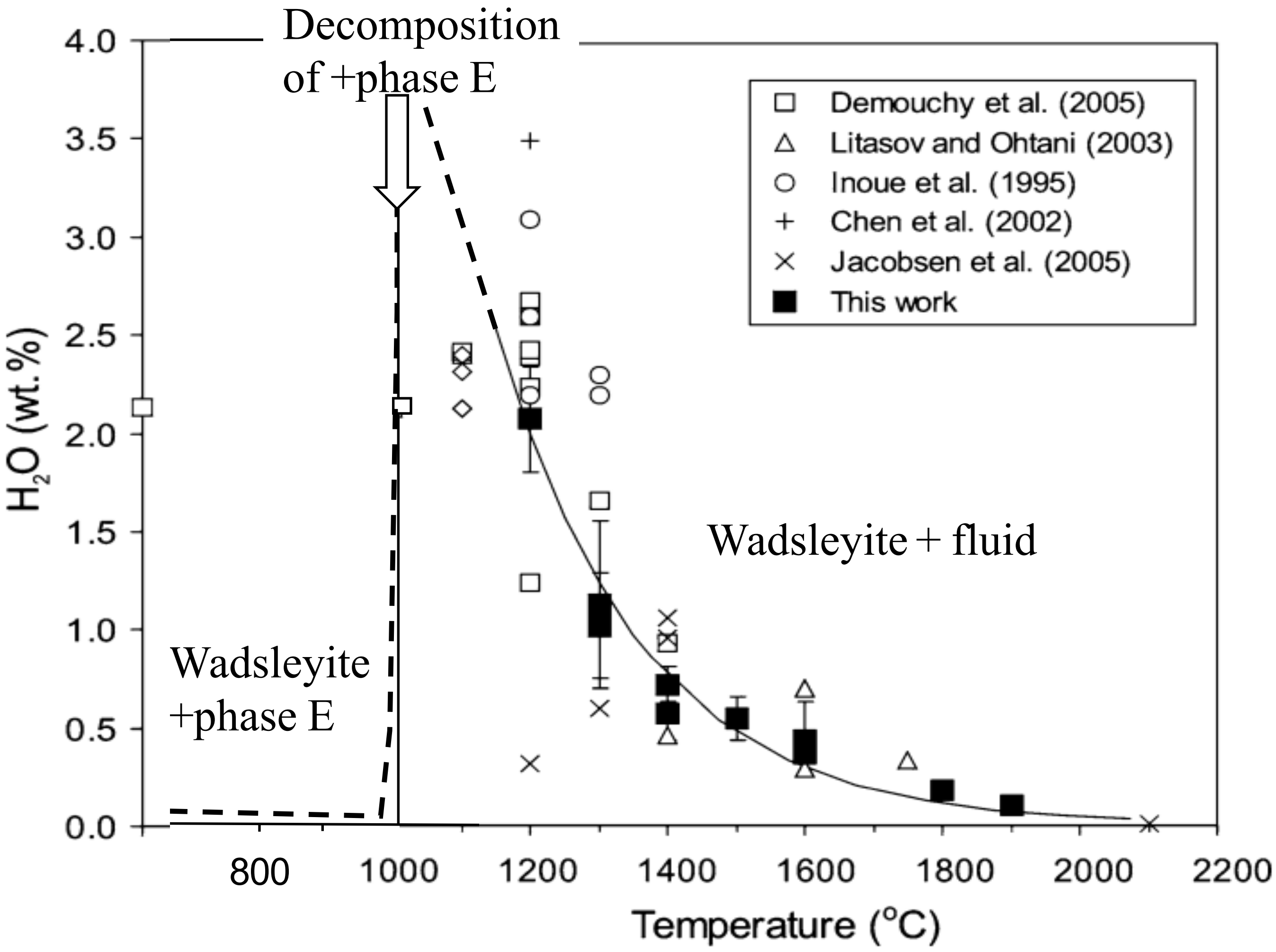
Mg_2SiO_4-11wt%H_2O



Hydrogen can be absorbed by hydrous minerals, such as SuB, Phase D.

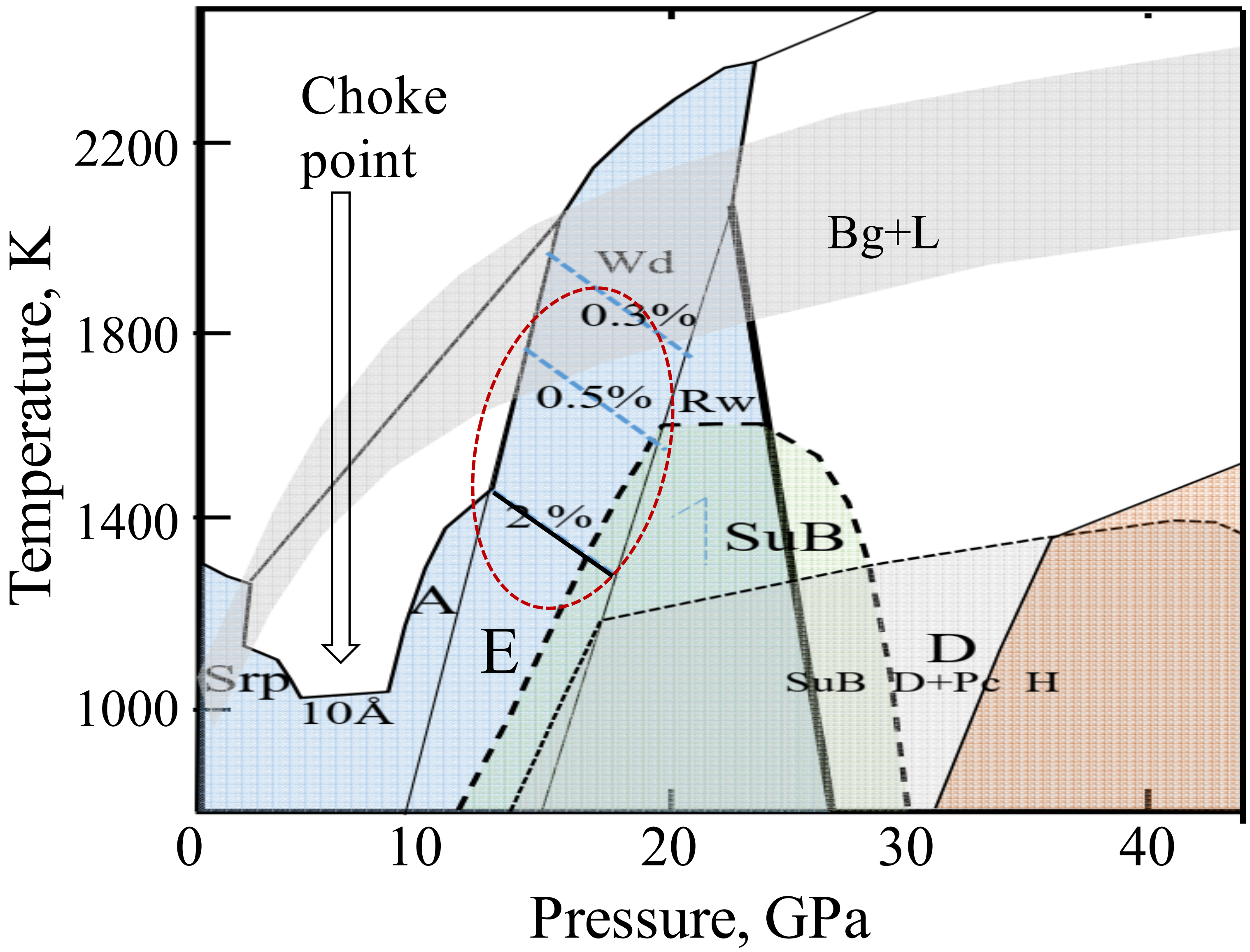
Hydrogen favors hydrous minerals compared to wadsleyite and ringwoodite.

Water content in wadsleyite at high temperature at 14-20 GPa (Litasov, Shatskiy, Ohtani, Katsura, 2011, modified)

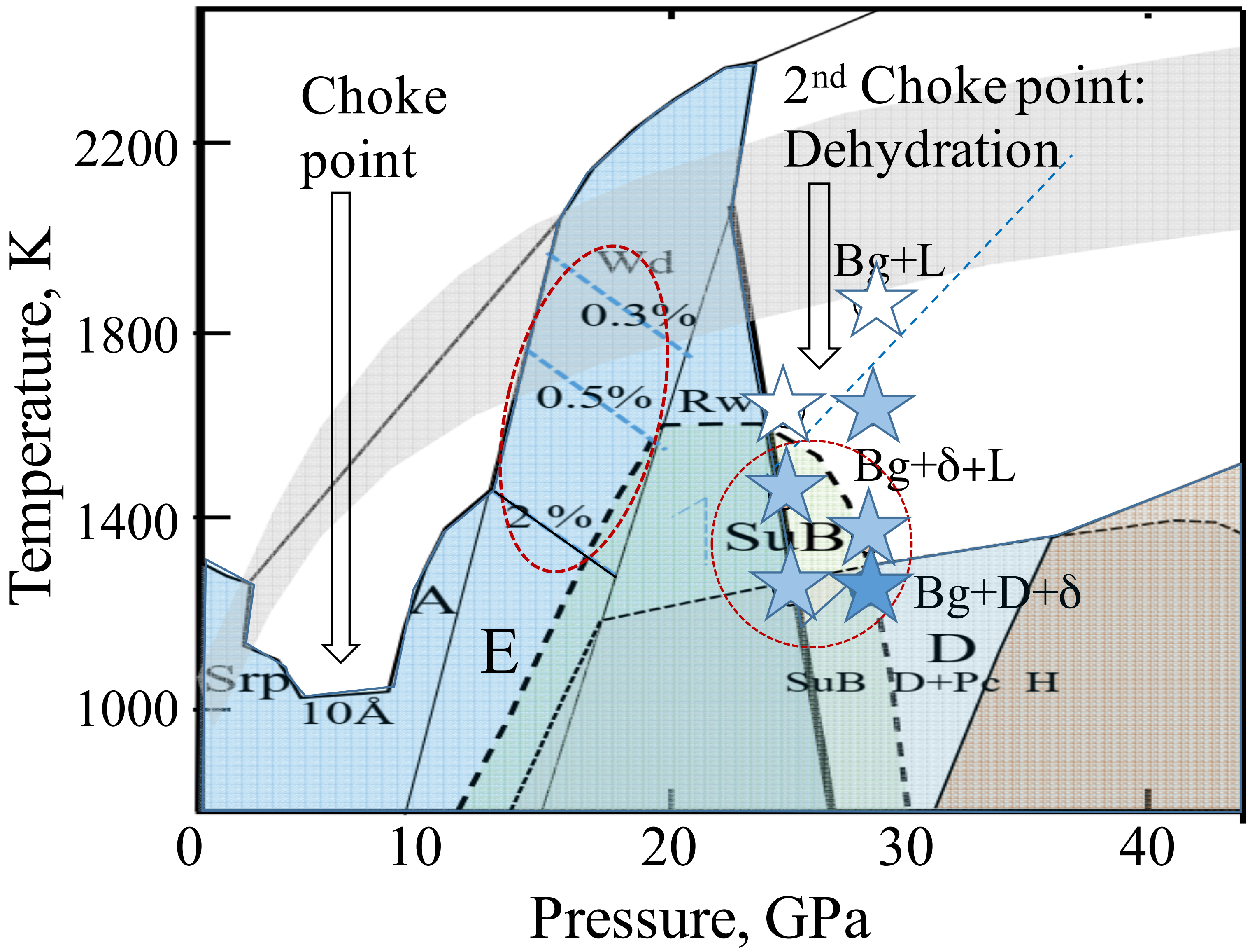


Dehydration of slabs due to decomposition of hydrous phases and decrease in H solubility in Wd/Rg with increasing temperature.

Dehydration sites in the mantle transition zone



Dehydration sites in the mantle transition zone

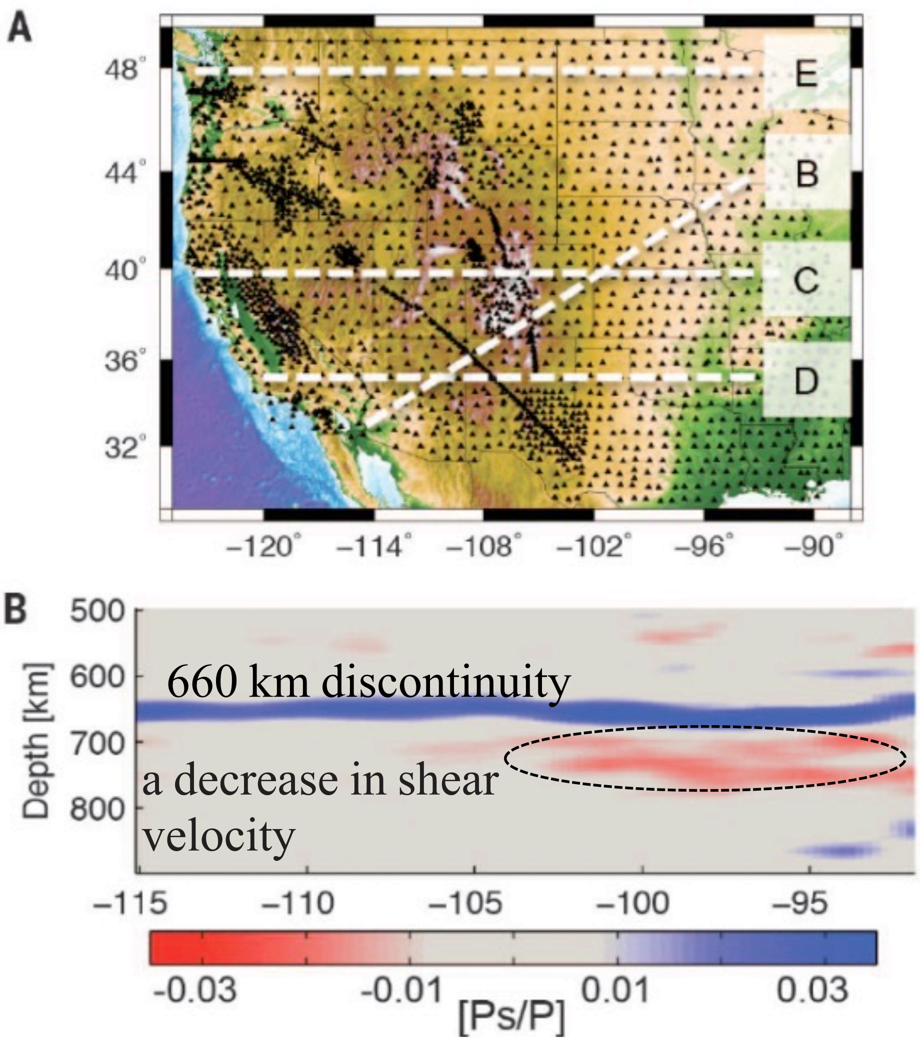


Choke point

2^{nd} Choke point: Dehydration

Anomalous low Vs and Q region at the top of the lower mantle,

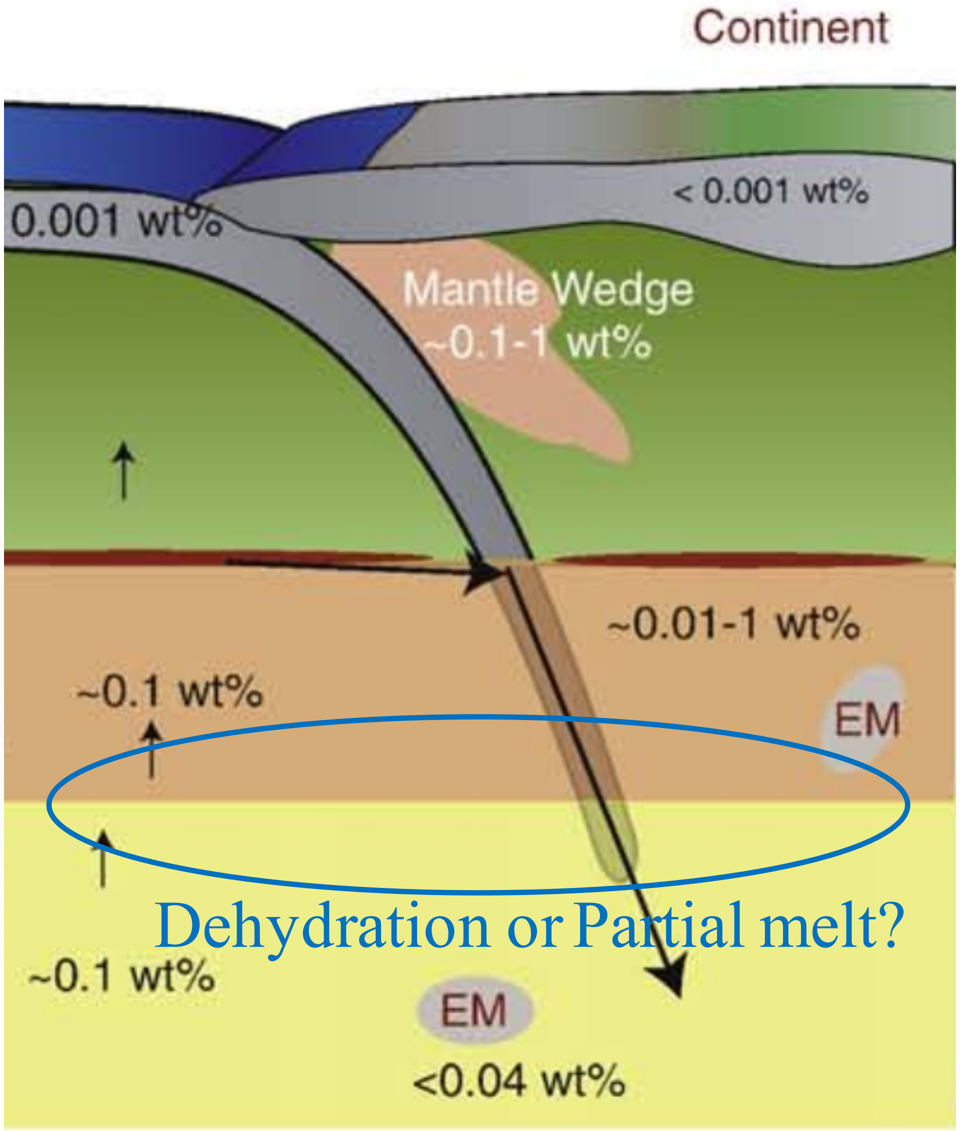
Karato et al. (201



660 km discontinuity

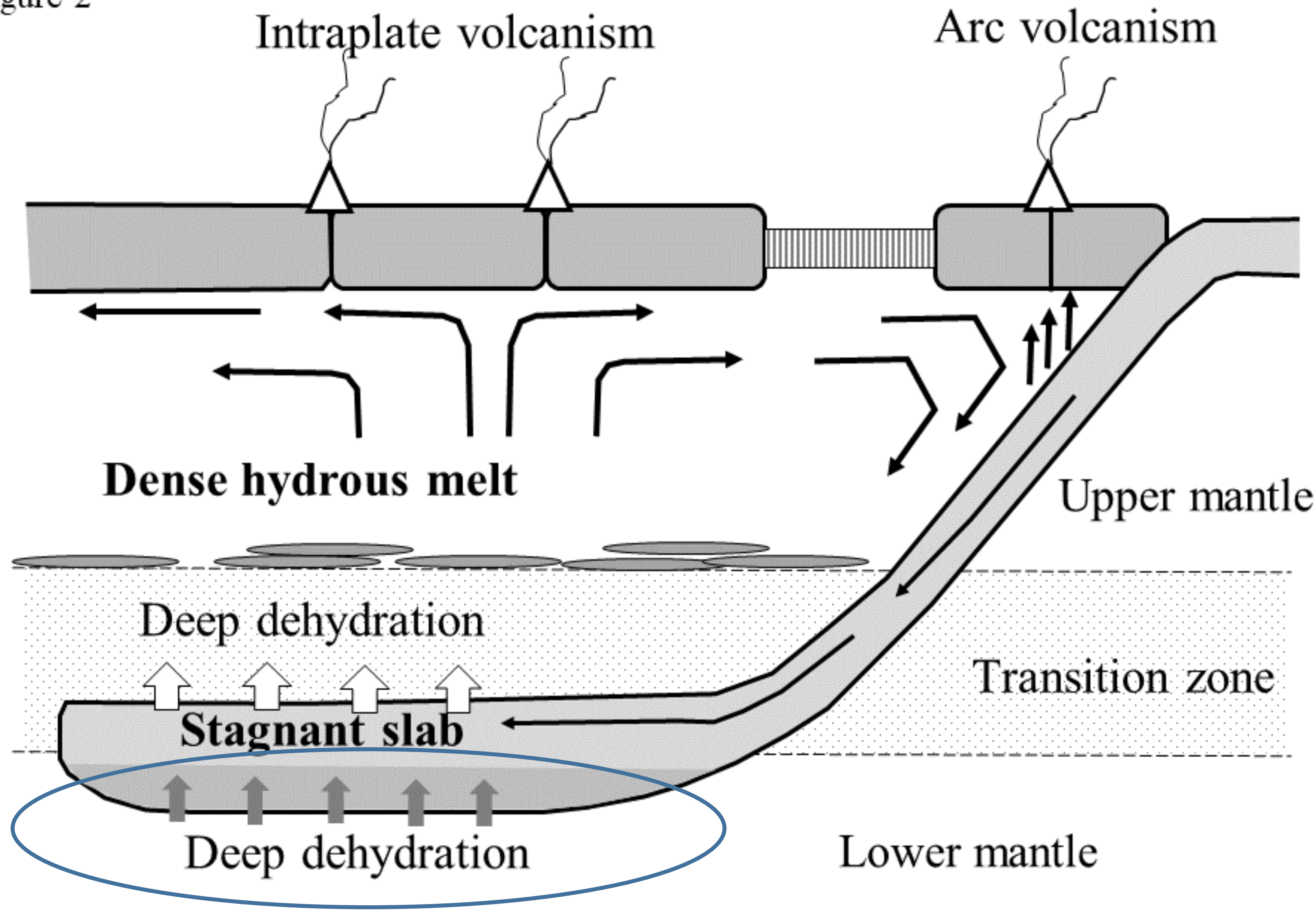
a decrease in shear velocity

Schmandt et al. (2014)



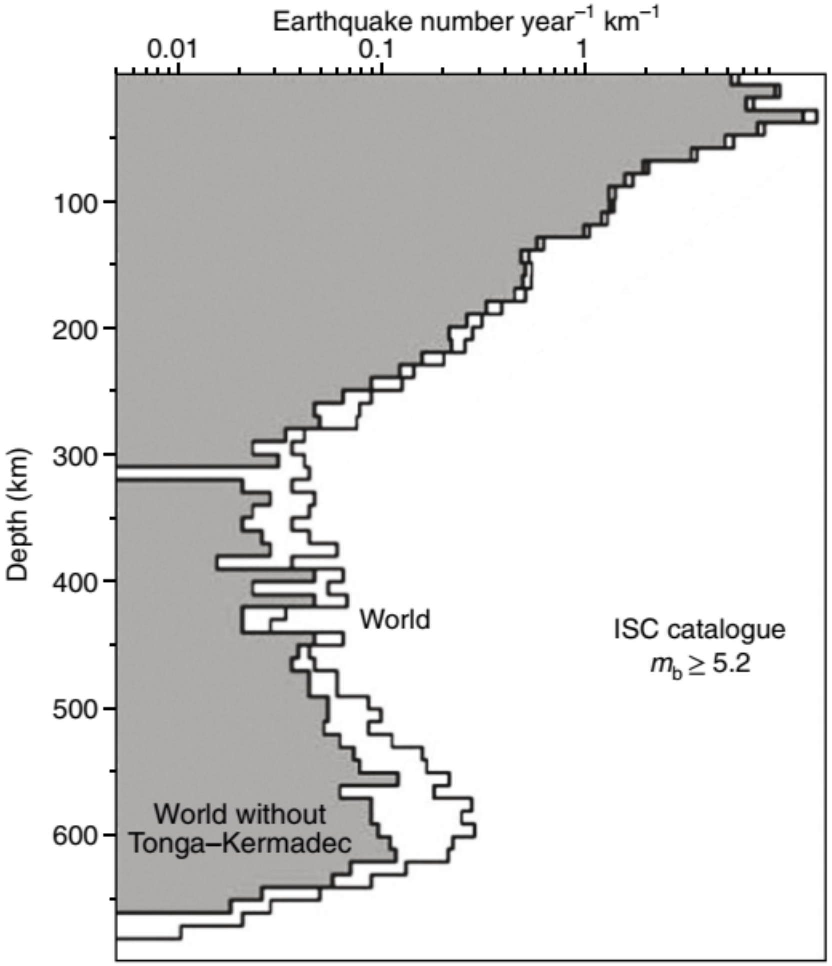
Dehydration or Partial melt?

Figure 2



Ohtani et al. (2018)

Several dehydration sites exist in the transition zone:



1. Dehydration of phase E, superhydrous phase B, phase D with increasing temperature.
2. Decrease of water contents in Wd/Rg with increasing temperature.
3. Decomposition of phase D and super B at the top of the lower mantle.

0.3wt%

0.3 wt%

4. Dehydration can trigger the deep mantle seismicity.

ΔV(dehydration)<0

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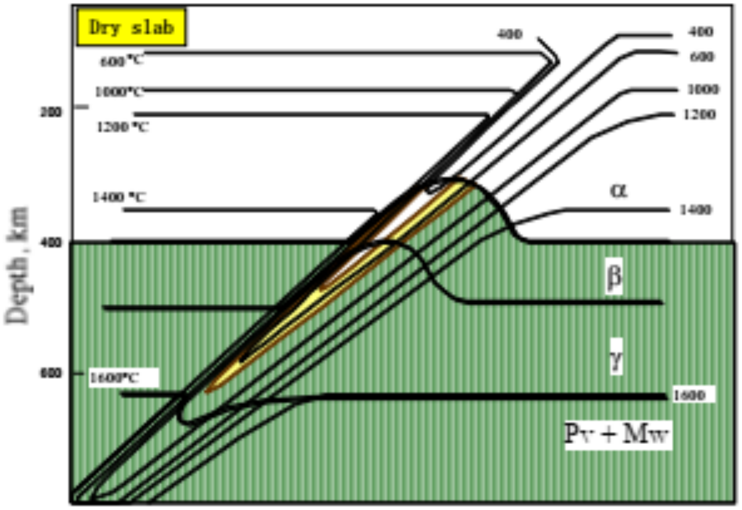
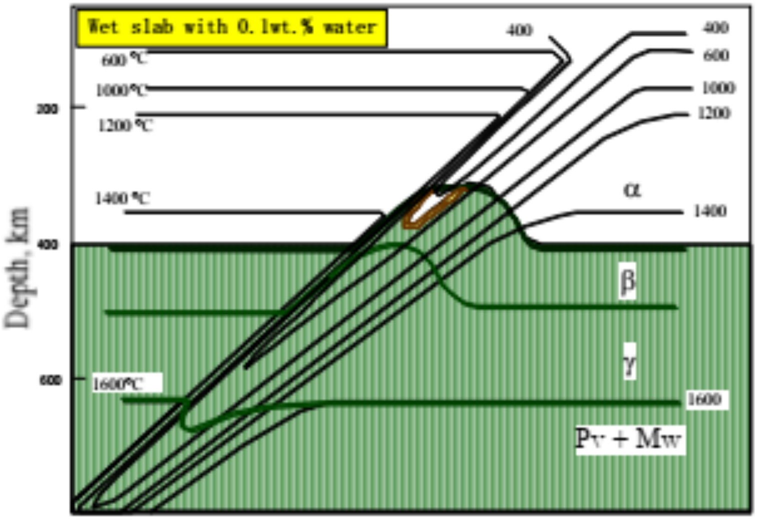
Effect of water on α–β transformation kinetics

Dry

Wet



Dip angle of subduction θ=45°; Temperature gradient 0.7°C/km; Subduction rate, 7cm/year; Grain size 5mm



Dip angle of subduction θ=45°; Temperature gradient 0.7°C/km; Subduction rate, 7cm/year; Grain size 5mm

No metastable olivine wedge:

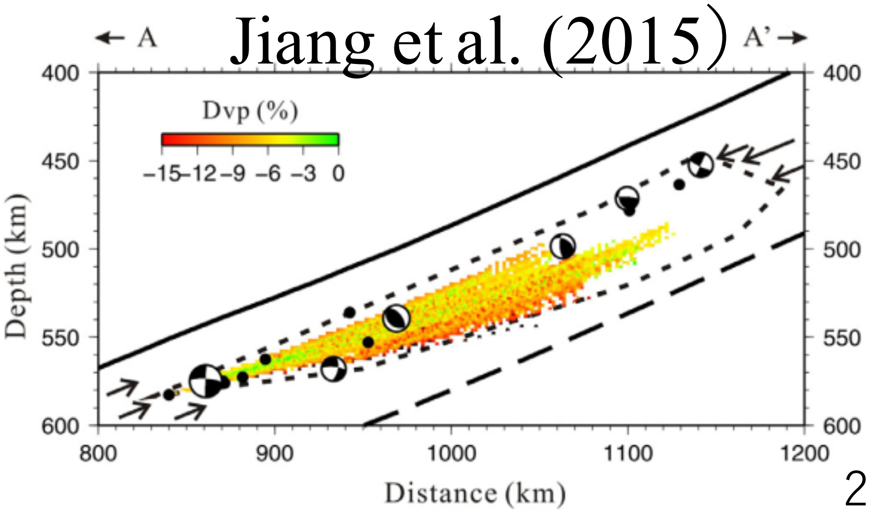
Tonga, (Koper and Wiens, 2000):

Metastable olivine wedge exists:

South-west Japan (Kawakatsu & Yoshioka, 2011):

Western Pacific slab (Jiang et al. 2015).

Jiang et al. (2015)



Effect of water in $\alpha-\beta$ transformation in olivine

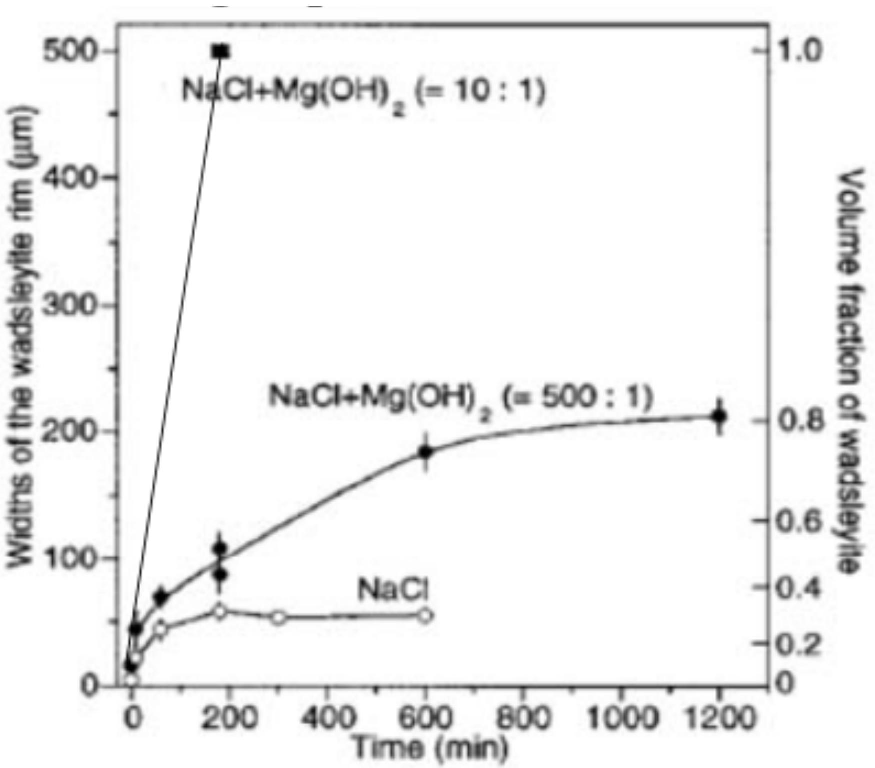
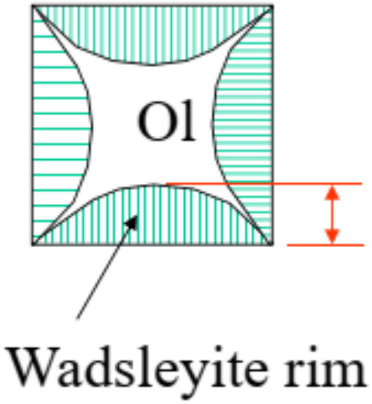
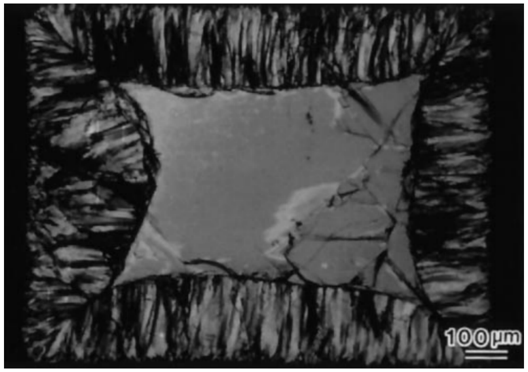


Fig. 2. Time dependence of the width and volume fraction of the wadsleyite rim in dry and wet runs at 13.5 GPa and 1030°C. The confining medium of the sample is also shown. The volume fraction of wadsleyite was estimated from widths of the wadsleyite rim. Time indicates the heating duration at the desired temperature.

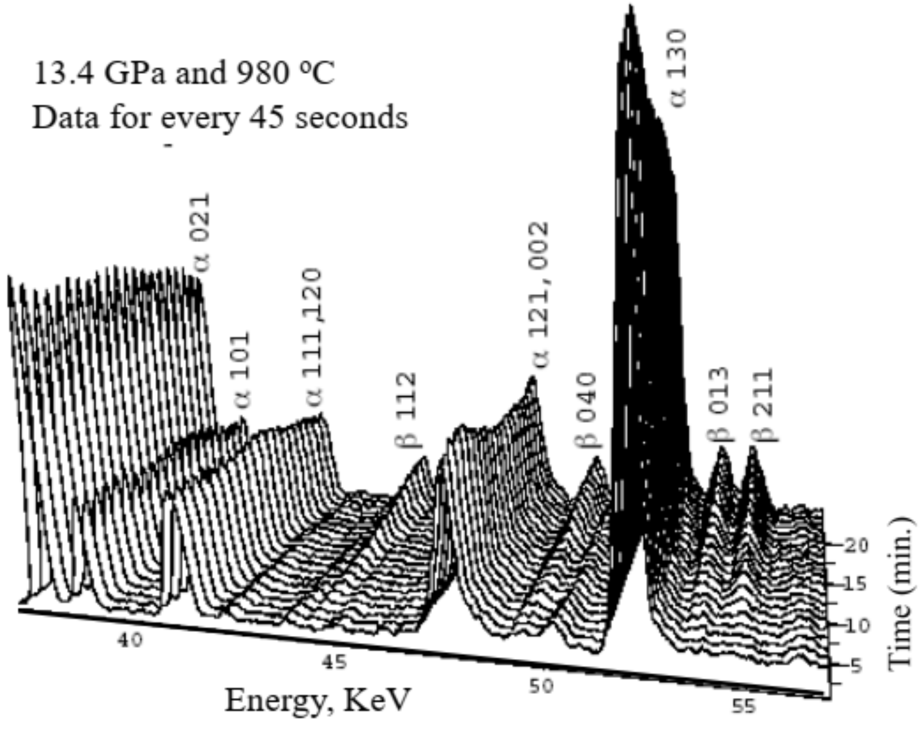
Kubo, Ohtani et al. (1998)

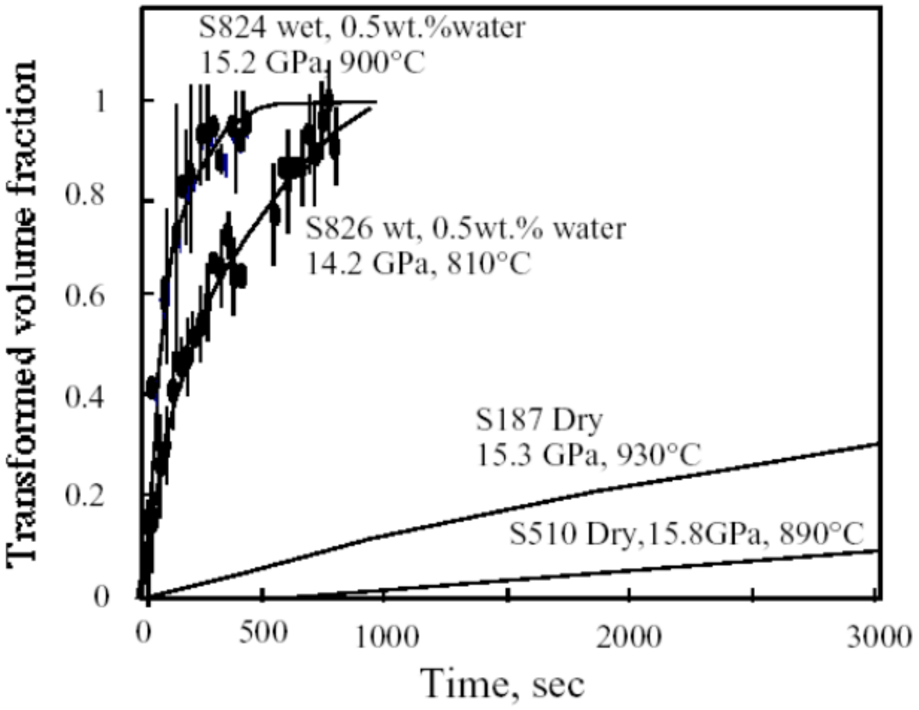




Hosoya, Kubo, Ohtani, Sano, Funakoshi (2005)

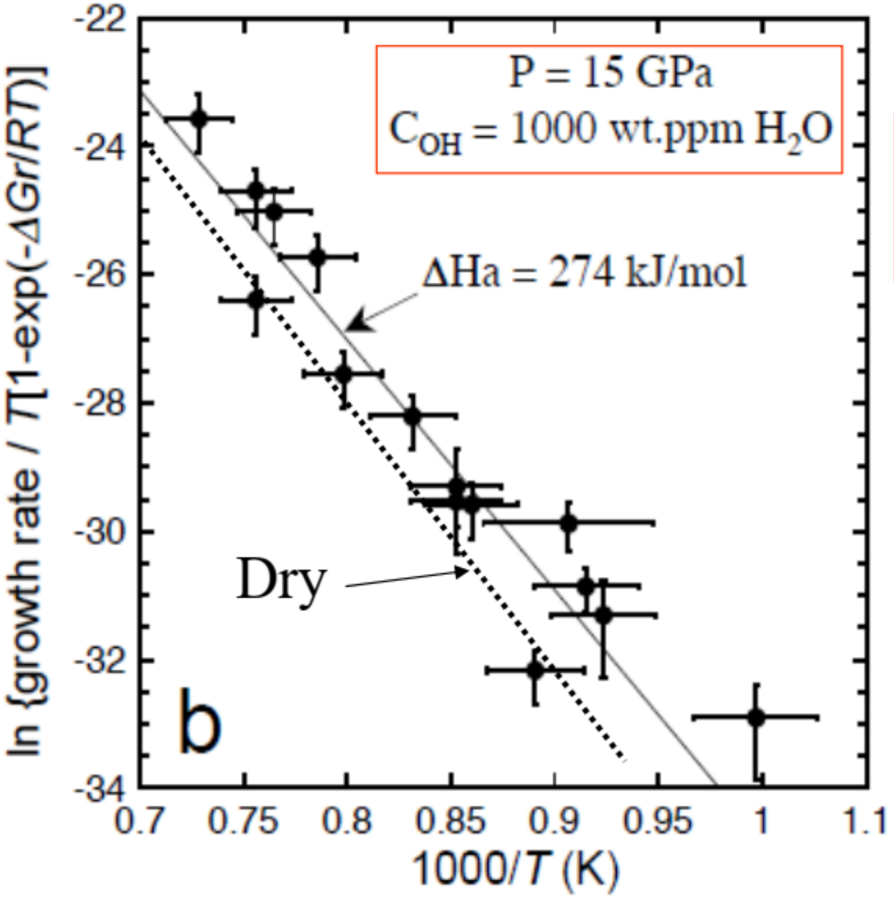
The reaction kinetics of α–β transformation in olivine Kawai-type high-pressure apparatus "SPEED-1500" installed in beamline BL04B1





Hosoya, Kubo, Ohtani, Sano, Funakoshi (2005)

The growth rates of wadsleyite as a function of temperature for the dry and wet experiments



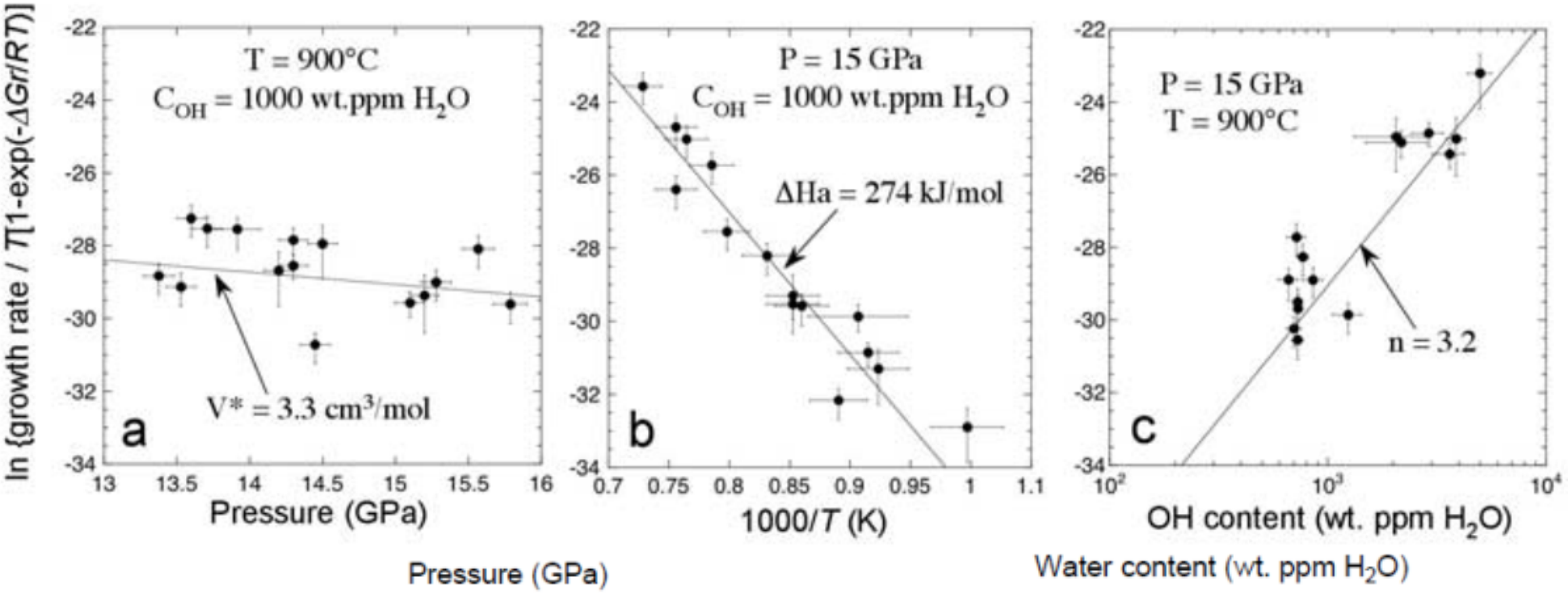
$$\dot{x} = ATC_{OH}^{\,n} \exp\left(-\frac{\Delta H_a + PV^*}{RT}\right)\left[1-\exp\left(\frac{-\Delta G_r}{RT}\right)\right]$$

ΔH_a is the activation enthalpy for growth,

V^* is the activation volume for growth,

ΔG_r is the free energy change of the transformation

Hosoya, Kubo, Ohtani, Sano, Funakoshi (2005)



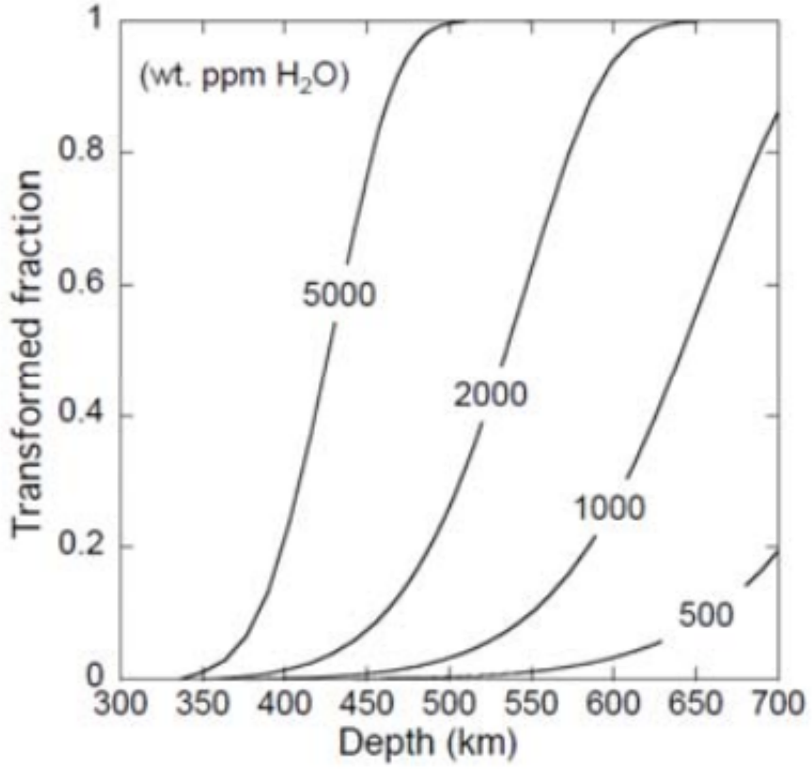
$$\dot{x} = ATC_{OH}{}^{n}\exp\left(-\frac{\Delta H_a + PV^*}{RT}\right)\left[1-\exp\left(\frac{-\Delta G_r}{RT}\right)\right]$$

where ΔH_a is the activation enthalpy for growth, V^* is the activation volume for growth, and ΔG_r is the free energy change of the transformation

$\ln A = -18.0 \pm 3.8$ ms^{-1} wt.ppmH$_2$O$^{-3.2}$, $n = 3.2 \pm 0.6$, $\Delta H_a = 274 \pm 87$ kJ/mol, and $V^* = 3.3 \pm 3.8$ cm^3/mol.

Hosoya, Kubo, Ohtani, Sano, Funakoshi (2005)

Effect of water on olivine-wadslyeite phase transition



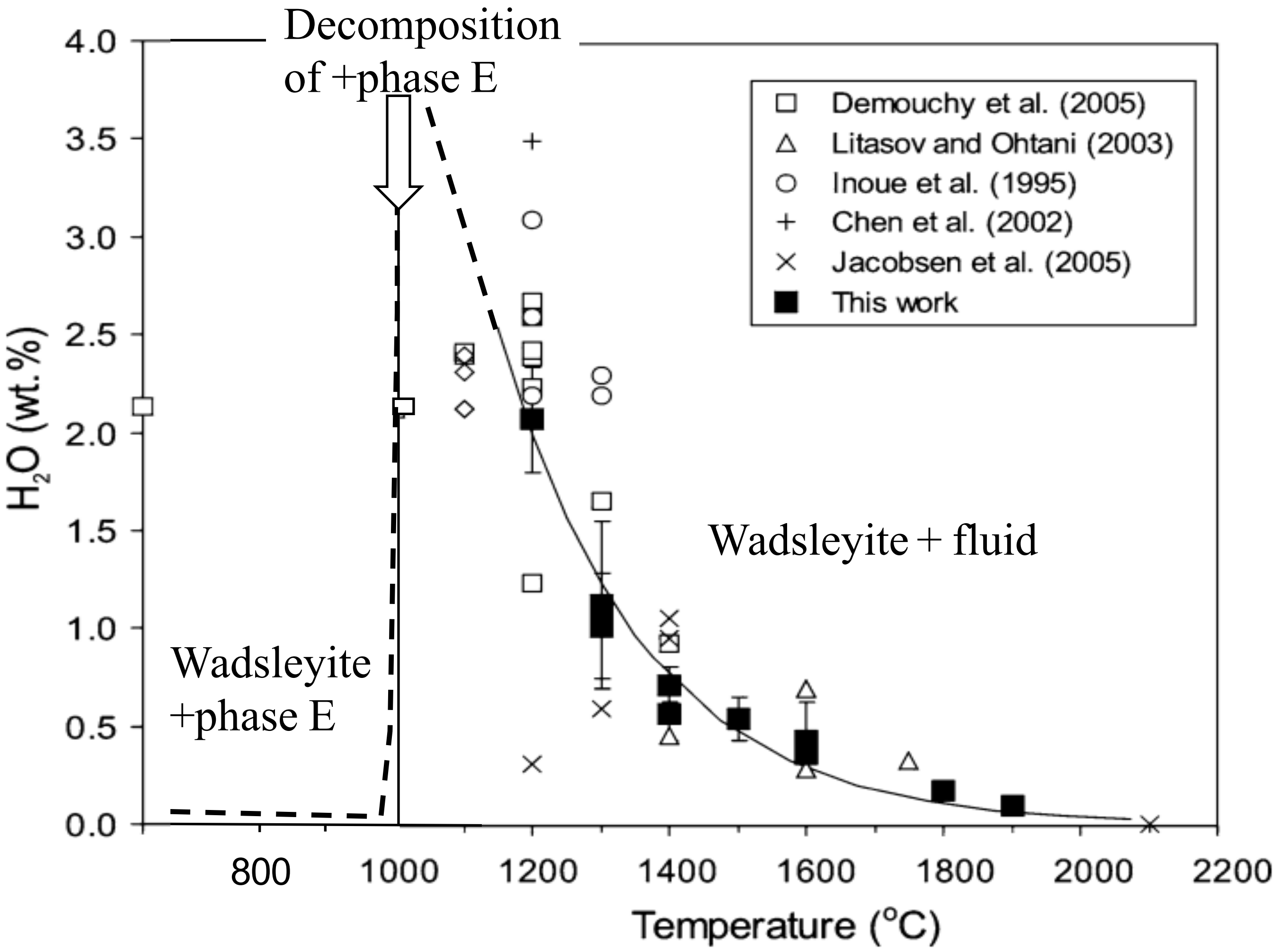
Temperature at 660 km depths is 600°C.

Thermal gradient of 0.6°C/km.

Vertical speed of subduction, 12 cm/year.

The P-T-t (Pressure-Temperature-time) path of the cold slab with water contents. **The metastable olivine can survive at the depths greater than the 650 km** in cold slabs with water less than **500 wt. ppm H_2O**.

Water content in Wadsleyite at high temperature at 14-20 GPa (Litasov et al., 2011, modified)



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Mechanism of deep earthquakes

1. **Water contents in olivine/wadsleyite/ringwoodite are low** when coexisting with hydrous phases, i.e., Hydrogen favors Hydrous phases compared to Ol/Wd/Rg.

2. **Dehydration occurs due to warming up of the slabs**, which also can trigger the deep mantle seismicity. $\Delta V(\text{dehydration})<0$

3. Sluggish $\alpha-\beta$ transformation can occur under the wet slab conditions, i.e., metastable olivine wedge exists even in the wet mantle transition zone, and the $\alpha-\beta$ transformation of metastable olivine can trigger the deep mantle seismicity. $\Delta V(\alpha-\beta)<0$
Metastable olivine wedge is NOT the signature of dry subduction.

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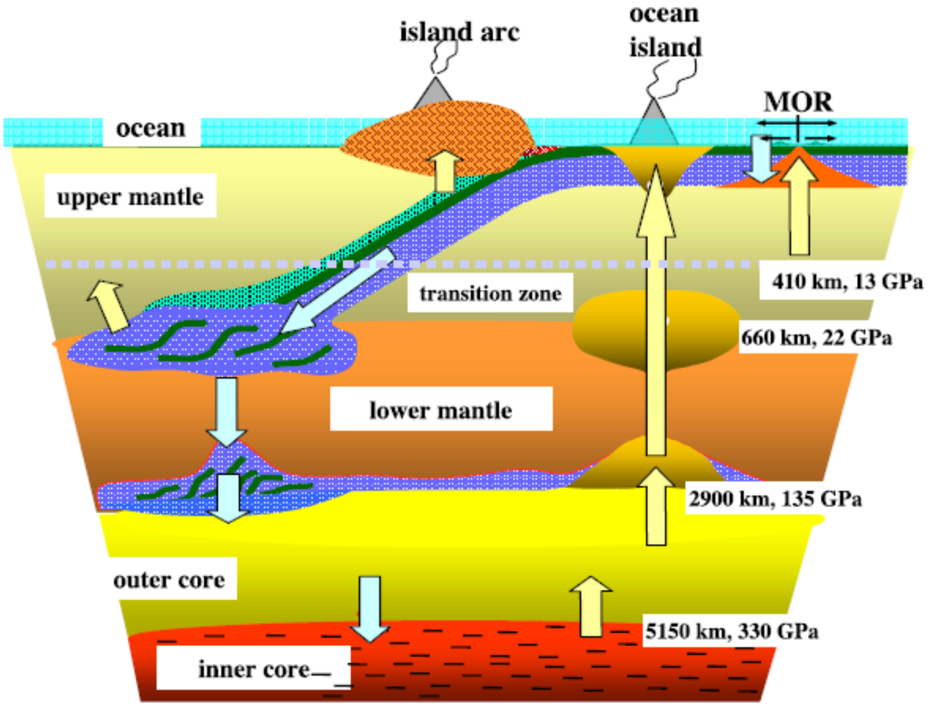
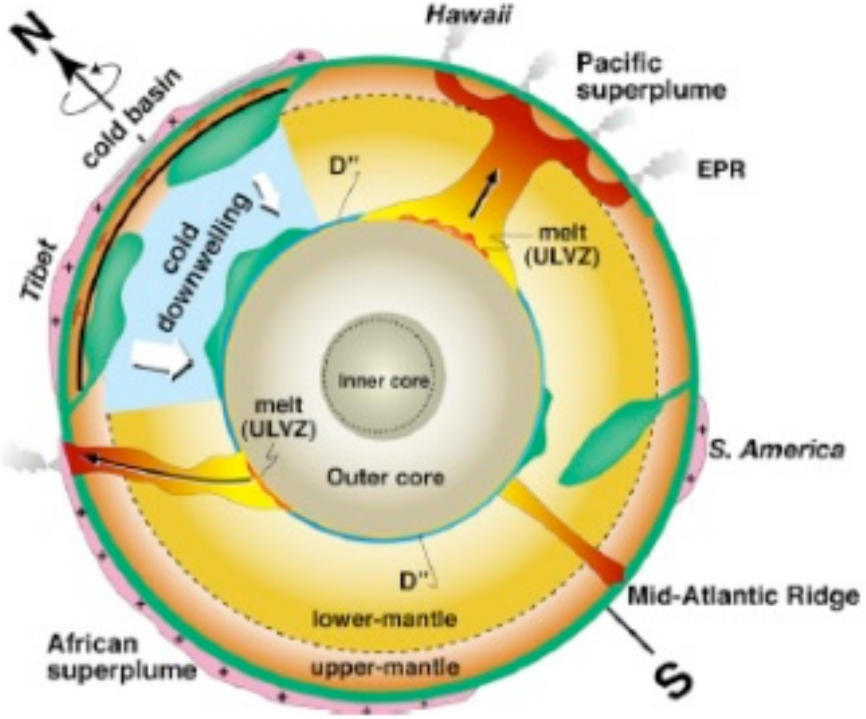
Transport of water into CMB



Ohtani (Elements, 2005)

Superdownwelling/super continents



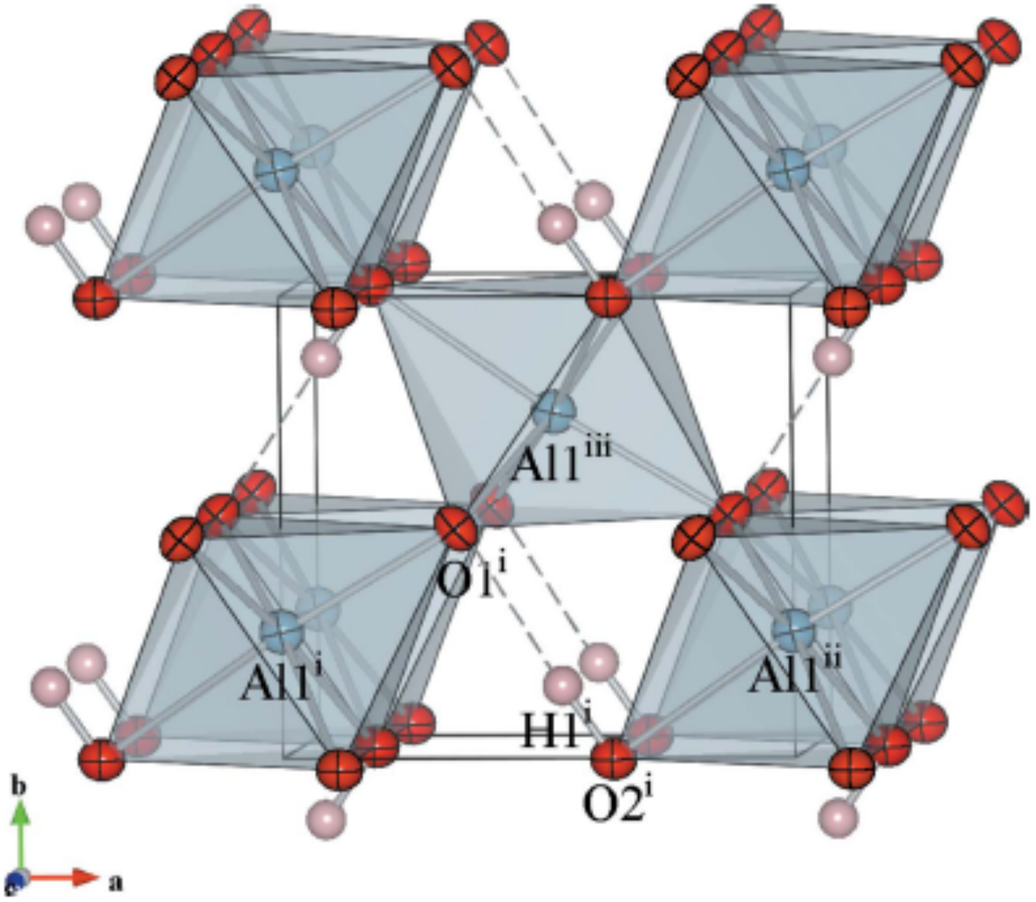
Maruyama et al. (GR 2007)

Candidates of the hydrogen carriers into the lower mantle

Phase D: $Mg_{1.14}Si_{1.73}H_{2.81}O_6$
Superhydrous phase B: $Mg_{10}Si_3O_{14}(OH)_2$
Aluminous Phase D: $Al_2SiO_4(OH)_2$

Phase δ: AlOOH Phase
Phase H: $MgSiO_2(OH)_2$
Aluminous phase H: $MgSiO_2(OH)_2$-AlOOH

Hydrous δ–phase (AlOOH)
Hydrous δ–phase H $MgSiO_2(OH)_2$ solid solution



Suzuki, Ohtani, Kamada (PCM 2000)
Bindi et al. (2014)

2Al = MgSi

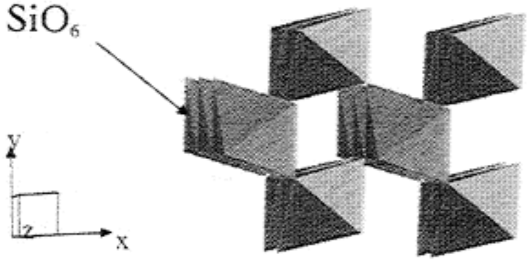
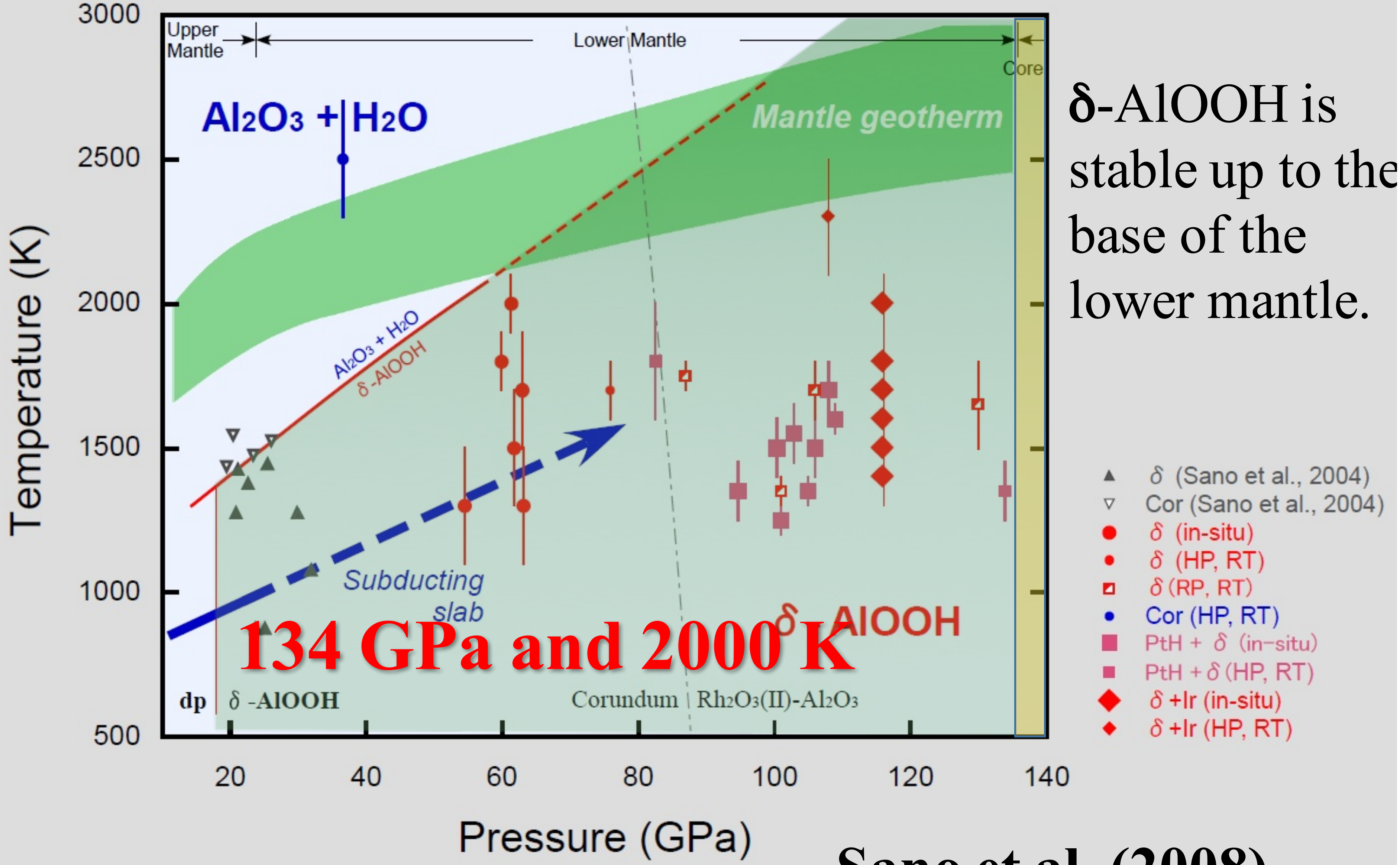


Figure 1. Structural similarity of δ-AlOOH and $CaCl_2$ type SiO_2. The positions of hydrogen atoms in δ-AlOOH are assumed to be the same as the other iso-structural compounds (e.g., *Christensen et al.*, 1976).

High pressure polymorph of SiO_2: $CaCl_2$ structure

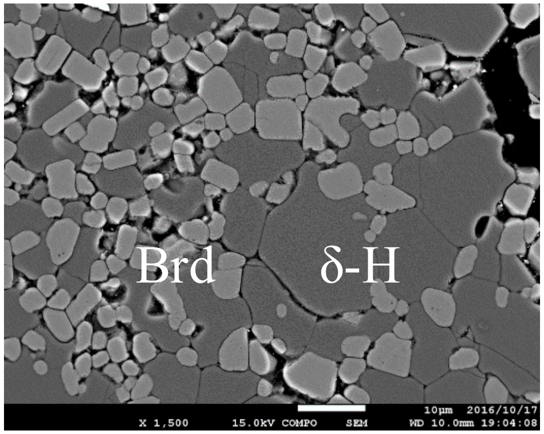
Phase δ-AlOOH



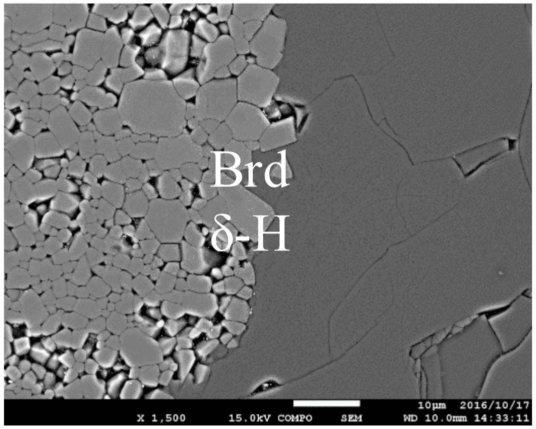
δ-AlOOH is stable up to the base of the lower mantle.

Sano et al. (2008)

δ-H solid solution coexists with Al-depleted bridgmanite



28 GPa, 1573K



28 GPa, 1373K

28 GPa, 1573 K

δ-H: $H_{0.21}\delta_{0.57}S_{0.22}$

Brg: $\mathbf{M_{0.94}A_{0.06}}$

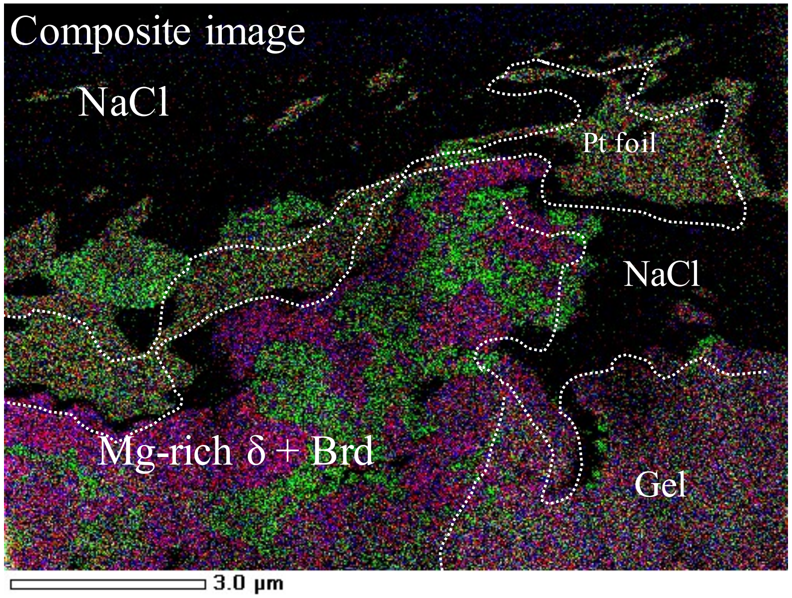
$K(Al_2O_3) = 9.8$

28 GPa, 1373 K

δ-H: $H_{0.59}\delta_{0.08}S_{0.33}$

Brg: $\mathbf{M_{0.98}A_{0.02}}$

$K(Al_2O_3) = 5.1$



68 GPa, 2110 K

68GPa, 2110 K

δ-H: $H_{0.43}\delta_{0.57}$

Brg: $\mathbf{M_{0.94}A_{0.06}}$

$K(Al_2O_3) = 4.8$

$H = MSi(OOH)_2$
$\delta = 2AlOOH$
$S = SiO_2$
$M = MSiO_3$
$A = Al_2O_3$

Coexitence with post-perovskite

120 GPa, 2000 K

δ-H: $H_{0.23}\delta_{0.77}$

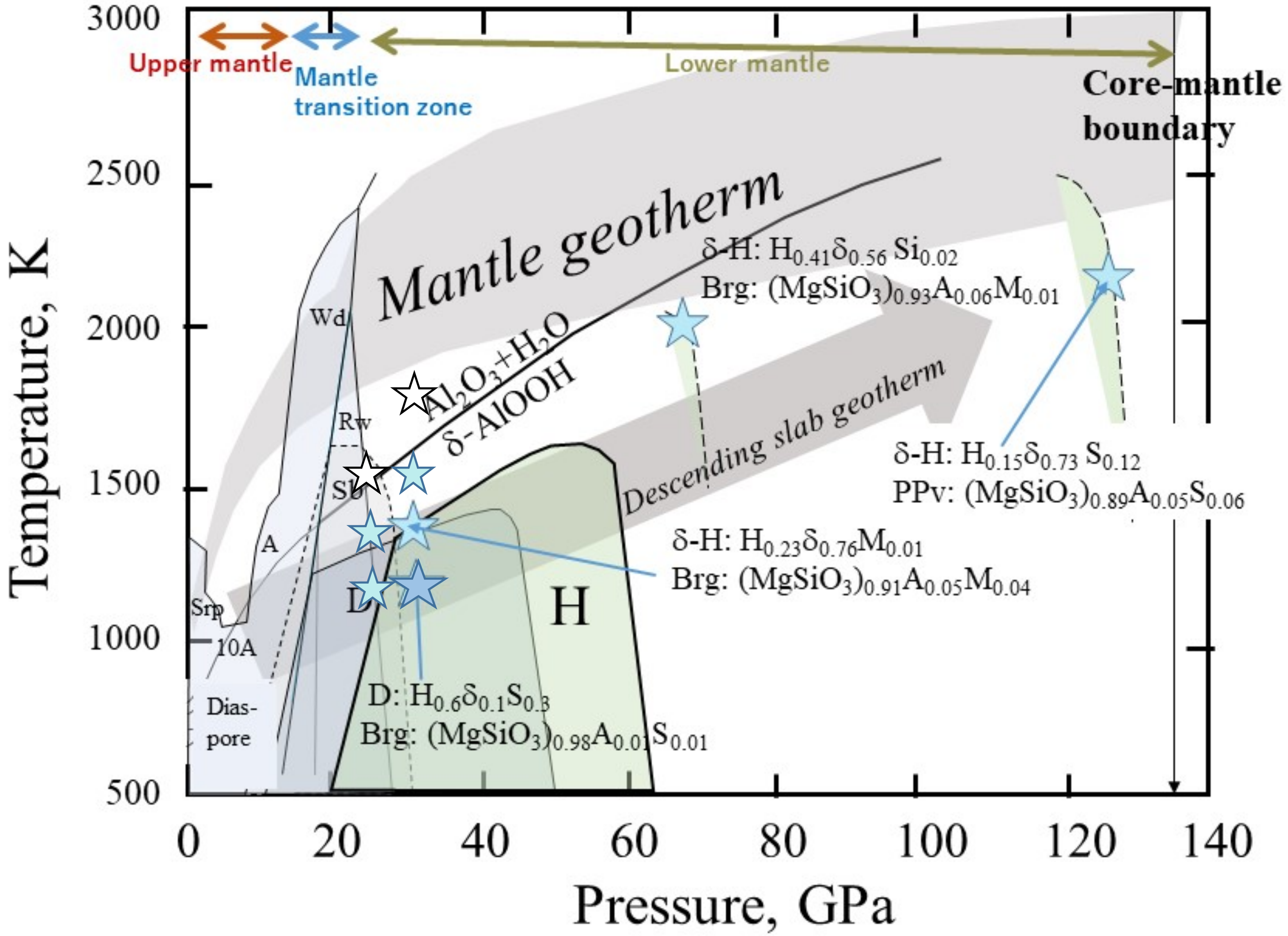
PPv: $\mathbf{M_{0.95}A_{0.05}}$

$K(Al_2O_3) = 5.9$

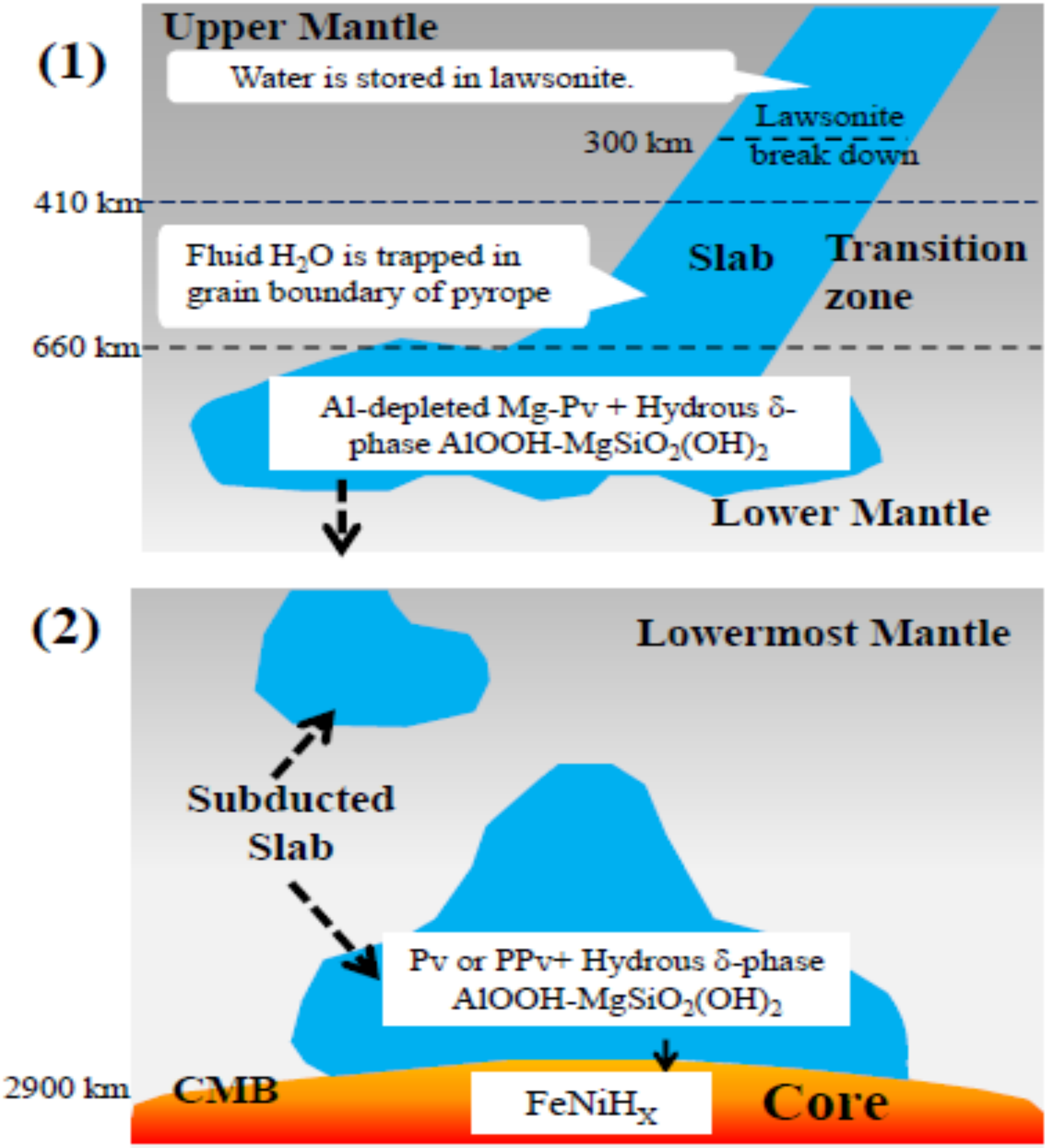
Ohtani et al., 2018)

δ-H solid solution coexists with Al-depleted bridgmanite

Ohtani et al. (2018)



Transport of water into CMB



Roles of hydrogen in the mantle

1. Mantle Transition zone (MTZ) is at least locally wet.
2. Metastable olivine wedge exists even under the wet upper mantle and transition zone, and it may trigger the deep earthquakes.
3. Dehydration in the mantle transition zone and the top of the lower mantle may cause deep earthquakes.
4. Wet lower mantle contains alumina-depleted bridgmantite/post-perovskite and hydrous δ-H solid solution.

Thank you for your attention!