Uncertainties in the stability field of UHP hydrous phases (10-Å phase and Al-bearing phase E) and deep-slab dehydration: potential implications for fluid migration and water fluxes at subduction zones

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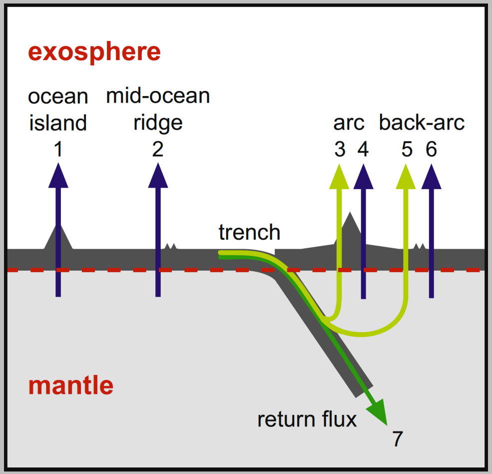
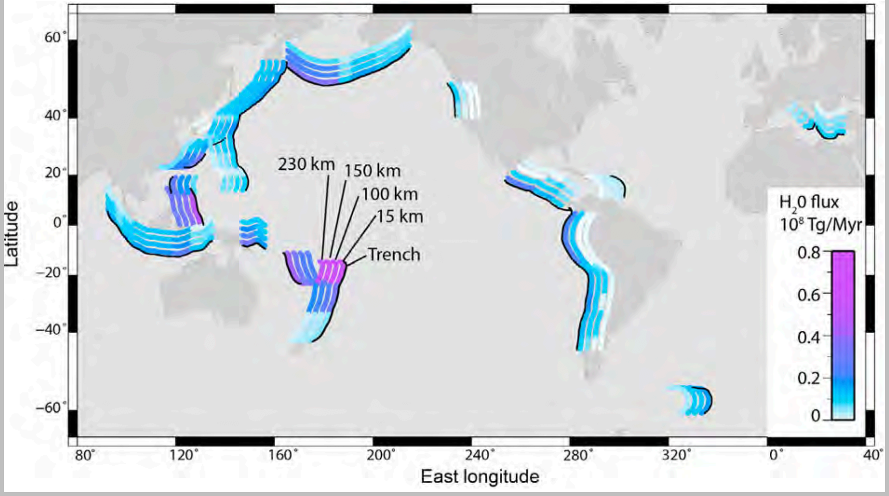
- The **subduction water cycle is a key process** for understanding the long-term evolution of surface water (sea-level), arc volcanism and volatile recycling, mantle hydration and convection…



- H_2O input into subduction trenches is 10 times higher than the input to the exosphere via ocean island and mid-ocean ridge volcanism [*e.g. Rüpke* et al, 2004]
- The return of water to the mantle via subduction is 50% greater than combined outfluxes at ocean islands and mid-ocean ridges [*Hirchmann*, 2018]
- Although most subducted H_2O is recycled partly through arcs, water subduction flux may have lead to a slight lowering of sea-level through the Phanerozoic [*Parai* & *Mukhopadhyay*, 2012]

Fig. 1 : Sketch of water exchanges between the exosphere and the mantle. The blue arrows 1 and 2 are the input from the mantle into the exosphere, including the part of residual water in depleted mantle that participate into arc volcanism (4,6). The green arrows (3,5,7) illutrate the recycling through subduction [*Parai* & *Mukhopadhyay*, 2012].

- The most **detailed work on water flux at subduction zones** comes from *van Keken* et al. [2011] who used a combination of **thermo-mechanical models** and **petrological modeling with Perple_X** [*Connolly*, 2009]. Their calculations have been used in a large number of studies.



- At present-day, about **30% of water input at trenches may return to the deep mantle** (beyond 230 km) within the slab.

Fig. 2 : Map of slab-water loss with depth in present-day subduction zones [*van Keken et al.*, 2011]

UHP phases in laboratory experiments

- **Thermodynamic calculations** of phase relations in peridotites beyond antigorite stability **and laboratory experiments show discrepancies**
  - ➢ In thermodynamic databases such as Holland and Powell [2011] (**H&P11**): **Absence of the aluminous 10-Å phase (TAP) and the Al-bearing phase E (Al-phE)** which may hold moderate amounts of H_2O (> 2 wt%)

- We use experimental studies that reported the stability field of TAP and Al-phE (see Fig. 3)
  - An "experimental gap" exists around 7 GPa and 700°C.
  - We consider two scenarios for the stability field of TAP and Al-phE to span the extreme cases
  - We build pseudosections of water content in subducted peridotite to be used in our petrological models.

Main question : **What is the impact of the UHP the hydrous phases (10-Å phase and Al-bearing phase E) on water fluxes at subduction zones ?**

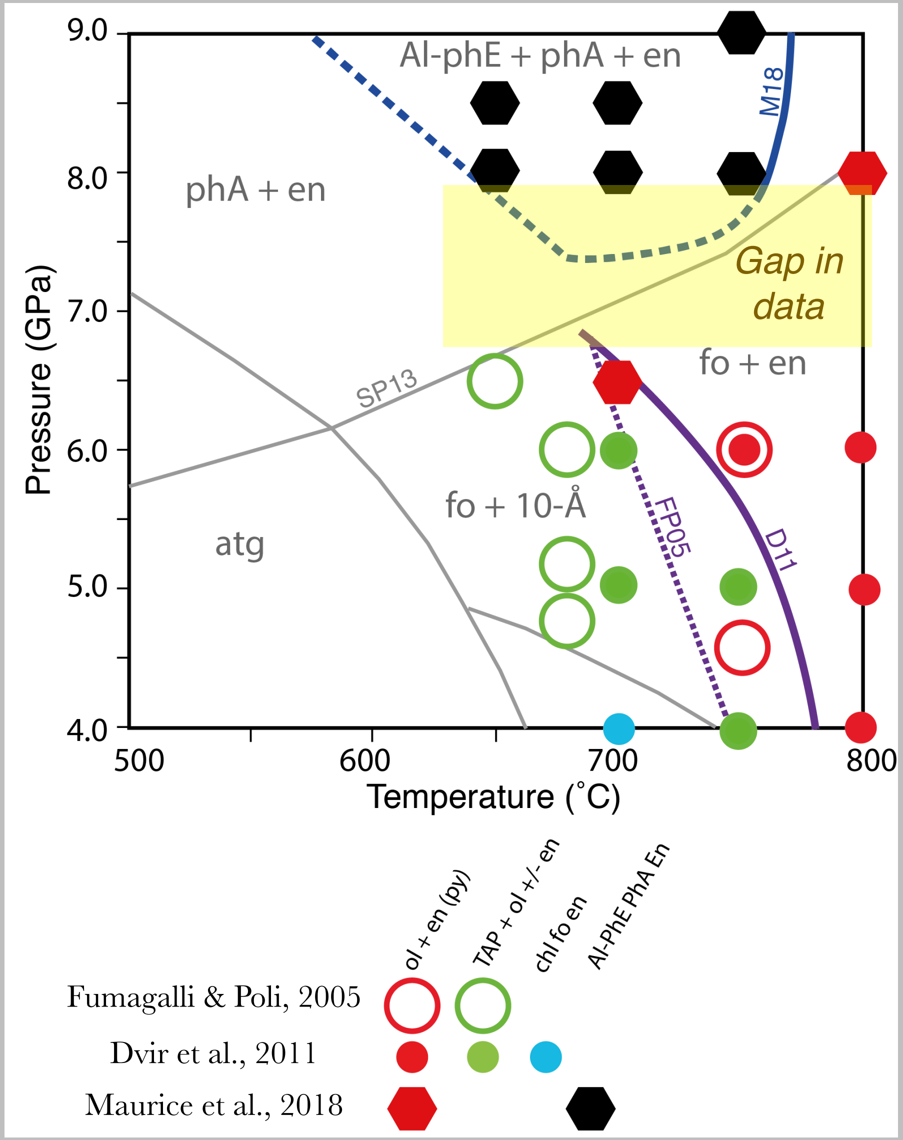


Fig. 3 : Experiments that reported the stability field of TAP and Al-phE in natural and multicomponent systems that include Aluminium.

Thermo-petrological modeling

- We use **kinematically-driven 2D thermal subduction models**
  - Realistic slab geometries are used
  - Stokes flow under Boussinesq approximation in the mantle wedge
  - Composite rheology (dislocation+diffusion creep) with rheological parameters of wet olivine
  - Prescribed motion of the slab + Full-coupling between mantle and slab below 75-km depth

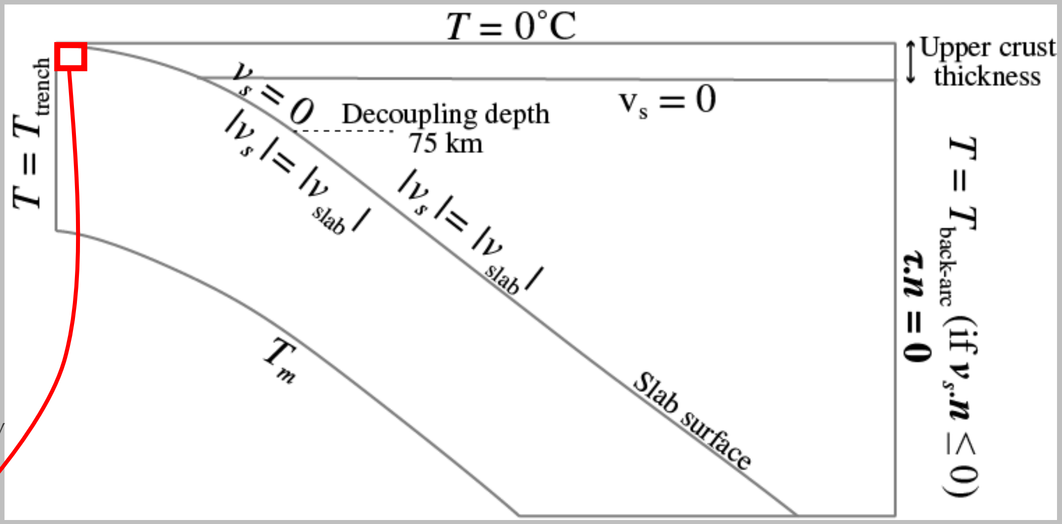


Fig. 4 (right) : Sketch of geometry and boundary conditions.

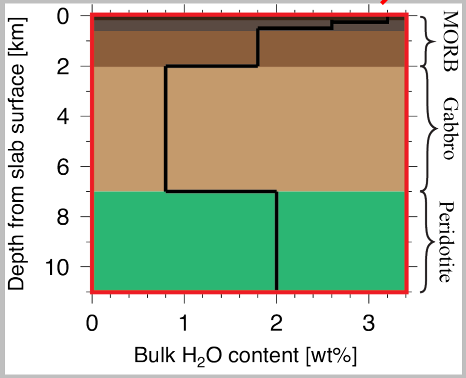
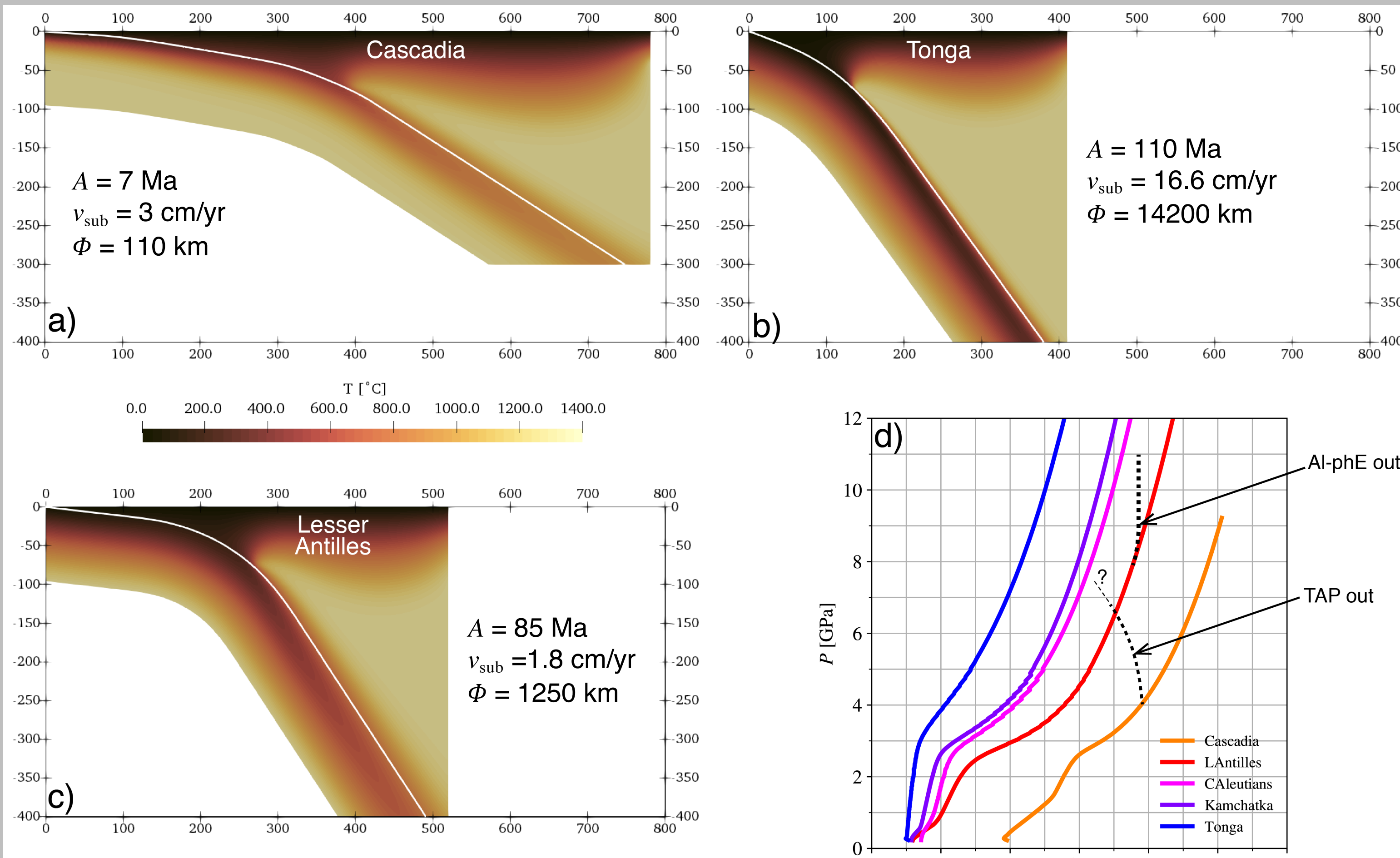


Fig. 5 : Sketch of bulk water content within the hydrated portion of the subducting plate at trench

- **Petrological model** : we adopt the generic lithologic model used in previous studies [e.g. van Keken et al., 2011]
  - **4-km thick serpentinized lithospheric mantle** at trench with a bulk water content of 2wt% (equivalent to ~15 % of mantle serpentinization)
- Water content in slab with depth (with P and T) is evaluated using thermodynamic calculations by Perple_X [*Connolly*, 2009]

- Calculations are performed with the code TerraFERMA [*Wilson* et al., 2016]

- Modeled P-T paths of the Moho show that the serpentinized mantle in hot (Cascadia) and “hot-intermediate”-to-“intermediate-cold” subductions (L. Antilles, Aleutians, Kamchatka; $1000 < \Phi < 7000$ km; hereafter collectively referred to as “intermediate”), may cross the sequence Atg → TAP and/or phA → Al-PhE



[*Cerpa et al., in prep.*]

Thermal parameter

$\Phi = v_{sub} \times A \times \sin(\alpha)$

with

v_{sub} : Subduction velocity

A : Slab age

α : Mean slab dip

Fig. 6 : Calculated potential temperature field for Cascadia (a), Tonga (b) and Aleutians (c). PT-paths (d) at the Moho calculated with and adiabatic gradient of 0.3°C/km

Note : The subduction parameters (A, v_{sub}) in our models are the same as in *Syracuse et al.* [2010] and *van Keken et al.* [2011]

Case study : the Lesser Antilles subduction zone

- We consider the Lesser Antilles subduction zone and two cases :
  - A cold case : Mantle potential temperature $T_m = 1300^{\circ}$C ; Adiabatic gradient $\alpha = 0.3^{\circ}$C/km
  - A warm case : $T_m = 1421.5^{\circ}$C ; $\alpha = 0.5^{\circ}$C/km
- Using Perple_X (with database H&P11):
  - Cool case : lithospheric dehydration at around 6 GPa, i.e. 185 km (water release at ToS at about a 150-km depth)
  - Warm case : lithospheric dehydration around 5 GPa, i.e. 150 km (water release at ToS at about a 130-km depth)

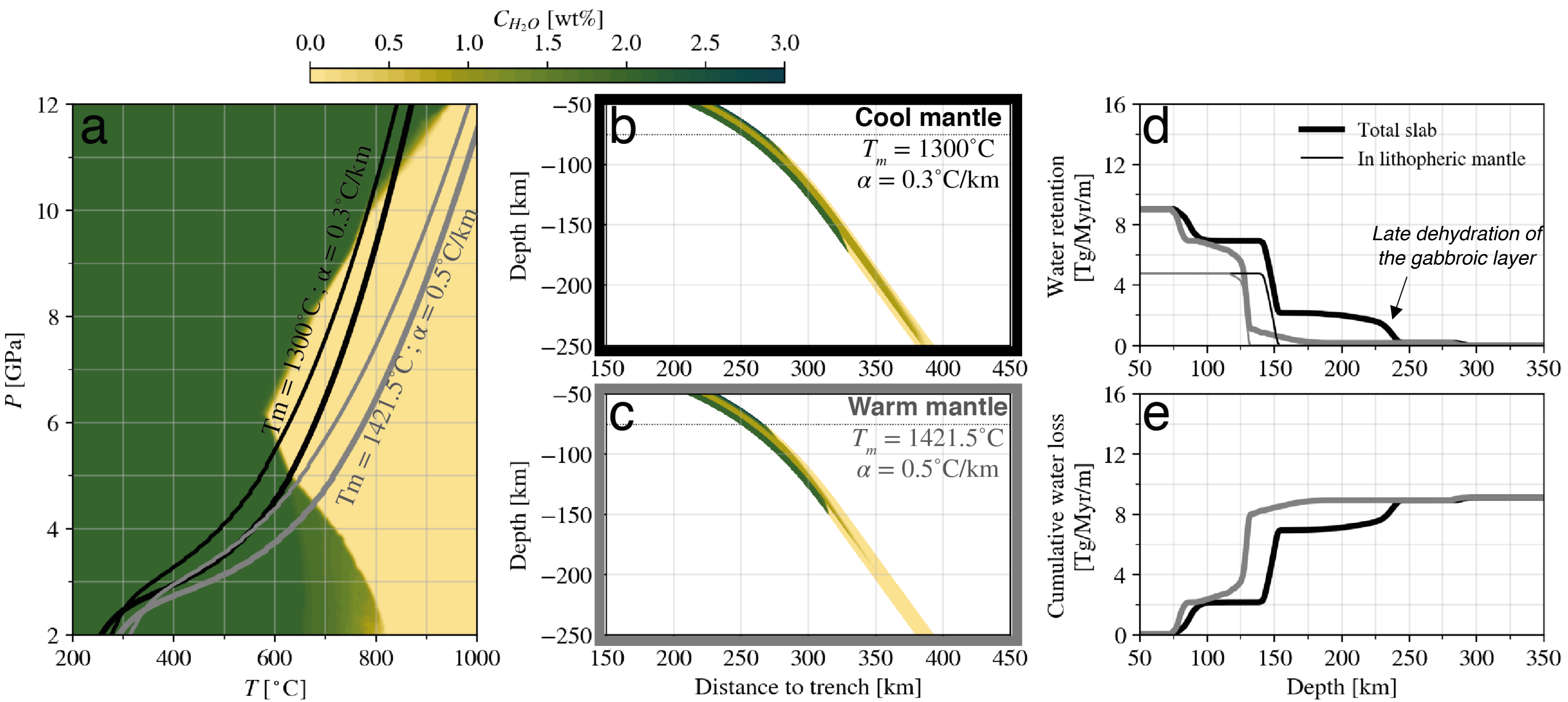


Fig. 7 : a) Pseudo-phase diagram of bulk water content of peridotite calculated with PerpleX, on top of which are represented the PT paths at the Moho (thick) and at the bottom of the 4-km thick hydrated mantle (thin) for a "cool-mantle" and a "warm-mantle" case. b) and c) are the water content within the slab for the two cases with decoupling depth indicated by the thin dotted line. d) Water input within entire slab (thick lines) and only within the lithospheric mantle (thin lines) with depth. e) Cumulative water loss with depth.

Water content in slab (Lesser Antilles)

- We perform models with reconstructed phase diagrams including the TAP and the Al-PhE, assuming end-members of their stability given the published experimental data

Making assumptions on the stability field of the TAP (around 7 GPa) that…

…minimizes its stability *…maximizes its stability*

- The presence of **the TAP and the Al-PhE delays the complete dehydration of the subducted mantle** in the Lesser Antilles model

- The presence of **the TAP and the Al-PhE may retain water in the subducted mantle up to a 300 km depth**.

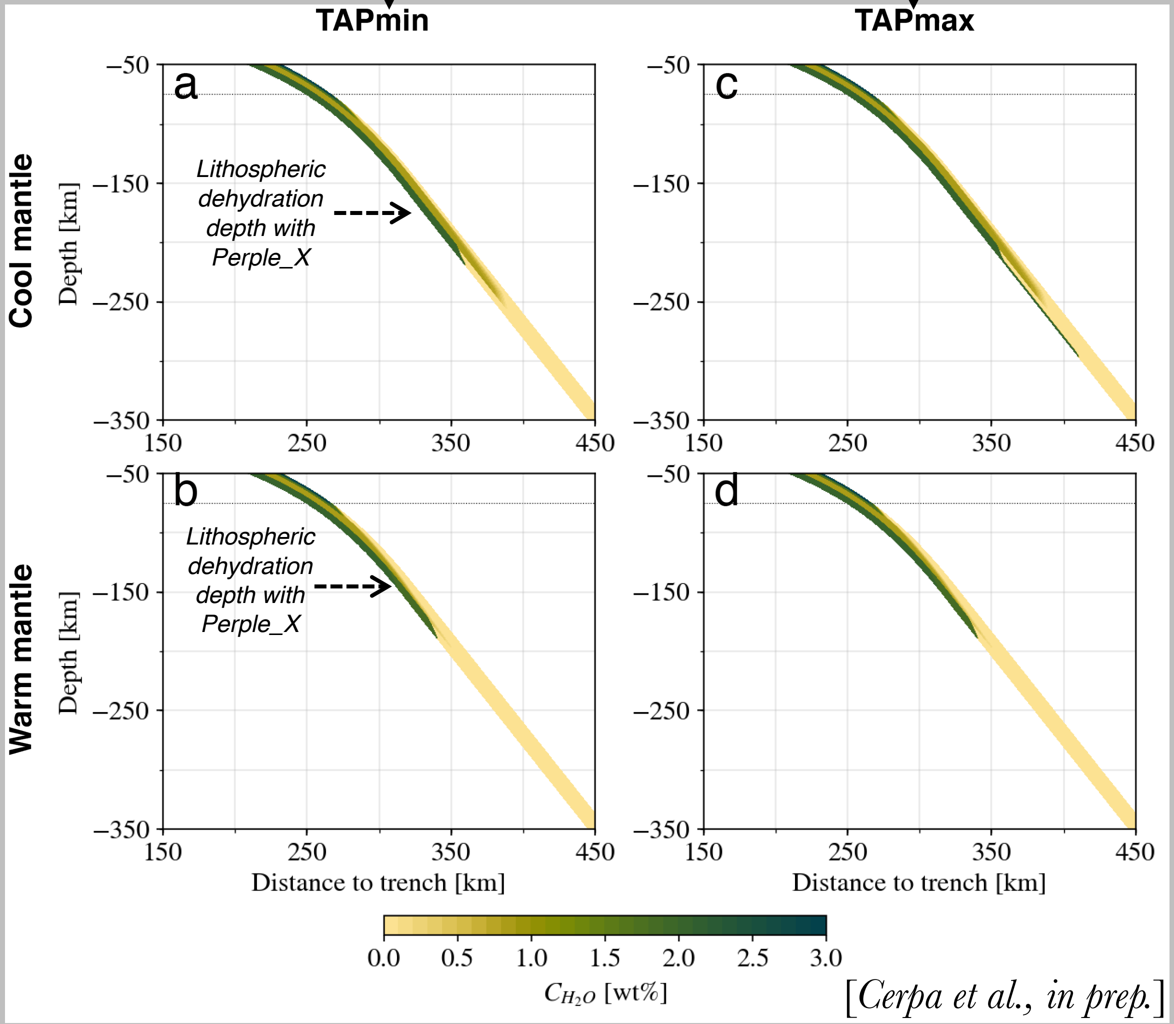
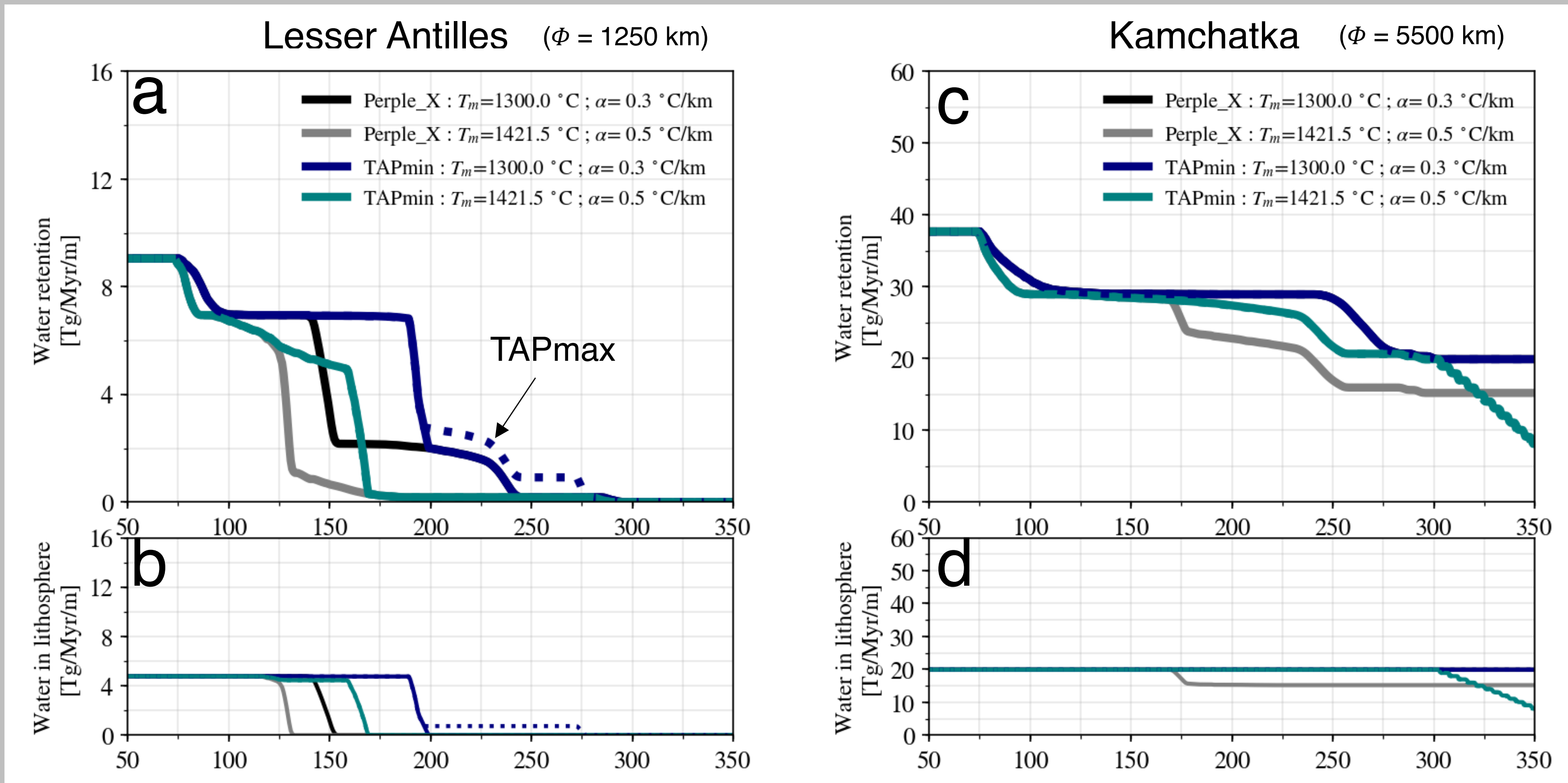


Fig. 8 : Water content in the subducting slab for the two cases (Cool and Warm) and the two assumptions (TAPmin, TAPmax) on the stability field of the TAP and PhE. The decoupling depth indicated by the thin dotted line.

Comparing water input for two subduction zones

Fig. 9 : Total water input in the slab (a,c) and only in the subducting mantle (b,d) calculated from the models of the Lesser Antilles (left) and Kamchatka (right).



- As shown above (Fig. 8), **dehydration of the lithospheric mantle occurs deeper** in the model of the Lesser Antilles when considering the presence of TAP and Al-phE. The warm and TAPmax case exhibits complete dehydration only at a 275-km depth.
- The model for Kamchatka never exhibits complete dehydration
- Lithospheric dehydration is retarded by TAP and phE only in the warm case.
- In the warm case, **water retention beyond a 350-km depth is lower when considering the formation of TAP and Al-phE** (with both TAPmin and TAPmax assumptions)

- We carry out a series of models for several representative transects of present-day subduction zones and we calculate both the depth of dehydration of the lithospheric mantle and water retention in the slab (Fig. 10)

- Accounting for the formation and breakdown of TAP and Al-phE the models show that the **dehydration of the lithospheric mantle occurs beyond predictions by Perple_X using the stability field of UHP hydrous phases in the thermodynamic database H&P11 (phase A and brucite):**
  - Delayed by ~10-20 km in Cascadia
  - Up to 150 km in the Lesser Antilles

- Because of the quasi-isotherm shape of the transition Al-phE→Ol predicted by experiments by *Maurice et al.*, [2018] **water retention within the slab in intermediate subduction zones may be less than predicted by Perple_X using H&P11** (formation of phase A and brucite at T>800°C and P>8 GPa)

[*Cerpa et al., in prep.*]

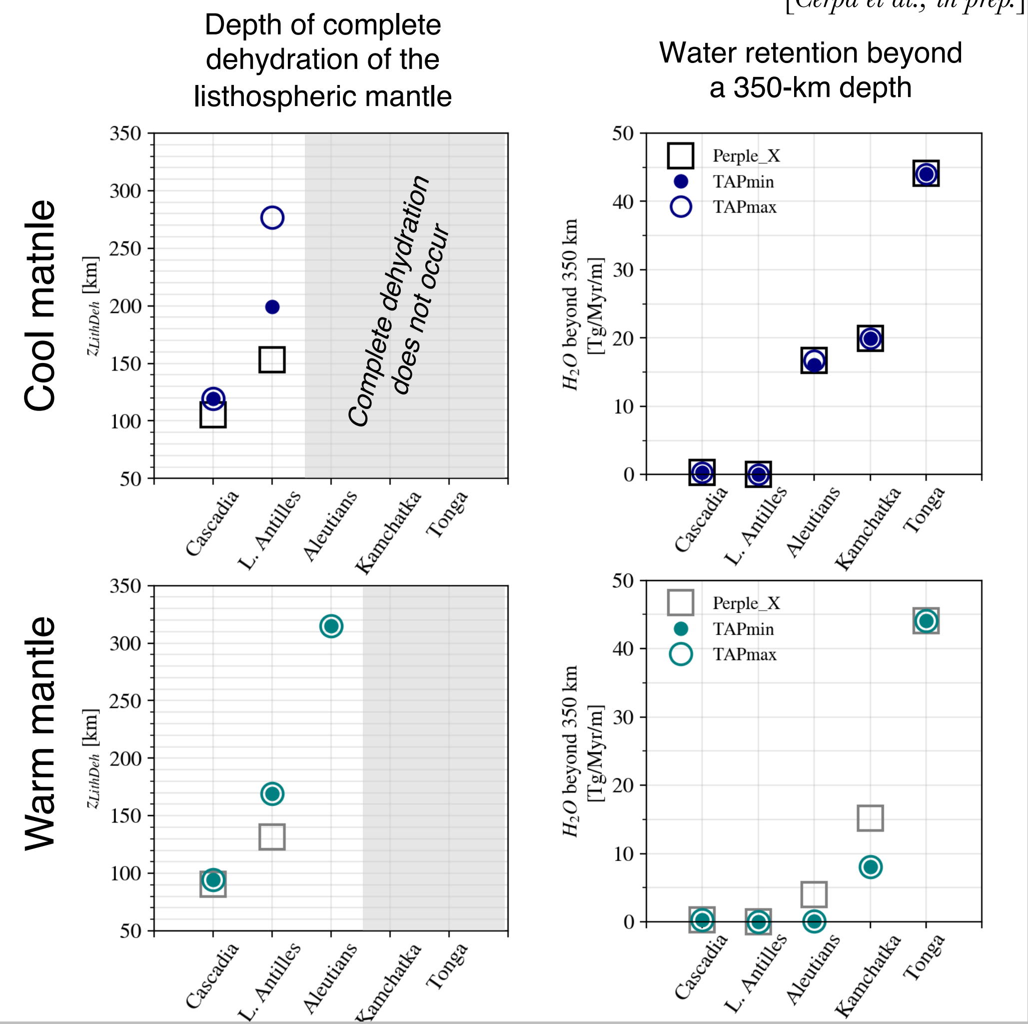


Fig. 10 : Depth of complete dehydration of the lithospheric mantle, if occurring in the models (first column), and water retention beyond a 350-km depth (second column), calculated for cool-mantle cases (top row) and warm-mantle cases (bottom row)

Concluding remarks

- Experimental studies on natural compositions consistently show the formation of aluminous-rich phases beyond antigorite stability but are neglected in thermodynamic calculations:
  - There is an experimental "gap" around 6.5-8.0 GPa and 650-750°C which precludes a precise determination of the choke point.
  - PT-paths within the lithospheric mantle of intermediate subduction zones (Lesser Antilles to Kamchatka) may cross the stability field of the 10-Å phase and of the Al-bearing phase E.

- Building pseudo-phase diagrams of water content accounting for the formation of TAP and Al-phE, our **thermal and petrological models** show that :
  - **Complete dehydration of the hydrated lithospheric mantle may be delayed** by 10-20 km for hot subduction zones and up to 150 km for intermediate subduction zones
  - **Water retention in the lithospheric mantle of intermediate subduction zones may be lower** than predicted by commonly used thermodynamic calculations (Perple_X) leveraging the databases (H&P11).

- The formation of **TAP and Al-phE within slabs may have important effects** on :
  - The **water release into the mantle wedge, fluid migration pathways and fluid focusing efficiency** towards the subarc region [*Wilson et al.*, 2014; *Cerpa et al.*, 2017]
  - The **global slab water flux into the mantle transition zone** which might have been overestimated for intermediate subductions [*van Keken et al.*, 2011]

References

Cerpa, N. G., Wada, I., & Wilson, C. R. (2017). Fluid migration in the mantle wedge: Influence of mineral grain size and mantle compaction. *Journal of Geophysical Research: Solid Earth*, 122(8), 6247-6268. DOI:10.1002/2017JB014046

Connolly, J. A. D. (2009). The geodynamic equation of state: what and how. *Geochemistry, Geophysics, Geosystems*, 10(10). DOI:10.1029/2009GC002540

Crameri, F. (2018), Scientific colour-maps. Zenodo. DOI:10.5281/zenodo.1243862

Dvir, O., Pettke, T., Fumagalli, P., & Kessel, R. (2011). Fluids in the peridotite–water system up to 6 GPa and 800 C: new experimental constrains on dehydration reactions. *Contributions to Mineralogy and Petrology*, 161(6), 829-844. DOI : 10.1007/s00410-010-0567-2

Fumagalli, P., & Poli, S. (2005). Experimentally determined phase relations in hydrous peridotites to 6· 5 GPa and their consequences on the dynamics of subduction zones. *Journal of Petrology*, 46(3), 555-578. DOI : 10.1093/petrology/egh088

Hirschmann, M. M. (2018). Comparative deep Earth volatile cycles: The case for C recycling from exosphere/mantle fractionation of major (H2O, C, N) volatiles and from H2O/Ce, CO2/Ba, and CO2/Nb exosphere ratios. *Earth and Planetary Science Letters*, 502, 262-273. DOI : 10.1016/j.epsl.2018.08.023

Holland, T. J. B., & Powell, R. (2011). An improved and extended internally consistent thermodynamic dataset for phases of petrological interest, involving a new equation of state for solids. *Journal of Metamorphic Geology*, 29(3), 333-383. DOI: 10.1111/j.1525-1314.2010.00923.x

Maurice, J., Bolfan-Casanova, N., Padrón-Navarta, J. A., Manthilake, G., Hammouda, T., Hénot, J. M., & Andrault, D. (2018). The stability of hydrous phases beyond antigorite breakdown for a magnetite-bearing natural serpentinite between 6.5 and 11 GPa. *Contributions to Mineralogy and Petrology*, 173(10), 86. DOI:10.1007/s00410-018-1507-9

Parai, R. & Mukhopadhyay, S. (2012) How large is the subducted water flux? New constraints on mantle regassing rates. *Earth and Planetary Science Letters*, 317, 396-406. DOI : 10.1016/j.epsl.2011.11.024

Rüpke, L. H., Morgan, J. P., Hort, M., & Connolly, J. A. (2004). Serpentine and the subduction zone water cycle. *Earth and Planetary Science Letters*, 223(1-2), 17-34. DOI : 10.1016/j.epsl.2004.04.018

Syracuse, E. M., van Keken, P. E., & Abers, G. A. (2010). The global range of subduction zone thermal models. *Physics of the Earth and Planetary Interiors*, 183(1-2), 73-90. DOI:10.1016/j.pepi.2010.02.004

van Keken, P. E., Hacker, B. R., Syracuse, E. M., & Abers, G. A. (2011). Subduction factory: 4. Depth-dependent flux of H2O from subducting slabs worldwide. *Journal of Geophysical Research: Solid Earth*, 116(B1). DOI : 10.1029/2010JB007922

Wilson, C. R., Spiegelman, M., van Keken, P. E., & Hacker, B. R. (2014). Fluid flow in subduction zones: The role of solid rheology and compaction pressure. *Earth and Planetary Science Letters*, 401, 261-274. DOI:10.1016/j.epsl.2014.05.052

Wilson, C. R., Spiegelman, M., & van Keken, P. E. (2017). Terra FERMA: The Transparent Finite Element Rapid Model Assembler for multiphysics problems in Earth sciences. *Geochemistry, Geophysics, Geosystems*, 18(2), 769-810. DOI : 10.1002/2016GC006702

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