

Limited subduction of water to mid-upper mantle depths predicted by the phase assemblages in hydrated peridotites with natural composition



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Motivation

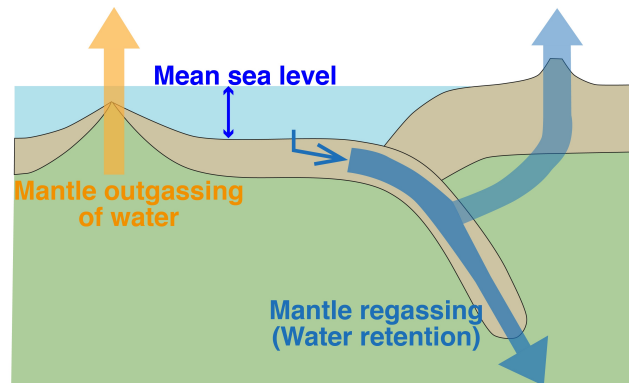


Fig. 1 : Sketch of deep-water cycle

- **Subduction of water partly controls the mean sea-level** over geological timescales [1] (i.e. imbalance between mantle outgassing and mantle regassing, Fig. 1)
- Reconstructions of sea-level suggest **less than ~100 m of decrease over the Phanerozoic** (or even a little increase, see Fig. 2)

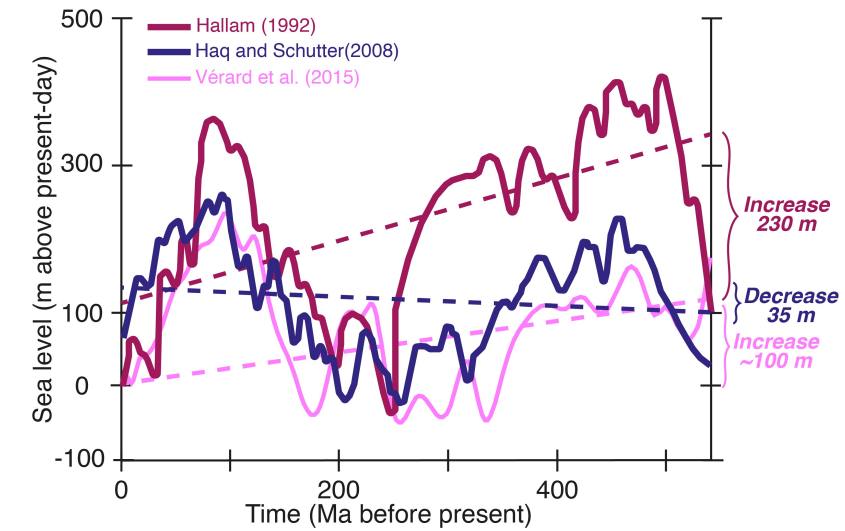


Fig. 2 : Reconstructed sea-level over the Phanerozoic from stratigraphic constraints [2,3] and a paleogeography model [4].

- **Subduction thermopetrological models** predict voluminous water retention in slabs at present-day (30% of H_2O entering the trenches [5])
⇒ **Predicted Global Water Retention (GWR) exceeds mantle outgassing by approximately 50%**
- If extrapolated over the Phanerozoic [1]:
⇒ **Mismatch between thermopetrological models and the stability of mean-sea level inferred from reconstructions**

Flaws in previous thermopetrological models:

- **Questionable petrological constraints of hydrated peridotite** at high pressure (P) and high temperature (T)
- **GWR extrapolated from ~200 km** to the deep-upper mantle
→ they found that the crust was the main H_2O carrier to depth

Main objectives of this study

- **Enhance the petrological modeling of hydrated peridotites** at high-PT conditions in numerical models of subduction zones using experimental data
- **Revise estimations of present-day GWR** in the deep upper-mantle

Modeling approach

- **2D thermal models** for 56 subduction transects
 - Slab geometries from *Slab2.0* [6] (up to 150-km depth)
 - Stokes flow + Boussinesq approximation in the wedge
 - Composite rheology (dislocation+diffusion creep)
 - Slab with prescribed motion
 - Slab-mantle coupling below a 75-km depth
 - Steady-state models

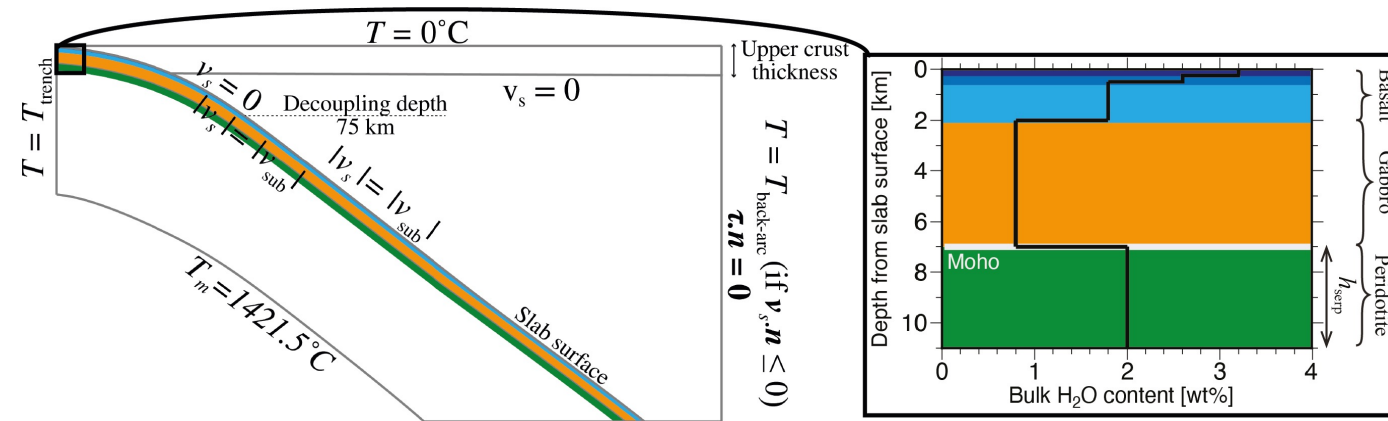


Fig. 3 : Sketches of geometry and boundary conditions for the thermal models (left) as well as of bulk water content within the hydrated portion of the subducting plate at trench (right)

○ Petrological model

- Generic lithologic model from Hacker et al., 2008 [7] (Fig. 3) :
 - Basaltic layers : 2-km thick
 - Gabbroic layer : 1.5-km thick
 - **Serpentinized mantle layer** : thickness h_{serp}
 → **bulk H₂O** of **2.0 wt.%** (~15 % of serpentinization)
- PT-dependent H₂O content given by **thermodynamic calculations from Perple_X** [8,9]
 - **except for the serpentinized mantle at high-PT conditions** (see next slide)

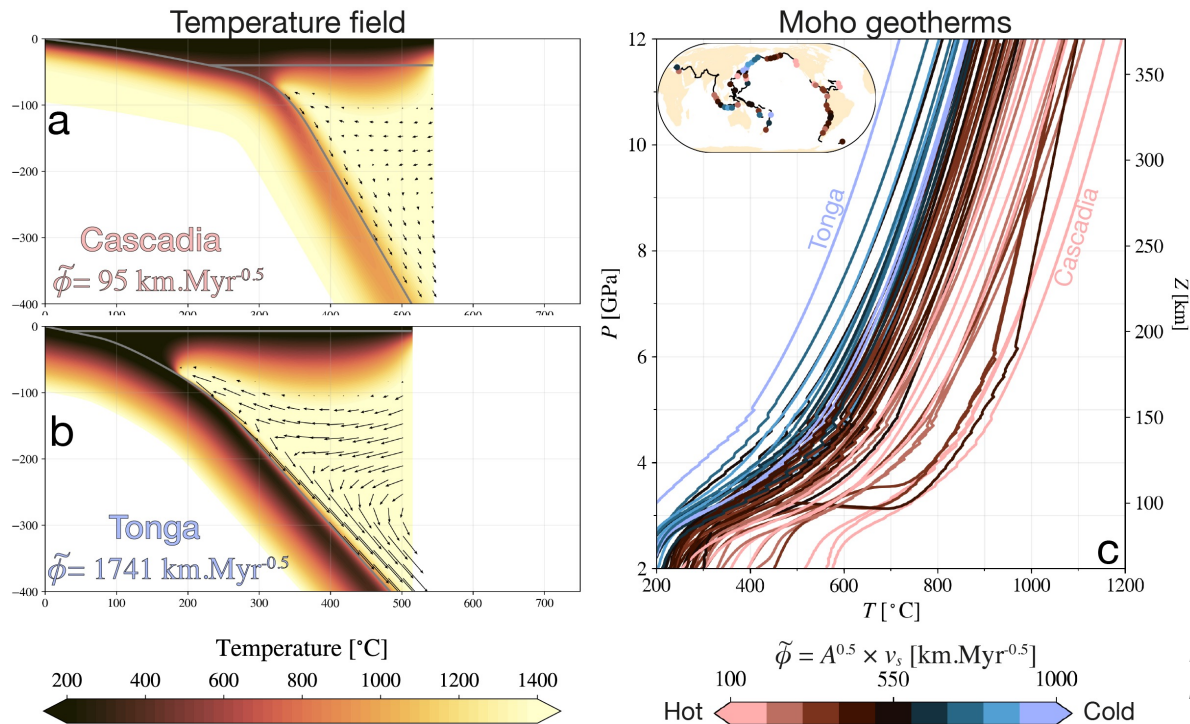


Fig. 4 : Calculated potential temperature field for Cascadia (a) and Tonga (b). PT-paths at the Moho (d) calculated with an adiabatic gradient of 0.5°C/km for the 56 transects. The paths are color-coded following a « modified » thermal parameter [10].

Peridotite modeling

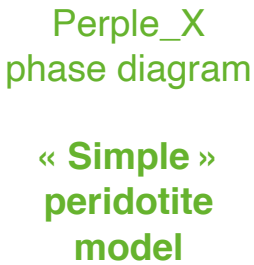
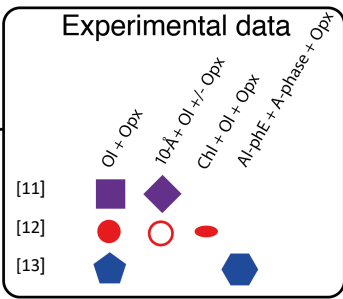
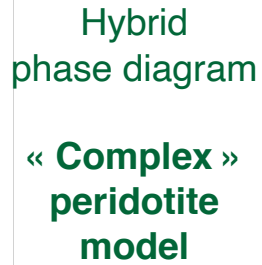


Fig. 5 : Perple_X phase diagram (left), experimental data (center), hybrid-phase diagram (right). Experimental data is from refs. 11,12,13. On the right panel, phase relations and H₂O contents (wt.%) are indicated in light blue.



- **Major differences between thermodynamic calculations and laboratory experiments on naturally-complex systems** (e.g. containing magnetite [13]) : **Absence of the aluminous 10-Å phase and the Al-bearing phase E (Al-phE)** beyond antigorite stability in the thermodynamic database of Holland and Powell 2011 [9]
- **We thus built a hybrid-phase diagram** (“Complex” peridotite model, see Fig. 5c) using experimental data at $P > 4$ GPa and $T > 600^\circ\text{C}$

Stability of hydrous minerals

- In the gabbroic layer, most Moho PT-paths cross the water line (breakdown of lawsonite) at 8–10 GPa
- The two petrological models show important differences for the peridotite layer :
 - At **P < 6 GPa** : **The stability field of hydrous minerals is widened in the complex model** (formation of 10-Å phase)
 - At **P > 6 GPa** : **The stability field of hydrous mineral is narrowed in the complex model** (Al-phE destabilized at ~800°C)
- **The Moho PT-paths of moderately cold transects (e.g. S. Kurile) cross the water line in the complex model** for peridotite but not in the simple model.

“Water line” : the last phase transition beyond which the (main) hydrous minerals are unstable

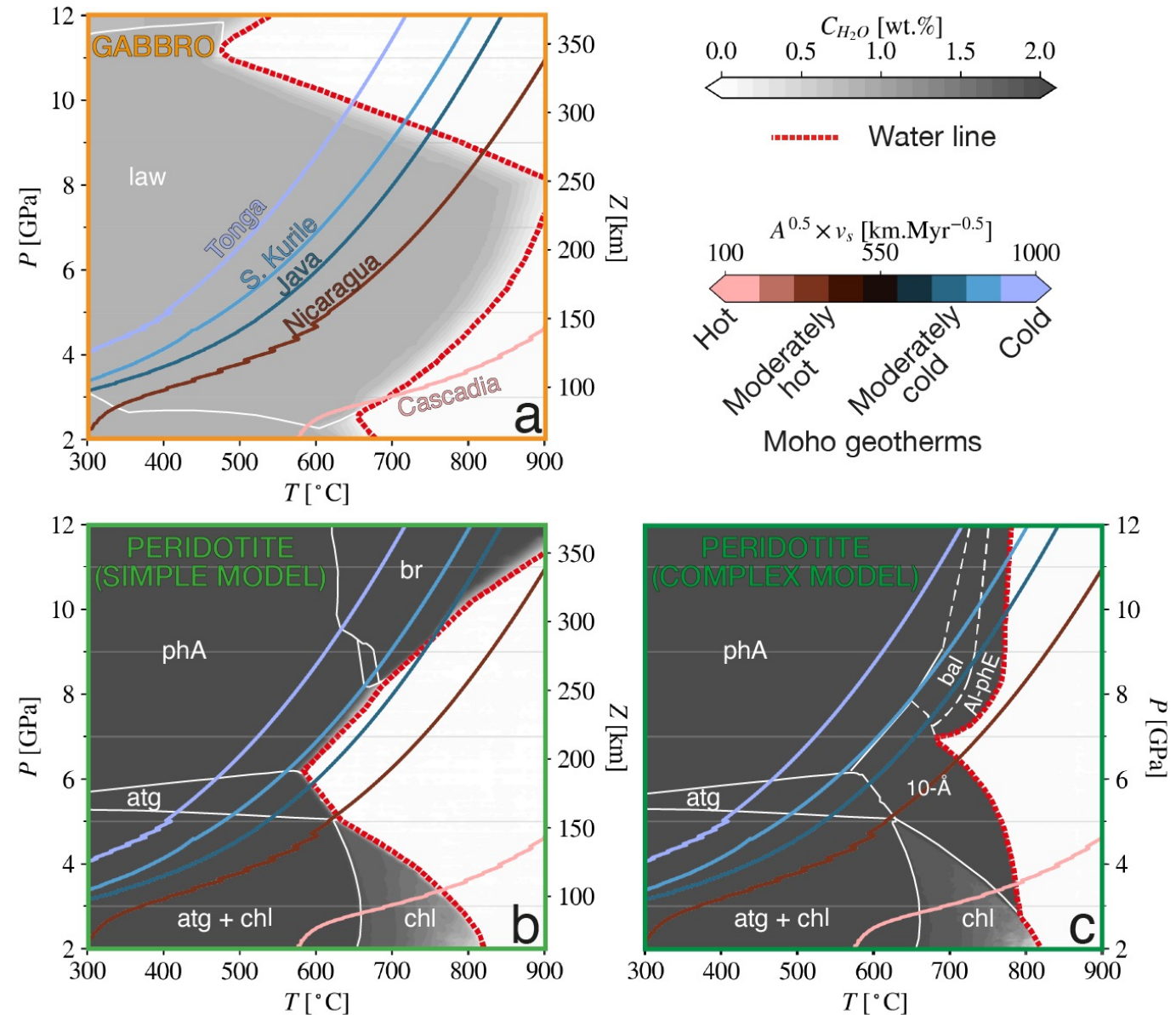


Fig. 6 : Diagrams of bound-H₂O content for a gabbro (a), a simple peridotite model (b) and a complex peridotite model (c) overlaid by the Moho geotherms for five selected transects.

Dehydration depths

- The basaltic layers mostly dehydrate at depths where the slab and the mantle become mechanically coupled.
- For all but the hottest transects (e.g. Cascadia) the gabbroic layer dehydrates at depths between 250 and 300 km.
- The complete dehydration of the peridotite layer depends on the petrological model. We divide the transects into groups:
 - Sub-group 1.1 : formation of 10-Å phase deepens the last dehydration by ~30-50 km in the complex model.
 - Sub-group 1.2 : formation of both the 10-Å phase and the Al-phE delays the last dehydration by ~100 km in the complex model
 - Group 2 : **breakdown of Al-phE induces a complete dehydration only in the complex model**
 - **Group 3 : gather the only transects able to convey H₂O to the deep-upper mantle in the complex model.**

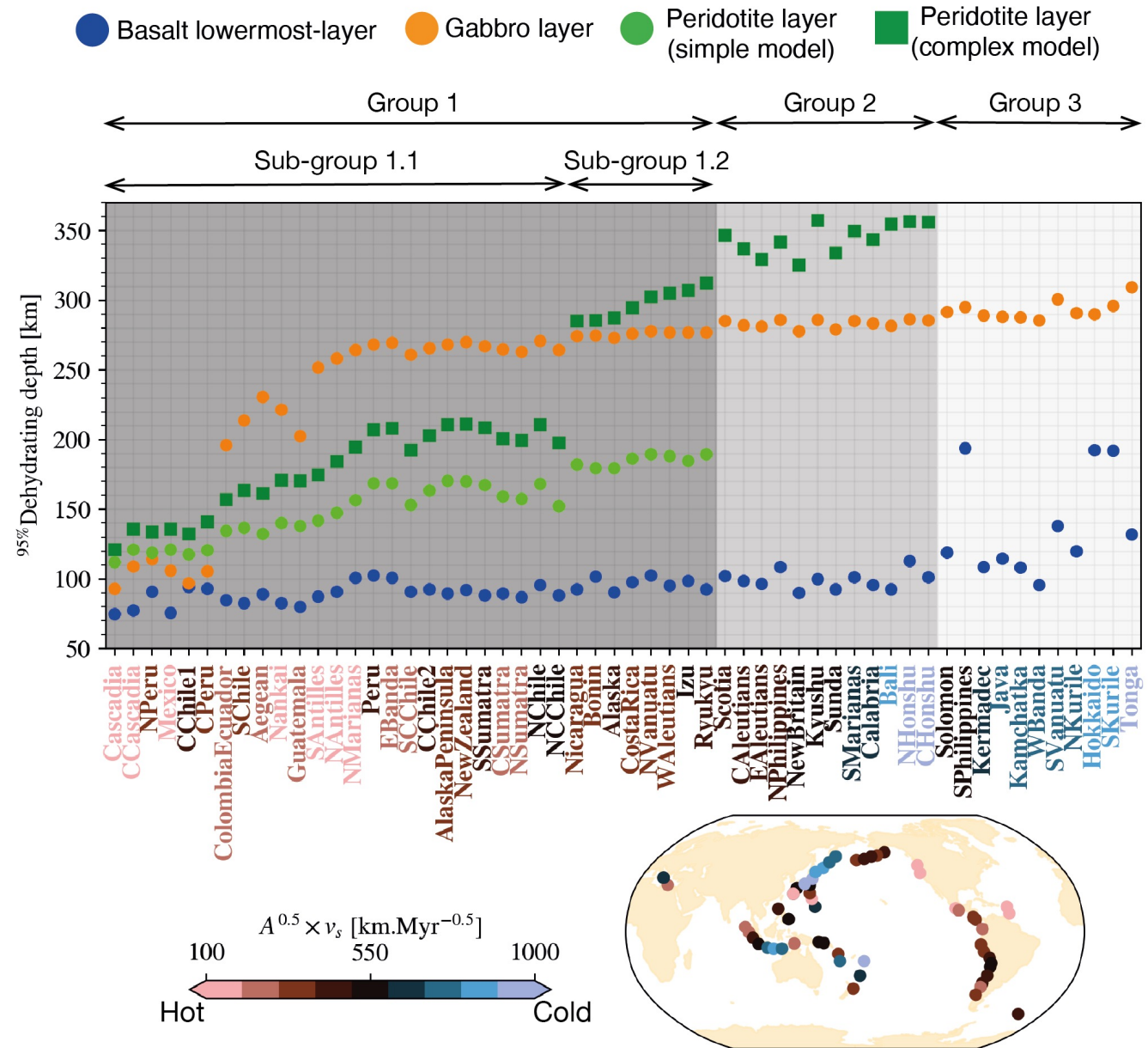


Fig. 7 : Depth of last dehydration of the lithologic layers for each subduction transect

Water retention

- We calculate the water retention at 230 and 350-km depths for the 56 subduction zones (see Fig. 8) :
 - At 230 km : Many SZ retain water as hydrous minerals are stable in both the gabbros and the peridotites (in both petrological models).
 - **At 350 km : In the complex model, only 4-5 SZ (Tonga, S. Vanuatu, Kermadec and the Kuriles) retain moderate to high amounts of H₂O.**
- Our estimated **GWR at mid-upper mantle depths (Fig. 9) with the complex model is comparable or slightly lower than the mantle outgassing of H₂O at mid-ocean ridges ($2.1 \pm 0.8 \times 10^8 \text{ Tg/Myr}$).**
- At 350-km depth, **only the initially-serpentinized mantle holds H₂O**

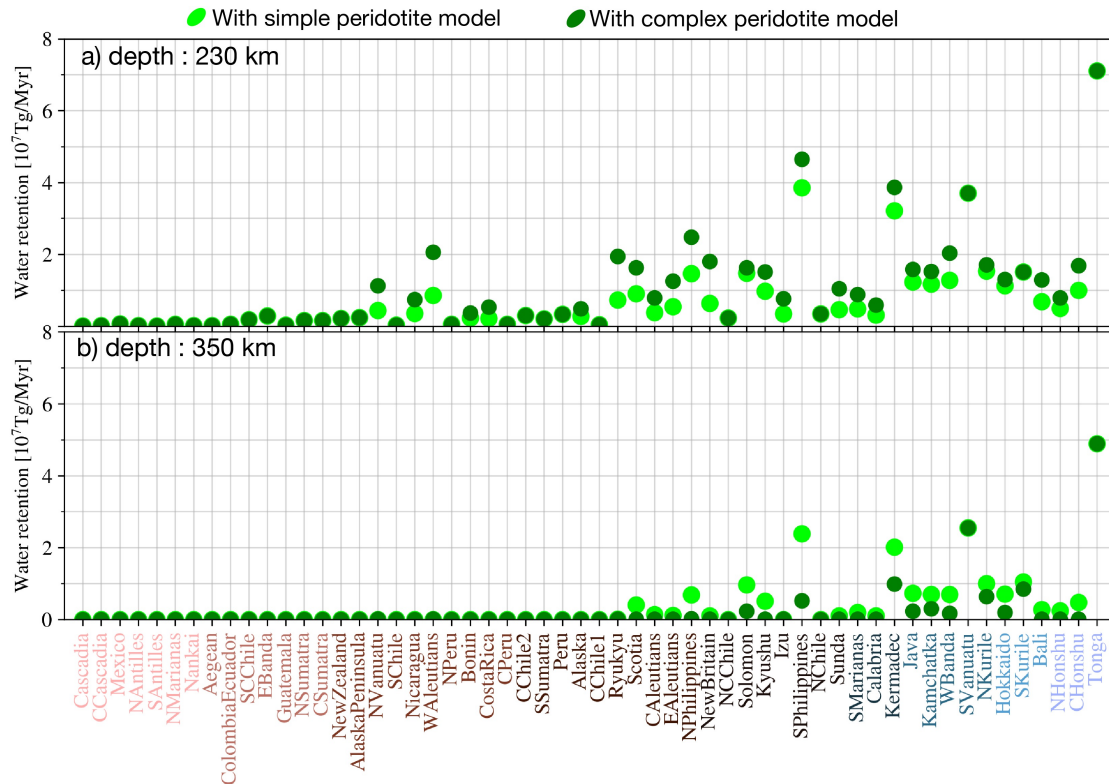


Fig. 8 : Water retention per subduction zone at depths of 230 km (a) and 350 km (b). The calculations with our two peridotite models are displayed.

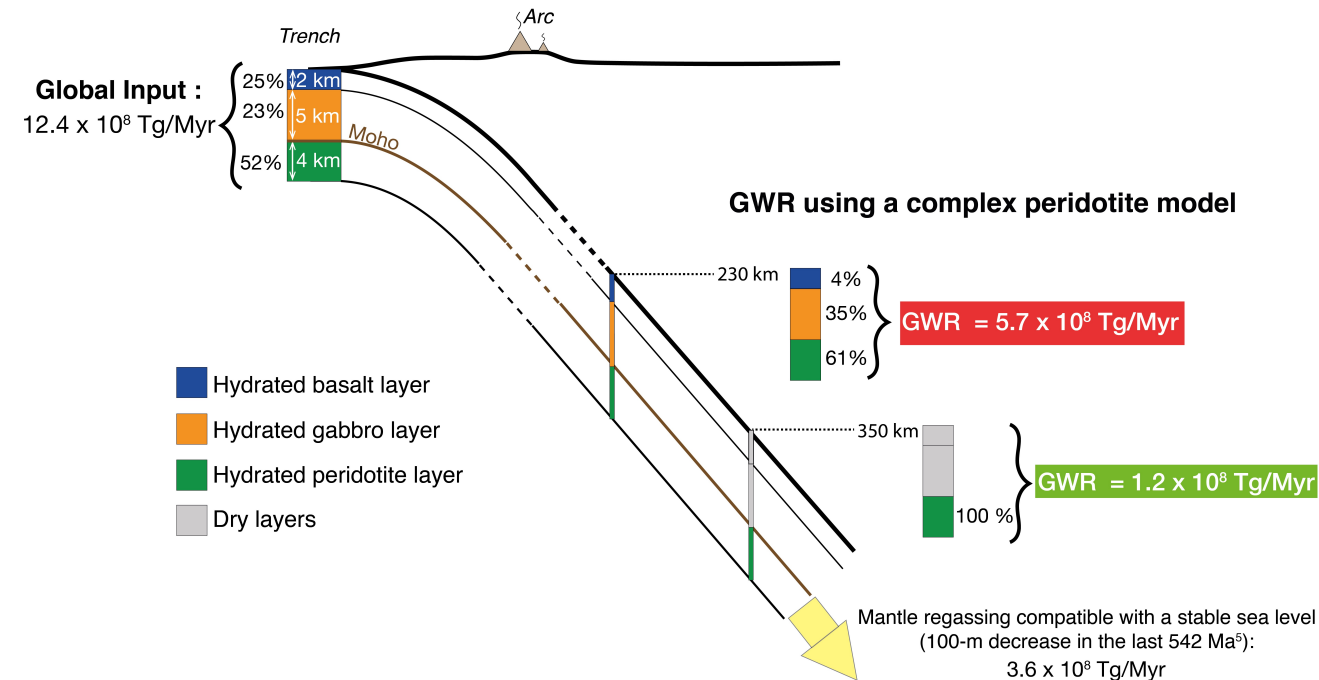


Fig. 9 : Global input of H₂O (Global Input) at the trenches of present-day subduction zones and Global Water Retention (GWR) predicted by the complex peridotite model.

Serpentinized thickness

- Geophysical studies (e.g. ref. 14) suggest that mantle serpentinization at trenches may vary from one subduction to another and overreach 4 km. We thus tested the sensitivity of our predicted GWR to the thickness of the hydrated mantle h_{serp} .
- **GWR increases with h_{serp} regardless of the petrological model but is 20 to 50% lower when using the complex peridotite model.**
- **GWR is compatible with a stable sea-level over the Phanerozoic** for h_{serp} of 4–7 km. Values of up to 8 km may be compatible with a limited decrease (of approximately 100 m).
- The range of globally-uniform h_{serp} that we found compatible with a stable sea-level is compatible with geophysical evidence of prominent outer-rise extensional faulting mainly occurring in the uppermost 5 km lithospheric mantle (Emry and Wiens, (2015) [14]).

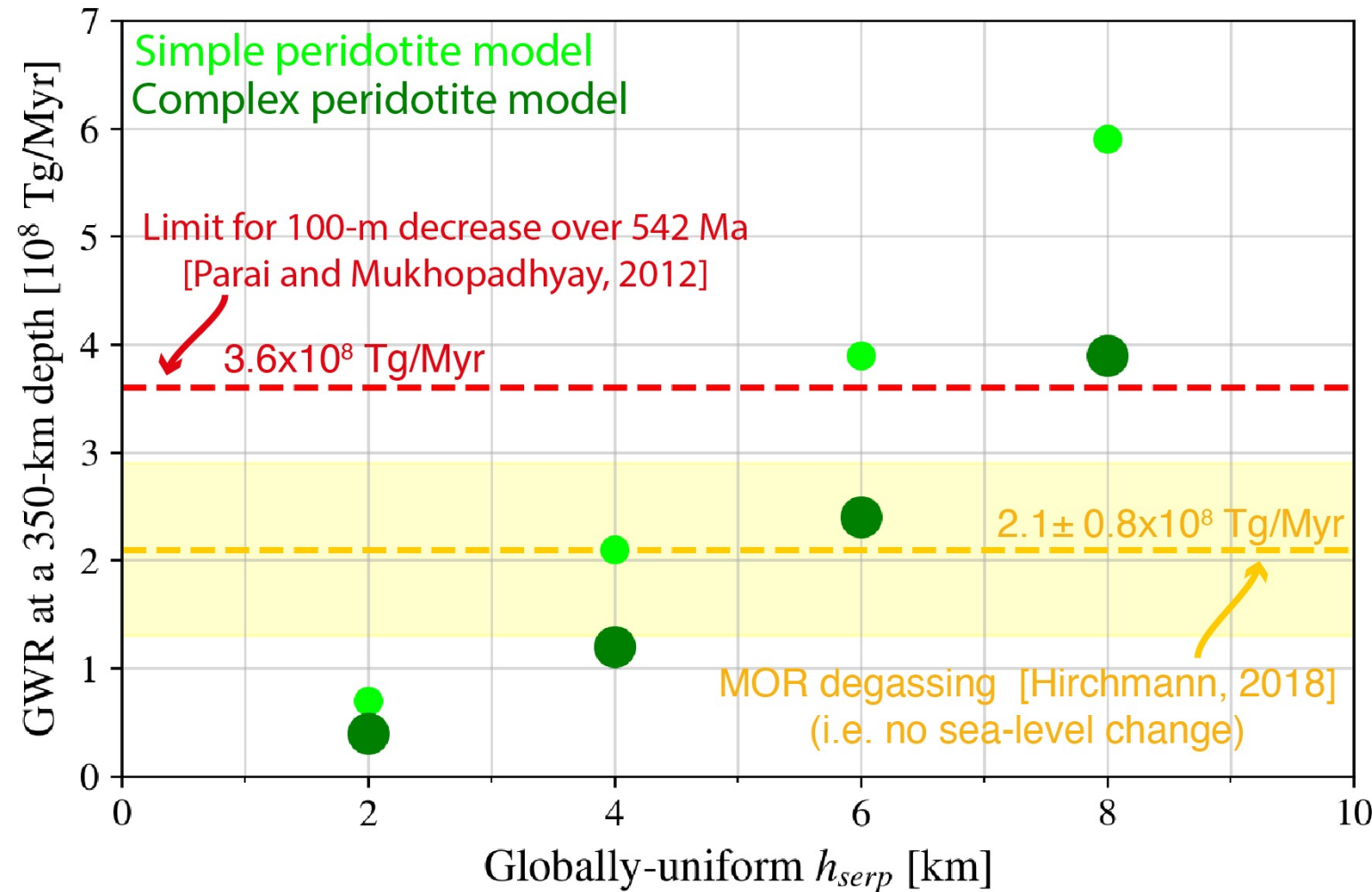


Fig. 10 : Behavior of the Global Water Retention (GWR) at a 350-km depth as a function of the globally-uniform thickness of the hydrated lithospheric mantle in the models (see Fig. 4).

Concluding remarks

Models		Global Input [10 ⁸ Tg/Myr]	GWR at 350 km [10 ⁸ Tg/Myr]
Simple peridotite	$h_{\text{serp}} = 4 \text{ km}$ $C_{\text{H}_2\text{O}} = 2 \text{ wt.}\%$	12.4	2.1 (17 %)
	$h_{\text{serp}} = 6 \text{ km}$ $C_{\text{H}_2\text{O}} = 2 \text{ wt.}\%$	15.6	3.9 (25 %)
Complex peridotite	$h_{\text{serp}} = 4 \text{ km}$ $C_{\text{H}_2\text{O}} = 2 \text{ wt.}\%$	12.4	1.2 (10 %)
	$h_{\text{serp}} = 6 \text{ km}$ $C_{\text{H}_2\text{O}} = 2 \text{ wt.}\%$	15.6	2.4 (15 %)
	$h_{\text{serp}} = 8 \text{ km}$ $C_{\text{H}_2\text{O}} = 2 \text{ wt.}\%$	18.8	3.9 (21 %)

Summary of our calculations of GWR exploring a range of petrological assumptions. The value between parenthesis is the ratio of GWR at a 350-km depth to the Global Input.

- Constraints from experimental data strongly affect the thermopetrological models of hydrated peridotites at high-PT.
- High-PT hydrous phases in hydrated peridotite destabilize at $T > 800^\circ\text{C}$.
- By mid-upper mantle depths only the lithospheric mantle in the coldest subduction zones carry H_2O .
- Our revised GWR is compatible with a stable sea-level over the Phanerozoic

For more details see our preprint : <https://eartharxiv.org/repository/view/1958/>

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