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Slab dehydration beneath forearcs: Insights from the southern Mariana and Matthew-Hunter rifts

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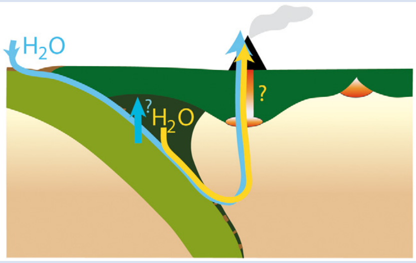
Abstract



The water flux delivered into the forearc mantle of currently active subduction zones remains poorly constrained. Estimates, which mostly derive from numerical modelling, have so far been untested, as shallow subduction processes are hindered by the serpentinised forearc mantle. Here, I examine the composition of near trench magmas from the southern Mariana and Matthew-Hunter rifts, which provides unique glimpses into slab dehydration underneath the forearcs of two modern subduction zones. The near trench magmas captured the water-rich slab fluids that usually serpentinise the cold forearc mantle. The near trench magmas possess higher markers in slab dehydration (Rb/Th = 3–141, Cs/Th = 0.04–17.79, H_2O/Ce = 436–23,531) than do arc and back-arc magmas, implying that the subducted plates might dehydrate efficiently within 80 km from the trench.

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Introduction

Subduction zones have efficiently cycled seawater between the Earth's surface and its interior to maintain the ocean masses over geological times. Seawater is removed from the oceans during alteration of the oceanic plate, and it is released back to the surface during dehydration of the sinking plate, which ultimately generates subduction zone magmas (Schmidt and Poli, 1998). Dehydration of the subducted plate is believed to be modulated by its thermal state (van Keken *et al.*, 2011). The slab thermal model predicts that cold slabs should release most of their subducted water beneath the volcanic arc front (~70 % slab dehydration), while warmer slabs should mostly dehydrate beneath the forearc (~90 % slab dehydration). Following this view, arc lavas from cold subduction zones should record greater involvement of water-rich slab fluids, while hot subduction zone arc magmas should be drier (Shaw *et al.*, 2008; Walowski *et al.*, 2015). Yet, slab dehydration beneath forearcs has largely remained theoretical due to the difficulties in direct observations, which are often obscured by mantle serpentinisation (Hyndman and Peacock, 2003). The forearc mantle is usually too cold to melt, and occurrence of forearc lavas that have captured the fluids released from the shallow part of the subducted slab is rare. However, knowledge of slab dehydration beneath forearcs is essential to understand whether subducted seawater can be returned into the lower mantle.

Stretching in the southern Mariana and in the Matthew-Hunter convergent margins within 100 km from the trench provides a unique window into the subduction processes that occurred above the shallow part of the subducted plate. Using chemical markers, the composition of the near trench magmas is investigated to better comprehend slab dehydration in the forearc of two modern subduction zones.

Geological background

The southern Marianas represent the southern end of the Izu-Bonin-Mariana (IBM) convergent margin, which has long been recognised as a typical example of a cold subduction system (slab age ~150 Ma) (Müller *et al.*, 2008; Syracuse *et al.*, 2010). To the south, the Eocene proto-arc crust has been recently stretched (<5 Ma) to accommodate the opening of the Mariana Trough above the shallow part of the subducting Pacific plate (<100 km depth to the slab). The SE Mariana forearc rift (SEMFR) is now floored with basaltic pillow lavas and lava flows ($SiO_2 < 59$ wt. %, $K_2O \leq 1$ wt. %), which erupted within ~80 km from the trench (Fig. 1a) (Ribeiro *et al.*, 2013). The SEMFR basalts host some olivine mantle xenocrysts (Fo_{90-92}), which can enclose fresh melt inclusions with a boninitic fingerprint (Fig. 2a, b) (Ribeiro *et al.*, 2015).

The Matthew-Hunter (MH) intra-oceanic arc has been proposed to represent a juvenile subduction zone, which initiated at ~1.8 Ma as a result of the collision of the Loyalty Ridge with the southern termination of the New Hebrides Trench (Patriat *et al.*, 2015). The young Australian slab (<34 Ma) (Davey, 1982) is now subducting along the MH Trench, so its slab would possess a warm to intermediate thermal structure (Syracuse *et al.*, 2010). Near trench rifting is accommodated by en échelon rifts and grabens, and transient spreading at ~90 km from the trench (Fig. 1b). A wide compositional range of volcanic rocks has been recovered within the rifts and in front of the trench, which include low- to medium-K tholeiitic basalts,

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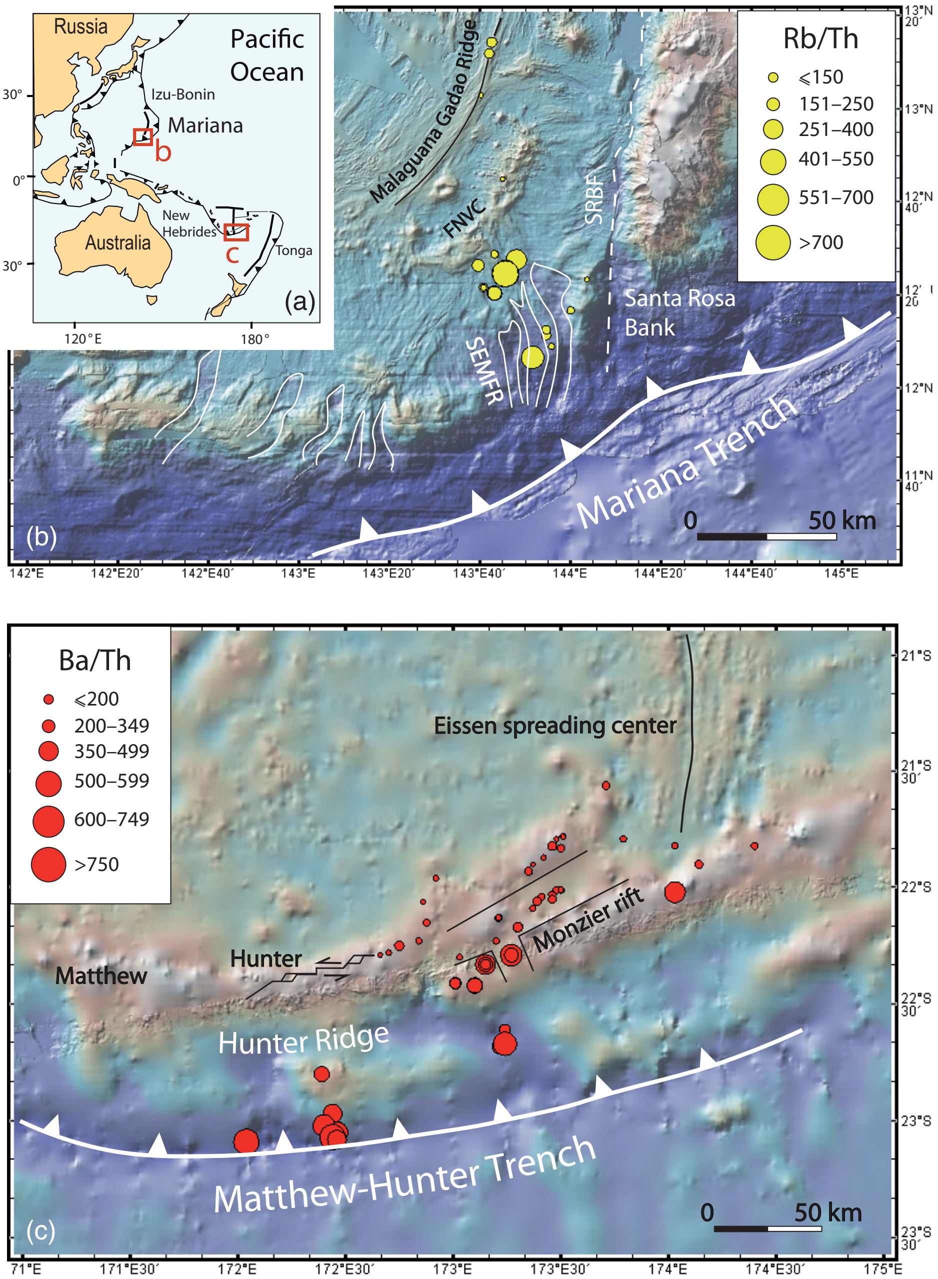

Figure 1 Geochemical maps. **(a)** Location map. The red boxes show the expanded area of **(b)** for the Mariana and of **(c)** for Matthew-Hunter convergent margins. **(b)** Rb/Th geochemical map in the southern Mariana convergent margin, designed using www.geomapapp.org. The Fina-Nagu volcanic arc: FNVC, Santa Rosa Bank fault: SRBF. **(c)** Ba/Th geochemical map of the Matthew-Hunter intra-oceanic arc.

rhyolites, adakites and boninites (Figs. 2a, S-1) (Patriat *et al.*, 2019). Occurrence of adakites, which are believed to represent melts of the subducted crust (Defant and Drummond, 1990), also suggests a warmer pressure-temperature (*P*-*T*) slab path in MH.

Characteristics of the near trench magmas

Using a compiled dataset (Table S-1), the composition of the SEMFR and MH magmas was examined (see Supplementary Information for details). Magmas were filtered for basaltic (≤56 wt. %) and boninitic composition, as well as minimally degassed volatile contents (S > 500 ppm or μg/g and CO_2 > 50 ppm or μg/g) to ensure that they reliably tracked subduction processes. Because most magmas degas upon ascent, their water contents likely represent minimum estimates.

Basalts, boninites, and associated olivine-hosted melt inclusions from the SEMFR and MH have ~2 wt. % H_2O on average (Danyushevsky *et al.*, 1993; Ribeiro *et al.*, 2015). The near trench magmas are strongly enriched in Rb/Th, Cs/Th and H_2O/Ce (Rb/Th = 3–141, Cs/Th = 0.04–17.79, H_2O/Ce = 436–23,531; Figs. 2b, 3a), as compared to their associated arc magmas (Rb/Th ≤ 68, Cs/Th ≤ 4, H_2O/Ce ≤ 9829; Table S-1), while they possess arc-like Ba/Th ratios (Ba/Th = 31–798). *P*-*T* conditions of the primary melt in equilibrium with the asthenospheric mantle were also constrained using a water sensitive geobarometer (Lee *et al.*, 2009). Near trench basalts recorded shallower *P*-*T* conditions of mantle melt equilibrium (averaged $T = 1289 \pm 26$ °C, $P = 0.84 \pm 0.17$ GPa for the SEMFR basalts,

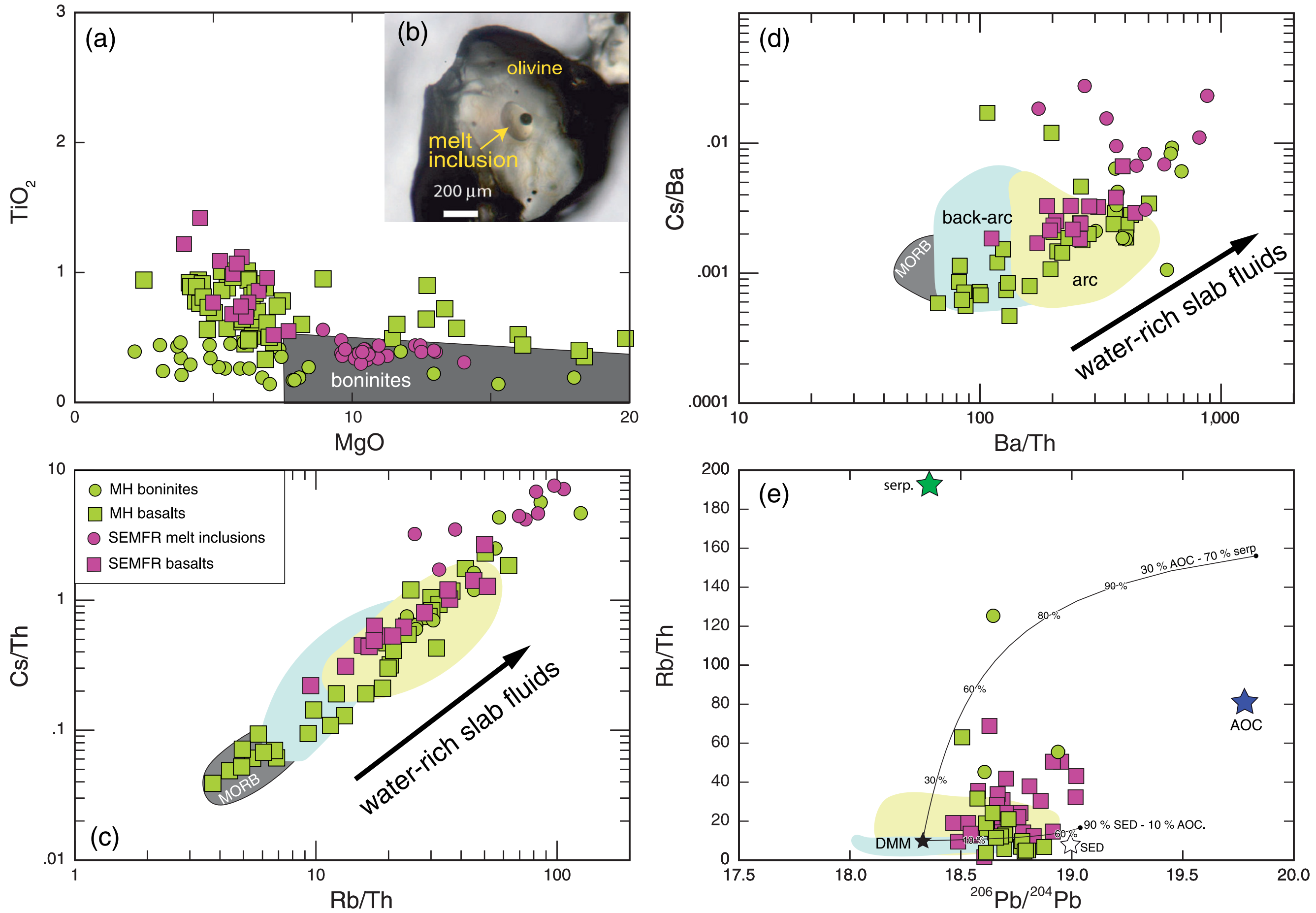

Figure 2 Geochemical features of the near trench magmas. **(a)** MgO *vs.* TiO_2 diagram. The southern Mariana olivine-hosted melt inclusions are primitive basalts with a boninitic fingerprint. **(b)** Picture of an olivine hosting a melt inclusion taken under a binocular microscope. **(c)** Cs/Th and **(d)** Ba/Th *vs.* Rb/Th diagrams showing a stronger enrichment in water-rich slab fluids (as shown by the higher Cs/Th, Ba/Th and Rb/Th) in the near trench basalts, as compared to arc and back-arc basalts. **(e)** Rb/Th *vs.* $^{206}Pb/^{204}Pb$ diagram tracking the origin of the water-rich slab fluids. Serp.: serpentinised mantle, sed.: sediments. Composition of the end-members is reported in Table S-1.

and averaged $T = 1270 \pm 26$ °C, $P = 1.03 \pm 0.17$ GPa for the MH basalts) than the back-arc basalts (averaged $T = 1278 \pm 26$ °C, $P = 1.05 \pm 0.17$ GPa for the Mariana Trough, and averaged $T = 1358 \pm 26$ °C, $P = 1.44 \pm 0.17$ GPa for the New Hebrides and north Fiji back-arc basins) and the arc basalts (averaged $T = 1308 \pm 26$ °C, $P = 1.58 \pm 0.17$ GPa for the Mariana arc, and averaged $T = 1305 \pm 26$ °C, $P = 1.19 \pm 0.17$ GPa for the New Hebrides arc) (Fig. 3b).

The shallow *P-T* conditions of mantle melt equilibrium recorded by the near trench basalts suggest that the asthenospheric mantle is melting just above the shallow part of a dehydrating slab. Infiltration of water-rich fluids into the asthenospheric mantle above the shallow subducted slabs allowed the near trench magmas to equilibrate with the mantle at shallower *P-T* conditions of mantle melt equilibrium than did the arc and the back-arc basalts. High Cs/Th, H_2O/Ce, Rb/Th, Cs/Ba, and shallow *P-T* conditions likely represent diagnostic features of near trench magmas.

Implications for slab dehydration beneath forearcs

Cold conditions are believed to prevail in forearcs, so that slab dehydration triggers mantle serpentinisation (Hyndman and Peacock, 2003). However, stretching of the pre-existing crust in the southern Marianas and MH has permitted the asthenospheric mantle to flux in and melt within 90 km from the trench, creating a new oceanic crust in the forearc. Hence, the SEMFR and MH magmas can provide unique insights into the composition of the slab fluids that are usually released to serpentinise the cold forearc mantle.

Slab dehydration can be inferred from chemical markers (H_2O/Ce, Rb/Th, Cs/Th, Ba/Th), which rely on the differential behaviour of the incompatible elements for the water-rich slab fluids. For instance, Ba, Cs and Rb are easily mobilised with the aqueous fluids and the sediment melts, while Th is only mobilised with the sediment melts (Pearce *et al.*, 2005). Similarly, H_2O is easily mobilised with the aqueous fluids, while Ce remains relatively immobile (Dixon *et al.*, 2002). Hence, their ratios can track the aqueous slab fluids. Because Cs is more easily mobilised with the water-rich fluids released during deserpentinisation, the Cs/Ba ratio has the potential to track the water-rich fluids released from the subducted lithospheric mantle. Using elemental ratios has the main advantage to minimise the effects of melting and fractionation, as the selected elements behave similarly during such processes. The higher proxies in arc magmas imply that they captured greater extents of slab-derived water than did the back-arc lavas (Figs. 2, 3), which has been interpreted as a dehydration peak beneath the arc (Ruscitto *et al.*, 2012) (Fig. 4a). The SEMFR and MH magmas recorded the highest markers of water-rich slab fluids (Cs, Th, Rb/Th, H_2O/Ce) yet

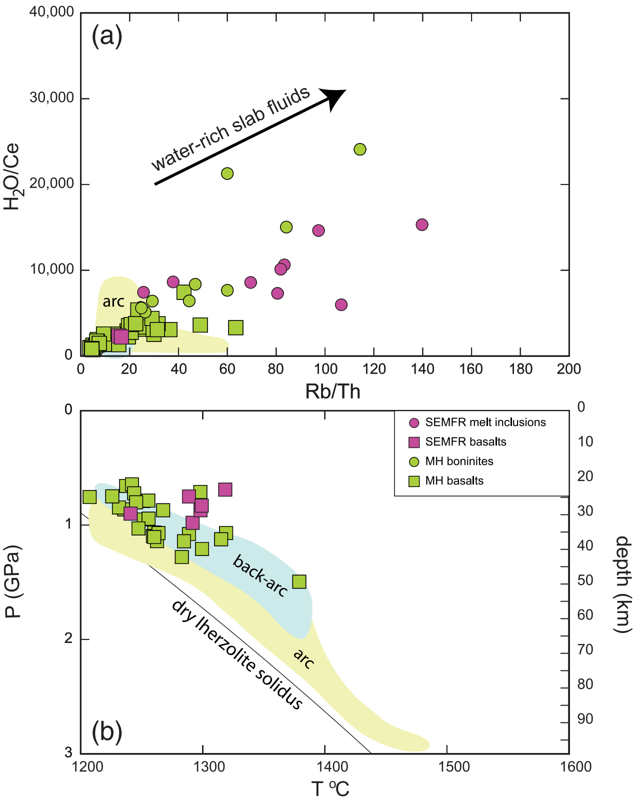

Figure 3 Slab dehydration in the forearc and *P-T* conditions of mantle melt equilibrium. **(a)** H_2O/Ce *vs.* Rb/Th diagram showing the stronger enrichment in water-rich slab fluids of the near trench magmas. The rough correlation between H_2O/Ce and Rb/Th indicates that H_2O/Ce also tracks the aqueous slab fluids. The different slope between the MH and SEMFR basalts likely reflect different slab lithology. **(b)** *P-T* conditions of the last primitive basaltic melt in equilibrium with the mantle (Lee *et al.*, 2009). Basalts were filtered for MgO ≥ 6 wt. %. $Fe^{3+}/Fe_T = 0.25$ was used for the arc basalts, and $Fe^{3+}/Fe_T = 0.17$ for the back-arc basalts and the near trench basalts (Kelley and Cottrell, 2009). An averaged water content of 1.90 ± 0.61 wt. % was used for the MH basalts, and of 2.53 ± 0.55 wt. % for the MH boninites. Error bars are 1σ standard deviation.

observed in subduction zone magmas (worldwide arc magmas display Rb/Th ≤ 111, Cs/Th ≤ 4, H_2O/Ce ≤ 10,612) (Figs. 2, 3a) (Ribeiro *et al.*, 2015), implying that most of the intra-slab water could be released beneath these forearcs (*i.e.* <100 km depth to the slab) (Fig. 4). Geochemical mapping further suggests that slab dehydration could peak at ~70 ± 5 km from the southern Mariana Trench, while it may peak within 10 km of the MH Trench (Fig. 1). The aqueous fluids were likely released from dehydrating a slab composed of 0–70 % serpentinised mantle, 10–100 % altered oceanic crust (AOC), and 0–90 % sediments. The SEMFR and MH magmas captured up to 60–80 % of this water-rich slab fluid (Fig. 2e). These results imply that dehydration of the subducted mantle likely triggered dehydration of the oceanic crust and subducted sediments in both settings. The warmer slab subducting underneath MH likely dehydrated earlier, and hence faster (*i.e.* within 10 km of the trench), than did the Pacific plate subducting underneath the southern Marianas. Mineral phases in subducted slabs with a cooler *P-T* path may thus retain a certain fraction of their bound water to break down deeper.

These observations further imply that both cold and warm to intermediate subducted slabs could efficiently dehydrate before reaching the volcanic arc front (Fig. 4a). Although the SEMFR and MH represent two modern examples of near trench spreading, where the inflow of asthenospheric mantle underneath the forearc facilitates shallow slab dehydration, the possibility that large fluxes of water could be released in the forearcs of modern subduction zones thus exists. Additionally, the metamorphic rock records suggest that most subduction zones could have a warmer thermal structure than previously estimated (Penniston-Dorland *et al.*, 2015), implying that both hot and cold subducted slabs could dehydrate efficiently beneath forearcs. Extensive slab dehydration beneath forearcs (≥70 %) is also supported by high pressure experiments (Schmidt and Poli, 1998), as well as by estimates of fluid fluxes released during shallow slab dehydration (Hyndman and Peacock, 2003; Savov *et al.*, 2007). But the extent of slab dehydration beneath forearcs requires additional investigations. If both hot and cold slabs mostly dehydrate beneath forearcs, slab dehydration alone might not suffice to sustain the water delivered into subduction zone magmas, and additional water reservoirs could be necessary. One possibility is that the subduction channel could contribute to the water delivered to subduction zone magmas, in addition to intra-slab water (Savov *et al.*, 2007; Marschall and Schumacher, 2012). A mélange zone, composed of subducted sediments, serpentinised mantle and a few blocks of mafic crust, is believed to form a viscous layer on top of most slabs (Cloos and Shreve, 1988). Serpentine group minerals and chlorite have the potential to carry large amount of water (8–13 wt. %) to at least ~150 km depth (Ulmer and Trommsdorff, 1995; Marschall and Schumacher, 2012). If entrained with the subducted plate, this mélange zone could thus transport some additional water and incompatible elements (Ba, Rb, Cs) to sub-arc depths to sustain the water delivery into the arc and the back-arc basin (Savov

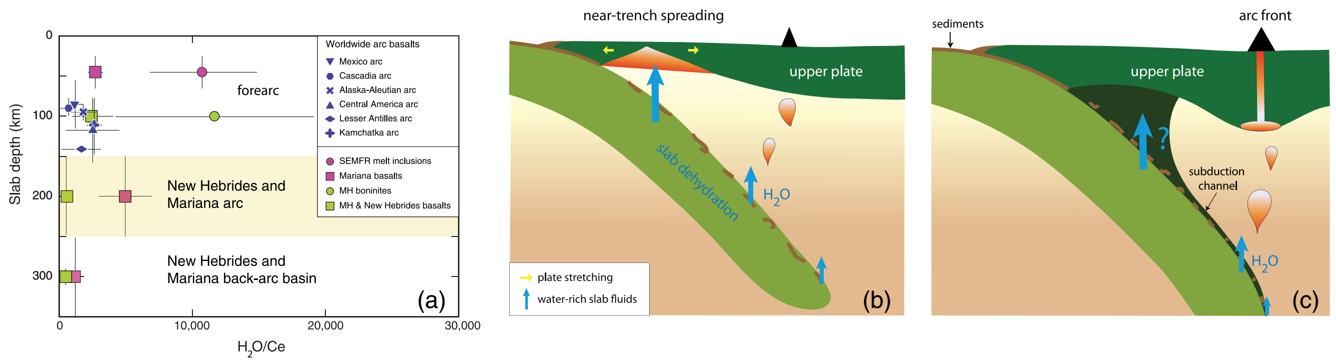

Figure 4 Enrichment in slab-derived water of the near trench magmas. **(a)** H_2O content *vs.* slab depth (km). The averaged composition of the worldwide arc and back-arc magmas are from Ribeiro *et al.* (2015). **(b, c)** Sketches illustrating the enrichment in water-rich slab fluids in the near trench magmas in MH and the southern Marianas **(b)**, and the contribution of the subduction channel to the water supplied beneath the volcanic arc front in long lived subduction zones **(c)**.

et al., 2007; Scambelluri and Tonarini, 2012). This process could provide a simple, alternative explanation to the similar average in markers of slab dehydration observed globally in arc magmas (Ribeiro and Lee, 2017) (Fig. 4). However, subduction of a mélange zone on top of the slab is not easily reconciled with some geophysical observations (Hyndman and Peacock, 2003). Further examinations of the forearc processes, and better quantifying of slab dehydration at shallow depths are thus essential to comprehend how subducted seawater can bypass subduction zones.

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Additional Information

Supplementary Information accompanies this letter at https://www.geochemicalperspectivesletters.org/article2203.

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