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An imbalance in the deep water cycle at subduction zones: The potential importance of the fore-arc mantle

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ABSTRACT

The depth of slab dehydration is thought to be controlled by the thermal state of the downgoing slab: cold slabs are thought to mostly dehydrate beneath the arc front while warmer slabs should mostly dehydrate beneath the fore-arc. Cold subduction zone lavas are thus predicted to have interacted with greater extent of water-rich fluids released from the downgoing slab, and should thus display higher water content and be elevated in slab-fluid proxies (i.e., high Ba/Th, H_2O/Ce, Rb/Th, etc.) compared to hot subduction zone lavas. Arc lavas, however, display similar slab-fluid signatures regardless of the thermal state of the slab, suggesting more complexity to volatile cycling in subduction zones. Here, we explore whether the serpentinized fore-arc mantle may be an important fluid reservoir in subduction zones and whether it can contribute to arc magma generation by being dragged down with the slab. Using simple mass balance and fluid dynamics calculations, we show that the dragged-down fore-arc mantle could provide enough water (∼7–78% of the total water injected at the trenches) to account for the water outfluxes released beneath the volcanic arc. Hence, we propose that the water captured by arc magmas may not all derive directly from the slab, but a significant component may be indirectly slab-derived via dehydration of dragged-down fore-arc serpentinites. Fore-arc serpentinite dehydration, if universal, could be a process that explains the similar geochemical fingerprint (i.e., in slab fluid proxies) of arc magmas.

1. Introduction

Subduction zones are one of the most important regions on Earth for volcanism, but the origin of such magmatism is unclear. The prevailing view is that arc magmatism is driven by hydrous flux melting by the passage of fluids released by prograde metamorphic dehydration reactions of the subducting slab (Grove et al., 2006; Kelley et al., 2010; Schmidt and Poli, 1998), but some recent studies suggest that arc magmatism might be largely driven by decompression in the convecting mantle wedge, with the effect of the slab fluids being secondary (England and Katz, 2010; Karlstrom et al., 2014; Turner and Langmuir, 2015a, 2015b). In the slab dehydration view, it is thought that the thermal evolution of the subducting slab, which controls dehydration, dictates where arc magmatism initiates. The depths at which dehydration takes place should thus depend on the initial thermal state of the slab (Peacock, 1990; Van Keken et al., 2011), which is primarily controlled by 1) the age of the plate, 2) the dip angle and 3) the rate of subduction (Syracuse et al., 2010). Indeed, cold and fast-sinking slabs, such as in the Marianas and Tonga, mostly dehydrate beneath the volcanic arc front, with remaining slab water contributing to back-arc magmatism or transported back into the deep mantle (Syracuse et al., 2010; Van Keken et al., 2011; Shaw et al., 2008) (Fig. 1A). However, the origin of arc magmas is likely to be more complicated. For example, for warm and young slab subduction, such as in Cascadia, thermal models predict that most of the intra-slab water is released well before the arc front (i.e., to serpentinize the cold fore-arc mantle) (Syracuse et al., 2010; Van Keken et al., 2011), suggesting that decompression melting may be the primary driver of arc magmatism.

Additional questions come from spatial and regional variations in arc water contents and various geochemical proxies for contributions from slab-derived fluids. For example, regardless of the type of subduction zone (cold or hot slab) and the location of the arc front in relation to when slab dehydration is predicted to occur, arc lavas display similar water contents (3.9 ± 0.45 wt%) (Plank et al., 2013; Walowski et al., 2015). Fluid-mobile versus fluid–immobile element ratios (H_2O/Ce, Rb/Th, Cs/Th, Ba/Th), which are thought to reflect fluid contributions from the slab, decrease in arc lavas with distance from the arc front (Fig. 2), as one might expect with progressive loss of water from the downgoing slab as it heats up (Plank et al., 2009; Van Keken et al., 2011). Yet, arc front lavas

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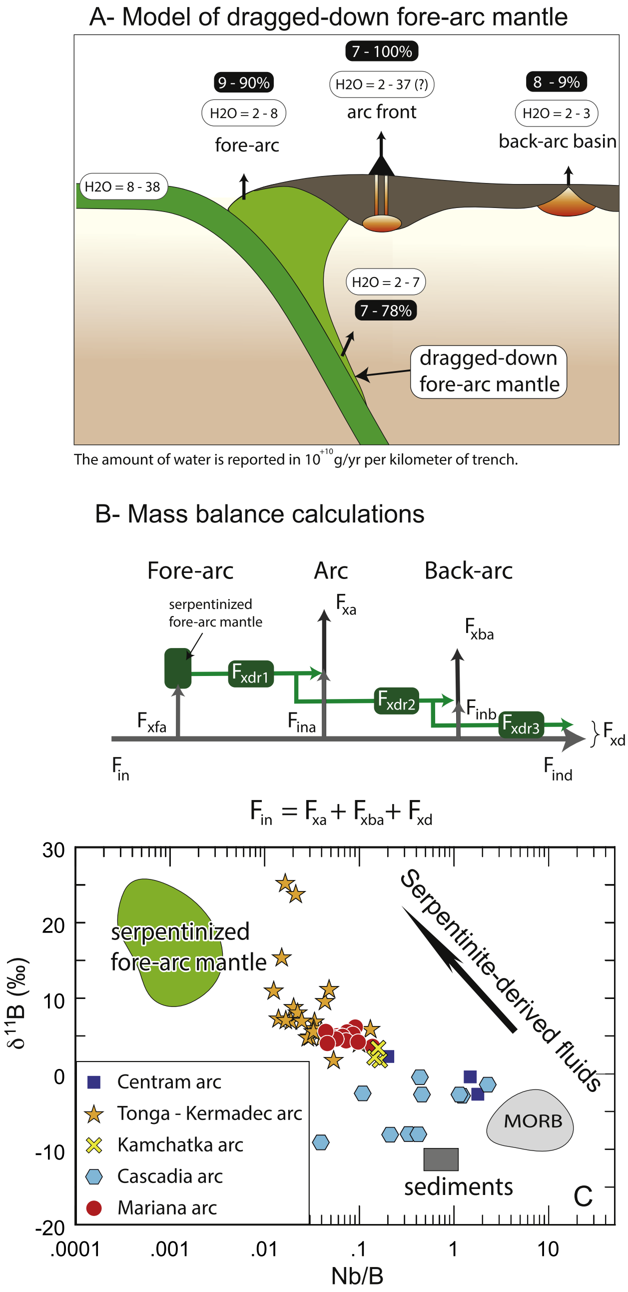

Fig. 1. Figures illustrating the potential role of the fore-arc mantle in the petrogenesis of arc magmas. A) Sketch showing the water budget of a typical subduction zone, with a dragged-down fore-arc mantle. The number represent the amount of water released from the downgoing plate for all the subduction zones investigated here (see Fig. 8 for details). The white numbers within a black oval represent the various water fluxes relative to the water influxes injected at the trenches (in %) as in Table 1 (i.e., for the fore-arc, F_{xfa}/F_{in}; for the arc, F_{xa}/F_{in}; for the back-arc, F_{xba}/F_{in}; for the water returned to the lower mantle F_{xd}/F_{in}). B) Sketch summarizing our mass balance calculations, as detailed in Eq. (1) and Eq. (5). Notations can be found in Table 2. C) Nb/B vs δ^{11}B diagram of Scambelluri and Tonarini (2012) used to decipher the contribution of the fore-arc serpentinites in arc lavas. Composition of the arc lavas are filtered for primitive composition (i.e., $SiO_2 \leq 56$ wt%, $MgO \geq 5$ wt%) whenever possible. We used the dataset of Ishikawa and Tera (1999) for the Marianas, Leeman et al. (2004) for Cascadia, Ishikawa et al. (2001) for Kamchatka, Leeman et al. (2017) for Tonga–Kermadec, Tonarini et al. (2007) for Central America (Centram), and Marschall et al. (2017) for the mid-ocean ridge basalts (MORB) using an averaged Nb content of 6.3 ± 9.6 ppm (Jenner and O'Neill, 2012).

Table 1
Subduction parameters used in our mass balance calculation and 2D fluid dynamic modeling, and results of our modeling. We only report the results of our successful runs that are within the mass balance limitations imposed by Eq. (12).

		L (km)	u_0 (mm/yr)	α (°)	Age slab (Myr)	C_{H_2O} in arc (wt%)	M in arc (km^2/Myr)	F_{xa} (g/yr/km)	C_{H_2O} in back-arc (wt%)	M in back-arc (km^2/Myr)	F_{xba} (g/yr/km)	F_x (g/yr/km)	F_{xdr} (g/yr/km)	F_{in} (g/yr/km)	F_{xdr}/F_{in} (%)	F_{xa}/F_{in} (%)	F_{xba}/F_{in} (%)	Type of subduction zones
Mariana	min	1400	15	56.9	147.8			4.61E+10				6.70E+10	1.70E+10		7.01	19.03		cold
	max	1400	50	61.5	151.6	6.14	80.00	3.74E+11	2.78	268.00	2.09E+10	3.95E+11	5.58E+10	2.42E+11	23.00	154.15	8.60	
Tonga	min									261.30			3.45E+10					cold
	max	1350	170	52.1	165.8	3.91	80.00	2.77E+10	1.6	649.90	2.91E+10	5.69E+10	3.45E+10	3.84E+11	9.00	7.23 8.00	7.59	
Alaska–Aleutians	min	2700	49	42.0	47.1								1.71E+10		11.06			cold
	max	2700	64	55.9	56.1	6.46	80.00	1.83E+10				1.83E+10	3.09E+10	1.55E+11	20.00	11.87		
Cascadia	min	1300	30	19.8	10.0								1.07E+10		12.84			hot
	max	1300	40	22.4	6.9	3.59	80.00	5.59E+10				5.59E+10	6.48E+10	8.33E+10	77.79	67.08		
	Average		**60**	**44.37**	**83.61**	**5.03**	**80.00**	**1.04E+11**	**2.19**	**393.07**	**2.50E+10**	**1.19E+11**	**3.32E+10**	**2.16E+11**	**15.36**	**48.32**	**11.57**	
	1δ		*51*	*17.01*	*69.39*	*1.48*		*1.51E+11*	*0.83*	*222.45*	*5.84E+09*	*1.55E+11*	*1.91E+10*	*1.29E+11*				