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 serpentinitised 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, Ca/Th = 0.04–17.79, H2O/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.

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.

Stretched 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 understand 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 (SiO2 < 59 wt. %, K2O ≤ 1 wt. %), which erupted within ~80 km from the trench (Fig. 1a) (Ribeiro et al., 2013). The SEMFR basalts host some olivine mantle xenocrysts (Fo92–93), 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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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 CO₂ > 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. % H₂O on average (Danyushevsky et al., 1993; Ribeiro et al., 2015). The near trench magmas are strongly enriched in Rb/Th, Cs/Th and H₂O/Ce (Rb/Th = 3–141, Cs/Th = 0.04–17.79, H₂O/Ce = 436–23,531; Figs. 2b, 3a), as compared to their associated arc magmas (Rb/Th ≤ 68, Cs/Th ≤ 4, H₂O/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 ± 26 °C, P = 0.84 ± 0.17 GPa for the SEMFR basalts,
and averaged $T = 1270 \pm 26 \, ^\circ\text{C}$, $P = 1.03 \pm 0.17 \, \text{GPa}$ for the MH basalts) than the back-arc basalts (averaged $T = 1278 \pm 26 \, ^\circ\text{C}$, $P = 1.05 \pm 0.17 \, \text{GPa}$ for the Mariana Trough, and averaged $T = 1358 \pm 26 \, ^\circ\text{C}$, $P = 1.19 \pm 0.17 \, \text{GPa}$ for the New Hebrides and north Fiji back-arc basins) and the arc basalts (averaged $T = 1308 \pm 26 \, ^\circ\text{C}$, $P = 1.19 \pm 0.17 \, \text{GPa}$ 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 back-arc basalts. High Cs/Th, H$_2$O/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$_2$O/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$_2$O 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$_2$O/Ce) yet
The aqueous fluids were likely released from dehydrating a slab composed of ∼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 asthenospheretic mantle underneather 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 mélangé 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 (Closs 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 mélangé 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 et al., 2007).

Figure 3 Slab dehydration in the forearc and P-T conditions of mantle melt equilibrium. (a) H2O/Ce vs. Rb/Th diagram showing the stronger enrichment in water-rich slab fluids of the near trench magmas. The rough correlation between H2O/Ce and Rb/Th indicates that H2O/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. %, FeO/Fe2+ = 0.25 was used for the arc basalts, and FeO/Fe2+ ≥ 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.

Figure 4 Enrichment in slab-derived water of the near trench magmas. (a) H2O 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).
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Supplementary Information

The Supplementary Information includes:

- Summary of Supplementary Information
- Sample Location
- Methods and Data Filtering
- End-member Compositions
- Effects of Magma Alteration and Degassing
- Figures S-1 and S-2
- Table S-1
- Supplementary Information References

Summary of Supplementary Information

In this section, I report:

- the location of the samples utilised in this study;
- the method and literature from which the dataset was compiled;
- the data filtering to ensure that the markers reliably track the slab fluids;
- how the effects of alteration and magma degassing were assessed to ensure a reliable dataset;
- Table S-1a, which reports the compiled major, trace element and water contents of the glass shards and the olivine-hosted melt inclusions from the southern Marianas (compositions of the melt inclusions are corrected for post-entrapment crystallisation, as published in the literature);
- Table S-1b, which reports the compiled major and trace element contents of bulk rocks and glass shards from the Matthew-Hunter convergent margin;
- Table S-1c, which reports the compiled volatile, major and trace element contents of glass shards, olivine-hosted melt inclusions and bulk rocks from the New Hebrides convergent margin;
- Table S-1d, which reports the composition of the end-members used for the mixing equations are also reported.
Sample Location

The Matthew-Hunter (MH) convergent margin is characterised by a wide variety of samples collected within 100 km from the trench (Sigurdsson et al., 1993; Patriat et al., 2019); while only tholeiitic basalts were collected in the SE Mariana forearc rifts (SEMFR) (Ribeiro et al., 2013a, 2013b) (Fig. S-1). Details can be found in Table S-1.

Figure S-1 (a) Location map of the southern Mariana and Matthew-Hunter convergent margins and sample location. The red boxes respectively show the expanded area of (b) for the Marianas and of (e) for Matthew-Hunter. (b) Bathymetric map of the southern Mariana convergent margin, which includes the SE Mariana forearc rifts (SEMFR), the southern Mariana Trough also referred as the Malaguana-Gadao Ridge, and the extinct volcanic arc chain, i.e., the Fina-Nagu volcanic arc. SRBF: Santa Rosa bank fault. (c, d) Pictures of the pillow lavas from the southern Mariana forearc rift (Dive YKDT-87, Expedition YK10-12) and associated photomicrograph (sample YKDT-86-R20) taken with a cross-polarised microscope. (e) Bathymetric map of the Matthew-Hunter convergent margin. The en-échelon and rifts and graben structures are from Patriat et al. (2019). Courtesy of M. Patriat.
Methods and Data Filtering

I compiled a dataset from the literature to examine the composition of the SEMFR and MH. To ensure tracking the slab-fluids, fresh glass shards and olivine-hosted melt inclusions, measured by in situ micro-analytical techniques, were screened where available. Data were filtered for basaltic (SiO$_2$ ≤ 56 wt. %) and boninitic composition, as reported in the literature, with a total sum of oxides equal to 100 ± 2 wt. % and LOI < 2 wt. % to ensure (i) freshness and minimise alteration, and (ii) filtering mineral phases (amphibole, ilmenite, biotite, …) that could modify trace element ratios. Fresh and primitive basalts were further filtered for minimally degassed volatile contents (CO$_2$ > 50 ppm and S > 500 ppm). The dataset is reported in Table S-1, and includes samples from:

- **SEMFR**: samples from the southern Mariana forearc rifts were previously collected during several marine expeditions, which include Thomas Thompson TN273, and Yokosuka YK08-08, YK10-12 and YK13-08. Detailed descriptions of the glass shards and olivine-hosted melt inclusions, along with the analyses of their major, trace and volatile elements (including analytical techniques and precisions) were previously reported (Ribeiro et al., 2013b, 2015).

- **Mariana arc and back-arc**: I compiled a published dataset for the Mariana arc and back-arc lavas (Hawkins et al., 1990; Gribble et al., 1996, 1998; Ikeda et al., 1998; Kent et al., 2002; Pearce et al., 2005; Wade et al., 2005; Stern et al., 2006; Shaw et al., 2008; Kelley and Cottrell, 2009; Kelley et al., 2010; Brounce et al., 2014). Compositions of the olivine-hosted melt inclusions corrected for post-entrapment crystallisation are reported as published in the literature.

- **Matthew-Hunter convergent margin**: I compiled a published dataset for the arc magmas (Maillet et al., 1986; Danyushevsky et al., 1993; Monzier et al., 1993; Sigurdsson et al., 1993; Sobolev and Chaussidon, 1996; Patriat et al., 2019; Kendrick et al., 2020).

- **New Hebrides arc, and New Hebrides and south Fiji back-arc basins**: I used a pre-compiled dataset from GEOROC (http://georoc.mpch-mainz.gwdg.de/georoc/) that was filtered for in situ analyses on glass shards and olivine-hosted melt inclusions (Peate et al., 1997; Sorbadere et al., 2011; Kendrick et al., 2014; Métrich and Deloule, 2014; Lima et al., 2017; Moussallam et al., 2019) to ensure sample freshness and in-situ volatile analyses. The whole rock dataset of Peate et al. (1997) was also used to have a representative composition of the New Hebrides arc and back-arc basin. I used the compositions of the olivine-hosted melt inclusions corrected for post-entrapment crystallisation as published in the literature.

The depths to the slab for the Mariana and New Hebrides arc and back-arc systems were estimated using the 3D model of subducted plates slab1.0 (Hayes et al., 2012) with GeoMapApp (www.geomapapp.org). I used the slab depths of Patriat et al. (2015) for MH convergent margin and those of Ribeiro et al. (2013b, 2015) for the SEMFR and the worldwide volcanic arcs and back-arcs.
End-member Compositions

The Pb radiogenic composition of the water-rich slab fluids was assessed using the averaged composition of the global subducting sediments (GLOSS) (Plank and Langmuir, 1998). I also used a Pb concentration (ppm) averaged between those of Pacific sediments subducting underneath the Mariana Trench (ODP Site 800) and Australian sediments subducting at the New Hebrides Trench (DSDP Leg 30 Site 286) (Plank and Langmuir, 1998) to estimate the Pb content of the subducting sediment, as the Pb content of GLOSS is too high as compared to that of the sediments of interests. The Pb isotopic composition of the Australian oceanic crust subducting at the New Hebrides Trench (DSDP Leg 30 Site 286) is not radiogenic enough ($^{206}\text{Pb} / ^{204}\text{Pb} = 18.242–18.529$) to account for the compositional variations of the MH magmas (Fig. 2) (Peate et al., 1997). Therefore, I consider that the oceanic crust subducting at the MH Trench has a similar composition to that of the Pacific crust subducting underneath the Mariana Trench (ODP Site 801) (Kelley et al., 2003), because the SEMFR and the MH magmas display similar composition (Fig. 2).

The trace element content of the water-rich slab fluid $C_f$ was assessed using experimentally determined partition coefficients $K_D$ (Johnson and Plank, 1999; Kessel et al., 2005) as:

$$C_f = K_D \cdot C_s$$

where $C_s$ represents the composition of the subducting sediments or oceanic crust as reported in the literature.

I also used the mantle source composition assessed by Ribeiro et al. (2013b), and the serpentine composition and associated fluid-inclusions of Cannaò et al. (2015) and Scambelluri et al. (2001) to estimate the Pb isotopic and trace element content of the water-rich slab fluids released from the subducted mantle. Composition of the end-members are reported in Table S-1d.

Table S-1 Compiled dataset for major and trace element composition of the fresh glass shards and olivine-hosted melt inclusions from the southern Marianas, the New Hebrides arc and back-arc basin, and Matthew-Hunter convergent margin. Compositions of the end-members used for the mixing equations are also reported.

Table S-1 is available for download (Excel) from the online version of the article at http://www.geochemicalperspectivesletters.org/article2203.

Effects of Alteration and Magma Degassing

Samples recovered on the seafloor can be subject to alteration processes that can modify the composition of the magmas, especially in incompatible, fluid-mobile elements (Rb, Ba, Cs) and water. Such incompatible elements can be easily mobilised with seawater brines or hydrothermal fluids that could circulate within the magma chamber (Kent et al., 2002). Despite their freshness, glass shards and olivine-hosted melt inclusions can still be prone to secondary alteration processes upon their genesis or after being emplaced onto the seafloor (Kent et al., 1999). However, the fact that the samples preserved their fractionation trends in Ba, Cs, Rb and Th (Fig. S-2) further indicates that the basaltic glasses retained their original composition. Hence, elements of interest can be used to reliably track the water-rich slab fluids.
**Figure S-2** Cs, H$_2$O, Rb vs. MgO contents in the Matthew-Hunter and SEMFR basalts, showing that fractionation trends remained preserved in the magmas.
Supplementary Information References


